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with the thesis

COMPUTER-ASSISTED CARTOGRAPHY FOR MONITORING SPATIO-TEMPORAL ASPECTS OF URBAN AIR POLLUTION

by

Alexandra Koussoulakou

18 december 1990

1. The creation and utilization of models is in favor not only in science but actually in every aspect of the social and every-day life. The difference is that in the former case the use of models is flexible in the sense that the model is adapted to reality as soon as it is realized that it does not describe it in a representative manner; in the latter case it is often the reality which is adapted to the models, even when it is realized that they are not representative.

2. Maps have always been treated as symbolic, allegoric or nostalgic elements in literature, in contrast with their mostly technical nature and their production for supporting practical applications.

3. For transferring information about spatio-temporal processes to a map-user, a well designed static map displaying dynamic processes, functions just as well as an animated one; it seems, however, that the user perceives faster when the representation is an "imitation" of the real process (i.e. change or movement displayed with animation) than the utilization of only the two dimensions of the plane for representing an essentially non-spatial process (this thesis).

4. "-Nous ne notons pas les fleurs, dit le géographe.
   -Pouquoi ça! c'est le plus joli!"
   -Parce que les fleurs sont éphémères.
   -Qu'est-ce signifie: 'éphémère'? ...
   -Les géographies, dit le géographe, sont les livres les plus précieux de tous les livres. Elles ne se démodent jamais. Il est très rare qu'une montagne change de place. Il est très rare qu'un océan se vide de son eau. Nous écrivons des choses éternelles.
   -Mais les volcans éteints, peuvent se réveiller, interrompit le petit prince. Qu'est-ce siginifie 'éphémère'?
   -Que les volcans soient éteints ou soeint éveillés, ça revient au même pour nous autres, dit le géographe. Ce qui compte pour nous, c'est la montagne. Elle ne change pas." (Antoine de Saint-Exupéry: **Le Petit Prince**. Gallimard, 1946, p.56)
   Although primarily intended as a metaphor, the geographer's view reflects, indeed, an old-fashioned concept of an atemporal geographic space. This concept has been dropped nowadays; the elements of the geographic space are not only considered and registered in their temporal context but better ways to visualize their temporal aspects are also sought.

5. "In that Empire, the art of Cartography attained such perfection that the map of a single province covered the space of an entire city, and the map of the Empire itself an entire province. In the course of time, these extensive maps were found somehow wanting and so the College of Cartography evolved a map of the Empire that was of the same scale as the Empire and coincided with it, point for point. Less attentive to the study of Cartography

succeeding generations came to judge a map of such magnitude cumbersome and, not without irreverence, abandoned it to the rigours of sun and rain. In the western deserts, tattered fragments of the map are still to be found, sheltering the occasional beast or beggar; in the whole nation no other relic is left of the Discipline of Cartography". (J.L. Borges: **Juares Miranda. Travels of laudable men** Book D, chapt. 14, english translation).
The map symbolizes here the impossible of transcribing the absolute reality into a human product; nevertheless, one cannot avoid thinking that if the existence of a **real** map at scale 1:1 is impossible (or possible only in the imagination of a story-teller such as Borges), the existence of a **virtual** map -stored in a database in a computer's memory- at the same 1:1 scale is actually very pragmatic.

6. The introduction of the Computer to the map creation process broadened the scope of Cartography and promoted its consideration as an autonomous discipline (and not as merely a supporting instrument for other disciplinary fields). It seems, however, that nowadays many tasks of the map creation process have been overtaken by computer firms lacking cartographic knowledge and approaching cartographic applications with a commercial, business attitude.

7. The concept of the local and the overall map reading levels for the temporal component displayed on a dynamic animated map (Ch. 7) bears some similarities with the two methods for describing movement in a fluid (App. II): it could be said that level III (i.e. what happens at a certain location during the whole time) corresponds to the Eulerian approach, while level IV (what is the trend of the movement) corresponds to the Lagrangian one.

8. The two best aspects of finishing a PhD Thesis:
   a. One feels that he/she now knows how things should have been done if one had to start all over again.
   b. One does not have to do that anymore.

9. The most serious problem one can have when living in a foreign country is the so called "cultural problem". The solution or creation of all other sorts of problems lies primarily there.

10. Itinerary maps and geometric plans were some of the most ancient forms of mapping, trying to answer the fundamental questions of man about his position in space. It could be argued, therefore, that the jobs of a surveyor and mapmaker are to be found among the oldest professional occupations.

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List of abbreviations

APO	Air Pollution Office
CAC	Computer-Assisted Cartography
CAD	Computer-Aided Design/Drawing
CBD	Central Bussiness District
CRT	Cathode Ray Tube
ED50	European Datum
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
GAA	Greater Athens Area
GIS	Geographical Information System
GR-D	Greek Datum
ICA	Internation Cartographic Association
LIS	Land Information System
LPG	Liquefied Petroleum Gas
NMS	National Meteorological Service
NMVOC	Non-Methane Volatile Organic Carbons
NTUA	National Technical University of Athens
RS	Remote Sensing
RIVM	Rijksinstituut voor Volksgezondheid en Milieuhygiene (National Institute of Public Health and Environmental Hygiene)
VOC	Volatile Organic Carbons
USEPA	United States Environmental Protection Agency
UTM	Universal Transverse Mercator

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CHAPTER 1. INTRODUCTION

Usually the literal meaning of the name by which a discipline is known is a mere indication of the origins and/or the general objective rather than of the true extent of the field of this discipline. **To draw[*] a (paper) map[**]** -although traditionally its original purpose- is nowadays only one of the many tasks of cartography, the main objectives of which could be described as **the collection, storage, processing and display of spatial information so that optimum use of this information can be made.**

The technological achievements of the last decades and, in particular, the fast developments in the fields of computer hardware and software had a tremendous impact on cartography. Although initially computers were introduced in order to *'draw paper maps'* in a faster and easier way than before, it soon became evident that the potential of computer cartography would extend far beyond the mere automation of the drafting process. The introduction of automation to other steps of the map creation process, such as data elaboration, pointed out the need for more clear and strict definitions and implementation of various processing tasks (e.g. spatial interpolation, generalization, smoothing, etc.). Various theoretical approaches have been followed and algorithms for practical implementations were developed. Since the development of informatics, the scope of cartography has also extended in the direction of map-use, cartography being considered as the process of transferring geo-information.

The positive outcome of the above trends was mainly twofold:
1. the scope of cartography was broadened, new methods and techniques came in use and the cartographic discipline came of age, since it started being considered as autonomous and not merely a supporting instrument for other disciplinary fields.
2. the enrichment of the field and the consequent need for clear and strict definitions for its scope, contents and methods stimulated the discussion of theoretical issues; various schools of cartographic thought emerged providing the theoretical background of the cartographic discipline.

Nowadays almost all cartographic tasks are carried out with the help of computers; computer-assistance is the norm rather than the exception in cartography.

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[*] in Greek, "**graphein**": to trace a line, to represent by lines, to draw, to use characters, to write.

[**] in Greek, "**chartes**" : leaf of paper, layer of papyrus bark, map.

The progress made during the last years in the fields of computer hardware and software has resulted in a number of further cartographic developments, the most prominent of which are discussed in the following.

The various tasks of the map creation process (collection, storing and retrieval, processing and cartographic display of spatial data) are carried out in an integrated way by means of the tools provided by geographical information systems. A geographical information system (GIS) is defined as a powerful set of tools for collecting, storing, retrieving, transforming and displaying spatial data (Burrough, 1986). Actually most of the concepts and the principles (i.e. the theoretical basis) behind GISs are those which were already being used by computer-assisted cartography during the last decades: the majority of the components of a GIS are nothing more than tasks of a computer-assisted map-creation process. Current GISs, however, tend to include more extended (with respect to CAC) possibilities for performing spatial analyses and establishing topological relations. A GIS is a new powerful application tool rather than a new theoretical concept, which has as its purpose to perform in an integrated, efficient and user-friendly way the tasks of the map-creation process (see Chapter 2). It could be argued, therefore, that a GIS is a modern, powerful tool for applied cartography and that the fields of cartography and GIS are the two sides of the same coin (i.e. spatial data handling).

The growing needs for handling spatial information and the computer hardware and software possibilities for applications in this area have promoted the creation of various GIS software packages and the establishment of a growing market for computerized spatial data processing. These commercial packages are nowadays enormously popular and are used for a variety of applications related to spatial data. Their users/operators come from various disciplinary fields; consequently they are not necessarily familiar with cartographic concepts and knowledge. This fact has both negative and positive aspects.

One of the rather annoying aspects of the fact that the commercial approach to spatial data handling has overruled the traditional one is the introduction of new terms for describing old things. This, of course, has probably happened in order to make some concepts easier to grasp and user-friendly; but except from creating confusion it does not really contribute anything new to the cartographic field (think for instance of the GIS term "rubbersheeting": is "transformation" that old and shabby?).

Confusion, however, is created not only by the introduction of neologisms but also by the variety of the disciplinary backgrounds of the users - meaning often unfamiliarity with cartographic concepts- which for the purposes of their work are confronted with diverse software packages often used as "black boxes". It is not unusual to find, (especially in computer graphics software journals) articles which attempt to explain and clarify "confusing" terms and processes, which, however, had no reason to be confused in the first place, since they refer to entirely different processes (e.g. "GIS vs. CAD", or, "GIS vs. CAD vs. data-base" etc).

Despite of such drawbacks, the situation has, however, great potential for cartography and GISs. First of all, a growing number of users is familiarized with spatial data concepts and methods for their processing and display. This fact opens more fields for cartographic applications and/or new developments within the field. The cartographic/GIS tasks tend to incorporate knowledge and methods of various disciplinary fields for their applications. In order to illustrate this trend a rather conventional approach to the tasks of cartography and GISs is used here for sketching the basic concepts and processes (it is described in more detail in the following Chapter). Assuming that **a.** the map creation process consists of the tasks of data collection, processing and display and **b.** that spatial data (and the resulting maps) are divided into two broad categories, namely **original** when they are directly observed from the (physical or social) environment and **derived** when they are extracted from already existing maps and documents the most usual cartographic/GIS tasks are these indicated with the shaded area in Fig. 1-1(a).

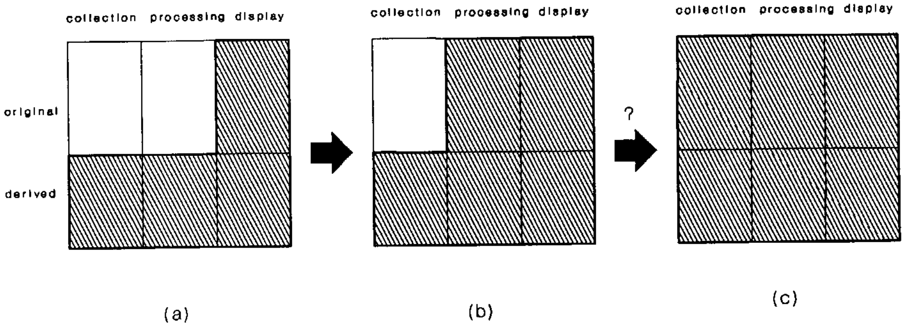


Figure 1-1. The expanding scope of cartography and GISs.

The current trend to integrate and combine knowledge from more disciplinary fields with traditionally cartographic ones is shown in Fig. 1-1(b). A prominent example of this trend, which has been made very clear in (GIS/LIS, cartographic, spatial data handling) conferences of the last

2-3 years (see e.g. proceedings of: GIS/LIS 1988, San Antonio; GIS/LIS 1989, Orlando; AutoCarto 8, Baltimore; EGIS [European conference on GISs] 1990, Amsterdam; 4th International Symposium on Spatial Data Handling, Zurich) is the coupling of spatial data with simulation models, developed originally within the fields and for the purposes of the respective disciplines . Finally, Fig. 1-1(c) is, possibly a vision for a completely automated GIS future with advanced data acquisition capabilities.

Another rather recent trend, manifested also in conferences of the last years (as above) is the consideration of spatiotemporal aspects. Both past (i.e. historical) data as well as future projections (e.g. predictions furnished by a simulation model) can be useful for decision support purposes. The interest can be focussed on two major areas: the storage and retrieval of spatio-temporal data (the design of temporal data bases) and their animated display (animated maps).

The fact that many GIS users have no or poor cartographic background and, consequently, are most probably graphically illiterate means that the produced maps are often poorly designed and, therefore, they do not fulfill their original purposes (i.e. be the basis for decision making, information, communication). Current cartographic research about this problem concentrates on the use of artificial intelligence (i.e. knowledge-based, object-oriented cartographic systems for map design).

The present work addresses some of the points mentioned in the previous, namely simulation modelling and the display of spatio-temporal phenomena and attempts to integrate them in a decision support tool. More specifically, the cartographic aspects of an environmental problem, namely the air pollution problem in an urban area are considered. The main purpose is to attempt to use cartography as a useful link between two "conflicting" areas i.e. a large urban agglomeration on one side and the quality of its physical (atmospheric) environment on the other (Fig. 1-2).

The need to convey information about the elements involved in air pollution in an urban area and also about the dynamic aspects resulting from the interactions among those elements is the general aim of the work. For this purpose, the properties and interactions of the elements involved are initially simulated with the help of an air pollution diffusion model. The visual display of the quanitative information furnished by the simulation model is the next step. The points of interest at this stage are the ways to extend the commonly used (i.e. 2-D) cartographic visualization methods by 3-D and animated map displays for showing time-depended changes. Having in mind the mentioned growing demand for animated map products, a further topic of interest is the performance of those new products (where are they useful? are they sucessful?); this can be assessed by examining the response of users to animated map products.

Figure 1-3 shows in more detail how the above main topics of interest are treated in the present thesis. Initially (Chapter 2) the principles of cartography are given (Fig. 1-3a), followed (Chapter 3) by the combination of cartography with environmental data (Fig.1-3b). The more specific environmental problem of urban air pollution and its modelling are the subject of Chapter 4 (Fig. 1-3c). Consequently the urban air pollution problem is examined in more detail in terms of its natural and man-made elements involved and in terms of its spatial aspects (Chapter 5; Fig.1-3d). The objective at this point is the development of a prototype of a software system for the cartographic processing and visualization of the causes and effects of urban air pollution. Apart from the spatial aspects of the subject temporal aspects are also considered and types of maps to be produced for the most important purposes of urban air pollution decision support are developed. The implementation of the prototype in a specific area of application, namely the greater area of Athens is then discussed (Chapter 6; Fig. 1-3e).

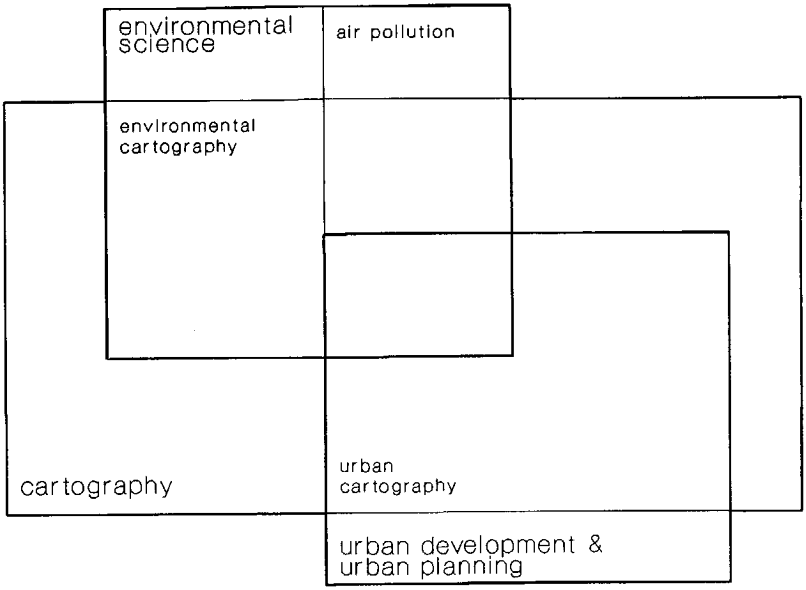


Figure 1-2. The main topics involved in the present work.

The final part of the work (Chapter 7) is concerned with the more specific topic of investigating the performance of animated maps. Since such map types were part of the products of the prototype proposed in this work and since, as already mentioned, the need and demand for this kind of map display is, in general, continuously growing, it was considered worthwhile investigating the response of users to some animated map displays (Fig. 1-3f).

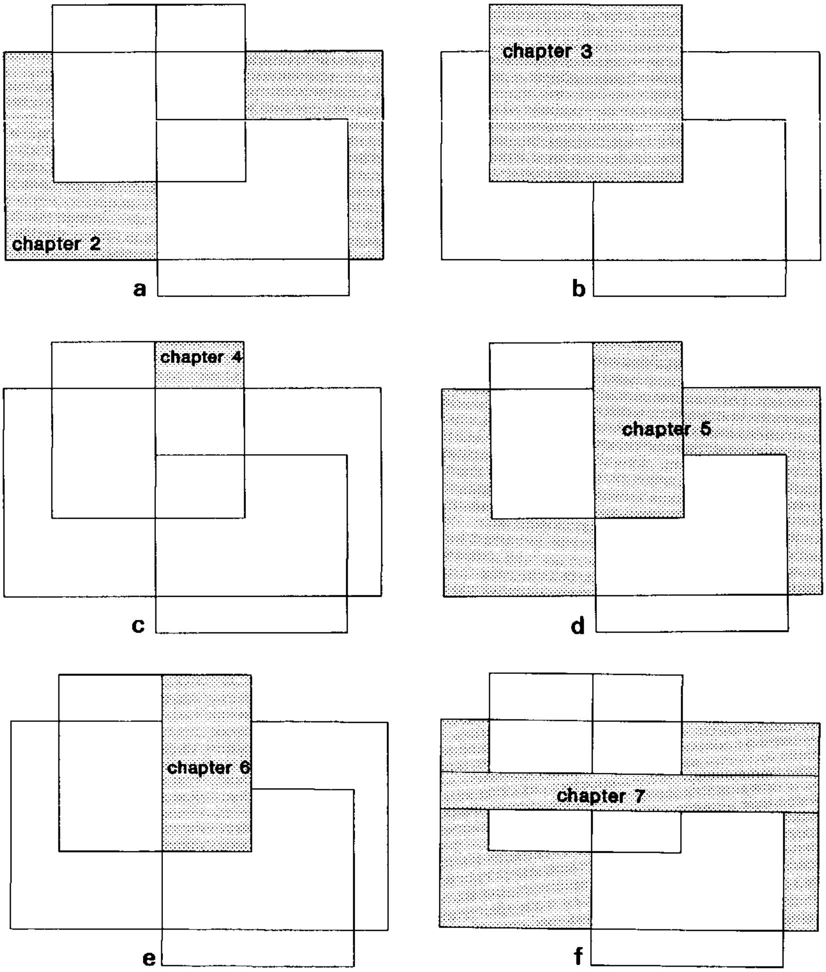


Figure 1-3. The structure of the present work.

The contents of the Chapters are given in more detail in the following.

Chapter 2 gives the theoretical background for the thesis. After the most prominent schools of cartographic thought are described in brief, the one which is followed here is presented in more detail. This approach combines the principles of cartographic communication and graphic semiology; according to it the two main components of the cartographic process are map creation and map-use. Map creation consists of collection, processing and display of the information to be mapped; these tasks form the subject of the following four chapters (i.e. 3-6) for the specific theme treated here (i.e. urban air pollution). Map-use aspects are considered in the following Chapter (i.e. 7).

The link between cartography and the specific application is made in Chapter 3. After a general framework of the environmental problem is presented, the contribution of cartography to environmental science is discussed and some examples of applications in this area are given. The temporal nature of environmental elements is pointed out and the consequent cartographic possibilities are briefly sketched.

Chapter 4 is concerned with the problem of air pollution in general and the specific case of urban air pollution in particular. It starts with the description of the physical mechanisms involved. Then the topics of air pollution simulation modelling and urban air pollution control are treated in more detail. Finally the spatial aspects of a system for urban air pollution control and decision support are introduced.

In Chapter 5 the theoretical background for the cartographic prototype proposed here is given. On the basis of the principles discussed already in Chapter 2 the cartographic products are identified externally (i.e. the elements to be mapped and their relations, the space involved) and internally (their cartographic representation, their accuracy). Computer aspects of the proposed prototype are introduced by means of flowcharts of the computer software programs which perform the map creation process.

In Chapter 6 the synthesis of what has been discussed in the previous chapters is presented. Initially a description of the physical environment in the case-study site (i.e. the urban and industrial area of Athens) and the elements involved in the area's air pollution problem are given, followed by the collection and preprocessing of the input data. Then the computer algorithms and software programs introduced in the previous Chapter are explained in more detail. Finally examples of the proposed maps are shown.

Chapter 7 is concerned with the more specific subject of map-use aspects of dynamic maps. After the general principles of dynamic map production aspects are given, a preliminary map-user test which was carried out in order to assess the performance of a number of dynamic maps is discussed. The content of the test and the results of the statistical analysis of the users' answers are presented and commented upon.

In Chapter 8 the final conclusions are drawn and possible future extensions of this investigation are proposed.

CHAPTER 2. BASIC CARTOGRAPHIC CONCEPTS

2.1 Introduction

This Chapter deals with basic cartographic concepts in order to sketch the cartographic framework of the present thesis (i.e. the collection, elaboration and visualization of spatial information in such a way that this information can be used efficiently for the tasks which have to be performed). In section 2.2 the main schools of cartographic thought are briefly reviewed. In the rest of the Chapter the components of the followed approach are described. In section 2.3 the process of map creation is sketched. The process includes the tasks of collection, selection, processing and display of spatial data; a brief overview of the graphic sign system is also given. In section 2.4 the final stage of the cartographic process i.e. map use is described in terms of map perception and map interpretation.

2.2 The field of cartography

Cartography has been continuously evolving during the last four decades and it still can be considered in transition. A factor of primary importance to the trend of this evolution is the level of information technology. The rapid progress which has been made in this field during the past few decades has, in general, increased the presence of computers in many aspects of people's lives. The fast developments in the fields of computers and computer graphics have also played a significant role in the evolution of cartography.

When computers were for the first time introduced to cartography, about four decades ago, the main idea was that they could speed up and perform more accurately the drafting process, once they were provided with the digital form of the desired image; the effort was therefore put to the "reproductive" form of digital mapping (Petchenik, 1982; Blakemore, 1985). During the late 1960s and early 1970s reproductive computer mapping continued to expand; meanwhile new trends occured, like implementation of more strict methods for data elaboration by means of mathematical, statistical and geometric techniques and integration of data sets obtained from different sources (e.g. photogrammetric and geodetic). Some interesting issues began to emerge out of the use of the computer for cartographic purposes. Since the use of a computer implies quantitative processes, an effort was made to describe in a quantitative manner the tasks to be carried out. While for some tasks (drafting, data elaboration) the result of such an effort was already successful a lot of questions emerged when it came to other elements of the cartographic process e.g. map design rules which are based on human perceptual functions (O'Callaghan et al. 1971). Such issues broadened the scope of cartography which by that time started being redefined as an autonomous discipline, in contrast with its past consideration as merely a supporting instrument (Meine, 1978; Morrison, 1980). As a consequence of the reconsiderations taking place within the cartographic field the need to re-identify the domain and the subject of the discipline emerged; as an outcome to this need new approaches to the theoretical background of cartography were attempted.

The traditional approach to cartography before the beginning of this period (i.e. before the early 1960s) is that of a **science of map design.** The first treatise of cartography as a science is done by E. Imhof (in the early 1960s) in his theory of map graphics (Kretschmer, 1980). According to Imhof the aim of cartography is research about the development of maps i.e. about their subjects, their form and methods of construction, the elaboration of rules for map drawing and map compilation. cartography is an applied science; its subject is not the earth surface itself but the representation of this surface; the primary objective of Imhof's approach is to achieve optical clearness in this representation (Kretschmer, 1980; Ormeling, 1982).

The most prominent new approaches to cartography and the respective schools of cartographic thought which have emerged during the late 1960s and the 1970s could be mainly summarized in the following (Kretschmer, 1980; Ormeling, 1982):

The Austrian cartographer Arnberger regards cartography as a **formalistic science** in contrast to Geography which is an objective science. This contrast has been pointed out clearly to avoid confusing the object of research work in Geography with that of cartography. In the mid- and late 1960s, when this view was developed and when the position of cartography was not clear, such confusion could be very probable. According to this school (known also as the Vienna school) cartography should be concerned with the development of methods and rules for the adequate transformation of spatial data into cartographic representations, and with the implementation and evaluation of these methods. In this sense cartography could be compared with other formalistic sciences such as mathematics and statistics; in the same way that mathematics and statistics can exist without any application and without caring who is using their formulas, the formalistic approach of the Vienna school suggests that cartography should be able to furnish methods of representation, reproduction and evaluation for every spatial discipline, no matter which.

In the same period (mid- and late 1960s) the work of Bertin develops. According to him cartography can be considered as **a part of Semiology** (i.e. the science of signs, the sign language). Bertin is the first to systematize the relations between data and their graphical representation by introducing the graphic (or visual) variables. According to him the aim of cartography focusses on the properties, means and limits of the graphic sign system, which is regarded as the language of the discipline. Graphics is a monosemic system of visual perception since each element is defined beforehand. This means that if the properties of the graphic sign system have been defined the rules of the system -which will be derived on the basis of these properties- can be universally applied, leaving no space for ambiguity. Bertin, indeed, defines properties and gives rules of the graphic sign system in his "Semiology of Graphics" (Bertin, 1967). Although these rules have been criticized -mostly by North American cartographers- as dictated arbitrarily and not concluded from experiments his work constitutes a structured treatise on graphics which is of great use to cartography.

In the second half of the 1960s **communication theory** is introduced to cartography and a new approach is born. The communication approach borrows concepts from the mathematical theory of communication in which the word "communication" is used in a very broad sense and implies all the procedures by which one mind may affect another (Shannon and Weaver, 1949). The basic concept behind the communication approach is the scheme: **transmitter** ---> **code** ---> **receiver** or the fundamental question "**how** do I say **what** to **whom**" (Koeman, 1971). According to this approach cartography is viewed as the discipline for transferring spatial information by means of maps. The communication "trend" occurred mostly in North American cartography where it was introduced by Board (Board, 1967). The concepts of the cartographic communication approach, however, were also to be found in the work of the Czech cartographer Kolácny (1968) and the Polish cartographer Ratajski (1973). The communication approach seems to be the one most broadly accepted, because it offers a global and comprehensive view of the discipline and a good framework for map evaluation. The aim of cartography according to this approach is the study of the processes which play a role in the information transfer by means of maps.

In the beginning of the 1970s a different approach to cartography is formulated by Salichtchev in the Soviet Union. According to him cartography is a scientific **method for the cognition of reality** by means of maps; its main tasks are the theoretical foundation and the practical elaboration of methods and techniques of map making and map use. Maps are regarded as "graphic - symbolic spatial models of the real world" (Salichtchev, 1978) and consequently mapping is a modelling process which aims at the profound understanding of the examined aspects of reality. For Salichtchev, therefore, the position of cartography is among the natural sciences; it is viewed as an independent interdisciplinary field of knowledge.

The schools which were briefly reviewed here show various views of cartography; each one of them is focussing at a different part of the discipline. Speaking in terms of semiotics it could be said that Bertin concentrates on **syntactics** (which concern the rules of the internal structure of a system of signs), Imhof and Arnberger on **semantics** (which concern the meaning of signs, in other words the relationship between signs and the concepts they represent), while the adherents of the communication approach concentrate on the **pragmatics** (which concern the interface between sign systems and their users) (Ormeling, 1982; Board, 1973).

Because of this diversity on one hand and because of the continuing technological transition on the other it has been difficult to adopt one unanimously accepted comprehensive definition of cartography. Even when such definitions are generally accepted (e.g. I.C.A., 1973) under the light of new developments new definitions are proposed (see e.g. Guptill and Starr, 1984, Morrison, 1986, Visvalingam, 1989). It seems that the common element which is found in all existing definitions of cartography is the **map** (Olson, 1983; Taylor, 1984b) and therefore cartography could be very simply described as "**the making and study of maps in all their aspects**" (Robinson et al. 1984).

An alternative way , therefore, to determine the domain of cartography is by studying its product, the map. Many definitions of what a map is are to be found in literature. Here the simple and general definition suggested by Robinson and Petchenik will be used, according to which "**a map is a graphic representation of the milieu**" (Robinson and Petchenik, 1976). The term "milieu" signifies place, but also one's surroundings or environment which consists of both tangible and intangible elements arrayed in space (Robinson and Petchenik, 1976). The reason for making maps, therefore, is to **represent** (i.e. describe, depict, portray, symbolize) **spatial** forms and relationships in a **graphical** manner (in contrast to other manners such as verbal, numerical, mental). The purpose of this representation is to **communicate** to the map users information about spatial arrangements of things (spatial distributions). The language (i.e. the method of communication established by a system of signs) for this purpose will be the graphical language formed by the **graphical sign system.** This view, which combines concepts of the cartographic communication approach with the principles of Bertin's semiological approach is nowadays adopted in the Netherlands and Germany (see e.g. Freitag, 1979 & 1980; Ormeling, 1982; Kraak, 1988); it is also the one followed in the present thesis.

The term "communication", however, is used here in a broad sense: it does not denote only transfer of information between a map and its user (optical-graphical communication) but rather the transfer of information which occurs during the whole cartographic process (i.e. the process which it takes to create and use a map). The components of this process are shown in Fig. 2-1.

The cartographic process can be viewed as a transmission of information I from the **cartographer** to the **map-user** by means of a **map**. This transmission (denoted by the arrows in Fig. 2-1) can be considered as a series of transformations of the transmitted information (see also Muehrcke, 1981).

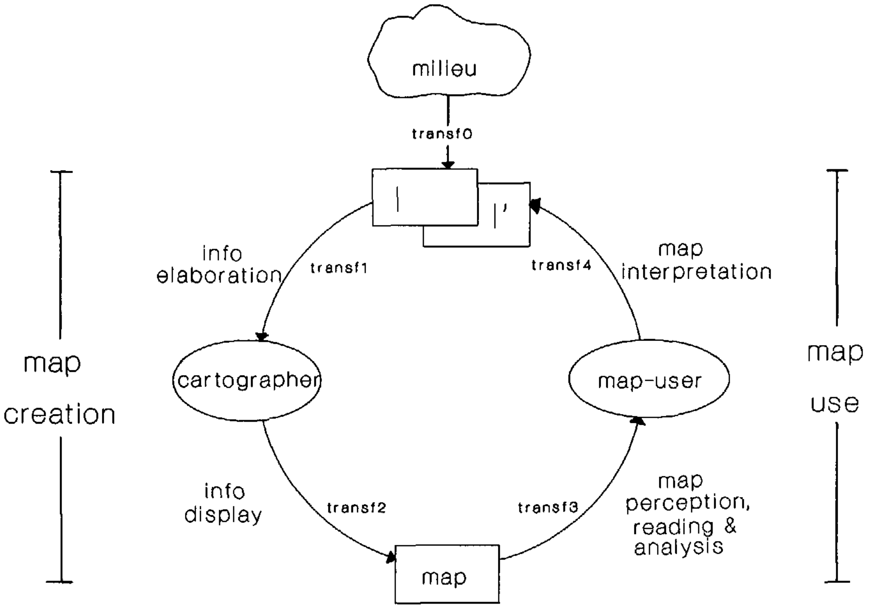


Figure 2-1. Overview of the cartographic process

The initial transformation (transf0) takes place when an aspect of the milieu is transcribed into information I which forms a cognitive model of reality (information is collected from the milieu through ground survey, RS procedures, censuses or through some combination of these methods). Although this transformation does not belong to the domain of cartography (see section 2.3) it is mentioned here, because it provides the initial information to be used in the cartographic process.

The first transformation of the carto-process (transf1) takes place during the **Elaboration of Information** (see section 2.3.1) In this stage the tasks of **selection**, and **processing** of data to be mapped take place. During the next transformation (transf2) the cartographer codes the processed information in a system of signs (the graphic sign system) and **displays** it on a map. This completes the **map creation** process (see Fig. 2-1).

The map-user identifies the signs displayed on the map and **perceives** information from it (transf3). This information is further mentally **interpreted** by the user and converted (transf4) into an image of the milieu, which actually is the final information transferred to the user (I'). In general, I and I' do not completely coincide (overlap). Part of the initial information I can be lost, either during map creation (e.g. by selection, simplification, generalization, smoothing etc. of data, by bad utilization of the graphic language etc.) or during map use (the user perceives the wrong message or/and misinterprets the perceived message). There can also be cases that new information emerges: if the user, for instance, combines elements or relations shown on the map with his/her own knowledge.

It is the task of the cartographer to try to make I and I' coincide as much as possible. This could be accomplished by evaluating I' and then making a feed back to I in order to improve the necessary elements in the map creation process (Ormeling and Kraak, 1990).

2.3 Map creation

As already mentioned in Chapter 1 the two main tasks of cartography nowadays are the representation of geometric aspects of the earth's surface on increasingly larger scales and the representation of thematic phenomena important for planning and decision making.

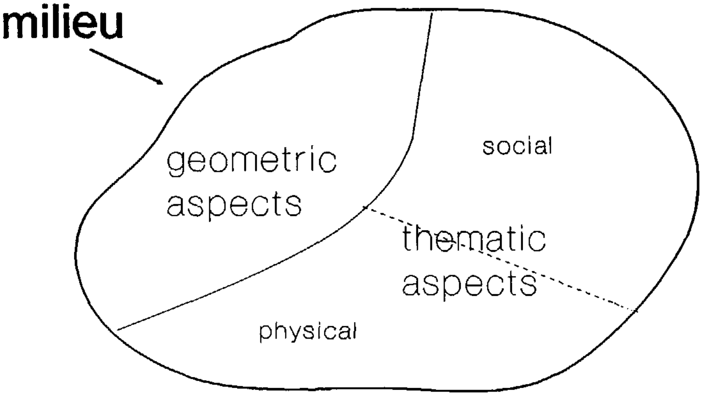


Figure 2-2. Geometric and thematic aspects of the milieu.

For the purpose of its cartographic representation, therefore, the milieu can be considered as consisting of two major types of aspects: **geometric** (i.e. topographic) and **thematic** (Fig. 2-2). Two subdivisions of thematic aspects can be further distinguished:

physical which include the whole set of phenomena occurring within the physical environment and **social** (or human) which include phenomena connected to man's activities and relations (see also section 3.2).

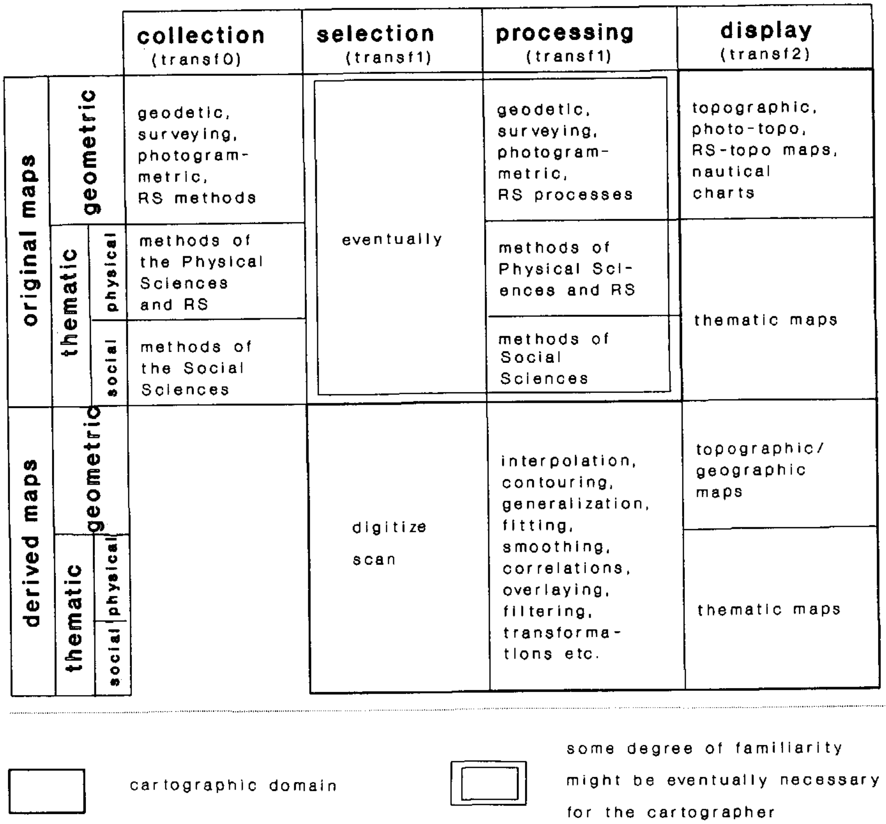
In general any map is a combination of a geometric and a thematic representation. Depending on the purpose of the map the interest might focus on the geometric or on the thematic representation or even equally on both (see also Chapter 5). The purpose of the map, therefore, indicates the amount of information which has to be extracted from the geometric or/and the thematic part of the milieu.

This information is extracted when an aspect of the milieu is transcribed into I (see Fig. 2-1), which actually establishes the domain from which cartographic data will be selected. These data can be classified according to two criteria: their **type** and their **origin**. The type of data i.e. **geometric** or **thematic** denotes the part of the milieu they are obtained from. The origin of data is the source from which they are generated: direct **observations** (or registrations) of concrete spatial phenomena or **conceptual models** which describe abstract spatial phenomena (Fig. 2-3). In practice these types of data are found on maps in combination rather than separately.

		data origin	
		observations / registrations (concrete phenomena)	**conceptual models** (abstract phenomena)
data type	**geometric**	geometric data [a road network]	geometrical model [graticule, isarithms, isopleths]
	thematic	thematic data [geology, pollution]	mathematical model [densities, potentials, simulations]

Figure 2-3. Classification of cartographic data and examples of phenomena they depict.

The type of data represented on a map can establish a criterion for a broad classification of maps. Maps can therefore be subdivided into **geometric** (i.e. topographic) and **thematic**, which are further divided in maps displaying **physical** spatial distributions and maps displaying **social** spatial distributions. Another criterion can be determined by the origin (source) of the cartographic data: when this source is a direct observation / registration or a direct generation of data from a conceptual model the map which will be created on the basis of these data is characterized as **original**; when the source of cartographic data is an already existing map the new map which will be constructed after transforming the elements of the source map, the map is characterized as **derived** (see also Dent, 1985).



			collection (transf0)	**selection** (transf1)	**processing** (transf1)	**display** (transf2)
original maps	geometric		geodetic, surveying, photogrammetric, RS methods	eventually	geodetic, surveying, photogrammetric, RS processes	topographic, photo-topo, RS-topo maps, nautical charts
	thematic	physical	methods of the Physical Sciences and RS		methods of Physical Sciences and RS	thematic maps
		social	methods of the Social Sciences		methods of Social Sciences	
derived maps	geometric			digitize scan	interpolation, contouring, generalization, fitting, smoothing, correlations, overlaying, filtering, transformations etc.	topographic/geographic maps
	thematic	physical				thematic maps
		social				

Figure 2-4. Data collection and map creation process.

This classification, which is based on **type of data** and **originality of source** sets a general framework for a comprehensive overview of the map creation process. The steps of the process are given in Figure 2-4 for all the types of maps distinguished here.

In practice, however, the steps of the map creation process are not as clearly divided as Figure 2-4 shows, neither is the transition between these steps always smooth. Nevertheless, this schematic description is attempted here in order to provide a conceptual, broad framework of the map creation process and also in order to sketch , very roughly, the cartographic and non-cartographic tasks during this process. As shown, in the case of original maps cartography is not involved in data collection, selection and processing. In some cases a certain degree of familiarity with the subject a cartographer is dealing with might be necessary, since he/she is responsible for its final presentation; however the theory and methods of data collection and processing belong to the fields of the respective sciences.

2.3.1 Collection and elaboration of information.

The collection of data for original maps of geometric type is a task carried out by geodetic, surveying, photogrammetric and remote sensing instruments and methods (Figure 2-4). A lot of automatic instrumentation is used nowadays such as automatic theodolites and telemeters, analytical photogrammetric instruments, aerophotogrammetric cameras etc. Similarly, the collection of data for original maps of the thematic type is done via instruments and methods of the relevant -physical and social-sciences (e.g. geology, geophysics, seismology, meteorology, environmental science, economics, social sciences, history, demography etc.). Automatic instrumentation is also available (e.g. for the measurement and recording of earthquakes, of meteorological phenomena, of the amount of environmental pollution, of the traffic load of a street etc.) For the purposes of thematic data collection for original maps remote sensing is also of importance since it gives the possibility to directly detect and record (physical) thematic phenomena such as land-use, vegetation and soil characteristics, water temperatures etc.

After their collection data have to be stored in a systematic and organized manner, taking in consideration the user's requirements for the following selection and processing steps. Such a systematic storage of raw data is done in databases. Since cartographic applications are usually concerned with both geometric and thematic aspects of the milieu, databases designed for cartographic purposes are expected to include information about locations, topological relations and attributes of objects.

For the case of original (geometric and thematic) mapping the creation of databases is a task of the respective disciplines responsible for data collection and processing. cartography makes use of these already existing databases by selecting the information which will be displayed on maps. In the case of derived maps (both geometric and thematic) the selection of information is performed by digitizing or scanning existing maps and organizing the selected information in databases; in this case cartography is directly involved in the creation of the databases.

The processing of data for the creation of original maps is a task performed by the sciences and technical areas involved in the collection of data (i.e. geodesy, surveying, photogrammetry, remote sensing, physical and social sciences). For the derived maps (geometric and thematic) data processing is an entirely cartographic task. This task includes operations such as interpolation and contouring, fitting, generalization, spatial correlation and overlay techniques, filtering, spectral analysis and in general methods of spatial statistics.

The last step is, then, the display of the map on the suitable output unit (plotter, printer, CRT), by converting its content in computer readable form on some kind of computer storage medium.

The integration of the cartographic and non-cartographic processes described here (i.e. collection, storing, retrieval and selection, processing and map display) into a powerful set of tools for manipulating spatial data has resulted in the development of Geographical Information Systems (Burrough, 1986).

2.3.2 Information display.

The final step of the cartographic map-creation process i.e. the display of information by means of a map involves the cartographical analysis of the information and the transcription of this information into graphical form according to the properties and rules of the graphic sign system.

The purpose of the information analysis is to find the characteristics of the available information in order to facilitate its transcription into graphical form. In general, information can be considered of consisting of a non-variable and a variable part: the non-variable part is called the **invariant** and the variable involves a number of variational concepts which are known as the **components** (Bertin, 1967 & 1983). The first step for the analysis of the information is to determine the **number** of components involved. Each component can be further identified by two aspects: its **length** and its **level of organization.** The length of a component describes the number of categories which we are able to identify in a given component. The level of organization is defined by the relations among components. Three levels of organization are distinguished: the **qualitative** (or nominal) level which can imply either association or differentiation, the **ordered** level which implies ranking and the **quantitative** level which implies use of a countable unit (Bertin, 1967 & 1983).

In the rest of this section the most fundamental properties of graphics with respect to cartography, as established by the work of Bertin, will be sketched very briefly.

Graphics is a monosemic, visual sign-system. It is one of the basic sign systems which have been developed in order to store, understand and communicate spatial information. As a visual system it utilizes the properties of visual perception i.e. it is spatial and a-temporal. That means that in an instant of perception it communicates the relationships among **three** sensory variables: the two dimensions of the plane and the variation of marks on the plane. As a monosemic system, it establishes logical, rational conditions for its utilization; in this sense it can be considered as a parallel to mathematics (i.e. the mathematics of the spatial perception).

The properties of the graphic sign-system apply, according to Bertin, within certain limits. In the first edition of "Sémiologie Graphique" (1967) only permanent maps on a sheet of white paper and under normal lighting conditions were considered. Since then, however, these properties have been applied for temporary maps (maps on screens) and Bertin himself distinguishes between "classic graphics" (the fixed image) and "modern graphics" (the transformable and reordable image) (Bertin, 1983; Kraak, 1988). Some types of visual perception are, however, still explicitly excluded such as movement (flickering of the image, flashing and blinking symbols, animated drawings, film). This point will be discussed in more detail in Chapter 7.

Within these limits the graphic system has eight components at its disposal for the transcription of information. These components of the graphic sign-system are called **visual variables** and are: **the two dimensions** of the plane and **the six retinal variables** size, value, texture, color, orientation and shape. The cartographer uses these visual variables to suggest **space.** The marks which are used for the transcription of information in a graphical form can, therefore, vary in relation to the two dimensions of the plane and in one or more retinal variable(s). These marks can further represent (i.e. have the form of) a point, a line or an area: this is known as **class of representation.** The resulting combinations of retinal variables and classes of representation are shown in Fig. 2-5. These combinations, in addition to the two dimensions of the plane, establish the scope of the graphic-sign system.

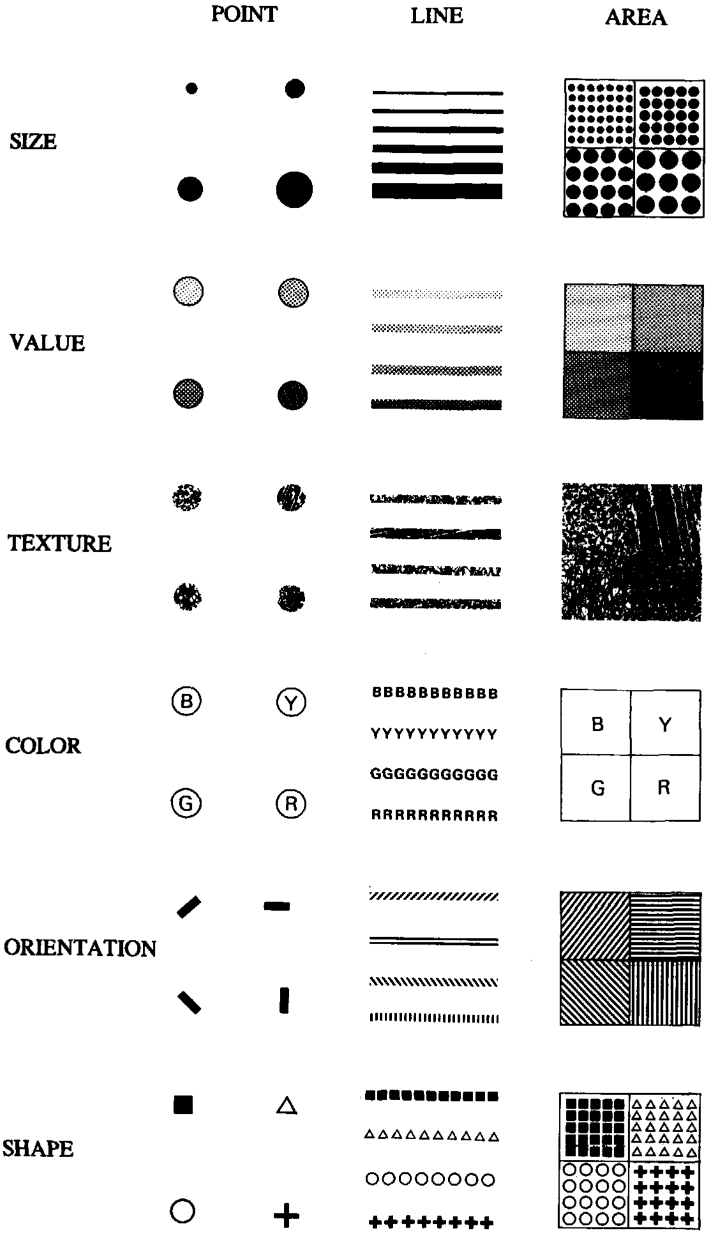
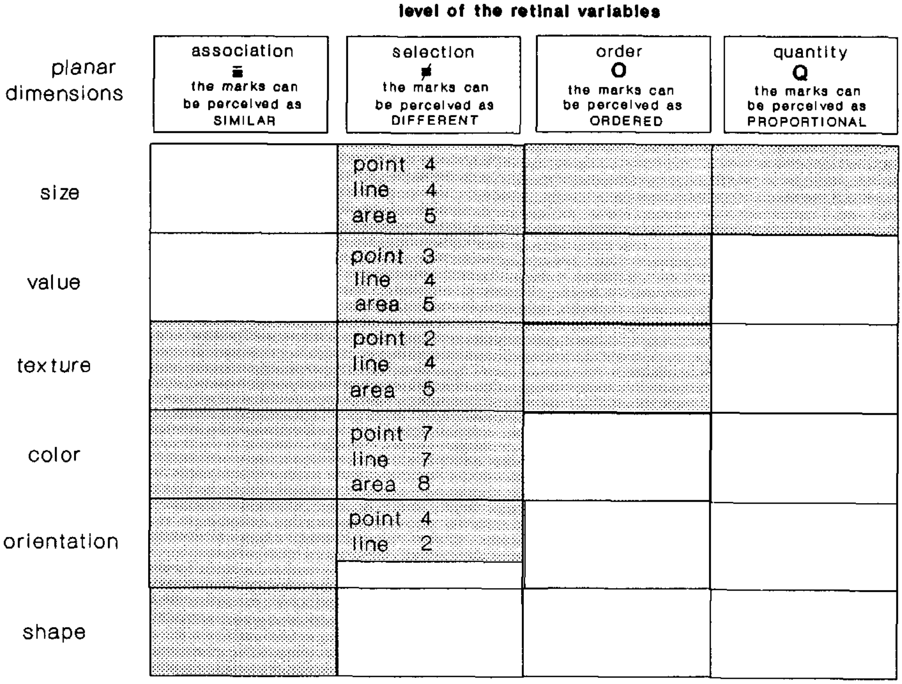


Figure 2-5. Retinal variables and their classes of representation.

The level of organization for the eight visual variables is summarized in Fig. 2-6. As shown, the plane is the only visual variable which possesses all four properties of visual perception (i.e. association, selection, order and quantity). For the retinal variables, the level of organization is indicated by the boxes drawn in a darker tint. As seen, no retinal variable possesses all four properties, which means that not every retinal variable is suitable for the graphical representation of each component of information.



level of the retinal variables

planar dimensions	association ≡ the marks can be perceived as SIMILAR	selection ≠ the marks can be perceived as DIFFERENT	order O the marks can be perceived as ORDERED	quantity Q the marks can be perceived as PROPORTIONAL
size		▨ point 4 line 4 area 5	▨	▨
value		▨ point 3 line 4 area 5	▨	
texture	▨	▨ point 2 line 4 area 5	▨	
color	▨	▨ point 7 line 7 area 8		
orientation	▨	▨ point 4 line 2		
shape	▨			

Figure 2-6. The properties of the visual variables.

The length of each component is unlimited, apart from selective perception (i.e. selective level of organization); for this case an empirical length is given for each class of representation (see numbers in Fig. 2-6).

2.4 Map use

Map use constitutes the second half of the cartographic process (see Fig. 2-1), during which the map user transcribes the information acquired from the map back to a mental picture of reality (I'). Map-use is considered as consisting of three main activities: **map reading, map analysis** and **map interpretation** (Muehrcke, 1983). Map reading is actually preceded by **map perception** during which the user is seeing the contents of the map but not actually elaborating them mentally (Robinson and Petchenik, 1976). During map reading the user determines the subject of the map and the manner in which the cartographer has depicted it. After viewing and identifying the elements of the map the user tries to analyze it by seeking possible patterns of the displayed spatial distributions. Finally the user tries to explain the nature of the displayed distributions, to find reasons for their presence and appearance i.e. to interpret the perceived information (Fig. 2-7; compare with Fig. 2-1).

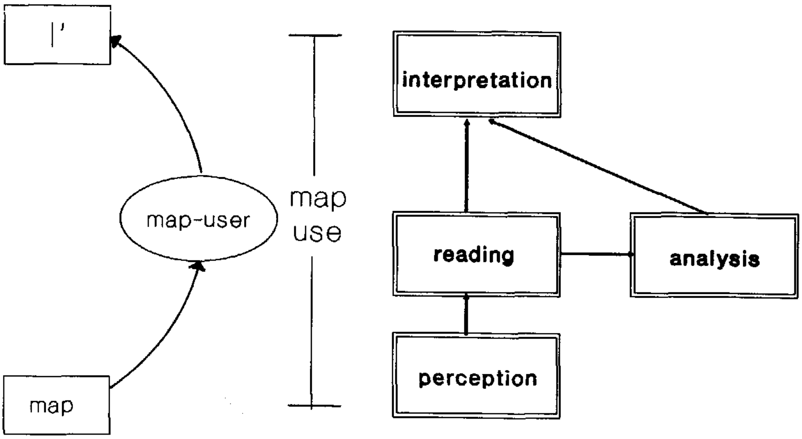


Figure 2-7. The map-use process.

2.4.1 Map reading

The first step to read a map is to identify its elements. Two sorts of map identification can be distinguished:
external identification during which the user identifies **in the mind** the invariant and the involved components. It is called external because it is independent from the graphic image itself.

internal identification during which the user identifies **in the drawing** the visual variables which correspond to the components.
The subject of map identification is treated in more detail in Chapter 5.

The user proceeds in reading the map by questioning it. There can be as many types of question as there are components. Within a certain type of question (i.e. one which concerns a certain component) three levels of reading are to be found: the elementary, the intermediate and the overall level. The map of Figure 2-8 is used to demonstrate possible questions which correspond to the three reading levels.

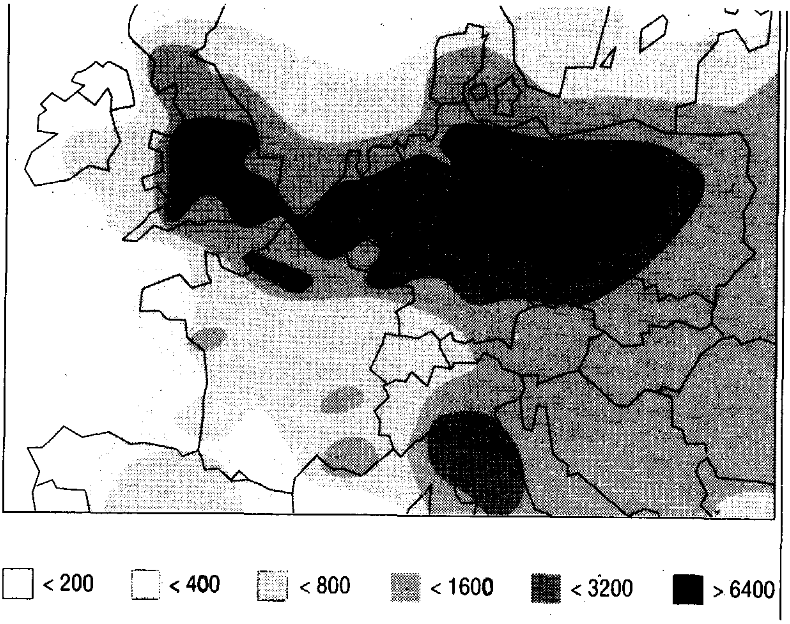


Figure 2-8. Calculated sulphur precipitation in grammolecule per hectare per year over Central and Northern Europe (source: RIVM, map from NRC Handelsblad). See text for examples of questions in the three reading levels.

At the **elementary** reading level questions are introduced by a single element of the component and they result in a single correspondence. Example: What is the amount of sulphur precipitation in Switzerland? Answer: between 400 and 800 grammolecules per hectare per year.

At the **intermediate** reading level questions are introduced by a group of elements or categories and result in a group of correspondences. Example: In which countries is the sulphur precipitation between 200 and 1600 grammolecules per hectare per year? Answer: Sweden, Denmark, Switzerland, Austria, Hungary, Yugoslavia, Rumania.

At the **overall** level questions are introduced by the whole component. Example: Where are the maxima of sulphur precipitation to be found? Answer: in the central and eastern part of the map.

Reading levels are also considered in Chapter 7, where an attempt is made to utilize this concept not only for the geographical but also for the temporal component.

2.4.2 Map analysis.

The purpose of map analysis is to clarify and put in order the visual information which is displayed on a map in such a way that the user is able to describe it. This description can be done in, mainly, two ways: in a **qualitative** manner by which the user describes the information verbally, after he/she has visually localized features of spatial interest, and in a more objective, **quantitative** manner. The latter is concerned with **cartometry** (measurements from maps) and **pattern comparison** (search for spatial order and spatial association).

The interest of map analysis lies in the fact that it offers the possibility to derive more information out of a map than is originally carried by the same data in non-spatial form.

2.4.3 Map interpretation

Map interpretation constitutes the last part of the cartographic process (Fig. 2-1). It could be argued, however, that it is not only a cartographic activity but that part of it lies beyond the scope of cartography, since it strongly depends on the map user's background (Ormeling, 1982). Actually all knowledge the user possesses could be helpful when it comes to map interpretation. In general the more knowledge a user has about the physical and the social aspects of the world (milieu) the more interested in interpreting information from maps he/she will be.

CHAPTER 3. ENVIRONMENTAL CARTOGRAPHY

3.1 Introduction

The purpose of this Chapter is to give an overview of some basic environmental concepts and to introduce cartographic aspects of the environmental system. Initially, general definitions and a brief description of the structure of the environmental system are given (section 3.2) They are followed, in sections 3.3 and 3.4, by the description of problems which have been created by human activities and attempts to cope with these problems with the methods of environmental science. In the following section (3.5) the importance of environmental cartography in particular is pointed out and some examples of its applications are illustrated. The link to the present work is made in section 3.6.

3.2 The environment

The term "environment" is originally derived from ecology, which is concerned with the relations between organisms and their surroundings; the term is used there to signify the surroundings of an organism. Similarly, for the case of human beings, the "environment" can be described (Bouwer and Klaver, 1987) as those parts of our surroundings which make life and existence possible. The term has, in general, a wide range of meanings; depending on the subject examined the emphasis might be put on either its "thematic" aspects (e.g. social and physical) or on its geometric (i.e. spatial) aspects. Here the term "environment" is regarded in the broader context of the "milieu" concept, described in Chapter 2. In this concept of the "milieu" - as given by Robinson and Petchenik (1976) - "environment" can be viewed as encompassing thematic (social and physical) aspects (compare Fig. 3-1 with Fig. 2-2).

The environment consists, thus, of two groups of elements: **social** (non-material) and **physical** (material). The former are the elements of a social / economical / psychological / juridical nature, which make up the social environment of a person (Fig. 3-1). The latter can be further divided into **natural** and **man-made** (artificial). The natural elements (which form man's natural environment) consist of **biotic** (plants and animals) and **abiotic** (soil, water, air).

Every individual lives in a part of the environment consisting of both social and physical elements. While the social elements in the environment of a certain individual might differ from the social elements in the environment of another individual, some physical elements of vital importance (such as air, water, food, living space etc.) are commonly shared. The relations of humans with the elements of the physical environment are therefore of essential importance.

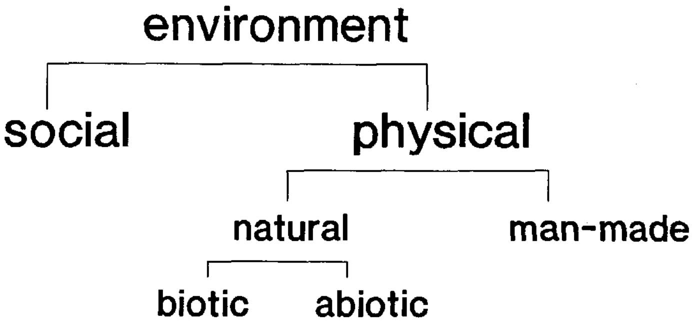


Figure 3-1. Environmental elements.

For the purposes of environmental science, which is concerned with the study of relations between man and environment and the problems resulting from these relations, the term "environment" has the following meaning (Boersema et al., 1986): "the physical, non-living and living surroundings of man, with which he has a mutual relation". This (narrower) definition of the environment which includes only the physical aspects of it will be used in this work; social elements of the environment, as described in the beginning of this section, will not be further considered here.

The environment can be considered (Boersema et al., 1986) as a system consisting of elements and their relations. These elements are grouped in four hierarchical levels: **landscapes, ecosystems, compartments** and **factors and components** (Fig. 3-2). Various types of landscapes can be distinguished on the basis of their spatial structure, function etc. The landscapes consist of ecosystems such as woods, fields, waters etc. as well as of man-made artifacts (constructions, institutions etc). Natural ecosystems are built up by abiotic and biotic compartments, the former being land (soil), water and atmosphere, the latter living organisms (flora and fauna). Man-made artifacts consist of materials. Finally, in the fourth level the factors and components of the compartments can be distinguished: physical and chemical (e.g. temperature, radioactivity, chemical bonds) in the natural compartments and raw materials for the man-made ones. A pictorial representation of the above elements and their levels is given in Figure 3-3.

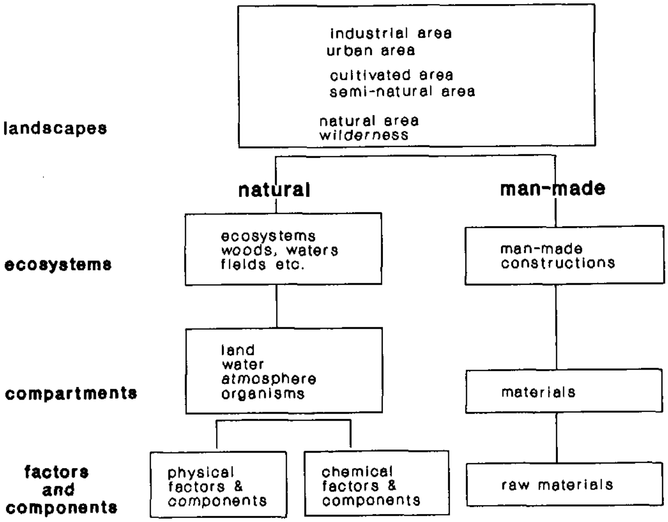


Figure 3-2. The environmental system (schematic).

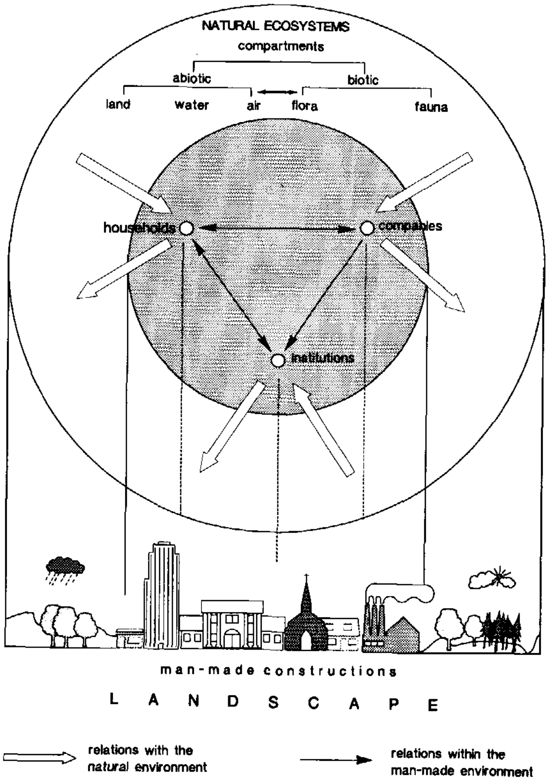


Figure 3-3. The environmental system (pictorial).

A constant flow of activities occurs between the elements of each level as well as between the different levels of the environmental system. Various substances are transferred from their sources by transport and reaction processes to natural (biotic and/or abiotic) receptors or sinks, where they are discharged and sequestered from further significant environmental activity (Duttweiler and Sanders, 1976). These substances can be either the products of natural, geochemical processes, or wastes of human activity; occasionally they might be intentionally injected into the environment, as for example pesticides. When they generate undesirable effects -for health, ecology, economics or aesthetics- upon one or more environmental subsystems they are characterized as pollutants (see also section 3.3). Figure 3-4 gives in a simplified way an example of how pollutants emitted because of man-made activities are transported among and within the abiotic compartments.

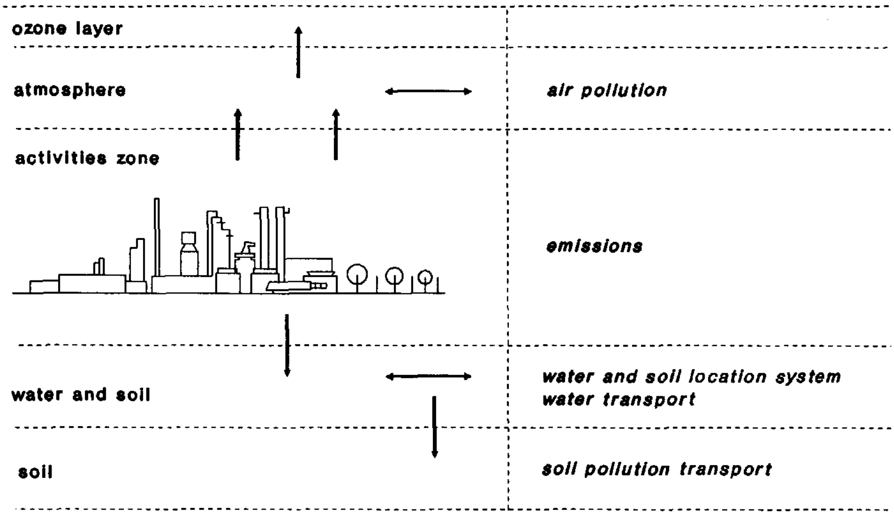


Figure 3-4. Transport of emissions in abiotic compartments.

The environmental activities and the consequent interrelations and influences between elements of the environmental system are critical for the rise of environmental problems. Since the environment is a complex interaction of many factors a change in one aspect of it will effect changes in the entire system (Fig. 3-5). For example atmospheric factors and components (i.e. the elements of the atmospheric mechanisms) may assist to the transport of air pollutants from their sources to receptors or sinks, which can be other environmental compartments such as living organisms, water and/or soil, or man-made objects and constructions (see Figures 3-3, 3-4). Transport of polluted water from a waste site (e.g. a municipal refuge) and contamination of ground water in aquifers is another common example. During transport the pollutants may participate in chemical or physical reactions that may transform them into other substances which may also be pollutants, or which may give rise to further pollutants (Duttweiler and Sanders, 1976).

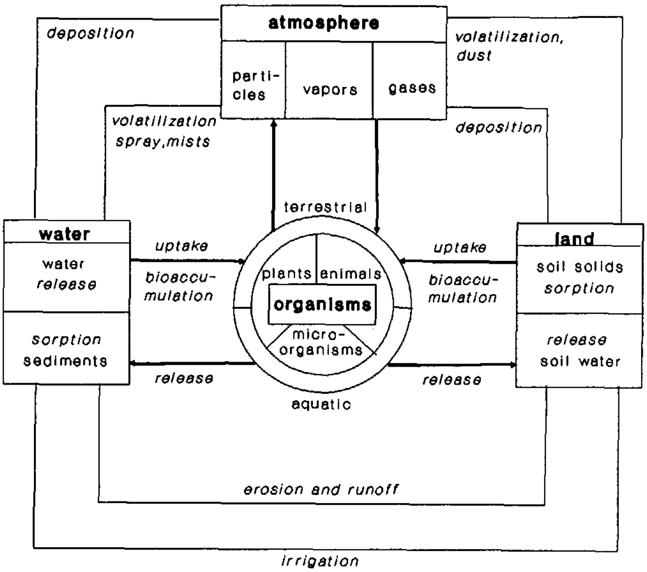


Figure 3-4. Pollution cycles among natural compartments of the environmental system .

Such cases are witnessed very often nowadays; one can easily recall pollution events having broad and/or local environmental consequences (e.g. acid rain, release and transport of radio- active or chemical wastes via waterways, influence of pesticides on food products etc.)

3.3 Environmental problems

While it is the natural (physical and chemical) mechanisms of the environmental system that enhance the evolution of environmental problems, those problems originate because of, mainly, man-made activities which destroy the existing balance and create dangerous situations within the environmental subsystems. An environmental problem is thus defined (Bouwer and Klaver, 1987) as "a situation which is experienced as an actual or potential disturbance of essential relations between man and environment or of the welfare of other organisms".

Environmental problems can be classified on the basis of the human activity (interference) which causes their appearance in the following groups (Boersema et al., 1986):

1. pollution (i.e. caused by addition of something).
2. exhaust (i.e. caused by elimination of something).
3. impairment (i.e. caused by change of something).
4. natural hazards

Environmental **pollution** is the introduction to the environment of chemical components and physical processes in quantities higher than the normal background levels, so that harm is inflicted on man, animals, plants, ecosystems or materials. From this definition it is seen that pollution occurs in every environmental subsystem: it starts from the lower one (factors and components, see Fig. 3-2) where, according to the origin of its cause, it can be characterized as chemical pollution (from chemical components such as SO_2, CO, NOx etc.) or as physical pollution (from physical factors such as noise, radio-active radiation etc.). According to which compartment it has moved to it is further characterized as air- water- or soil-pollution. The pollution of environmental compartments can further harm the status of human beings (in the way air pollution does, for example) or/and of ecosystems via flora and fauna (one can think here of acid rain or radioactive emissions) finally reaching human beings again.

Environmental **exhaust** is the disappearance of environmental components with such a speed or/and extent that it becomes dangerous for the existence of those components. Biotic or abiotic components (water, productive soil, fish, certain animals) which gradually vanish are an example of environmental exhaust.

Environmental **impairment** is a concept broader than exhaust or pollution. The term is used to indicate decreased quality in compartments, ecosystems or landscapes (impairment in soil structure, deterioration or/and vanishing of a forest, rearrangements in a landscape etc.)

Environmental **hazards** (natural events which occur seldom but might have big consequences) are another particular group of environmental problems. Earthquakes, avalanches, volcanic eruptions are some examples.

The pressure which environmental problems have created during the last decades for nature and man has stimulated an increasing awareness of the true extent of those problems. The environment is no longer regarded as the natural world around man, which can restore the changes caused by man's activities (as it was believed in the past), but as a system interrelated with the activities, and with limitations which have to be considered. It appears necessary, therefore, to protect the environment not only by conserving its important areas but by analyzing and understanding its processes. In this way:

1. environmental problems can be detected and monitored.
2. the impact of man's activities upon the environment can be assessed better.

The techniques and instruments offered by modern technology have contributed a great deal to the development of monitoring programs (local, national or international). Satellites and Remote Sensing are an example with many potential applications in this field, such as for instance thermal pollution of water bodies, vegetation cover, soil moisture, radioactivity etc.

The importance of man-environment interrelations points to the need to asses the impact of a future human activity and to regulate this activity (e.g. by imposition of laws, for example) in order to reduce the impact when this is necessary. Environmental impact assessment (EIA) and environmental impact statement (EIS) are concerned (Gregory and Walling, 1981) with estimates of future environmental changes caused by a proposed action as well as with the impact of these changes on man's future well-being. Several methodologies have been developed for the formulation of an EIS; one of them is the well known Leopold method (see e.g Leopold et al., 1971; Gregory and Walling, 1981) The method involves the so-called Leopold matrix, which lists a number of project actions along the horizontal axis and certain environmental characteristics (which might be affected by these actions) along the vertical axis. The magnitude and importance of each impact is indicated by a number ranking from 1 (least severe) to 10 (most severe).

Identification of areas of impact and general quantitative estimates are nowadays gradually replaced by quantitative estimates of the extent of changes. A prerequisite for such an objective is the development of modelling strategies which allow for prediction of the effects of human activities and for simulation of alternative scenarios. More details about the use of simulation modelling for environmental purposes is given in Chapter 4.

The fulfillment of tasks as the ones described in this section requires the contribution of many disciplines the combination of which forms the interdisciplinary field of environmental science.

3.4 Environmental science

Environmental science is defined (Boersema et al., 1986) as "the interdisciplinary science which is concerned with the relation between man and his environment and with the potential and actual problems in this relation"; the purpose of environmental science is to give the ways to solve or avoid these problems.

A number of basic disciplines (physics, chemistry, biology, laws, geography, cartography etc.) contribute to the purposes of the environmental science. Within these disciplines specialisms are to be found which are explicitly directed to environmental problems: environmental chemistry, environmental technology, environmental biology, environmental laws, environmental cartography etc.). The area of environmental cartography and the spatial aspects of environmental elements which it introduces will be briefly reviewed in the following section.

3.5. Environmental cartography

Environmental cartography is concerned with the creation of maps which display the status of elements and their relations within the environmental system. Environmental maps, therefore, can be divided in two main groups (Fig. 3-6).

1. maps displaying the status of one or more environmental (physical) elements in the various subsystems of the environmental system (e.g. type and quality of vegetation, water temperature, water quality, soil moisture, soil erosion, slope stability etc.)
2. maps displaying environmental processes either natural or caused by human activities.
    - i. In the first group (natural processes) maps or time series of maps displaying the appearance, evolution and consequences of phenomena such as earthquakes, volcanic eruptions etc. are to be found.
    - ii. In the second group belong the so-called environmental degradation maps on which the influence of man's activities upon the environment is shown (air-, water-, soil- or noise pollution, radioactive radiation, acid rain etc.). Because of the importance and the frequent appearance of such environmental problems this special group of impact study maps tends to dominate the study and representation of the environment, holding an interest for both scientists and general users (I.C.A., 1980)

Environmental maps introduce the spatial component of the environmental system and of the environmental problems. Characteristics of the spatial component are (Bouwer and Klaver, 1987): location, form,

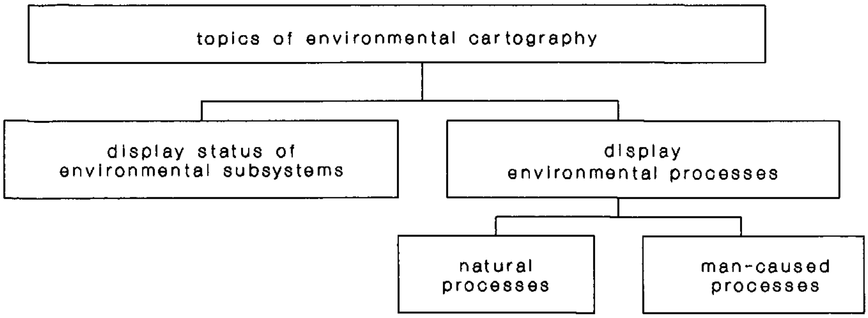


Figure 3-6. Topics of environmental cartography.

extend, distance and scattering. Environmental influences and processes are determined to a large extent by the combination of the spatial characteristics of their sources and their effects. The location of a source affecting the environment, for example, influences the location of the effect; the extent of a source also determines the extent of the effect etc.

Maps reveal such spatial characteristics of environmental phenomena; they visualize spatial distributions of physical (natural and/or man-made) environmental elements (and possibly indicate their causes), detect environmental thresholds and enhance the comprehension of a variety of environmental conditions. In this way they provide useful means by which cartography can contribute to managing of environmental events (environmental problems in particular) and therefore be of use to the purposes of environmental science.

Although the general cartographic principles remain the same a wide field of applications has been created for environmental cartography, the main reasons being the growing environmental problems, needs and awareness, the developments within the cartographic field itself and of course the increasing technical facilities offered by computer hard- and software. An overview of the transition environmental mapping went through during the last 30 years is given by Ormeling (1989).

Some of the cartographic trends discussed in Chapter 1 (such as integration of modelling and temporal aspects with cartographic processes) find an excellent field of applications for the purposes of environmental mapping: the environmental system, as already seen, is a dynamic system: spatial models can simulate environmental impacts and interactions, predict future situations and compute changes as a function of time; for the visualization of such spatio-temporal phenomena cartography can make use of dynamic map displays, presenting the changes animated on a computer screen.

Some examples of environmental maps which are shown in the following attempt to give a general impression of the contents and the use of maps concerned with environmental subjects. All three groups of Fig. 3-6 are represented; type_1 means that the map displays a situation in an environmental subsystem, type_2i that it displays a natural process and type_2ii a man-caused process.

Figure 3-7. Map displaying soil moisture in the Netherlands [type_1]. The map was made on the basis of a weather-satellite photo containing temperature information. Since temperature differences are due to differences in soil properties (the drier the soil the easier it cools down) the soil moisture map was derived from the temperature information on the photo. The example gives an idea of how satellite images can contribute to environmental subjects. (source: Floor, 1989).

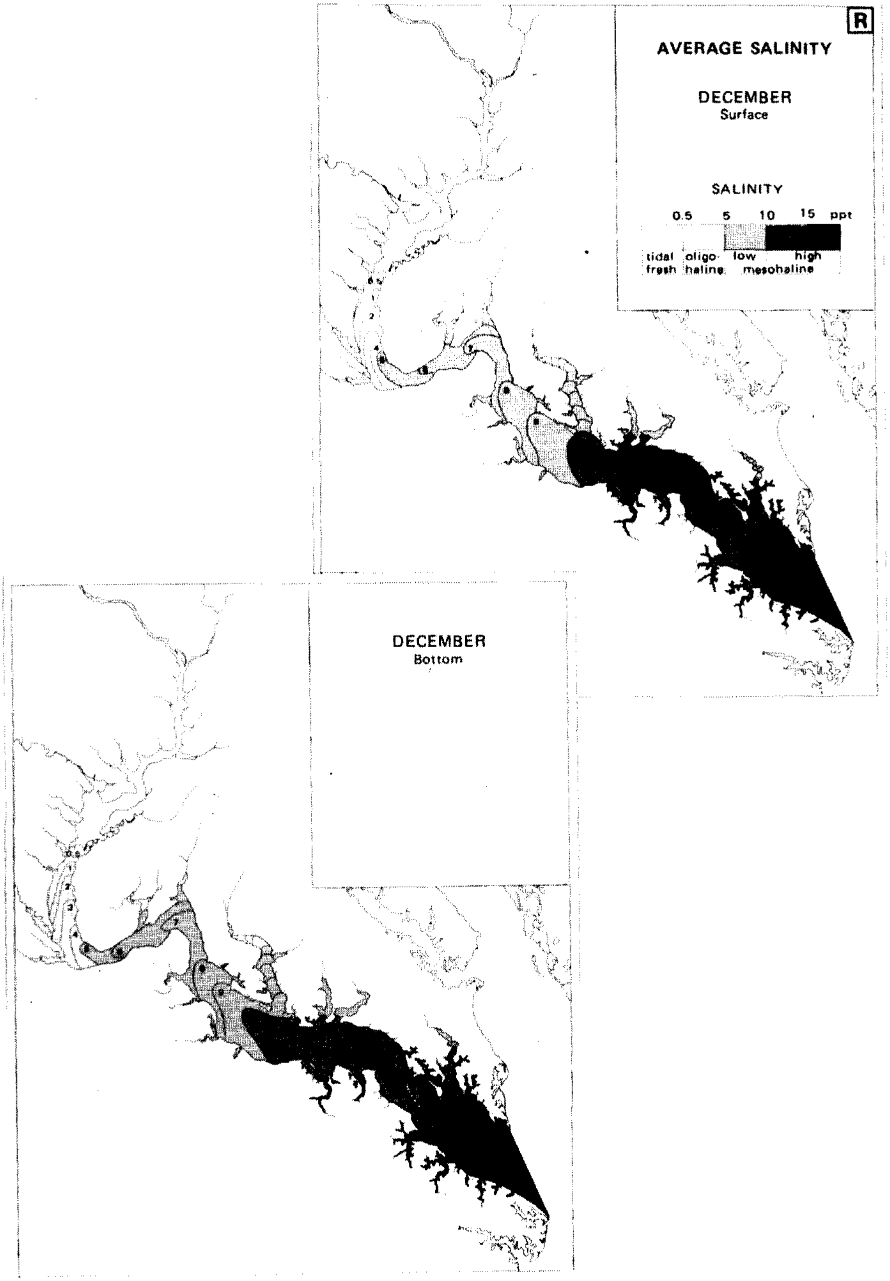


Figure 3-8. Average monthly salinity at surface and bottom in the Potomac river estuary for the month December [type_1]. Data refer to the period 1965-1976 (source: MDNR, 1979).

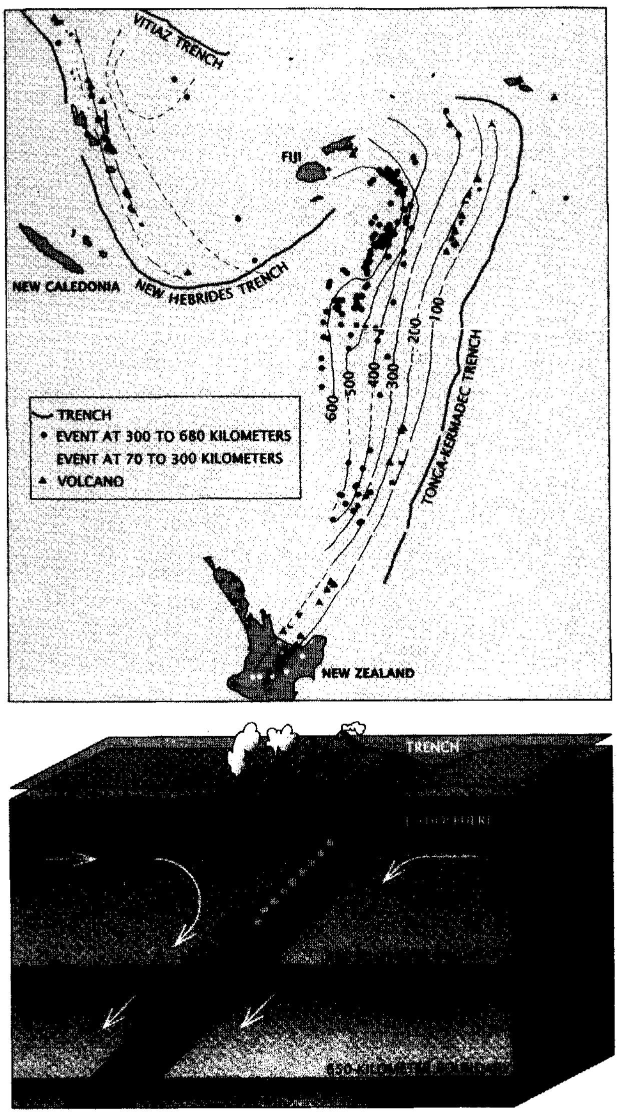


Figure 3-9. A two-dimensional map showing focal depths of deep earthquakes in the southwestern Pacific, in combination with a three-dimensional block diagram which is a reconstruction of the Earth's interior in the same area [type_2i]. On the two-dimensional map it can be seen that the focal depths of earthquakes along the Tonga-Kermadec trench fall along a series of parallel contour lines of increasing depth. The zone between the contours (known as Wadati-Benioff zone) is seen in the block diagram below tracing the subduction of a lithospheric plate. The earthquakes take place within the descending slab of the plate. Molten material rising from the plate feeds the line of volcanoes (source: Frohlich, 1989)

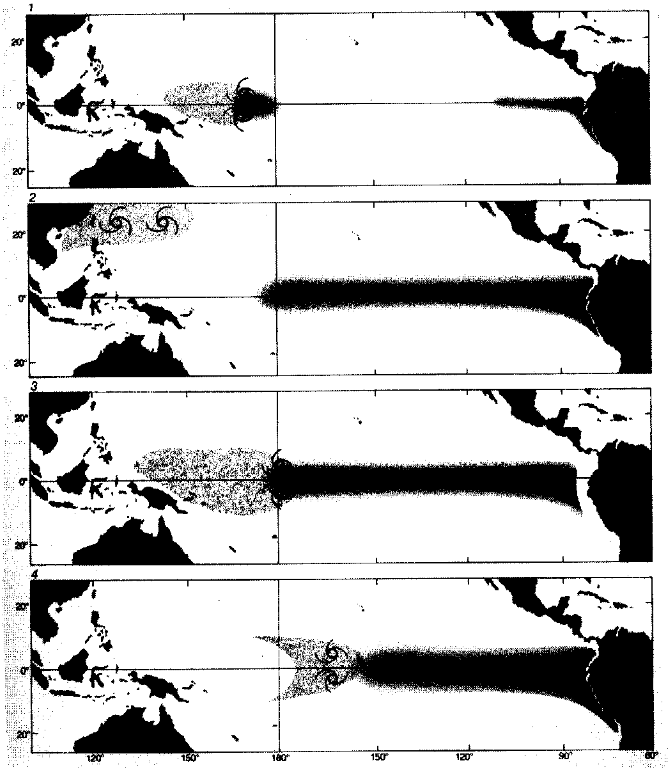


Figure 3-10. This series of maps gives an example of the dynamic nature of environmental phenomena and the potential which Computer cartography has for their display. The maps depict a phenomenon known as El Niño: warming of the sea surface in the equatorial Pacific. The name El Niño (the Spanish term for the Christ child) has been used by local fishermen to describe the appearance annually around Christmas time of warm water off the coast of northern Peru and Equador [type 2_i).

1. Cyclones form on both sides of the Equator in pressure troughs (light grey) in the South Pacific.

   Cyclones set off subsurface waves which push warm water toward the Central Pacific and warm the sea surface there and in South America.
2. The warming spreads.

   The North Pacific trough and its cyclones appear, but they are too far North to generate waves at the Equator.
3. Because of this the sea surface off South America cools from September to November.

   The northern trough moves back to the Equator.
   - If it spawns no cyclones, El Niño ends.
   - If cyclones form, new waves burst, which pull warm water to the east; the water then pulls the trough behind it.
4. The waves strike South America; the sea surface there warms again (source: Ramage, 1986).

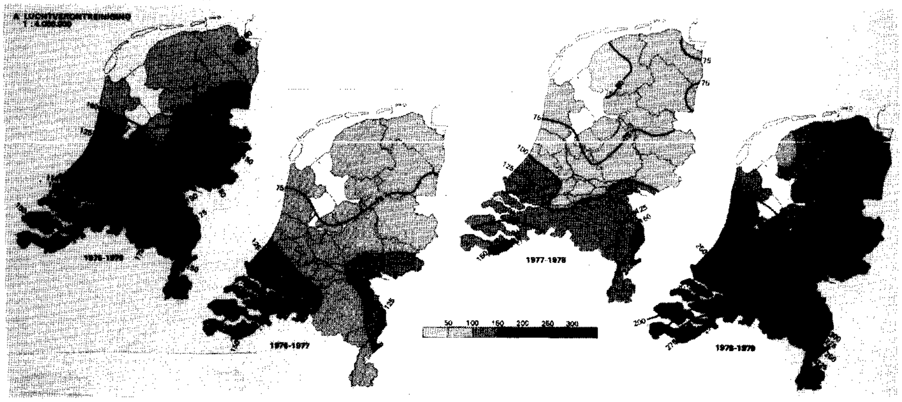


Figure 3-11. Concentration of SO_2 in the atmosphere of the Netherlands [type_2ii]. The contour values show daily average values of SO_2 concentration (in micrograms/m^3) which have been exceeded more than 7 days per year. According to established norms the daily average SO_2 concentration of 250 micrograms/m^3 should not be exceeded more than 7 days per year. From the last map (period 1978-1979) it is seen that this limit has been exceeded which means that alarm conditions have been reached (source: RIVM , from: de Grote Bosatlas, 1988).

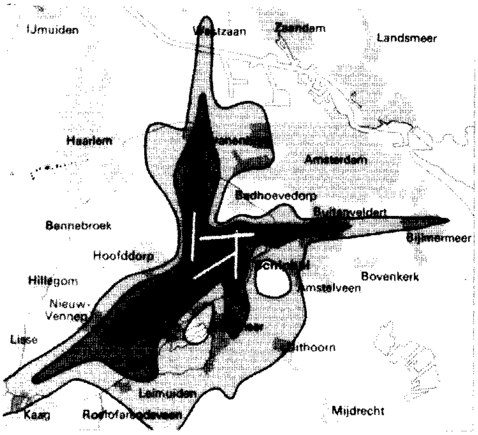


Figure 3-12. Noise pollution around Schiphol airport [type_2ii] (source: Nationaal Lucht- en Ruimtevart Laboratorium 1987, from: de Grote Bosatlas, 1988).

From these examples the potential of computer-assisted cartography for monitoring and displaying environmental processes can be seen. While conventional cartography is suited rather for type_1 maps, CAC (3-D and dynamic cartography, in particular) allow one to portray a wide range of environmental processes, which, by their nature, take place in 3-dimensional space and in time (type_2i and type_2ii maps).

CHAPTER 4. AIR POLLUTION

4.1 Introduction

In this Chapter an overview of the air pollution problem is given. Initially the various categories of the problem are described with respect to their spatio-temporal extent and the main elements involved are mentioned (section 4.2). These elements i.e. sources and their emissions, atmospheric mechanisms and the resulting atmospheric concentrations of air pollutants are then discussed in more detail (sections 4.3, 4.4 and 4.5). In section 4.6 the more specific subject of air pollution simulation modelling is treated. An overview of the simulation model used for the purposes of the present work (model RAM) is given in section 4.7. A feedback is then made (section 4.8) to include all discussed elements in the concept of an air pollution monitoring and control system. Finally, the visualization of the spatial distributions involved in such a system is introduced in section 4.9.

4.2 The elements of air pollution

As it was seen in the previous Chapter, environmental pollution is generated because of, mainly, two reasons (Fig. 4-1):

1. Anthropogenic (i.e man-made) activities: they destroy the existing environmental balance and generate the sources from which pollutants are emitted.

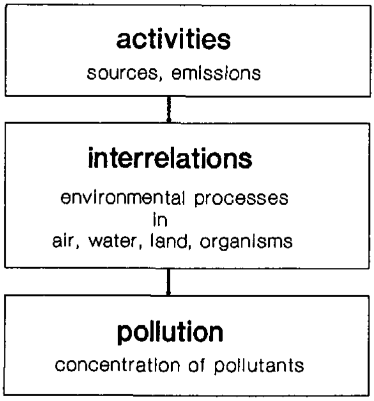


Figure 4-1. Generation of environmental pollution.

2. Interrelations within and among the various components of the environmental system: they are responsible for the transport and

diffusion of pollution in the environment.

The pollutants which are emitted into the abiotic compartments of the environmental system (i.e. atmosphere, water and land, see Chapt. 3), are transported within the same compartment and finally they may reach other abiotic and biotic compartments of the system (Fig. 4-2, see also Fig. 3-4).

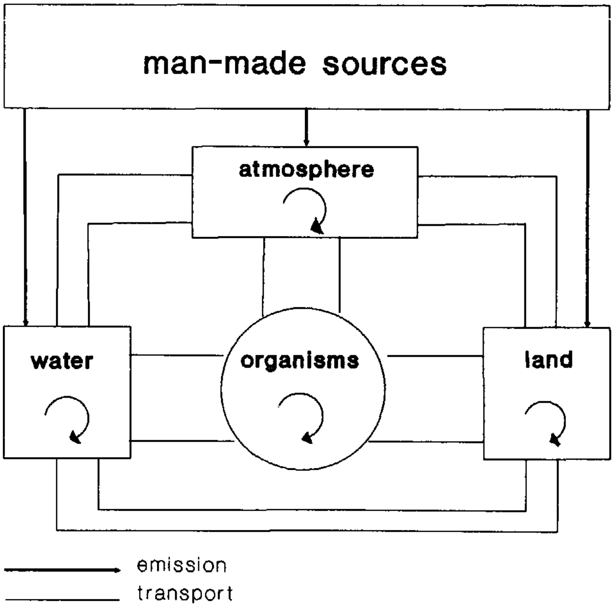


Figure 4-2. Transport of pollutants emitted from man-made sources.

This work is concerned with the generation and transport of pollution within one of the abiotic environmental compartments, namely the atmosphere. An overview of the nature of atmospheric pollution will be given in the following.

The existence of atmospheric pollution (the term "air pollution" is also often used) over an area is the result of a sequence of interrelated processes (Fig. 4-3). The air pollutants are emitted from places called sources. The released pollutants are transported, diffused (i.e spread out, dispersed) and occasionally chemically transformed by means of various atmospheric mechanisms. These mechanisms are created by interactions of the physical and chemical atmospheric factors and components. The degree of presence of a pollutant in the atmosphere is expressed quantitatively by the so called ambient concentration* of the pollutant.

The polluted atmosphere has adverse effects on air pollution receptors; a receptor may be an organism (a person, a plant, an animal) or some man-made material.

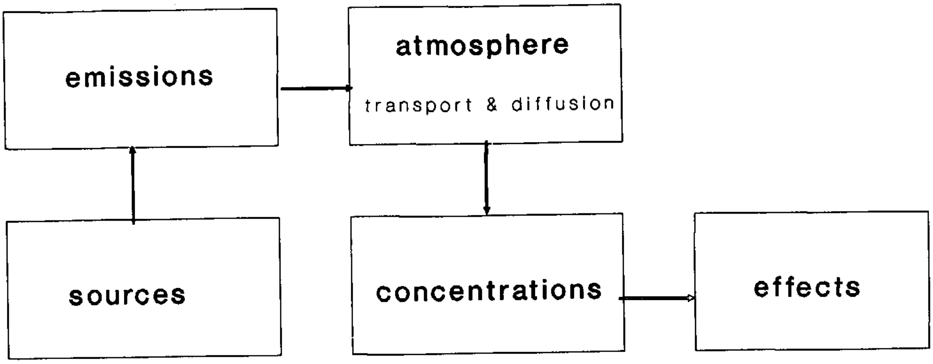


Figure 4-3. The elements of air pollution.

A more extensive description of the elements of air pollution i.e. sources and their emissions, atmospheric mechanisms and concentrations is given in sections 4.3, 4.4 and 4.5 respectively. A brief overview of the categories (spatial and temporal) of the air pollution problem precedes.

4.2.1 Categories of the air pollution problem.

When considering the air pollution problem one should recognize that there is not only one problem, but rather a number of distinct air pollution problems (Stern et al., 1984). These different problems - distinguished mainly by their different spatial (horizontal & vertical) and temporal extent- are: local, urban, regional, continental and global (Fig. 4-4.). The spatial dimension concerns the magnitude of space which is involved in the problem. The horizontal extent shows how much of the earth's surface is involved; the vertical extent how much of the atmosphere's depth is of interest for the problem. The temporal dimension indicates the time that the problem takes to develop as well as the time needed for the problem to be resolved.

A typical example of a **local** air pollution problem is the pollution caused by traffic in a city street. The horizontal extent of the problem is the length of the street itself; the vertical extent is the height of the buildings at the sides of the street. The emitted pollutants are transported by horizontal and vertical convective air currents within the street canyon (Fig. 4-5). The time scale can extend from a few minutes to one hour.

The traffic density and consequently the emissions can change within an hour by a factor larger than two; by restricting the traffic, therefore, local problems can be resolved in some minutes.

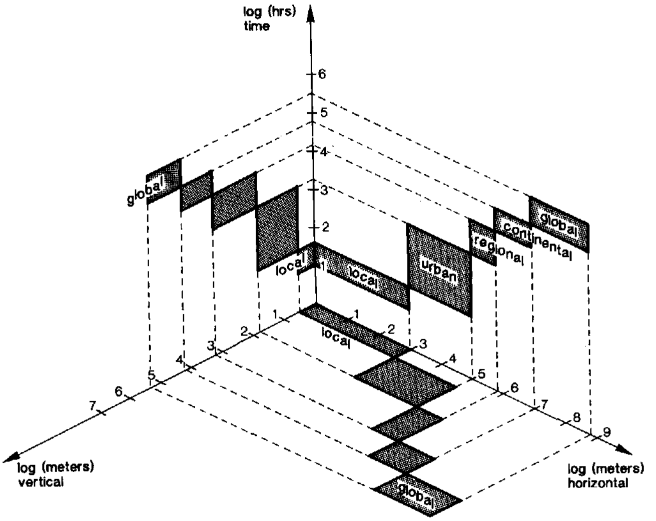


Figure 4-4. Categories of the air pollution problem.

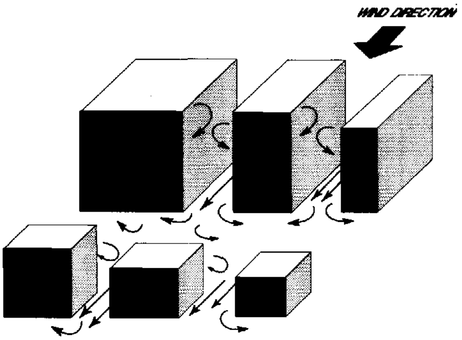


Figure 4-5. Local air pollution.

Figure 4-6. The urban case: total sulphur compounds in the atmosphere over Tel Aviv, annual mean. (From: Kadmon, 1983).

In the case of urban air pollution the emissions emanate from sources existing in the city and its suburbs such as industrial stacks, traffic, combustion from central heating of buildings. The horizontal dimension of the air pollution problem is the diameter of the urbanized area (Fig. 4-6); the vertical dimension extends up to 1.5 km approximately. The ventilation of an urban area (and consequently the transport and diffusion of air pollutants) is done by mainly two mechanisms: a horizontal wind flow which moves the pollutants laterally and a vertical movement which brings pollutants to the upper levels of the atmosphere and clean air down to ground level. When such mechanisms cease, pollution concentrations in the area may reach critical limits. The usual time unit for measuring (or simulating) pollution concentrations for the urban case is that of an hour: it takes a few hours for a critical situation to occur and it also takes some hours for the reduction of emissions and concentrations to an acceptable level. This work will be concerned with the case of urban air pollution.

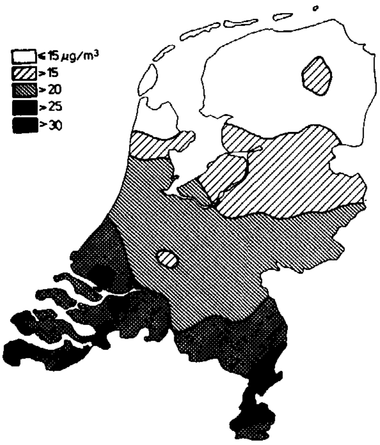


Figure 4-7. The regional case: yearly average SO_2 concentrations (in $\mu gr/m^3$) in the Netherlands for 1986. (From Bouwer and Klaver, 1987).

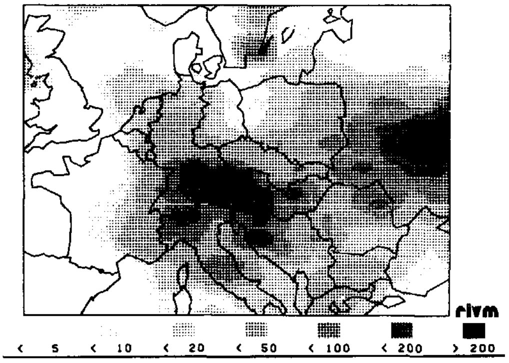


Figure 4-8. The continental case: Dispersion of Caesium-137 over Europe (cumulative deposition in 0.1 GBq/m^2). Source: RIVM.

Regional air pollution is the result of emissions and concentrations in an urban area, its suburbs and the surrounding countryside to a horizontal extent of hundreds of kilometres (Fig. 4-7). Vertically the problem occurs within the troposphere (i.e. to a height up to 10 km). Usually the pollution originates from the transport of polluted air from a city (or cities) to the countryside. Additional non-urban sources can also contribute to the problem; some examples of such sources are : burning of fields and agricultural wastes, crop spraying with pesticides, disposal of agricultural waste (e.g. from processing animal and vegetable products) etc.

Continental air pollution involves the transport of pollutants through international boundaries. An example is the transport of sulfur oxides through European countries; the oxides are washed out of the air in the form of acid rain* causing increased sulphur deposition in water, soil and materials (Fig. 4-8.)

A **global** air pollution problem involves all of the earth's surface and the atmosphere (i.e. up to a vertical extent of 150 km). It is the result of the accumulation of emissions from man-made and natural sources (e.g. all kinds of industrial and urban emissions, nuclear tests, volcanic eruptions etc.) which are transported around the globe. Such processes evolve at a slow rate and it usually takes some decades before their results can be detected. A very well-known contemporary global air pollution problem is the destruction of the ozone layer (Fig. 4-9). This layer, which exists at the lower parts of the stratosphere (i.e. at a height of 10-30 km) absorbs energy in the ultraviolet (UV) wavelengths emitted by the sun; if by any means depleted, the UV radiation at ground level will increase, with harmful effects on humans, flora and fauna. The most harmful air pollutants for the ozone layer are chlorofluorocarbons (CFC) generated from the use of sprays and nitrogen oxides (NOx) emitted from plane and missile exhausts.

Another well-known global problem is the greenhouse effect, caused by large concentrations of CO_2 in the atmosphere: the inward transmission of radiation from the sun is permitted, but its outward re-radiation from the ground is prevented. The result is that the equilibrium temperature rises, causing in the long term heating of the earth, which, in turn, might lead to climate modification, melting of polar ice, raising of sea level and flooding in coastal areas.

Other contaminants, such as suspended particulates have the ability to absorb and scatter solar energy and therefore to reduce the amount of solar energy that penetrates the earth's surface; the long term result is the cooling of the earth and the increase of polar ice.

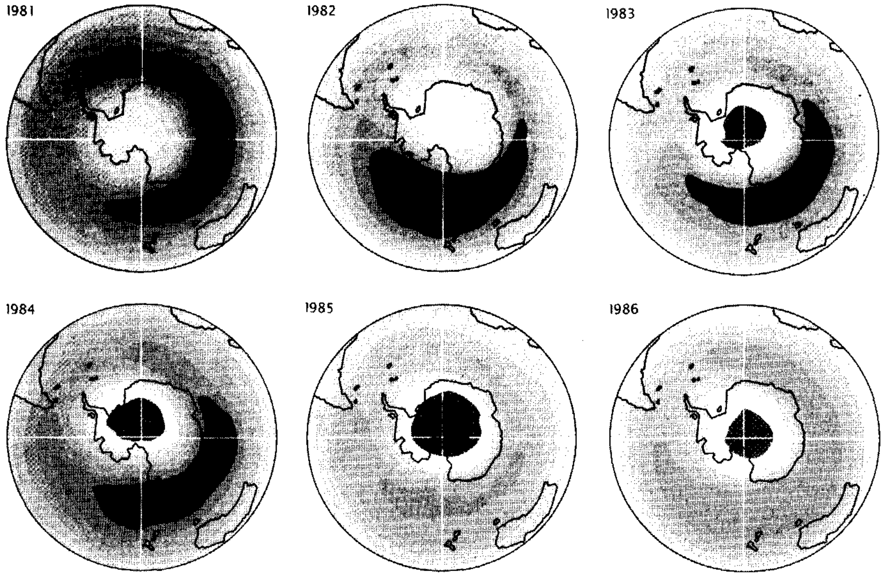


Figure 4-9. A series of maps displaying ozone levels in the atmosphere of the southern hemisphere. The maps are based on data from NASA's Total Ozone Mapping Spectrometer (TOMS). Black indicates 150-180 Dobson units and is followed by gray and blue (in the original drawing) tints,indicating increasing levels of ozone. It is seen that the depleted region is broader than the Antarctic continent; the maps show the decrease in the presence of ozone in the region (source: Stolarski, 1988).

These changes are examples of the so-called inadvertent climate modification, the long-term results and interactions of which are not easy to predict. For the abatement of global air pollution continuous international cooperation is necessary.

4.3 Sources of air pollution and their emissions

4.3.1 Sources

According to their environmental characteristics (see e.g. Chapt. 3) sources of air pollution can initially be divided in two groups: **natural** and **man-made** sources. Both of these groups can be further divided (Fig. 4-10):

1. on the basis of their mobility in stationary and mobile sources.
2. on the basis of their spatial characteristics in point, line, or area sources.

Natural sources are generated by processes taking place among the natural elements of the physical environment. Some examples of natural air pollution sources are:

- an erupting volcano which emits atmospheric particles and gases such as SO2, H2S etc.
- a forest fire emitting smoke, CO, NO, NO2 etc.
- a dust storm transporting atmospheric particles.
- oceans emitting salt particles which cause corrosion.
- plants and trees emitting hydrocarbons.
- hot streams which emit sulfur gases, causing local odour problems.

		natural	man-made
stationary	point	*	*
	line	*	–
	area	*	*
mobile	point	–	–
	line	–	*
	area	–	*

Figure 4-10. Categories of air pollution sources; the most commonly used categories are shown with asterisks.

Natural sources have always been active; in general they are the result of natural environmental processes which, although they occasionally might cause irreversible changes, in general they are not considered to threaten the balance of the environmental system.

Man-made sources are the sources generated by peoples' activities. Consequently, they can be found near or within populated areas, in places where people work and live, and thus, expose themselves to the sources' emissions. Some examples of air polluting sources generated by man are industries, traffic, heating of buildings etc.

Stationary sources are the sources with a fixed location. The most important type of stationary sources, from the point of view of quantities of pollutants emitted to the atmosphere, are industrial sources. Each industrial source emits relatively consistent qualities and quantities of pollutants; the sort of pollutants as well as the emitted quantities depends on the type and magnitude of the industry. A paper industry, for example, emits the same kind and the same quantity of pollutants, unless a major change in its process is made. Another type of considerable stationary sources are the burners of central heating in buildings. Other minor stationary sources are: waste disposal and on-site incineration. In this application **industry** and **central heating** sources will be considered.

A **mobile** source of air pollution can be defined as one capable of moving from one place to another under its own power (Stern et al., 1984). Mobile sources consist of many different types of vehicles (Fig. 4-11), powered by engines using different cycles, fueled by a variety of products and emitting various amounts of pollutants. The predominant mobile air pollution source in all industrialized countries, however, is the automobile, powered by a four-stroke cycle engine and using gasoline as a fuel (op.cit.). From the different types of mobile sources shown in Figure 4-11 the most typical sources of an urban area (i.e. car, bus, taxi, motorcycle) will be considered in the present application.

As it was already mentioned, pollution sources can also be divided in **point**, **line** and **area** sources. Although actually all sources are individual and therefore they can be considered as point sources the concepts of line and area sources are used for pragmatic reasons (i.e. for convenience of applications). The geometric identification of the source depends, of course, on the category of the air pollution problem (section 4.2.1), which is defined, among others, by its spatial extent. In other words the geometric identification of a source is -like its cartographic representation by a point, line or area symbol- mainly a matter of scale: a street will be probably considered as a line source in the case of a local air pollution problem, while for the purpose of an urban problem it will not be treated separately but rather incorporated in a larger area source.
Mobile sources on a fixed route are considered as forming a line source; the emissions of the source are estimated from the quality and quantity of individual mobile sources on it. Mobile sources with non-fixed routes are usually treated as area sources: in the case of an urban traffic

network, for instance, emissions from cars are converted to emissions from a number of area sources (cells) covering the city. In cases of small stationary sources or cases where certain emission parameters are not available emissions can also be considered areal. In Chapter 6 which is concerned with the practical application of this work for the area of Athens these assumptions will be described in more detail.

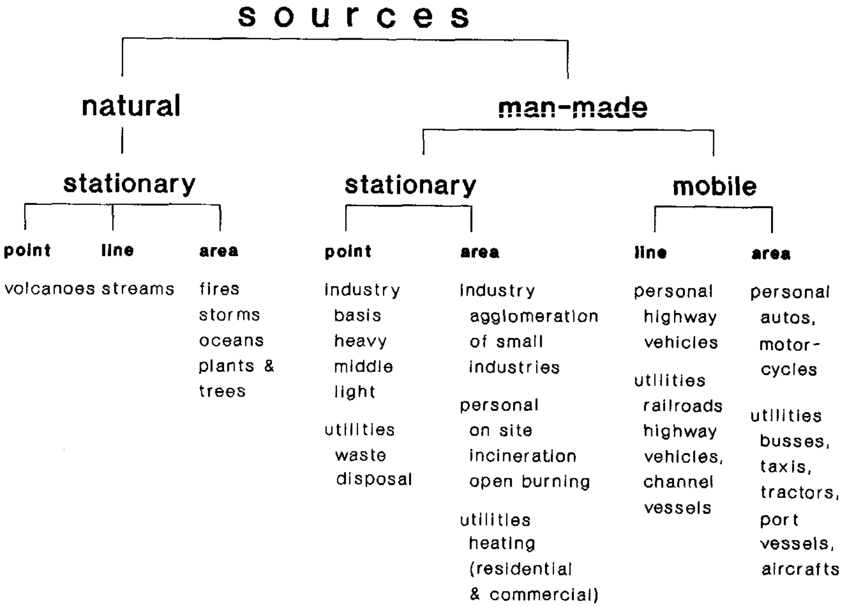


Figure 4-11. Examples of air pollution sources.

4.3.2 Emissions

The rate of release of a pollutant from a source into the atmosphere is given by the so-called **emission rate.** For point sources the emission rate is expressed in mass units of pollutant per time unit (e.g. gr/sec); sometimes it can also be found expressed in volume units per time unit i.e. flow units (e.g. m^3/sec). For line sources the emission rate is expressed in mass units of pollutant per time unit and length unit (e.g. gr/sec m). For area sources the emission rate is expressed in mass units of pollutant per time unit and area unit (e.g. gr/sec m^2).

The gaseous pollutants added in the greatest quantities to the atmosphere by human activities are (Manahan, 1984): Carbon monoxide (CO), Sulphur dioxide (SO_2), Nitric oxide (NO), Nitrogen dioxide (NO_2), Hydrocarbons (HC), particulate matter (particles), smoke and lead (Pb).

Pollutant	**Description**
Carbon monoxide (CO)	Invisible, odourless gas formed from combustion of gasoline, coal etc; largest man-made part comes from automobiles.
Sulphur dioxide (SO_2)	Heavy, pungent colourless gas formed from combustion of coal, oil etc.
Nitric oxide (NO)	Colourless, odourless gas formed from fuel combustion.
Nitrogen dioxide (NO_2)	Red-brown toxic gas formed from fuel combustion.
Hydrocarbons (HC)	Group of gases formed from car exhaust and combustion of oil.
Particles	Emitted from industry and cars.
Smoke	Black particles with a diameter less than 1μm, originating from the combustion of residue fuel oil and diesel
Lead (Pb)	Emitted from cars and battery manufacturing industries.
Ozone (O_3)	Secondary pollutant produced in photochemical reactions.

Figure 4-12. Main atmospheric pollutant gases generated by human activities.

Internal combustion engines are sources of **Carbon monoxide (CO)**. Maximum levels of this toxic gas tend to occur in urban areas with heavy traffic, especially during rush hours. The fact that CO is emitted close the ground (i.e. some centimetres) and its physical tendency to concentrate near the ground surface can cause situations where large concentrations occur locally. It has been observed that atmospheric levels of CO in urban areas are positively correlated with the density of automobile traffic and negatively correlated with the wind speed. It is, primarily, urban atmosphere which is charged with large CO concentration levels; in remote rural areas the levels are much lower.

Sulphur compounds enter the atmosphere in a very large extent through human activities, primarily the combustion of fossil fuels. Coal is the primary source of anthropogenic (i.e. man-generated) **sulphur dioxide (SO_2)**. In order to keep SO_2 emissions at acceptable levels sulphur has to be removed from coal (coal used for energy contains large amounts of sulphur). It is also possible to remove sulphur from stack gas after combustion. SO_2 is a pollutant which in a very large extent is released to the atmosphere from industrial activities; in other words the great percentage of the total SO_2 release in an area is due to industry. Thus it can be said that the presence of SO_2 in the atmosphere is indicative of the total pollution charge of an urban area, since its presence is directly connected with the degree of industrial activity and the magnitude of the area.

The two most important **nitrogen oxides** are **nitric oxide** NO (colourless, odourless) and **nitrogen dioxide** NO_2 (pungent, red-brown). NO and NO_2 are the two most significant gaseous polluting oxides of nitrogen. Very often they are considered in combination, under the name of nitrogen oxides (NOx). Practically all NOx produced by human activities enters the atmosphere as a result of the combustion of fossil fuels, in both stationary and mobile sources. NOx last about 5-6 hours in an urban environment (SO_2 lasts much longer).

Petroleum products, mainly gasoline are the source of most of the anthropogenic polluting **hydrocarbons (HC)** in the atmosphere. Another source of hydrocarbons are automobiles, especially those without pollution control devices. Hydrocarbons are usually divided in two classes: methane (CH_4) and all other non-methane volatile organic carbons (NMVOC).

Particles (also known as particulates or particulate matter) appear in a wide range of sizes and are made up of a variety of materials (see also section 4.4.2 and Figure 4-20). Pollutant particles are emitted mainly from industrial stacks and cars.

Smoke is formed by black particles having a diameter less than 1μm and originating from the incomplete combustion of residue fuel oil and diesel. It can be dangerous in combination with other pollutants such as SO_2. The main sources of smoke emissions are industry, burners of central heating and cars using diesel.

Lead (Pb) is emitted to the atmosphere by some cars and battery manufacturing industries. Its property to accumulate with time in the human organism makes it particularly dangerous, especially for children.

Ozone (O_3) is produced in photochemical reactions* among HC and NOx; large quantities of ozone are to be found in the stratosphere (i.e. up to a height of 50kms, see Fig. 4-18). Large concentrations can occur at ground level if extensive vertical atmospheric mixing occurs.

			source type		pollutant emitted
stationary	industry	basis	oil refinery, chemics, mettalurgy, seaport industry, nuclear reactor		SO_2, H_2S, H_2SO_4, HF, NH_3, NO, NO_2, HC, CO, smoke, fume, dust, odor
		heavy	machine manufacture, ship building, power station		CO, SO_2, HC, NO_2, NO
		middle	manufacture of straw board, artificial fibres and ceramic products, cement industry		SO_2, HF, dust
		light	tannery, textile and food industry		odor
	heating		burners of central heating		SO_2, NO, NO_2, CO, HC, particulate matter
mobile			four-stroke cycle (Otto cycle) engine (gasoline)	auto, truck, bus, aircraft marine, motorcycle, tractor	HC, CO, NOx
			two-stroke cycle (gasoline)	motorcycle, outboard motor	HC, CO, NOx, particulate matter
			diesel	auto, truck, bus, railroad marine tractor	NOx, particulate, SOx
			gas turbine (jet)	aircraft, marine, railroad	NOx, particulate
			steam (oil, coal)	marine	NOx, SOx, particulate

Figure 4-13. The most important types of man-made air pollution sources and their emissions.

4.3.3 Emission inventory

An emission inventory of a certain area consists of the listing and description of air pollution sources in the area and of the quantities of pollutants emitted by them. Mainly three types of emission inventories are to be found depending upon the quantity and precision of their information (Hammerle, 1976): **gross estimation, rapid survey** and **comprehensive inventory** (Fig. 4-14). For all types of emission inventories (gross, rapid or comprehensive) the emissions of the various pollutants from their sources are not directly available, but they are derived with the use of estimation procedures. What is originally available are raw data on fuel consumption (i.e. types of fuel used in the area such as gasoline, diesel oil, natural gas, LPG etc., quantities of consumed fuel) and on the relative activities and processes taking place in the area (i.e. combustion in industries and for heating, other industrial processes according to the type of the industry, data on traffic, information about waste disposal etc.). On the basis of those data and additional technical information, estimation procedures are established for the sources of the area and pollutant emissions are calculated.

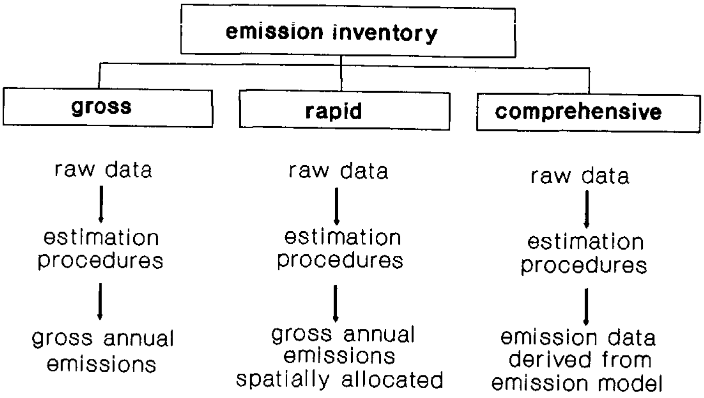


Figure 4-14. The three types of emission inventories.

An example of an estimation procedure is the calculation of industrial emissions from information about industrial combustion. Existing standards for industrial combustion give the quantity of emitted pollutant(s) per quantity of fuel consumed (e.g. X kg of SO_2 per Y tons of diesel); in this way the quantities of pollutants emitted in a certain time period (e.g. a year) can be obtained from the total quantity of fuel consumed during this period. If more technical information is available (e.g. exit temperature of the gases from the stack, stack diameter etc.) additional parameters can be derived (e.g. gas volume, gas exit velocity etc.) which can be of use in cases of air pollution simulation modelling.
Another example is the estimation of emissions from traffic; this is a task which requires information on:

1. traffic volume and composition of traffic (i.e. the different types of vehicles such as taxis, buses, motorcycles, tracks, private cars etc.)
2. quantities of fuel consumed by each vehicle type and the respective emission factors for the pollutants of interest.
3. Spatial characteristics of the traffic network (e.g. for each line source - i.e. street or part of street - in the traffic network data such as coordinates and sub-area in which the street belongs should be available).

On the basis of these data the quantities of pollutants emitted in all individual line sources of the network can then be calculated.

A **gross estimation** inventory is usually concerned with a large geographic area and contains summary statistics for sources and emissions in the area on an annual basis. Data are usually obtained in the office from written documents and statistics. This is the least accurate method for determining emissions : although the total quantities of fuels (or other consumed materials) may be precise, the conversion factors for determining emissions are not, because these factors depend on characteristics of various processes on which no detailed information is available.

A **rapid survey** inventory is also concerned with annual source statistics and emissions. Calculated emissions, however, are more precise than in a gross estimation mainly for two reasons:

1. The major point sources in the area (e.g. up to 50-100 sources) are contacted by questionnaires and more detailed information about their processes is obtained.
2. The geographic location of all sources is recorded, either precisely (e.g. for the major point sources), or approximately (e.g. by grouping minor sources as area sources and assigning them to a general geographic area with certain characteristics).

This subdivision is based on the fact (Hammerle, 1976) that a community or geographic area tends to divide into areas of homogeneous fuel use, just as it tends to divide into areas of homogeneous land use. In general the type of fuel used in a residential area is a function of the age of the community, since it depends on the age and therefore the type of installations; The age of communities is, in general, related to their distance from the centre (core) of the community: older areas are found in and around the centre, new areas near the suburbs.

For the purpose of emission inventories the geographical areas are divided into zones on the basis of common characteristics, such as: topography, census statistics (land use, population density) and fuel use patterns (op. cit.). The first step is to obtain or create a map of the area showing the major topographic features such as rivers, lakes, traffic network, political and administrative boundaries etc. The census tracts are then indicated on the map and subdivided further in zones according to census information (e.g. land use or/and population density). Finally fuel use data are collected for the area and allocated to the zones on the map.

A **comprehensive inventory** contains more detailed information than the rapid survey about both point and area sources, since it considers all parameters involved in their emissions. Point sources which exceed a minimum level of emissions (about 100 tons per year) are included in the **point sources inventory** together with data such as: name, address and telephone number of industry, stack height, stack diameter, gas exit velocity and volume, gas exit temperature, emission rate, location of stack(s) (i.e. coordinates), operating time schedule (daily, weekly, yearly), existing control equipment, age of installation, type of fuel used, sulfur and soot content of fuel, description of the industry's production processes etc.

All other sources are included in the **area sources inventory** which, therefore, contains:

1. minor point sources (i.e. small industries)
2. zones with emissions of geographic areas (from central heating and traffic.)

Usually in comprehensive inventories zones are constructed on a square grid basis and therefore area sources have the form of square cells of a grid covering the entire area. Comprehensive inventories were developed for the purposes of making available the necessary data for use in mathematical atmospheric dispersion models, where quite detailed information is required.

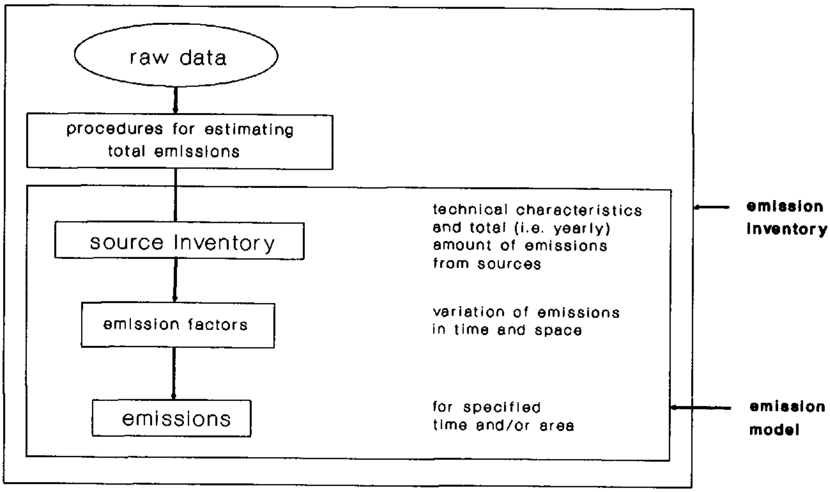


Figure 4-15. Concept of the emission inventory and the associated emission model.

A comprehensive inventory is finally expressed in the form of the so-called **emission model** (Fig. 4-15), which gives the total amount of emissions in the study area (from the source inventory) and the temporal & spatial variations of these emissions. By combining the total emissions and the emission factors it is possible to calculate emissions for a specified time and/or subarea. The more detailed and representative the emission model the more accurate the results from the use of the emission inventory will be.

The main uses of an emission inventory concern **research** and **control** purposes (Hammerle, 1976),(Fig. 4-16). Research uses are concerned with the relations between sources and emissions of pollutants and their concentration levels in the atmosphere. Such uses are mainly oriented towards **atmospheric dispersion modelling** and **effect studies.** Dispersion modelling (or air quality simulation modelling) is a way of expressing in a quantitative manner the dynamics of the atmosphere and consequently of the atmospheric effects upon air pollutants. Models are used in practical applications for prediction of future conditions, for assessment of the contribution of emissions and/or meteorological conditions to the ambient air quality, evaluation of alternative plans etc. Such a model is also used for the purposes of the present work; a more detailed discussion on modelling is to be found in sections 4.6, 4.7 and Appendix II.

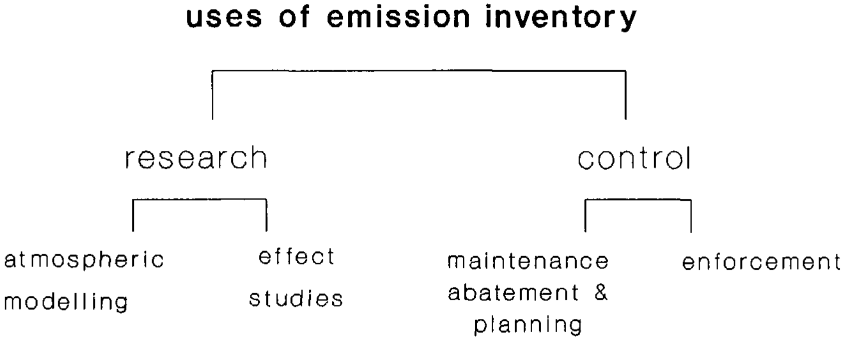


Figure 4-16. Uses of an emission inventory.

The purpose of effect studies is to estimate the effects of air pollution upon biotic and abiotic environmental elements on the basis of historical records about emissions and concentrations. **Primary** effects are concerned with humans and **secondary** effects with plants, animals, soil and visibility. **Control uses** can be further divided into the development of **maintenance** and **abatement control strategies** (including land use and transportation planning) and **enforcement** i.e. control of the compliance status of sources.

Because of the large amount of data involved in an emission inventory the most efficient way to implement it is via a computerized system for data storage and processing. The computerization of an emission inventory can be considered as consisting mainly of two steps:

1. computerize the estimation procedures and the emission model (Fig. 4-15).
2. build up a computer-assisted system for further uses of the inventory. In Figure 4-17 a general concept of such a system is given.

The emission data files for point, area and line sources are the result of the emission inventory and contain data on sources and emissions of the most important pollutants. These files are used as an input to various programs, which perform mainly the following tasks:

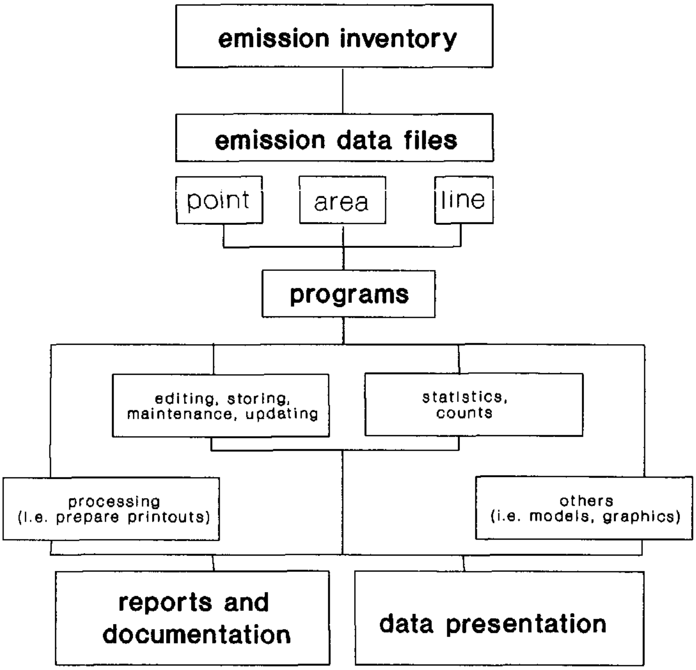


Figure 4-17. Concept of a computerized system for further uses of an emission inventory.

a. editing, sorting, maintenance and updating of data files.

b. access and retrieval of data in the form of summary statistics and counts.

Summary statistics might for example be used to create groups of emission data on the basis of:

- the size of the respective geographical area.
- selected source categories.
- selected pollutants.
- point / area / line sources in order of size.
- controlled / uncontrolled emissions.

Counts -which are necessary for status reports- might give information on:

- number of sources by source category or geographic area.
- missing data items.
- identification numbers of sources.

- compliance status of sources.

c. preparation of data for further possible uses by other programs (e.g. change of format, unit conversion etc.) and/or preparation of output for documents and reports (e.g. tables).
d. other uses, such as implementation of a computer simulation model, programs for data presentation (maps, diagrams etc.).

4.4 The atmosphere

The atmosphere can be defined as "the whole mass of air* surrounding the earth". It plays a vital role in maintaining and nurturing life on earth, mainly by:

1. Protecting from the outer space environment. The atmosphere absorbs cosmic radiation from outer space, as well as most of the electromagnetic radiation of the sun, transmitting only near-ultraviolet, visible, near-infrared radiation and radio-waves (Fig. 4-16). It also absorbs energy re-emitted by the earth in the form of infra-red radiation. In this way (i.e. by absorbing radiation from the sun and radiation re-emitted by the earth) the atmosphere maintains the heat balance of the earth.
2. Providing substances* necessary for living organisms. Such substances are carbon dioxide (CO_2) for plant photosynthesis, oxygen (O_2) for respiration and nitrogen (N_2) for plants and bacteria (Manahan, 1982).

4.4.1 Major regions of the atmosphere

The atmosphere extends vertically up to a height of about 500 km. It can be divided into a number of different regions depending upon the system of classification. The most commonly used system divides the atmosphere according to variations of temperature with altitude. In the troposphere and the lower layer of the mesosphere (Fig. 4-18) the temperature generally decreases with height; in the stratosphere, the upper layer of the mesosphere and the thermosphere an increase of temperature with height occurs.

4.4.2 Composition of the atmosphere.

The atmosphere is a mixture of gases, vapours and particles held in suspension.

A **gas** is composed by widely spaced molecules*, moving in all possible ways in empty space (one gas even penetrates easily into another), colliding and rebounding as they move (Heath, 1960). The gaseous state is one of the three states of matter; in the general case any substance can exist, under the appropriate conditions as a solid, a liquid or a gas. In the solid state the molecules are closely packed; in the liquid state the molecules are more spaced apart and capable of more motion. In the gaseous state the molecules are even more widely spaced and also

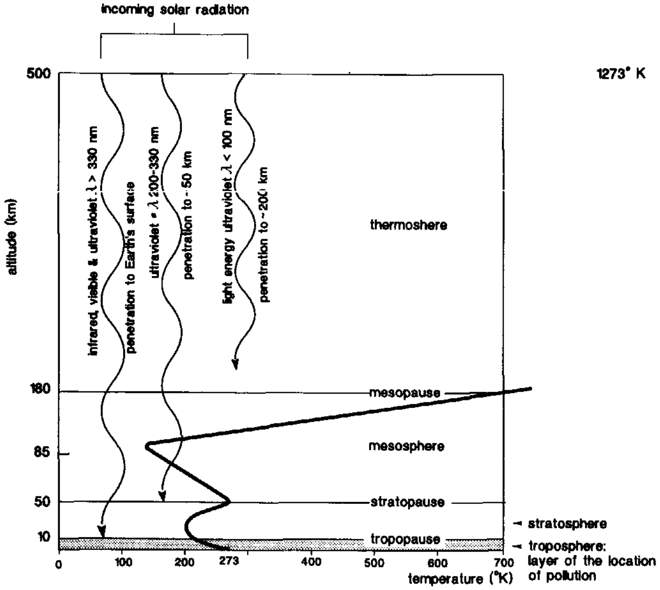


Figure 4-18. Major atmospheric regions

capable of more motion than in the solid and liquid states. As an example the three states of iodine are shown in Fig. 4-19.

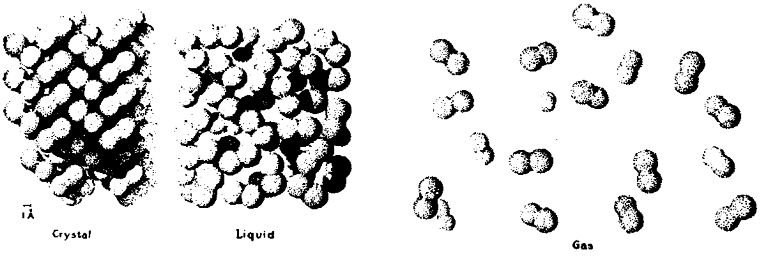


Figure 4-19. Solid, liquid and gas state of iodine (from Heath, 1960)

Vapours are nothing else but gases whose liquid form is more familiar in nature: upon boiling, for example, water becomes steam which is gaseous water, or water vapour.

The **suspended particles** encountered in the atmosphere are aggregates of many molecules, sometimes of similar molecules, often of dissimilar ones;

their behaviour varies in the atmosphere. Some of the suspended particles can react chemically with atmospheric gases or vapours to form different compounds. When two particles collide in the air they tend to adhere to each other, forming progressively larger and larger particles by agglomeration. In this way a particle may become too heavy to remain airborne. The process by which particles fall out of the air to the ground is called sedimentation (see also section 4.5).

The two major components of dry air (i.e. without considering vapors) at ground level by volume are **nitrogen** (78.08%) and **oxygen** (20.95%). Minor components are **argon** (0.934%) and **carbon dioxide** (0.034%). Air may also contain **water** from 0.1 - 5% (by volume) with a normal range of 1 - 3%. Finally, a number of gases known as **noble gases** (hellion, krypton, xenon etc.) and **trace gases** exist in very small quantities in the atmospheric environment.

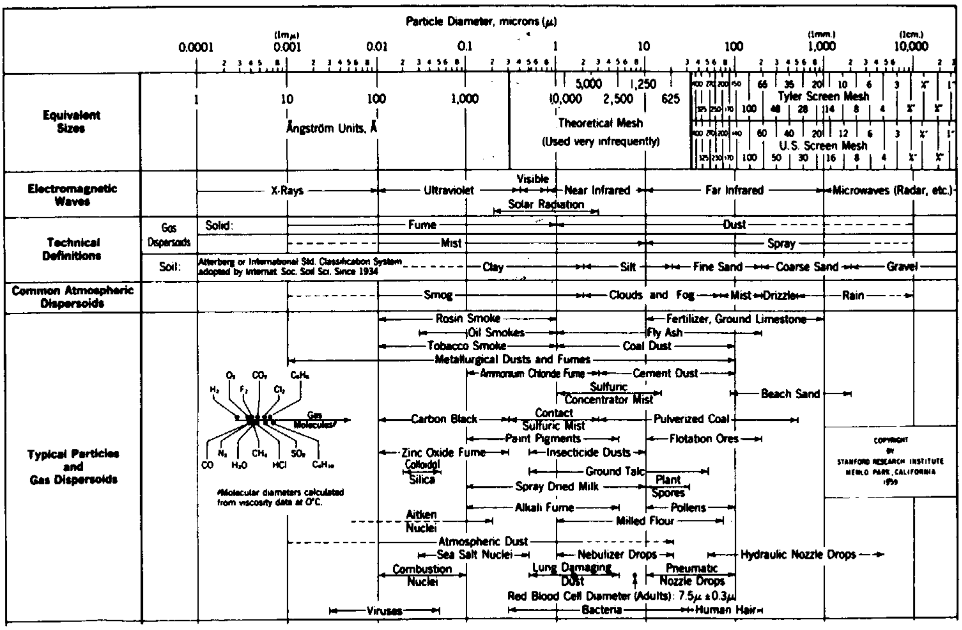


Figure 4-20. Characteristics of particles and gas dispersoids. (From Stern et al., 1984).

4.4.3 Atmospheric phenomena and meteorology

Meteorology (Manahan, 1984) is the science studying atmospheric phenomena such as wind, heat, transition of liquid water to vapour water (and vice versa) in the atmosphere; it is also concerned with the movements of air masses within the atmosphere. These movements can be classified in three main types, according to their magnitude and duration (Fig. 4-21). Long distance movements have a magnitude of thousands of kilometers and last from some days to some weeks. Cyclones belong in this class. The branch of meteorology dealing with such long distance movements is known as **macrometeorology**. Medium distance movements are of a few hundreds of kilometers and last from some hours to some days: land- and sea-breezes, valley- or mountain-winds are of this type. These belong in the area of **mesometeorology**. Small distance movements occur over areas less than 10 km and last from some minutes to some hours : dispersion of gases from an industrial stack, turbulence around the location of a high building etc. They are studied by **micrometeorology** (Zoumakis, 1984, Manahan, 1982).

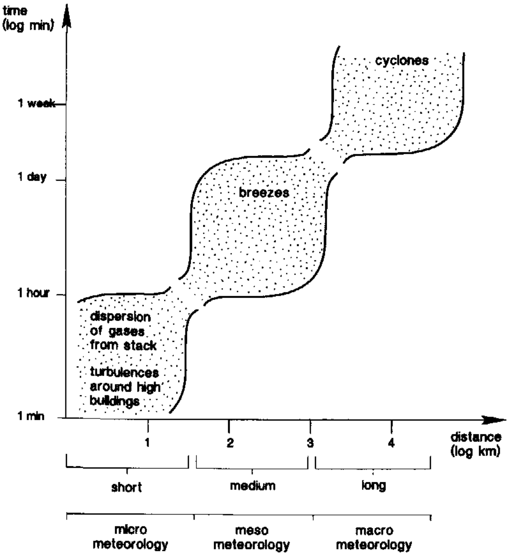


Figure 4-19. Movements of atmospheric masses.

4.4.4 Atmospheric phenomena related to air pollution.

The most important atmospheric phenomena related to air pollution are: **wind** , heat expressed in terms of **ambient temperature** (i.e. atmospheric temperature), **solar radiation**, **moisture** and **visibility**.

4.4.4.1 Wind

We call wind the horizontally moving air; vertically moving air is referred to as an air current (Manahan, 1982). Wind is the result of the pressure differences caused by the heating and cooling of the atmosphere by the sun. The wind is the primary atmospheric mechanism for the diffusion* of air pollutants. Three characteristics of the wind are critical for the diffusion process: wind speed, wind direction and turbulence. The direction of the wind determines the direction of transport of air pollutants in the atmosphere, while wind speed and turbulence are critical for the dilution of pollutants.

Wind speed is usually expressed in meters/second; another way commonly used in meteorology is the Beaufort scale. In Figure 4-22 the correspondence between the two scales is shown as well as the effects of the various wind speeds.

Beaufort scale	description of wind	effects of the wind	speed (m/sec)
0	calm	smoke rises upwards	0 - 0.2
1	quite	wind direction indicated by direction of the smoke, but not by vanes	0.3 - 1.5
2	light breeze	wind is sensed on face, leaves make light noise, vanes move	1.6 - 3.3
3	weak breeze	leaves and thin twigs move	3.4 - 5.4
4	moderate breeze	wind carries away dust and papers, moves twigs and thin branches	5.5 - 7.9
5	cool breeze	small trees begin to swing; "white horses on top of sea-waves	8.0 - 10.7
6	strong wind	strong branches in movement, wind wistles through electricity cables, difficult to use umbrellas	10.8 - 13.8
7	very strong wind	whole trees move, difficult to walk against the wind	13.9 - 17.1
8	stormy wind	wind throws down twigs from trees	17.2 - 20.7
9	storm	small damages to houses	20.7 - 24.4
10	heavy storm	wind uproots trees; serious damages to houses	24.5 - 28.4
11	hurricane storm	extensive damages caused by storm	28.5 - 32.6
12	hurricane	heavy destructions	over 32.7

Figure 4-22. Wind speed characteristics (data from Höhn, 1955).

It has been observed that wind speed varies with height: in general it increases with height (Fig. 4-23); the phenomenon is known as the vertical wind shear.

The vertical wind shear varies with topography and land use profile.

Mountains, hills, trees, buildings and other obstructions produce varying vertical wind shears. Figure 4-24 shows variations of the vertical wind shear with land use profile.

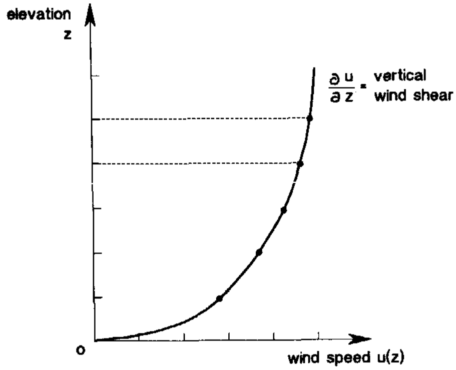


Figure 4-23. Vertical wind shear over a smooth surface.

One of the effects of wind speed which is important to air pollution is the dilution of pollutants released at the point of emission. In the example of Fig. 4-25 the source is a stack which emits continuously to the atmosphere an air pollutant with an emission rate of six (6) mass units per second. The space towards the direction of the wind is considered divided by imaginary vertical planes every one (1) meter. When the wind speed is 6 m/sec, one (1) unit of pollutant mass is to be found between two

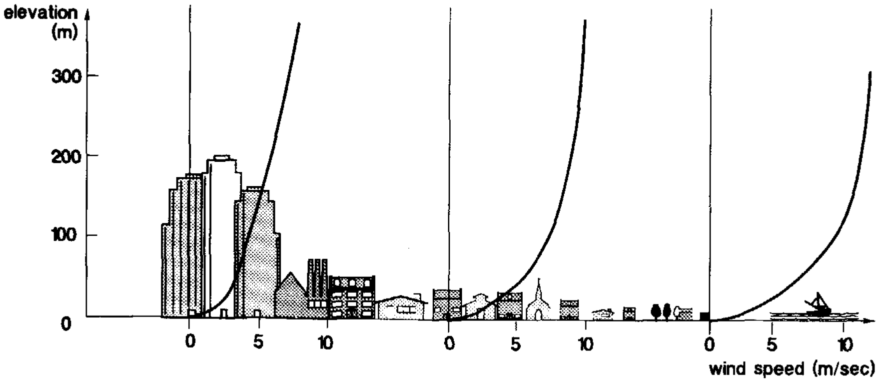


Figure 4-24. Vertical wind shear over different surfaces.

consequent vertical planes. When the wind speed decreases to 2 m/sec, there are three (3) pollutant mass units between the same two consequent planes. The dilution takes place along the direction of the wind at the height of the emission point. For this reason wind speed used in estimating dispersion from the stack should refer to the stack top. Wind speed also affects the travel time from source to receptor: halving of the wind speed doubles the travel time. It also affects the rise of the emitted gas above the stack (the so called plume* rise): the stronger the wind the lower the rise.

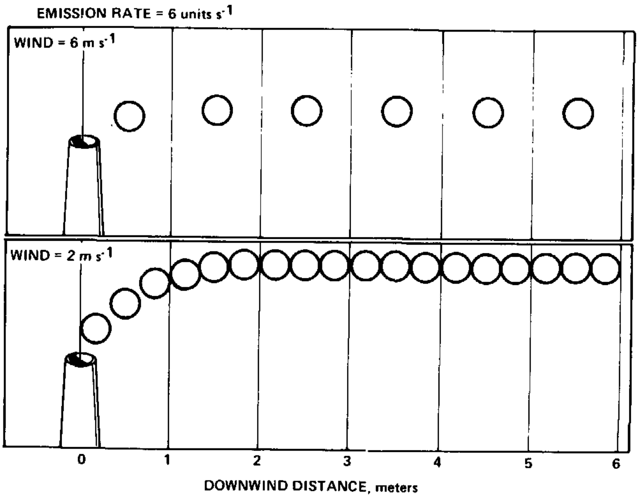


Figure 4-25. Dilution by wind speed. (From Stern et al., 1984)

The **wind direction** varies considerably with height: in low altitudes the wind shifts clockwise with height, while in higher altitudes it shifts counterclockwise with height (Stern et al., 1984).

A very important process for the dispersion of air pollutants is that of **turbulence**. Turbulence is the highly irregular motion of the wind. The results of turbulence are called turbulent eddies. There are mainly two different cases which cause the generation of turbulent eddies:
a.when air moves past objects, eddies are set in motion as a result of mechanical turbulence.
b.when parcels of superheated air are rapidly rising from the heated surface of the earth and a larger part of the surrounding atmosphere descents in a slower motion, the result is thermal turbulence which also forms eddies.

As it was discussed before in this section wind speed increases with height and this phenomenon is known as the vertical wind shear (Figs. 4-23, 4-26). The vertical wind shear $\partial u/\partial z$ has a maximum value near the ground surface and decreases progressively upwards. After a certain elevation the value of the wind shear reaches zero, which means that from this elevation upwards the horizontal wind speed remains constant. In this upper layer where $\partial u/\partial z = 0$ the horizontal wind flow is uninterrupted i.e. free from turbulence. In the layer beneath, however, the flow appears quite complex due to vertical wind shear and to random vertical motions within the air.

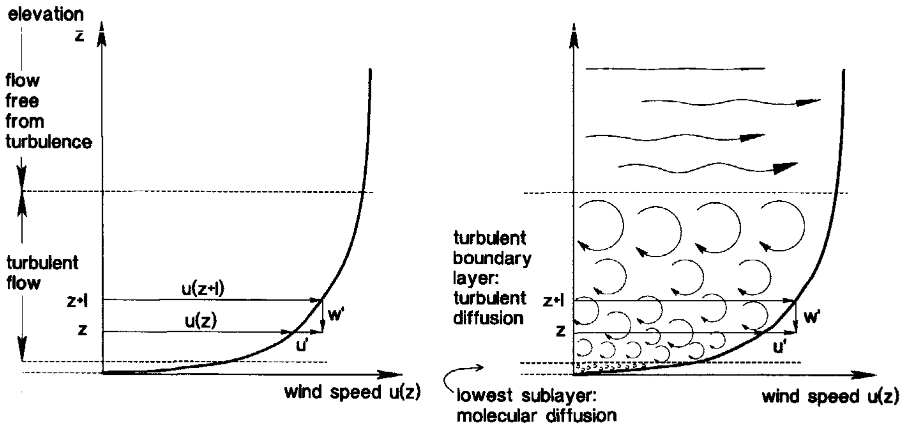


Figure 4-26. Wind flow over a smooth surface.

This complex motion of air could be visualized as a smooth mean flow on which large numbers of eddies are superimposed. Each eddy moves with the mean flow velocity u(z) to which its own internal motions (identified with the components u' and w') are added to give the instantaneous velocity at any given point (Fig. 4-26). Thus, in the turbulent layer discrete 'lumps' of fluid exist, which are displaced by a turbulent action to a characteristic distance known as the **mixing length** (or mixing layer) l, before they merge with the surrounding fluid (McIntosh and Thom, 1969). Thus, the characteristic length l of an eddy is the distance to which the eddy can move without losing its properties (e.g. its momentum). The magnitude of l decreases downward through the boundary layer until $l=0$ at the ground surface. In the lowest sub-layer there is in fact no turbulence but only collisions among molecules, which result in the so-called molecular diffusion.

Eddy diffusion (or turbulent diffusion) is the most important process of those which make up the whole mechanism of atmospheric diffusion. During eddy diffusion the atmospheric eddies described previously cause polluted air to be mixed with relatively unpolluted air; in this way polluted air of successively lower concentrations is caused to occupy successively larger volumes of air (Stern et al., 1984). Eddy diffusion is most efficient when the length of the eddy is similar to the length of the body of polluted air being diluted (Stern, 1968, Zoumakis, 1984); the lengths refer to the same plane which is the vertical plane. In Fig. 4-27 three different cases of eddy diffusion are shown. In the first one (a) the length of the eddies is very much smaller than the initial length l_c of the pollutant gas cloud: masses of (unpolluted) air flow into the cloud and turbulence causes its growth; thus the size of the cloud has increased and the concentration of pollutant inside the cloud is now lower. In the second case of eddy diffusion (b) the length of the eddy is much larger than the length of the pollutant cloud; the cloud behaves like a flowing object transported through the flow field almost unaltered. In the third case (c) the length of the eddies is similar to the length of the pollutant cloud. The body of the cloud is subjected to spiral distortion and, finally, disintegration.

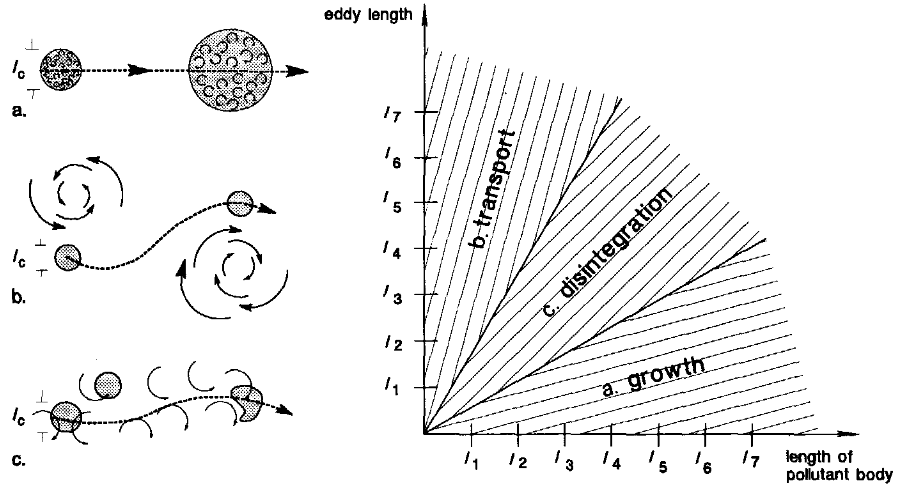


Figure 4-27. Cases of eddy diffusion

A simple example of a single point source (e.g. an industrial stack) and a single receptor can be used to summarize the diffusion process generated by the wind. During its transit over the distance between source and receptor the polluted body of air exiting from the stack (i.e. the plume) does not remain a cylindrical tube of the same diameter as the interior of the stack from which it was emitted. The three main atmospheric mechanisms contributing to its transformation are:

1. Wind speed: if the wind speed is greater than the speed of gases when they exit the stack the wind will stretch out the plume (see e.g. Fig. 4-25) until the plume speed will equal the wind speed.

2. Wind direction: because wind direction rarely keeps constant over time but it usually fluctuates from its mean value the plume does not follow a true straight line between the source and the receptor; it usually moves according to the meandering of the direction of the wind about the straight line.
3. Turbulent diffusion: turbulent eddies in the air and in the plume cause mixing of polluted and unpolluted air. This is done by movements of masses of pollutant from the plume into the surrounding air and by movements of (clean) air masses into the plume.

All these processes tend to make the concentration of the plume upon its arrival to the receptor less than its concentration on release from the source; the sum of all the processes is what is called diffusion.

4.4.4.2 Temperature

Temperature is defined as "the degree of hotness or coldness of anything, usually as measured on a thermometer". The most important element of atmospheric temperature for air pollution cases is the variation of atmospheric temperature with height: as it was mentioned in the previous section vertical changes of temperature create thermal turbulence, which contributes to the dispersion of pollutants.

The layer of the atmosphere which is involved in air pollution events is the troposphere (Fig. 4-18). In the troposphere temperature generally decreases with height. For dry air the rate of decrease of temperature with height is 1 degree centigrade per 100 meters i.e. the temperature decreases 1 degree centigrade when the elevation increases 100 meters. This rate is known as the dry adiabatic lapse rate or neutral stability (Fig. 4-28). Such atmospheric conditions neither prevent nor enhance the dispersion of pollutants. An alteration of temperature with height can also differ from the dry adiabatic lapse rate. When the lapse rate is greater than 1°C/100m (Fig. 4-28, Fig 4-29a) the atmosphere is called

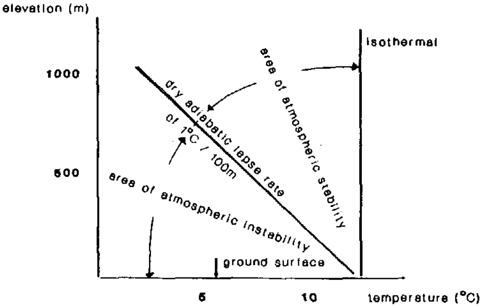


Figure 4-28. Temperature vs. height: stability.

instable; under such conditions vertical movements of air masses take place and dilution of polluted air is easier, because the movements of air masses cause the mixing of polluted and unpolluted air. When the lapse rate is less than 1°C/100m (Fig. 4-28, Fig. 4-29b) the atmosphere is more stable; it does not promote dispersion of pollutants, because it is not suitable for the generation of turbulent motions and diffusion. Temperature might also increase with height (Fig. 4-29c): the phenomenon is called temperature inversion and the result is an extremely stable atmosphere, which prohibits vertical circulation of air and traps the pollutants over the area of emission, preventing their dispersion.

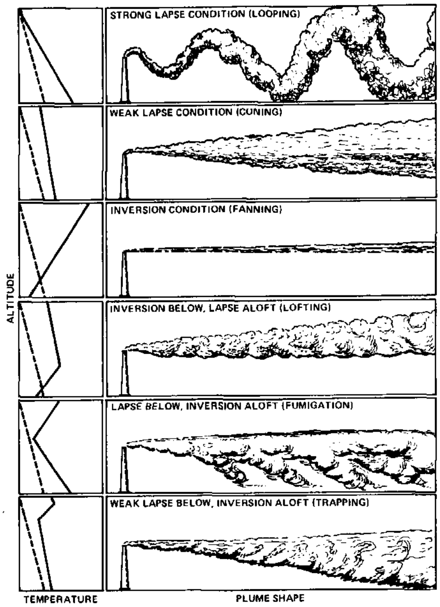


Fig. 4-26. Lapse rates and resulting plumes; the dry adiabatic lapse rate is shown with the dashed line, the isotherm is shown with the dotted line.

4.4.4.3 Solar radiation, moisture and visibility.

Interesting interactions of **solar radiation** and air pollutants have been observed (Stern, 1969). Pollutant aerosols can limit the effectiveness of solar beams by causing a loss of the beams' energy used to heat the earth-atmosphere system; on the other hand solar radiation can create pollution problems: one of the most-known cases is the formulation of photochemical smog by ultraviolet radiation in the presence of certain pollutants (such as nitrogen oxides and hydrocarbons).

Atmospheric and terrestrial **moisture** is important to air pollution, since precipitation (rain and snow) is the most effective cleaning mechanism of the atmosphere; moisture also contributes to the formation of acid rain.

The primary interest of **visibility** in relation to air pollution is that it can provide trends which may be indicative of air quality trends: worsening of visibility in an area over the years can be attributed to growing air pollution. (Visibility is measured in meters).

4.5 Concentration of air pollutants in the atmosphere

The concentration of an air pollutant -which is actually the result of atmospheric processes upon the gases emitted from the polluting sources- can be expressed by either of the two following ways:

1. by a gravimetric designation i.e. weight of gas per unit volume of air. It is usually given in micrograms per cubic metre ($\mu gr/m^3$, where $1\mu gr = 10^{-6} gr$), or in milligrams per cubic metre (mgr/m^3).
2. by a volumetric designation i.e. parts per million (ppm) by volume of air, or parts per billion (ppb) by volume of air.

Conversion between $\mu gr/m^3$ and ppm (assuming atmospheric temperature of 25° C and atmospheric pressure of 760mmHg) is given by the following formula (Stern et al., 1984) :

$$1\mu gr/m^3 = 1ppm \times 41.3 \times \text{molecular weight} \qquad \text{(eq. 4-1)}$$

In air pollution literature and practice terms such as **ambient concentration, ambient air quality, ambient air** are often found. The term ambient is used in order to distinguish pollution in the air outdoors, caused by the atmosheric mechanisms described in previous sections, from contamination of the air indoors by the same substances (Stern et al., 1984).

Large ambient air pollutant concentrations can cause harmful effects to human health and welfare, to vegetation and animals, to materials and structures (e.g. metals, stone, dyes, paper, leather etc.) ; finally they can have harmful effects upon the atmosphere, soil and water. For example a 24-hr average concentration of 500 $\mu gr/m^3$ soot can cause breathing, heart and bloodcirculation problems to chronic lung and heart patients; a 24-hr average concentration of 250 $\mu gr/m^3$ soot, lasting for some days causes aggravation of lung patients' condition; 1 year average concentration of 100 $\mu gr/m^3$ SO_2 or soot cause breathing problems to children and to some groups of adults (DCMR, 1982). Air quality standards and air pollution control aspects are discussed in more detail in section 4.8.

The ambient concentration of a pollutant over an area can be obtained mainly by two ways:

1. by measuring directly, via suitable instrumentation, the present values of certain air pollutants at the stations of a monitoring network.
2. by calculating, via a simulation model the values of certain air pollutants at locations selected by the user, provided that data on meteorological conditions and on emission parameters are available. Such a quantification of atmospheric processes and effects is known by many terms in literature such as: **air pollution diffusion modelling** or air pollution dispersion modelling or air pollution simulation modelling or air quality simulation modelling etc. More aspects on diffusion modelling will be discussed in the next section (4.6).

The various pollutants dispersed in the atmosphere are in general removed by physical mechanisms or chemical reactions; actually what is meant by 'removal' is that the pollutants will be removed out of the atmospheric compartment only, but they will be further transported to other environmental compartments (soil, water, organisms). Only very fine particles (i.e. with a diameter less than 0.2μ) and gases such as CO -which does not react rapidly- stay in the atmosphere for longer periods. The main removal mechanisms are (Stern et al., 1984) sedimentation, deposition (dry and wet) and chemical reaction.

Sedimentation is the settling of particles due to gravity. The settling velocity of the particles is a function of their diameter and density. Particles with a diameter less than 20μ are considered to disperse as gases; thus air pollution dispersion models are valid for particles less than 20μ. Particles with a diameter between 20μ - 100μ disperse as gases but they are moving downward in the atmosphere according to their settling velocity. Finally, particles larger than 100μ fall so rapidly that no dispersion takes place.

Dry deposition of particles is due to impaction with vegetation near the ground surface or to chemical reactions with the surface. **Wet deposition** can take place in clouds by cloud droplets (rainout) or below clouds by precipitation.

Chemical reactions throughout the plume are treated as exponential losses with time. The loss of concentration is a function of time and pollutant half-life (half-life is the time required to lose 50% of the pollutant).

A summarized overview of the most important elements of air pollution (sources, emissions, concentrations, effects) is given in Figure 4-30 for some of the most important atmospheric polluting gases. A positive sign indicates a contribution of the gas to the problem, a minus sign amelioration; a double sign means that the effect of the gas varies. Concentrations are given in pieces per billion (ppb); only for chlorofluorocarbon they are given in terms of chlorine atoms.

gas	greenh. effect	ozone deplet.	acid depos.	smog	decreased self-cleansing atmosphere	decreas. visib.	major anthropogenic sources	anthropog./ total emis. per year (millions of tons)	average residence time in atmosph.	average concentr. 100 years ago (ppb)	approximate current concentrat. (ppb)	projected concentr. in yr 2030 (ppb)
CO					+		fossil-fuel combustion, biomass burning	700/2000	months	?, N. Hem. 40-80,S.H. (clean atmosph.)	100-200,N.H 40-80,S.H. (clean atmosph.)	probably increasing
CO_2	+	+/−					fossil-fuel combustion, deforestation	5500/5500	100 yrs	290000	350000	400000 to 550000
CH_4	+	+/−			+/−		rice-fields, cattle, landfills, fossil-fuel production	300 to 400/ 550	10 yrs	900	1700	2200 to 2500
NOx: NO & NO_2		+/−	+	+	-	+	fossil-fuel combustion, biomass burning	20 to 30/ 20 to 30	days	.001 to ? (clean to incustrial)	.001 to 50 (clean to industrial)	.001 to 50 (clean to industrial)
N_2O	+	+/−					nitrogenous fertilizers, deforest., biomass burning	6/25	170 yrs	285	310	330 to 350
SO_2	-		+			+	fossil-fuel combustion, ore smelting	100 to 130/ 150 to 200	days to weeks	.03 to ? (clean to industrial)	.03 to 50 (clean to industrial)	.03 to 50 (clean to industrial)
chloro-fluoro-carbons	+	+					aer. sprays, refrigerants, foams	1/1	60 to 100 years	0	about 3 (chlorine atoms)	2.4 to 6 (chlorine atoms)
O_3	+			+	-							

Figure 4-30. An overview of air pollution elements (data from Graedel and Crutzen, 1989).

4.6 The simulation modelling of environmental pollution

As mentioned earlier in this chapter (section 4.2) this work is concerned with the case of atmospheric (i.e. air) pollution and with the implementation of a mathematical model for simulating air pollution. In order to give a broader view of the field of environmental simulation modelling a brief overview of the subject will be given before the atmospheric modelling is discussed in detail.

The purpose of environmental simulation modelling is to predict the distribution of wastes in the environment and to describe the mechanisms by which the generation of wastes by industrial and domestic activities finally results in pollutant concentrations within the environment (Lee and Wodd, 1977). Models for simulating diffusion of pollutants into the environment have been developed for almost all of environmental subsystems: models are to be found for air pollution, water pollution (river and estuaries), solid wastes, noise pollution and diffusion of pollutants through biological / ecological systems (Fig. 4-31).

The state of development differs greatly for the different environmental subsystems. The most advanced models can be found in the area of air (and also noise) pollution, while the less developed are the ones concerning biological/ecological subsystems. A short description of modelling in the areas of **air pollution**, **water pollution**, and **solid waste pollution** is given in this section.

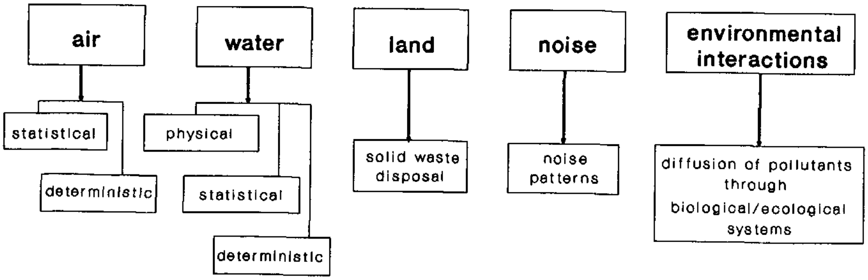


Figure 4-31. Classification of models for simulating environmental pollution.

In the area of air pollution there is a continuous development of new and improved techniques, especially for the modelling of urban, multiple source pollution. Most models are designed for air pollution control purposes although some are integral parts of wider, planning models.

These (mathematical) models can be grouped into two main categories: **statistical (empirical)** and **deterministic** models. Both require input on emissions and meteorology. Also required are input data on ground level concentrations of air pollutants: they are necessary for the operation of the statistical models, and they are used indirectly in the case of deterministic models for calibration and/or correlation purposes.

Statistical air pollution models are not concerned with assumptions regarding the physical character of the described process; they do not account for the meteorological or physical background mechanisms. They only consider more general descriptions of the observed phenomena, using statistical tools and methods for the evaluation of the process. They summarize environmental data by forming statistical descriptions of physical phenomena on the basis of measured data about these phenomena; they carry out statistical analyses such as: probabilities of a certain occurrence, examinations of trends, studies of correlations, statistical distributions, regression analysis etc. Therefore, what statistical models mainly do is to express the relations between these factors in the form of statistical descriptors (e.g. regression formulae) which, if high levels of correlation are achieved can be used for predictive purposes. Statistical simulation models can be developed for areas exposed to pollution from single or multiple sources; however, they can only be developed properly when long term records of meteorological conditions and ground level concentrations of pollutants are available.

Thus, one of the main limitations of statistical models is their limited application: for situations other than those for which they are developed (i.e. for another geographical area, or if emissions from sources change considerably) statistical models cannot function. Another serious drawback is their residence upon a continuous supply of data.

Deterministic air pollution models can overcome these limitations to some extent. Such models are useful for analyzing the atmospheric phenomena. They provide the user with a variety of interrelating atmospheric parameters which can be manipulated during the simulation, according to the purpose of the use (e.g. answer "what if" questions, predict regulatory conditions, or undesired cases etc.). These models will be discussed in more detail in sections 4.6.1, 4.6.2, 4.6.3 and 4.7.

Both groups of mathematical atmospheric models (statistical and deterministic) attempt, in fact, to express in a quantititative manner the same physical processes, but from a different point of view. Statistical methods are interested in conventional indicators, in "signs" of physical processes, whereas deterministic models try to get insight into the physical-atmospheric mechanisms which produce the various concentration levels in the atmosphere. In cases of applications, however, deterministic and statistical approaches to the modelling of air pollution may be integrated. For instance, basic physical processes such as diffusion can be probed to gain insight into which statistical model may be the most suitable for analyzing environmental quality data. Also, by examining the physical model one can obtain evidence to conclude if certain environmental factors may be considered as independent variables, or where possible correlation may arise etc.

Modelling of **water** pollution is not as advanced as air pollution modelling. However, similar modelling principles may be used (e.g. Gaussian type models, the principles of which will be given in later sections). Given that the aquatic environment is extremely complex (predictions of the impact of wastes may have to take into account many parameters which are difficult to describe mathematically such as: dispersion coefficients, chemical reactions, absorption mechanisms, biological effects etc.) the models in use, especially the ones of Gaussian type, might be oversimplistic. Models which have been used to predict the behaviour of aquatic systems deal both with the diffusion of pollutants into the environment and the depletion of resources. There are mainly three types of models for aquatic systems: **physical, statistical** and **deterministic** models.

Physical models are basically hydraulic models. They involve the construction -in scale- of a solid physical model representing characteristics (topography etc.) of the studied area. They are often costly and time-consuming and their major disadvantage is that they only apply to one system.

Statistical models involve - as in the case of air pollution - the use of extensive past data. The data are subjected to regression analyses in order to determine correlation levels upon which basic predictions are then made.

Deterministic models - as in the case of air pollution - are based on the use of exact mathematical formulations to describe the movement of substances in the environment. The main types of such mathematical deterministic models are: **analytical** for solving the problem analytically by means of differential equations and **numerical** for solving the problem numerically with possibility of programming its solution on a digital computer.

Considerable attention has been paid to the modelling of **solid waste disposal** but most of the models are normative in nature. The general purpose of such models is to devise an optimal disposal pattern, when the sources and quantities of solid waste are given. The models also attempt to define the technical options and the optimum disposal locations in order that environmental standards are met and costs are kept low.

4.6.1 Mathematical (deterministic) simulation modelling of air pollution

A deterministic mathematical air pollution simulation model will be used for the purposes of the present work. Such a type of model, which actually is (Turner, 1979) a mathematical expression of the effects of the atmosphere upon air pollutants can give insight into the behaviour of the real-world (i.e. atmospheric) system and describe interrelation between different processes involved in the dispersion and transport of pollution. In this way potential air pollution impact can be estimated. Apart from this the model can be utilized for a number of additional purposes, such as the study of pollution episodes, the study of the efficacy of various pollution abatement strategies, the determination of regulations needed to implement standards to prevent significant deterioration of air quality etc.

Models, therefore, can be a powerful tool for environmental problem-solving, decision-making and planning activities. Their value lies, mainly, in the following facts (McCuen, 1975):

1. Most systems and problems in nature are dynamic i.e. they vary with time; it is very important to consider, when comparing project alternatives, the effects of changes which occur in the system over a period of time.
2. When making a decision it may be very important to perform risk evaluation. For this purpose it is necessary to evaluate the effect, which the changes in the components of the system will have upon the output.
3. In addition to predicting the response of the system a model can be used in order to get insight into the subsystems and/or external factors which influence the output and to evaluate their relative importance.
4. Verification of a model can be a useful process. If it is used in combination with information provided from other resources (e.g. a monitoring network) it can identify deficiencies and indicate improvements of the existing information; on the other hand possible deficiencies in the structure of the model itself can be detected through its verification by means of already existing reliable information.

Models, however, are by no means perfect; they have both advantages and disadvantages. In general, it can be said (Frenkiel and Goodall, 1975) that their power lies in the complexity of the systems they can examine, while their weakness is a result of the simplistic assumptions that may be used in some or all of the component parts of the system they simulate.

As it was mentioned in the previous section, two ways are mainly followed in order to obtain the pollution load (i.e. the ambient pollutant concentration) over an area, namely, measurements and simulation modelling. By following the former i.e. by performing a survey of pollution concentrations via direct measurements, only the current distribution of the pollutant is obtained and possibly an historical account on the changes of the distribution if series of past data are available; no information on the relative contribution of each existing source to the total air pollution concentration is provided. Such information on relative contributions from the various types of sources is very important in decision- and policy-making, as for example in planning industrial, commercial and residential developments. In those cases an assessment of the air pollution impact of a proposed plan prior to its construction is much more efficient than only monitoring the air quality status after the plan has been implemented in order to simply record its environmental impact and possibly in order to impose additional controls.

The two methods (i.e. measurements and simulation modelling) can of course be used in combination. Because pollutant concentrations are highly depended on local sources (Keddie et al., 1975) a very dense (particularly for urban areas) and, consequently, expensive network of monitoring sites is necessary in order to provide a reliable pattern of the distribution of pollutant concentrations. In such a case diffusion modelling can assist in the spatial interpolation of measured concentrations provided of course that the necessary emission parameters are available for each source. Furthermore, in many instances (op.cit.) a model can indicate the distribution of a pollutant over an area in a much quicker and cheaper way than a monitoring network. The prediction of pollutant distributions over an area can also indicate the most suitable locations for placing monitoring stations. A monitoring network, on the other hand, is useful because it can provide baseline information about the distribution of pollutant concentrations (i.e. provide the pattern of the distribution); it can also assist to the calibration or/and validation of the model.

In general, when both measurements from a network and simulation results from a model are used, one is interested to know:

1. the temporal performance of the model i.e. the relation between measured and simulated values over a time period for each station of the network separately.
2. the spatial performance of the model i.e. the relation between measured and simulated values at a certain moment in time for all stations in the network (i.e. over the space involved).

For the comparison of simulated (i.e. calculated by a simulation model) and the respective measured concentrations various statistical techniques are proposed in literature. Some commonly used statistical techniques for analyzing model performance are, for instance:

- residual analysis: measure of variation of residuals by calculating the standard deviation of residuals.
- regression analysis and construction of scatter diagrams.
- calculation of correlation coefficients (temporal and spatial) etc.

4.6.2 Types of mathematical air pollution simulation models

As mentioned before a mathematical air pollution simulation model is a way to express in mathematical terms the effects of atmospheric phenomena upon air pollutants. These phenomena and effects are (Fig. 4-32):

1. plume rise i.e. the rise of gases exiting from a stack as a result of their velocity and high temperature; for the purposes of calculations it is assumed that diffusion starts from the top of the raised plume.
2. advection i.e. transport of pollution within the atmosphere.

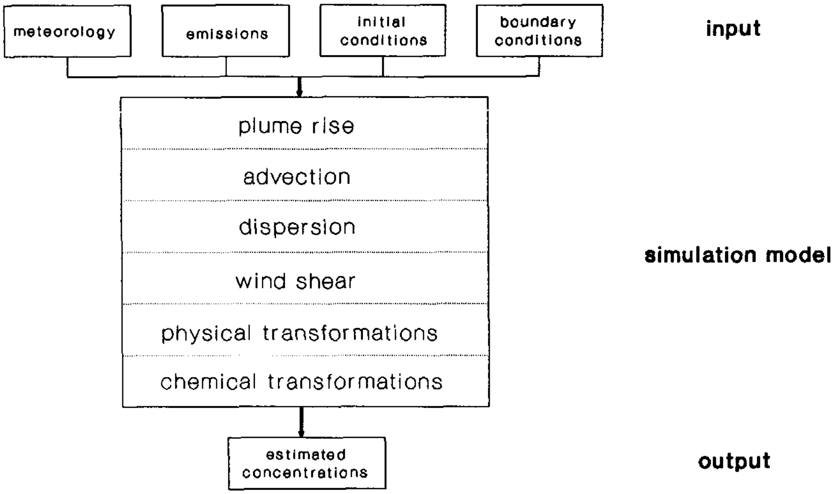


Figure 4-32. Phenomena and effects involved in mathematical air diffusion modelling.

3. diffusion i.e. dilution by wind and turbulence (see section 4.4.4.1).
4. wind shear (see section 4.4.4.1).
5. chemical and physical transformations (i.e. removal mechanisms as described in section 4.5).

All models consider effects 2 and 3 ; consideration for effects 1, 4 and 5, however, are not always to be found incorporated into models (Turner, 1979).

Input to models requires data on meteorology and emissions (see also section 4.6.1). Some models might also need initial conditions about the distribution (in 2-D or 3-D space) of pollutant concentrations or/and boundary conditions (e.g. background concentration).

A wide variety of models is available. Their common purpose is to establish a mathematical description of the processes which generate concentrations of pollutants in the atmosphere. If we consider an arbitrary volume of air V_a then the variation with time of the average concentration of a pollutant in this volume is determined by a number of processes, so that:

rate of advection into V_a
rate of change of + rate of diffusion into V_a
the average concen- = + rate of emission into V_a
tration in V_a - rate of physical loss out of V_a
+ rate of chemical products within V_a.

All mathematical air pollution simulation models are concerned with the mathematical description of the above continuity (conservation of mass) equation; the degree of simplifying assumptions varies among different models.

In Figure 4-33 an overview of the generic types of models is given. In order to give an example of the mathematical and physical background which consists their basis, the derivation of the two models mostly used for regulatory applications (i.e. Gaussian and Gradient-transport) is given in Appendix II.

In this work an algorithm based on the Gaussian model will be used. Before giving the theoretical basis and the assumptions of this particular algorithm (section 4.7) the theoretical basis of the Gaussian model will be described in more detail.

gradient transport	eulerian grid multibox	lagrangian box trajectory	particle-in-cell (pic)
gradient transport models express the change of concentration with respect to time as a function of diffusion, advection and emissions they are most appropriate when the turbulence is mos confined to scales which are small relative to the pollutant volume; it is suitable for continuous line and area sources at ground level (such as traffic emissions in urban areas); it is not appropriate for elevated point source diffusion, until the plume has grown larger than the space scale the model is mostly used for regulatory applications in eastern european countries	an eulerian multibox model consists of a number of elements of constant volume, in a fixed spatial grid covering the entire region of interest; pollutants are allowed to flow through the boundaries of each element as a result of advection, diffusion, sources and sinks the multibox simulation produces time histories of average pollutant concentrations with spatial resolutions determined by the size of the grid elements; usually the horizontal dimension of a grid element is a few kilometers eulerian grid multibox models are the most comprehensive approach to simulating air quality on a regional basis; however, they require a lot of input data and preprocessing effort they are not suitable for calculating local effects from strong sources, but rather to simulate for a few days the "typical" or "worst-case" conditions	lagrangian box (trajectory) models simulate the time history of pollutant concentrations within boxlike elements of constant volume as they flow along the direction of the wind the box might have more than one layers between the terrain surface and the level of the inversion height; as the box flows across the source, pollutants may flow in through the bottom of the source and diffuse vertically through the layers; horizontal transport of pollutants across the boundary of the box is not allowed the horizontal dimension of the box is on the order of few kilometers the models consider chemical reactions they work best in areas with relatively uniform source distribution and meteorology, where the number of trajectories is small, otherwise calculations might be extended	this type of model uses the concept of the so-called marker particles, each marker representing a fixed mass of pollutant an eulerian grid is used; the markers are introduced into the grid where emissions occur and area tracked as they are transported and dispersed throughout the 3D grid by the wind; at the end of any time interval the con- centration of a pollutant at any grid element is obtained by summing the masses represented by the particles still found in the element PIC models are suitable for accurate 3-D simulations of concantrations produced by localized sources they do not consider chemical reactions another serious limitation is the large number of particles they have to track

Figure 4-33(i). Generic types of mathematical air pollution simulation models.

rollback	one box	gaussian plume	gaussian puff
the basic assumption is that the concentration of a pollutant is directly propor*tional* to the strength of the source emissions of that pollutant the objective of rollback models is to determine the degree to which source emissions must be reduced if some desired air quality has to be obtained the models are easy to use their *basic* limitations are: they do not consider changes in spatial and temporal variation of emissions they do not consider changes in meteorology the fact that nearby sources make a larger contribution is not recognized they do not consider chemical reactions rollback models are officially sanctioned by EPA for use in developing implementation plans for the satisfaction of air quality standards	one box models assume that pollutants are uniformly mixed throughout a box of air with a volume fixed in space; horizontally *the box* covers the region where sources are distributed, vertically the box extends up to the *inversion* lid no in- and out transport of pollutants from the box is considered the concentration *is directly* proportional to the emission rate and to the distance between source-receptor; it is *inversely proportional* to wind speed (and therefore residence time) and inversion height one box models *are* useful for making first approximations of concentrations; they are suitable for estimating average *concentrations* over large area sources although in their original form they do not account for chemical transf*ormations* they can be modified to do so	gauss*ian* plume models assume that the concentration of a plume emitted from a single point source (i.e. a stack) is a function of source strength, average wind velocity and two diffusion parameters; the turbulent diffusion in the direction of the wind is negligible and in the cross-*wind* and vertical directions is assumed to produce a gaussian distribution of concentrations it can *also* be used for multiple point sources and for line and area sources the models account for loss *mechanisms*, but not for chemical reactions the limitations of the models: the wind field is constant *complex terrain* not considered calm winds and low inversions not considered chemical reactions not consid. advantages *of the models* are their simplicity and ease; they are officialy sanctioned by EPA and they are the most frequently *used, especially* in Western countries	in their simplest form, gaussian puff models track a puff of pollutant emitted from a point source, as it is blown down*wind* and diffused in a gaussian manner concantrations from multiple *sources* can be calculated by summing the concentrations from individual sources gaussian puff models can be used for *light* wind conditions they do not consider terrain complications or chemical reactions they are best applied to cases of few sources and few nearby receptors for widely distributed sources and multiple receptors the large number of trajectories required, makes the use of the model *prohibitive* gaussian puff models are not widely used

Figure 4-33(ii). Generic types of mathematical air pollution simulation models.

4.6.2.1 The Gaussian model

The Gaussian model is undoubtedly the most frequently utilized mathematical tool for calculating atmospheric diffusion; its use is almost exclusive when it comes to practical, 'engineering' implementations of air pollution diffusion (Melli and Spirito, 1982).

For the description of the principles of the model a three-dimensional coordinate system is employed (Fig. 4-34), having:
- its origin on the ground.
- the source (a stack of height h_s) located at the origin.
- the **x** axis downwind (i.e. along and toward wind direction) from the source.
- the **y** axis crosswind.
- the **z** axis vertically.

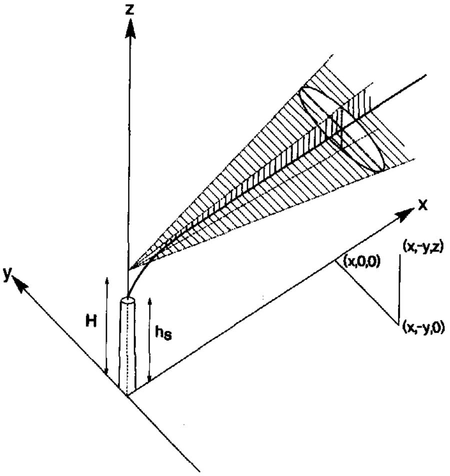


Figure 4-34. Coordinate system used for the Gaussian model.

The basic principles of the model are as follows:
1. Concentrations from a continuously emitting point source are proportional to the emission rate.
2. The concentration of a pollutant decreases when wind speed increases (see also Fig. 4-22 in section 4.4.4.1); concentrations at ground level, however are greater for higher wind velocities, because the plume is immediately forced downward, before the pollutant can be dispersed over a broader area.
3. The time averaged (usually about one hour) pollution concentrations in the crosswind and vertical directions are described by Gaussian (i.e. normal, bell-shaped) distributions (Fig. 4-29, 4-30). The

horizontal and vertical standard deviations σ_y, σ_z of the distribution of concentrations (they will be discussed later in this section) are related to the levels of turbulence in the atmosphere and they increase with distance from the source.

The assumptions most often found in simple implementations of the Gaussian model are:

1. The pollutant considered does not undergo chemical reactions or other removal mechanisms during its travel away from the source.
2. When reaching the ground (or the top of the mixing layer) the pollutant is reflected back to the plume centerline. This phenomenon is known as eddy reflection (see also Appendix II).

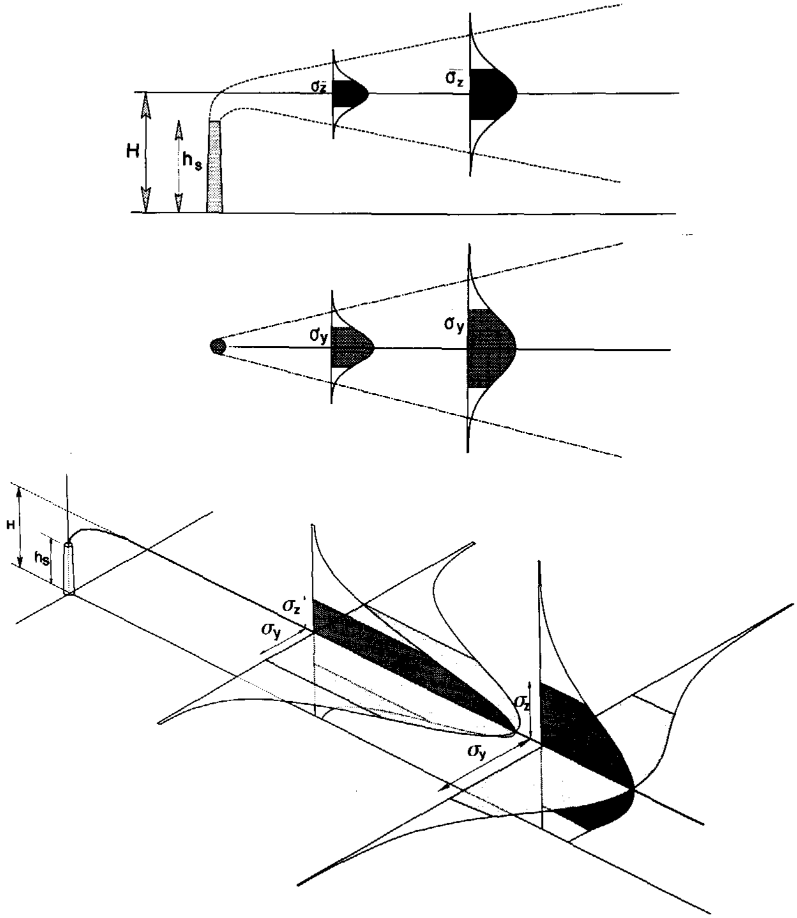


Figure 4-35. A Gaussian plume(a): vertical cross-section.
(b): horizontal cross-section.
(c): three-dimensional view.

The following symbols are used in the equations of the Gaussian model (eqs. 4-2 through 4-7):
c: concentration
S : emission rate
u : wind speed
σ_y : standard deviation of horizontal distribution of concentration
σ_z : standard deviation of vertical distribution of concentration
π : 3.141592
L : mixing height
h : physical stack height
H : effective height of emission
x: downwind distance
y: crosswind distance
z: receptor height above ground

The basis of the Gaussian model is a simple formula, assuming constant wind speed and complete eddy reflection. Three variations of the formula are used (eq. 4-2, 4-5, 4-6), depending on atmospheric stability conditions (compare with equations in Appendix II).

For **stable** conditions (unlimited vertical mixing i.e. a very high mixing height) the concentration c is given by:

$$c = S \frac{1}{2\pi u} \frac{g_1}{\sigma_y} \frac{g_2}{\sigma_z} \tag{eq. 4-2}$$

where:

$$g_1 = \exp(- \frac{1}{2} \frac{y^2}{\sigma_y^2}) \tag{eq.4-3}$$

$$g_2 = \exp[- \frac{1}{2} (z-H)^2 / \sigma_z^2] + \exp[- \frac{1}{2} (z+H)^2 / \sigma_z^2] \tag{eq. 4-4}$$

For **unstable** or **neutral** conditions, with $\sigma_z > 1.6L$ the concentration c is given by:

$$c = S \frac{1}{u} \frac{g_1}{\sigma_y \sqrt{2\pi}} \frac{1}{L} \tag{eq. 4-5}$$

where g1 as in (eq. 4-3).
It is assumed that both H and z are below the mixing height L; if H or z is above L, then c=0.

For **unstable** or **neutral** conditions, with $\sigma_z < 1.6L$

$$c = S \frac{1}{2\pi u} \frac{g_1}{\sigma_y} \frac{g_3}{\sigma_z} \tag{eq. 4-6}$$

where:

$$g_3 = \{\exp[-\frac{1}{2}(z-H+2NL)^2/\sigma_z^2] + \exp[-\frac{1}{2}(z+H+2NL)^2/\sigma_z^2]\} \quad \text{(eq. 4-7)}$$

Usually an evaluation of g_3 with N varying from -4 to +4 is sufficient, because the series converges rapidly.

Several methods exist for the estimation of the **dispersion parameters** σ_y and σ_z, such as (Stern et al., 1984):

1. Measurements of wind fluctuations.
2. Classification of wind direction traces in order to determine turbulence characteristics of the atmosphere. Turbulence characteristics are then used for estimation of dispersion coefficients.
3. Classification of atmospheric stability.

The third method, which is often used in practice, is briefly reviewed here. Atmospheric stability has been classified by Pasquill on the basis of wind speed, insolation and cloudiness (Pasquill, 1961), (Fig. 4-36).

Surface wind speed (m/s)	Insolation			Night	
	Strong	Moderate	Slight	Thinly overcast or ≥ 4/8 low cloud	≤ 3/8 cloud
<2	A	A–B	B	—	—
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

(for A–B, take the average of values for A and B, etc.)

Figure 4-36. Pasquill stability classes

The dispersion parameters σ_y, σ_z were expressed in terms of distance downwind from the source for each Pasquill stability class by Gifford (Gifford, 1976), (Fig. 4-37).

The parameters σ_y, σ_z can be found either by estimation from the graphs of Fig. 4-37, or from tables which have been developed on the basis of those graphs. As an example, estimations of σ_y, σ_z developed by Briggs for urban and rural situations are shown in Figures 4-38 and 4-39.

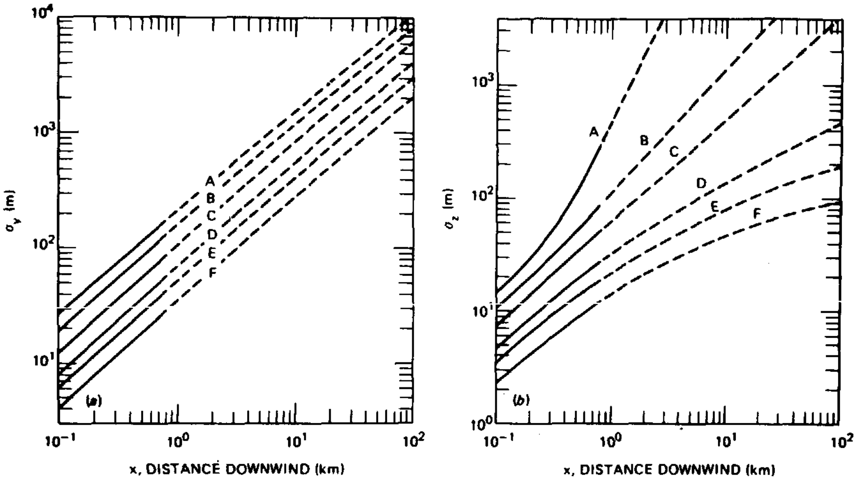


Figure 4-37. Pasquill-Gifford curves

Urban Dispersion Parameters by Briggs (for Distances between 100 and 10000 m)

Pasquill type	σ_y, m	σ_z, m
A–B	$0.32x\ (1 + 0.0004x)^{-0.5}$	$0.24x\ (1 + 0.001x)^{0.5}$
C	$0.22x\ (1 + 0.0004x)^{-0.5}$	$0.20x$
D	$0.16x\ (1 + 0.0004x)^{-0.5}$	$0.14x\ (1 + 0.0003x)^{-0.5}$
E–F	$0.11x\ (1 + 0.0004x)^{-0.5}$	$0.08x\ (1 + 0.0015x)^{-0.5}$

Figure 4-38. Briggs formulae for σ_y, σ_z (urban case).

Rural Dispersion Parameters by Briggs (for Distances between 100 and 10000 m)

Pasquill type	σ_y, m	σ_z, m
A	$0.22x\ (1 + 0.0001x)^{-0.5}$	$0.20\ x$
B	$0.16x\ (1 + 0.0001x)^{-0.5}$	$0.12\ x$
C	$0.11x\ (1 + 0.0001x)^{-0.5}$	$0.08\ x\ (1 + 0.0002x)^{-0.5}$
D	$0.08x\ (1 + 0.0001x)^{-0.5}$	$0.06\ x\ (1 + 0.0015x)^{-0.5}$
E	$0.06x\ (1 + 0.0001x)^{-0.5}$	$0.03\ x\ (1 + 0.0003x)^{-1}$
F	$0.04x\ (1 + 0.0001x)^{-0.5}$	$0.016\ x\ (1 + 0.0003x)^{-1}$

Figure 4-39. Briggs formulae for σ_y, σ_z (rural case).

4.6.3 Other options of models

Various formulae exist for the estimation of **plume rise**, H-h_s (Fig. 4-34, 4-35). The most commonly used are those of Briggs (see e.g. Briggs, 1975, Hanna, 1982).

In regulatory applications it is often of interest to know the **maximum impact** of a single source. Gaussian type models have been useful for determining maximum ground level concentrations from a single source. Maximum concentration usually occurs within 10-20 kms from the source, assuming flat terrain. Determination of maximum concentration from multiple sources, however, is a difficult and time-consuming task. Some models may propose certain methodologies for looking for maximum concentrations in an area; for this purpose, however, data over a long period are required (e.g. a year) and multiple model runs have to be performed so that an indication of the most-polluting sources is obtained empirically.

For estimating concentration (at a certain receptor location or at multiple receptor locations) mathematical air diffusion models actually use the concept of diffusion from a single point source or/and a single line source which, actually, is derived also from a point source (see e.g. Petersen, 1978). Differences between these models occur only in the details of how the area source summation is carried out and how meteorological parameters are included. Some models, for instance, perform an integration over both the alongwind and the crosswind dimensions of the source (op. cit.). Other models use the so-called **narrow plume hypothesis** which is based on the observation that point sources in the atmosphere tend to be long and narrow and therefore the component of the diffusion in the crosswind direction can be neglected. Consequently, the concentration at a point (Gifford and Hanna, 1971) can be influenced only by sources in a narrow plume-shaped upwind sector. Therefore, models based on the narrow plume hypothesis consider the variation in emission rates from each area source only in the alongwind direction. In order for such an assumption to give acceptable results, however, receptors should be located within area sources or emission rates should not vary markedly from one area source to another (Stern et al., 1984).

4.7 The RAM air quality simulation algorithm.

For the purposes of the present application a computerized version of an algorithm based on a mathematical air pollution simulation model is used. The designation of the algorithm is **RAM**; it is one of the atmospheric dispersion algorithms on the User's Network for Applied Modelling of Air Pollution system (UNAMAP) developed by the U.S.E.P.A. (United States

Environmental Protection Agency). RAM is a method of estimating short-term dispersion using the Gaussian model (Novak and Turner, 1976). It can be used to estimate concentrations of stable air pollutants emitted from urban point and area sources for averaging times from one hour to one day. The location where the concentrations will be estimated is selected by the user; in this way the spatial variation in air quality for the whole area or for a part of it can be derived. RAM can also estimate maximum concentrations, although the procedure required for this purpose requires a lot of time and computer memory.

Air pollution control agencies can use RAM to predict ambient air quality levels, primarily over the 24-hour averaging time period. For this purpose the values of the necessary meteorological parameters (see section 4.7.2) have to be forecast with sufficient accuracy. Such ambient air quality predictions can be useful for locating mobile air sampling units and/or assisting with emission reduction tactics. RAM can be used by urban planners in order to determine the effects of new developments (e.g. new source locations) and/or the effects of short-term control strategies upon air quality.

The accuracy of the predictions of the algorithm depends mainly on:
1. the ability to forecast the values of the meteorological parameters.
2. the accuracy of the emission inventory.
3. the assumptions of the air quality algorithm itself.

4.7.1 Theoretical basis of the algorithm.

The basic principles of the RAM algorithm are as following (Novak and Turner, 1976 and 1978):

It is assumed that emissions from continuous sources are stretched along the direction of the wind according to the wind speed. This means that the stronger the wind the greater the dilution of the plume (see Fig. 4-24). The input wind speed data in RAM are assumed to be representative for a height of 10m above ground. For estimating dispersion from a stack the wind speed should refer to the stack top (section 4.4.4.1) a power law increase with height is used in RAM; this law accounts for increase in wind speed with height from the point of wind speed measurement to the stack top.

The distribution of concentrations resulting from a continuous emission from a point or an area source is considered to be Gaussian in both the horizontal and vertical directions (see Fig. 4-34, 4-35). The atmosphere is assumed to be a single layer in the vertical direction i.e. a layer with the same rate of vertical dispersion throughout its extent with the exception of stable layers aloft which inhibit vertical dispersion. RAM assumes complete eddy reflection from the ground and from the vertical layer above. In such a case the portion of the distribution that would extend beyond the barrier is "folded back"; this is equivalent to a virtual mirrored source beneath the ground or/and above the layer (see e.g. section 4.6.2.1. and Fig. AII-9 in App. II).

The minimum average time used in RAM is one hourly period; estimates are made using the mean meteorological conditions for that hour as if **steady-state** conditions had been achieved.

Concentrations are additive i.e. the total concentration of a pollutant at a receptor is the sum of individual concentrations from each point and area source to that receptor. Concentrations for an averaging time longer than one hour are the arithmetic mean of the hourly concentrations during that period.

The **effective emission height** for the case of point sources is the physical stack height plus the plume rise (Fig. 4-34, 4-35). The calculation of plume rise in RAM is derived from the stack gas temperature, the stack diameter and stack gas exit velocity using the methods of Briggs (see section 4.6.3). These methods have been developed to include effects of downwash in the lee of the stack, of plume rise due to momentum and of plume rise due to buoyancy. Details about the methods are discussed in: Briggs, 1975, Hanna, 1982 and Novak and Turner, 1978.

As already mentioned, RAM calculates concentrations from point and area sources.

For the calculation of concentrations from **point sources** the same Gaussian formulae given in section 4.6.3.1 are used. The values of the dispersion parameters σ_y and σ_z are determined as functions of upwind distance and stability class. The stability classification used in the algorithm is that of Pasquill. For urban conditions the formulae of Briggs are used (see Figure 4-38); for rural conditions values derived from the Pasquill-Gifford curves are used (Fig. 4-37).

Concentrations from **area sources** are calculated using the narrow plume simplification (section 4.6.3). More details over computations and formulae used in RAM can be found in Novak and Turner, 1976 and 1978.

4.7.2 Characteristics of the algorithm.

The **input data** required by RAM are emission and meteorological data and, depending on the receptor options used, the program may also require receptor data. Emission data are further distinguished in point source data and area source data.

Point source data consist of the following, for each source:

1. Cartesian (x,y) coordinates of source location.

2. Physical stack height.
3. Stack inside top diameter.
4. Stack gas temperature.
5. Stack gas exit velocity.
6. Pollutant emission rate.

Area source data consist of the following, for each source:
1. Cartesian coordinates of the southwest corner of the area source (area sources must be squares).
2. Effective emission height.
3. Side length of area source.
4. Total emission pollutant rate for the area.

Meteorological data consist of hourly values of the following:
1. Wind direction (measured clockwise from North).
2. Wind speed.
3. Stability class (according to Pasquill classification).
4. Mixing height.

Vertical wind shear (i.e. change of wind direction with height, see section 4.4.4.1) is not included in RAM. This means that the direction of flow is assumed to be the same at all heights over the area. As a consequence, the taller the effective height of a source, the greater the error in calculating the direction of the plume transport.

Meteorological data can be input to RAM by either of the following ways:
1. As hourly values of the previously given parameters, directly specified by the user.
2. As hourly values of the same parameters (plus temperature) contained in a large file with data for one year; this file is the result of a special meteorological preprocessor program (program RAMMET) which can be optionally used in order to determine the above values from meteorological observations.

The input data for RAMMET consists of **surface** data and **upper air** data, given in the standard format used by meteorological offices. Surface data (usually available in hourly records) are: year, month,day, hour, cloud ceiling (i.e. height of lower cloud layer), wind direction, wind speed, temperature and cloud cover (i.e. density of cloud layer). Upper air data are the minimum and the maximum mixing height for each day of the year; RAMMET interpolates from the twice-a-day mixing height to obtain hourly values. The program determines hourly meteorological data for wind direction, wind speed, temperature, stability class and mixing height. These data are written to a file with one record per day for the entire year, which is then used as input to RAM (Fig. 4-40).

If the user chooses to define the receptors, he/she should input to RAM the Cartesian coordinates of the location of each receptor. Only one receptor height above the ground level is allowed for one execution of the model.

The RAM algorithm uses the assumption of a flat plane to simulate the terrain; therefore it should be used for applications over level or gently-rolling terrain, where this assumption is reasonable. In reality, under unstable conditions plumes may tend to rise over terrain obstructions; under stable conditions plumes remain in the same height but alter their path in response to the terrain features, having thus a different direction locally than that specified by the average wind direction for the area. RAM does not make concentration estimations for topographic complications and the greater the departure from flat terrain, the larger the error in the estimated concentrations will be.

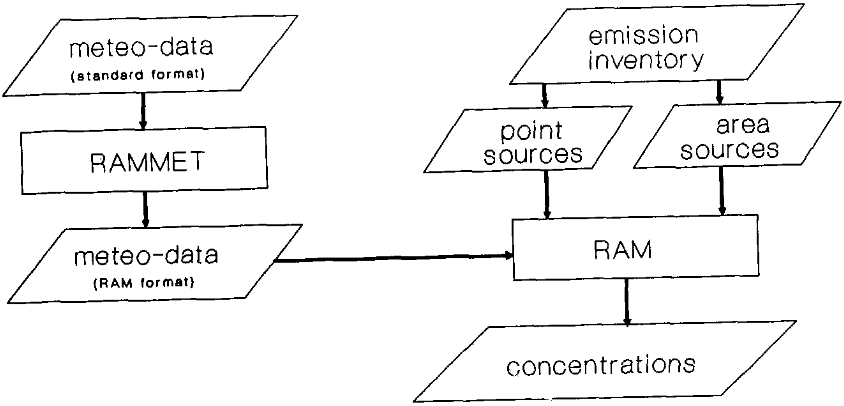


Figure 4-40. General flow diagram of RAM.

RAM is suitable for inert pollutants i.e. pollutants which are stable chemically and physically; it does not therefore account for chemical reactions. A general loss of pollutant with time, however, can be considered by specifying the pollutant half life (see section 4.5).

The algorithm has the option of calculating dispersion in two types of areas, namely **urban** and **rural**. The values of the dispersion parameters for urban area are those recommended by Briggs (see Fig. 4-38, section 4.6.2.1). The values of dispersion parameters for the rural version are based on the Pasquill-Gifford curves (Fig. 4-37, section 4.6.2.1).

4.8 Air pollution control

The objective of air pollution control is to reduce the emission of primary pollutants to the atmosphere in order to **prevent air pollution effects** i.e. adverse responses of humans, animals, vegetation and materials exposed to the atmosphere. A highly simplified concept of air pollution control is given in Fig. 4-33, consisting of three basic components:

1. elements generating air pollution i.e. sources, emissions, atmospheric transport/diffusion and concentrations.
2. air pollution effects.
3. control procedures.

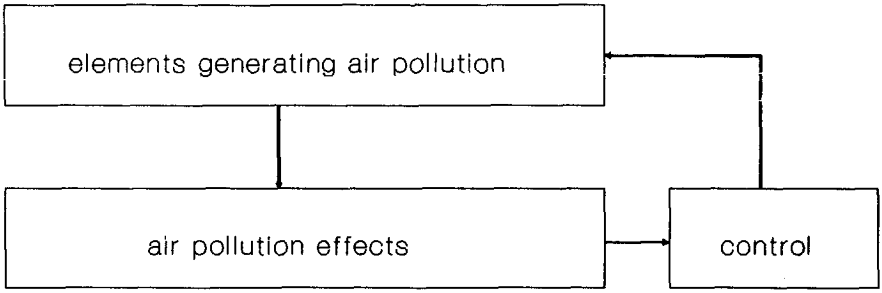


Figure 4-41. The main components of air pollution control.

Two sorts of air pollution control can be distinguished (Stern et al., 1984): tactical and strategic.
Tactical air pollution control is concerned with short- or intermediate-term episodes (i.e. lasting from some minutes to some hours), which usually occur in an urban environment. **Strategic** air pollution control is concerned with the reduction of pollution levels in a long term perspective (i.e. for five, ten or fifteen years) for all categories of the air pollution problem i.e. from local to global. A general model of an air pollution control system for both sorts of control is shown in Fig. 4-42. It can be seen that the elements generating air pollution constitute the kern of the system. Apart from these elements which have already been discussed, the rest will be briefly reviewed here.

For the purposes of **tactical** control e.g. in a case of an urban air pollution episode a scenario has to be ready for immediate implementation in order to prevent hazardous air pollution effects on the organisms and materials exposed to the pollution. The scenario will be based on:

1. the air quality monitoring data i.e. the values of the concentration of pollutants measured at the stations of the air pollution monitoring network of the urban area.
2. the meteorological forecasts about calm, inversion or/and stagnation conditions in the area.
3. the capability of computing pollution concentration under the forecasted meteorological conditions; such a predictive computation is also known as a pollution forecast. A (quantitative) pollution forecast is usually done via pollution simulation models, such as the ones discussed in the previous sections (4.6 and 4.7).

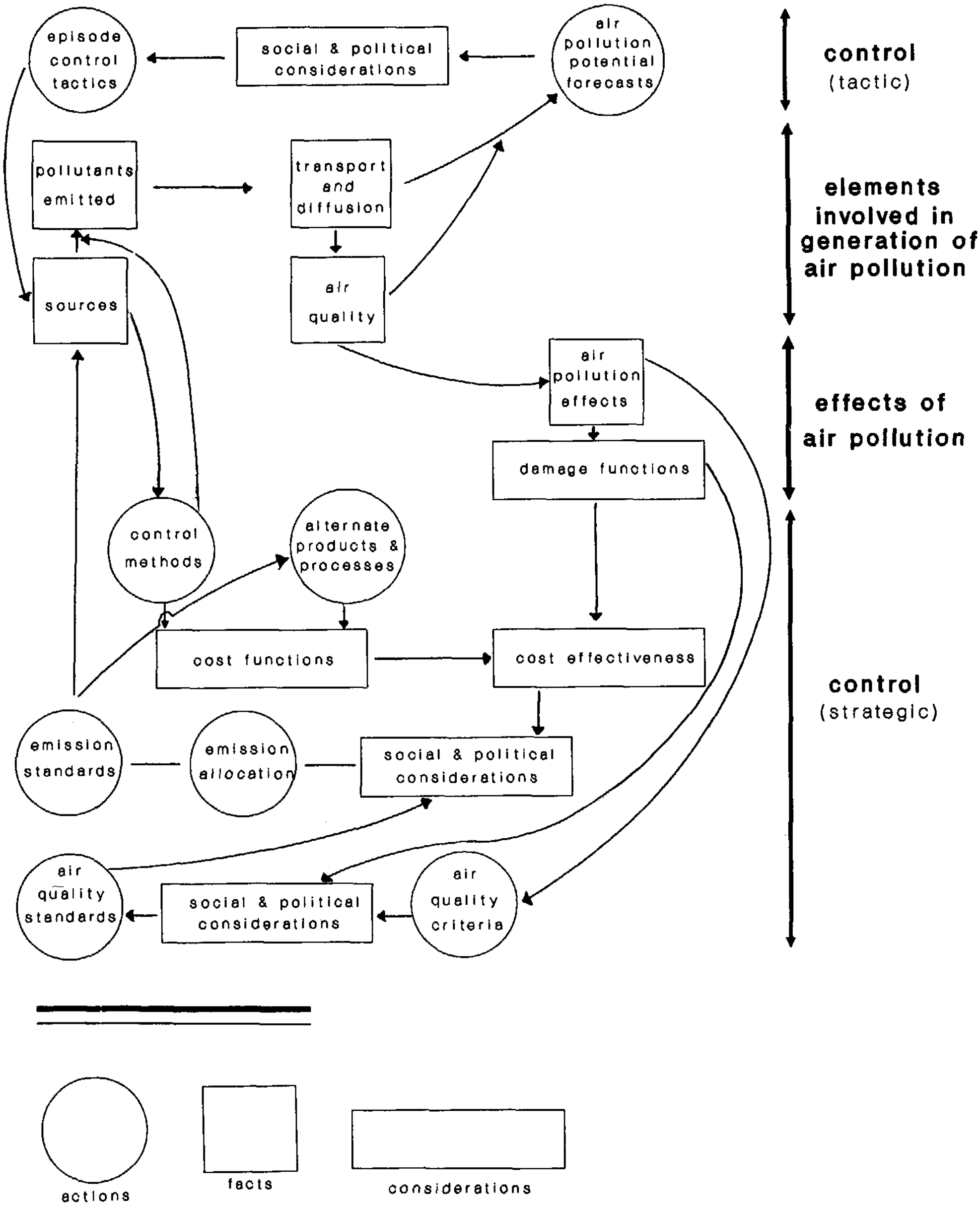


Figure 4-42. Concept of an air pollution control system.

On the basis of the predicted and the measured concentrations a number of various measures for the reduction of emissions can be followed; the strictness of the measures will be determined by the measured air quality as well as by the expected one. If the meteorological and the air pollution forecasts indicate a strong possibility for the air pollution level to hold or to increase for the coming few hours measures have to be taken according to the severity of the level (i.e. alert, warning or emergency). When taking such measures, however, the **social and political** costs involved have to be considered, openly discussed and generally accepted in advance (e.g. possible inconveniences for the population, disturbance of the usual city life etc.)
The **episode control tactics** consist of imposing strict limitations on sources during the episode (e.g. curtail or cease certain pollution producing industrial activities, impose restrictions on traffic etc.)

Control methods for sources can be implemented by mainly three ways:
1.by removing partially or totally the pollutants released into the atmosphere by using the suitable devices e.g. filters on stacks.
2.by changing or improving the raw materials used in the production or combustion processes e.g. improve the quality of fuel in industry and/or traffic.
3.by changing operations in the pollution producing process so that the emissions of pollutants will decrease.

If **alternate products and processes** are implemented it is possible to provide the same utilities to the public but decrease pollutant emissions. Such alternative solutions must also consider the associated costs.

The **damage functions** are the economic burdens (i.e. costs) which result from air pollution effects, that is, the costs from pollution damages to human health, damage to vegetation, materials etc.

The interrelation of damage functions and cost functions determines the **cost effectiveness** of an air pollution control strategy.

Some examples of **air pollution effects** were given in section 4.5. In order to prevent such effects the concentrations of pollutants in the atmosphere must be lower than the levels at which such effects occur. Air pollution effects usually determine the **air quality criteria** used for air pollution control. In general three levels of criteria are to be found: **alert** level, **warning** level and **emergency** level criteria. These criteria state how the air pollution effects are associated to the various air quality levels (i.e. pollutant concentration levels); see e.g. Fig. 4-43 for such criteria in the USA. The concentration level which the jurisdiction wishes to maintain is called an **air quality standard** . Before reaching these standards **social and political considerations** have also to be examined. An air quality standard is a value of air pollution concentration indicative of the air quality level which has to be maintained; it is not a primary control process. Only by imposing **emission standards** for the sources the air pollution can actually be controlled.

Emission allocation is the allocation of the control effort to the several responsible groups (industries, institutions, companies, landlords etc.). An emission allocation is imposed by the jurisdiction after considering the **social and political** issues associated with the subject.

	average time	alert	warning	emergency
SO_2	24 hrs	800 ug/m	1600 ug/m	2100 ug/m
	8 hrs			
	1 hr			
particles	24 hrs	375 ug/m	625 ug/m	875 ug/m
	8 hrs			
	1 hr			
SO_2 & particles	24 hrs	65 x 10 ug/m	261 x 10 ug/m	393 x 10 ug/m
	8 hrs			
	1 hr			
CO	24 hrs			
	8 hrs	17 mg/m	34 mg/m	46 mg/m
	1 hr			
O_3	24 hrs			
	8 hrs			
	1 hr	200 ug/m	800 ug/m	1000 ug/m
NO_2	24 hrs			
	8 hrs			
	1 hr	1130 ug/m	2260 ug/m	3000 ug/m

Figure 4-43. Alert, warning and emergency level criteria in the USA.

From Figure 4-42 it is seen that for both tactical and strategic control the final step is the **control of sources**; this means that air pollution control is applied by, finally, imposing limitations to sources. For the case of tactical control severe limitations are imposed to sources (e.g. reduce emissions and/or cease source operation); for strategic control purposes emission limitations are applied according to emission standards.

In practice different approaches to the implementation of air pollution control strategies (i.e. long term) are followed. The two main types are the following:

1. the strategy which is based on the development and establishing of emission standards.

2. the strategy which relies on the development and imposition of air quality standards.

Actually either approach involves the other (emission standards can be derived from air quality standards and vice versa); when it comes to practical implementation the choice is based on pragmatic reasons.

There also exists a third approach which combines the promulgation of air quality standards and financial incentives, such as taxes and restrains for pollution producing activities or/and subsidies for pollution control.

4.9 Spatial aspects of an urban air pollution control system

The air quality status in an area (i.e. the concentrations of air pollutants) is determined by the presence and interactions of a number of natural and man-made elements (Fig. 4-45, see also Chapt. 3). These elements can be considered as **primary** (or direct) when they are producing and transporting air pollutants; such elements are the sources and their emissions and the atmospheric conditions (meteorology); the primary elements generating air pollution constitute -together with air quality- the kern elements of an urban air pollution control system as described in the previous section (Fig. 4-42; compare also with Fig. 4-3). Other elements which influence the primary ones can be considered as **secondary** (or indirect) such as topography and the urban developments and activities taking place in the area. Figure 4-44 shows schematically how these two groups of pollution generating elements are linked in practice.

By their nature both primary and secondary elements are of significance when viewed within their spatial context; their visual representation is therefore a cartographic task. In this section the main themes to be displayed cartographically for the purpose of supporting decisions related to urban monitoring and control are introduced. In the following Chapter the contents of the maps are identified in detail.

The purpose of the proposed maps is, mainly, twofold:

1. to simply display the status of certain air pollution generating elements e.g. concentrations calculated by the simulation model or measured at the stations of the network, emissions, wind etc. (analytical maps).
2. to display a combination of elements in order to assist in conducting evaluations about the air pollution problem in an urban area. Air pollution, like many of the pressing problems facing mankind nowadays, is ecological in nature i.e. it involves a number of interrelated physical elements interacting with each other (Chandler, 1976; see also Chapt. 3). More complex maps (inventory maps) displaying the status of these various elements allow for making visual correlations which can be useful in case the displayed elements are physically interrelated.

Earlier in this Chapter the physical elements involved in urban air pollution were described. These elements determine the control actions to be taken by the air pollution office of an urban area. As already mentioned, these control actions are either tactical (i.e. a scenario for pollution episodes) or strategic. Strategic control is basically concerned with establishing and keeping air quality and emission standards: monitoring the air quality levels, checking the compliance status of industries with respect to emission rates and other technical characteristics or establishing buffer zones are some examples. Apart from this primary use (i.e. for the purpose of urban monitoring and control) the proposed maps also intend to enhance environmental evaluations and to be of use as visual (cartographic) aids for urban decision support. The air pollution office, therefore, is not the exclusive user of such information relative to pollution control: the urban planners should also be able to make use of the system, since they are directly concerned with the effects of the air pollution problem and their abatement in an urban area. The air pollution effects and control are also of interest to the general public,

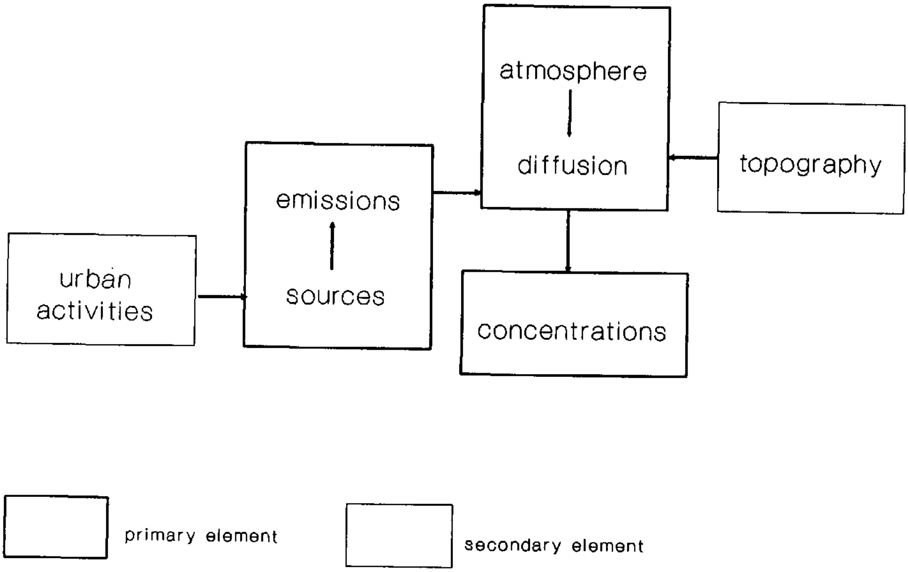


Figure 4-44. Primary and secondary air pollution generating elements.

which is very often affected by them (see also section 4.8). For this reason an information interface between the pollution office from the one side and the urban planners and general public from the other should exist.

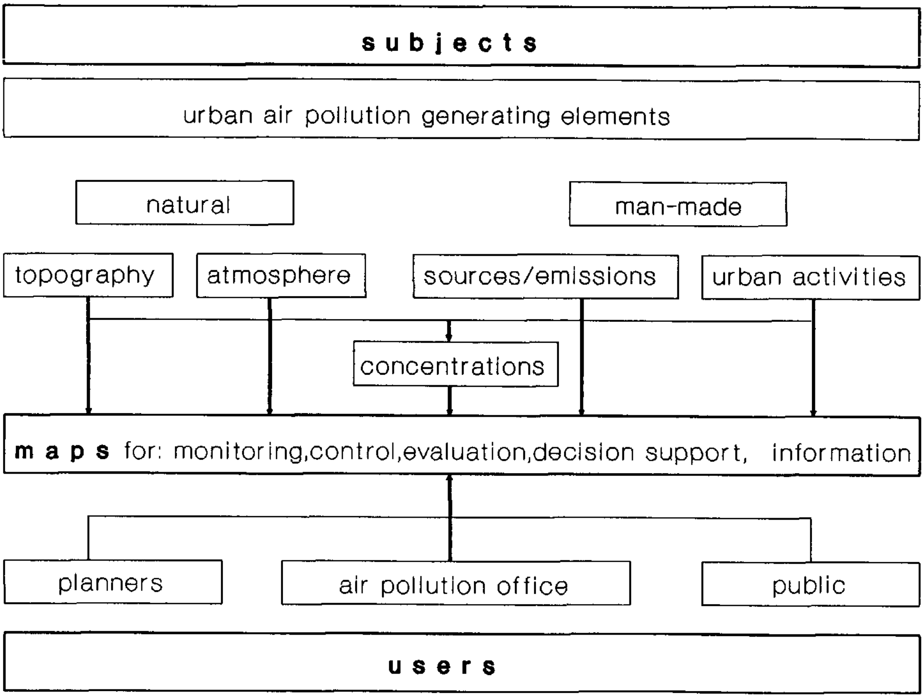


Figure 4-45. The main subjects and users of the proposed maps.

Summarizing (Fig. 4-45), it could be said that the main groups of subjects to be visualized are determined by:

1. the pollution generating elements and their relations with each other.
2. the tasks and needs of the users involved

In the following Chapter these topics will be discussed in more detail, in order to derive the subjects to be mapped (visualized) and, in a next step, their cartographic representation.

CHAPTER 5. A CARTOGRAPHIC PROTOTYPE FOR URBAN AIR POLLUTION.

5.1 Introduction

In this Chapter a prototype of a softawre system for the cartographic processing and visualization of the causes and effects of urban air pollution is described. In section 5.2 the context of the Chapter is given. The themes of the maps, which were briefly introduced in the previous Chapter, are further discussed in section 5.3. The remaining elements of external map identification (i.e. scale and projection) are also discussed in the same section. In section 5.4 the elements of internal identification are considered (mainly accuracy aspects) as well as the cartographic representation of the mapped themes. Computer science aspects are introduced in the following section (5.5), where a general overview of the map creation process is given by means of flowcharts of the computer software programs used.

5.2 The map elements.

In Chapter 2 it was mentioned that the identification of the elements of a map involves two processes: the process of **external** identification which is independent of the graphic image itself and during which the invariant and the involved components are identified mentally, and the process of **internal** identification during which the visual variables which correspond to the components are identified in the drawing. Map identification was given there (section 2.4.1.1) from the user's point of view i.e. as part of the map reading process. Nevertheless, these same map elements are already determined during the map creation process. In other words the questions which a map user asks when he/she is confronted with a map are the same questions that a cartographer asks (or has to ask) in order to create this map. The elements of map identification, therefore, constitute the points to be considered for the creation of any map.

The two main questions which are asked for the external identification are:
1. what is the **theme** (i.e. subject) of the map ?
2. what **space** is involved ?

The answer to the first question is given by the **title and legend** of the map which describe the invariant and the involved components; the answer to the second question involves a **dimensional** aspect (scale) and a **situational** aspect (geographic shape as determined by a projection) (Bertin, 1967; Bertin, 1983)

During internal identification the link between the components of the information and the corresponding visual variables is made, i.e. the **cartographic representation** of the mapped information is considered. Internal identification also involves the concepts of **accuracy** and **generalization** (op. cit.).

In the remainder of this Chapter the elements of external and internal identification for the maps proposed in this thesis are described.

5.3 External identification.

5.3.1 The physical elements involved in urban air pollution.

As mentioned in the previous Chapter the main subjects to-be-mapped for the purposes of urban air pollution monitoring and control are determined by the physical elements generating air pollution (and their interrelations) and the tasks and needs of the users. The primary and secondary physical elements which were introduced in section 4.9 and are further discussed here are:

1. Topography and terrain characteristics of the area.
2. Meteorological processes affecting transport and diffusion of pollution, such as wind, precipitation, temperature, humidity, inversions etc.
3. Urban activities and developments related to air pollution such as city extent, population characteristics, city and population growth through time, land-use, traffic load etc.

	Pollution Office	Urban Planners	Public
Topography	*	*	*
Meteorology	*	*	
Urban activities	*	*	
Sources and Emissions	*	*	
Air quality	*	*	*

Figure 5-1. The main topics to be mapped for each user group.

4. Air pollution sources (i.e. location and type) and their emissions as given by the emission inventory.
5. Air quality information such as: simulated and measured

concentrations, changes in air quality through time, alarm conditions, air pollution indicators (e.g. complaints of citizens about unpleasant effects) etc.

Figure 5-1 shows the physical elements which are of main interest for each user group. Each of these five groups of physical elements will be discussed in the following sections (5.3.1.1 to 5.3.1.5) in more detail and its influences upon the rest of the elements will be pointed out (the influencing elements will be given in **bold** letters, the influenced in *italics*). These elements and their influences upon each other are visually summarized in Figure 5-2.

5.3.1.1 Topography.

Topography is an aspect which can be considered as secondary (see section 4.9), since it influences other physical elements involved in urban air pollution such as the wind field, the land use or even the diffusion of pollutants in an area.

Topography influences the *three-dimensional air flow* over an area (see also section 4.4.4.1). **Natural obstructions of the terrain** such as mountains, hills, etc. influence the speed and direction of the wind horizontally and vertically. Other topographic features such as **water bodies** (e.g. lakes, rivers) **green zones** (e.g. forests, parks), **man-made constructions** (e.g. big buildings), are also determining the nature of the (3-D) wind field over the area. Apart from airflow, topography also determines the patterns of *temperature*, *precipitation* and *humidities* (Chandler, 1976). Among the most important changes induced upon the microclimate of the area are -from the point of view of urban planning- the changes caused by large buildings or building groups. For example, in the case of coastal towns having high summer temperatures, blocks of high buildings along the sea front should be avoided, since they would form an obstacle to the penetration of the sea-breeze into the city center, where usually heat islands develop (see following section).

The characteristics of the terrain influence also the *land-use pattern* of an area: e. g. the location of residential space, the location of sources and their pattern of distribution, the pattern of the traffic network etc. and possibly the *emissions from traffic*: cars driving on an ascending road will release more pollutants, since they operate in a low gear.

Terrain characteristics might also be critical for the *concentration* or the dilution of pollutants, especially when they are combined with certain atmospheric conditions: in a case of a temperature inversion, for example, the generation of air currents (i.e. the vertical movement

1. 3-D form of terrain
2. water
3. green
4. buildings
5. wind
6. temperature
7. solar radiation
8. moisture/precipitation
9. visibility
10. landuse
11. traffic density
12. population
13. migration
14. land coverage
15. city profile
16. age of buildings
17. industries (sites)
18. industries (sort)
19. industries (emissions)
20. traffic network
21. traffic emissions
22. C.H. emissions
23. concentrations
24. alarm conditions
25. traffic control
26. industrial control
27. monitoring stations
28. secondary pollutants
29. population reports

influenced elements

influencing elements

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1																													
2																							■						
3										■																			
4																													
5	■	■	■	■						■					■														
6	■			■	■					■		■		■	■														
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28						■	■	■																					
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Figure 5-2. The elements involved in urban air pollution and their interrelations (for explanation see sections 5.3.1.1 to 5.3.1.5).

of air masses) within the inversion layer is prevented and the pollutants are trapped vertically (see section 4.4.4.2). If the inversion takes place in the lower layers of the atmosphere (e.g. up to some hundreds of meters), the presence of natural terrain obstacles (mountains, hills etc.) is of significance, since these will prohibit the transport and dispersion of pollutants horizontally (see also Chapter 6 where the situation in the Athens basin is described).
Vegetated open spaces filter the air passing over them. It has been observed that concentrations of pollutants at the centers of green areas (e.g. city parks and forests) are lower than in the margins (Meetham, 1945; Hill, 1971). Green zones can abstract particulate matter and gaseous pollutants (Saunders and Wood, 1974).

Topographic features -both natural and man-made- are also important for the location of air pollution *monitoring stations*. For instance, monitoring stations should not be located in the neighborhood of large, tall buildings, since the turbulent eddies generated will affect the local concentrations, which, therefore, will not be representative for the nearby area (Stern et al., 1984).

5.3.1.2 Meteorology.

In the previous Chapter (section 4.4.4) it was mentioned that the most important meteorological phenomena related to air pollution are: **wind** (speed and direction), **temperature** (horizontally and vertically), **solar radiation, moisture and precipitation** and **visibility**.

Apart from the topography of the urban area its meteorological conditions should be considered, when selecting the *location of air polluting sources* (e.g. industries). Important industrial sources should not be cited in areas subject to light winds (as are, for instance the low-elevated areas) and to temperature inversions (Singer and Smith, 1970; Arnold and Edgerley, 1967).

Meteorology is of primary importance for the *air quality status* of an urban area since it determines the dispersion and dilution of the air pollutants. The effects of wind and temperature upon air quality have already been described in section 4.4.4.1 and 4.4.4.2 In the previous section the significance of their combined influence for the generation of alarm conditions was also mentioned. Another meteorological factor which can contribute to the formulation of secondary pollutants* in combination with temperature is solar radiation (formulation of photochemical smog). The role of atmospheric and terrestrial moisture have also been mentioned in section 4.4.4.3.

Meteorology is also of significance for the selection of the sites of air pollution *monitoring stations*. Seasonal climatological patterns of prevailing winds and frequency of temperature inversions should be considered for that purpose (Stern et al., 1984).

5.3.1.3 Urban background and activities. Historical developments.

The features of an urban landscape are of great influence to the climate of the area. The artificial constructions and materials comprising an urban unit alter the meteorological properties of the air above urban areas and tend to create a distinctive local type of (man-modified) climate, the urban climate (Chandler, 1976). Climatic features such as wind, temperature, humidity (i.e. moisture / precipitation), undergo changes which influence the pollution levels in the area.

Wind speed is generally lower in built-up areas than over rural areas (Chandler, 1965; Landsberg, 1956; Munn, 1970; see also Fig. 4-20). The direction of the wind within a city is controlled by the form of the buildings (see Fig. 4-5), by the patterns of streets and open spaces and by the form of the terrain (section 5.3.1.1). The pattern of airflow around buildings is a very critical factor for the diffusion of pollution from traffic. Concentrations in streets oriented at right angles to the wind are strongly affected by the turbulent eddies which are formed in such situations (see Fig. 4-5; see also: Nicholson, 1975). It has also been observed that, in general, the broader the street the greater the turbulence and, consequently, the lower the air pollution level: but even in narrow streets with tall buildings (i.e. the so-called "street canyons"), provided that they are oriented along the wind direction, the wind speed is enhanced by the so-called "venturi effect"* and the pollutant concentrations are kept low (McCormick, 1971). Therefore, each city's airflow pattern is unique; for this reason the development of an urban airflow model for a city is important for studying the air quality within the city. Especially when simulation models are implemented an urban airflow model representative for the particular city will provide more accurate meteorological input to the simulation model which will result in more accurate predictions of the air pollution levels.

Temperature is strongly influenced by urban settlements. Built-up areas are often covered by warm air (i.e. warmer than the air in their surroundings), which is known as a "heat island". Air temperature can also vary from one part of a city to another, due to different land use patterns (Chandler, 1976). Apart from spatial, also temporal variations in temperature have been detected over urban areas. In general, urban heat islands develop most during nights (the temperature difference between urban and rural surroundings may extend from 5° C to 11° C : Chandler, 1965; Bornstein, 1968; Peterson, 1969; Oke and East, 1971). After dawn the urban/rural temperature difference starts to decrease and might even reverse so that a "cold island" develops over the urban area (Chandler, 1976). **Land-use** is the most important factor determining the development of a heat island in an urban area (Clarke and Petersen, 1972). Other factors critical for the development of heat islands are the size of the city (expressed in **population** terms), the **wind speed**, and the **land coverage** (i.e. the density of the built-up area). Parks, open spaces, gardens, lakes, water bodies etc. distributed within an urban area tend to weaken the heat island. The **form of the buildings** can also be important for the creation of a heat island: tall buildings shade the streets and the nearby open spaces (parks, courtyards) of a city, resulting, therefore, in a cooling effect. The form of the buildings viewed in the context of the whole urban area (i.e. the so-called **city profile**) is, therefore, of significance. The highest day-time temperatures have been found to occur in a ring around the CBD (Ludwig and Kealoha, 1968). Patterns of *relative humidities* in cities are related to the form of the heat islands, which, as seen, depend on land use and land coverage (i.e. urban building density) (Chandler,1967). Influences of urban areas upon precipitation patterns have not been proved (Chandler, 1976).

Of historical importance -mostly from the urban planners' point of view- for the evolution of the air quality in an urban area are the **changes** which have occurred in the area through time e.g. patterns of internal migration which have contributed to the expansion of the city and the increase of the population, changes in land use such as expanding industrial areas, possible diminishing of the natural forests and green areas in and around the city etc.

The **land-use** pattern is closely associated to the spatial distribution of the various types of stationary and mobile *sources* (i.e. location and type of industries, central heating installations, pattern of the traffic network and traffic density. Other urban elements, such as **population density, land coverage** (i.e. density of urban settlements) are directly associated with the pattern of *emissions from central heating* installations; the **age of the buildings** is also critical in this case, because it is associated, in general, with the quality of the installations (i.e. boilers, burners) and therefore the quality and quantity of emissions (see also section 4.3.2). Since the pattern of emissions directly corresponds to the pattern of concentrations in an urban area (Chandler, 1976) all the above factors are of significance to the **air quality status.** Land-use, the pattern of the traffic network, traffic densities and population densities are elements which have also to be considered when locating air pollution *monitoring stations* (Stern et al., 1984).

5.3.1.4 Sources and emissions.

The pattern of air pollutant concentrations in an urban area is primarily influenced by the airflow conditions (section 5.3.1.2) and by the pattern of emissions (section 5.3.1.3).; the latter is, in turn, determined by the spatial distribution, the sort (type) and other technical characteristics of the **emitting sources.** In section 4.3.2 it was seen that the various types of sources generate different pollutants: the presence of SO_2, for instance, is primarily attributed to industrial activities, CO is directly connected to the density of automobile traffic and its emissions, smoke is released from industrial stacks and central heating burners. The overall land-use pattern, therefore, is indicative of the general emission patterns of the various pollutants. The local characteristics of the land-use will determine possible emission variations (e.g. old buildings with aged central heating installations will probably produce larger quantities of emissions (see section 4.3.3); an area with battery manufacturing industries will have higher lead emissions than its surroundings etc.).

In general the pattern of **emissions** is closely related to the pattern of *concentrations*, particularly during stability and light wind conditions. The diffusion of different air pollutants, however, after their emission will vary according to their physical (aerodynamic) properties, in combination with their height of release. For example, SO_2 can drift farther away from the source of its release than, for instance, smoke (Chandler, 1976). Since SO_2 is also released mostly from industrial stacks i.e. at a height of some tenths of meters, the maximum ground level concentrations will not be found in the neighborhood of the source, but rather at a distance of a few hundreds of meters. CO emissions from traffic, on the other hand, will undergo a completely different dispersion process, because release occurs near the ground and because of the physical tendency of CO to fall to the ground surface (see section 4.3.2). Similarly, smoke emissions from central heating burners are released at relatively low heights (lower than industrial stacks) and are trapped by the turbulent eddies generated around buildings: consequently the highest concentrations are expected to be found in the nearby vicinity. Another interesting aspect of smoke dispersion is that smoke tends to spread vertically rather than laterally (except at times of weak winds and strong atmospheric stabilities); in general the lateral spread of SO_2 in a city is much greater than that of smoke (Chandler, 1965). Concentrations due to traffic emissions fall off very rapidly in streets which lead away from the main traffic highways (Reed, 1966; Motto, 1970).

The location and the emissions of air pollution sources in the urban area are also of importance for the selection of sites for *monitoring stations* (in combination with other meteorological and urban data, as seen from the previous sections). Various types of quantitative models exist for this purpose, which use climatological, emission and population data as input (Smith and Egan, 1979; Stern et al., 1984). The models' output can rank sampling locations by concentration threshold, frequency of exposure to certain concentration thresholds, or can rank sampling locations for maximum sensitivity to emission changes, for coverage of a maximum number of sources or for coverage of as large as a geographical area as possible.

Industrial emission information can also be used for *controlling* the compliance status of industries.

5.3.1.5 Air quality.

In Chapter 3 the interrelations between the different compartments of the environmental system and the resulting pollution cycles were mentioned (see Figures 3-3 and 3-4). An interesting aspect of such interrelations with respect to urban pollution is the effect which **air quality** in an urban area might have on *water pollution* (and, consequently, in the longer run on soil pollution). A typical example are the so-called "scrubbing" processes taking place in industries in order to remove particulate and gaseous pollutants from stack emissions (Chandler, 1976). These processes can result in water contamination and therefore convert an air pollution to a water pollution problem. It is important to be aware of such possibilities within an urban area.

In section 5.3.1.2 it was seen that meteorological elements such as *solar radiation*, *moisture* -although not among the main air pollution generating elements- can contribute negatively to the air pollution problem. In the longer run, however, the status of air quality in an urban area affects the chemistry of the city's air and is one of the factors inducing climatic changes. Consequently, it can be said that the above mentioned elements are -in a longer term i.e. from the climatological point of view- affected by air pollution.

The pattern of the distribution of air pollution concentrations is one of the indicative factors for the location of air pollution *monitoring stations* (see section 4.6.1 and Ouelette et al., 1975).

When concentrations exceed certain limits (e.g. alert, warning and emergency, see section 4.8) traffic and industrial *control of sources* has to be implemented.

Another indicator of the air quality status in an urban area and possibly an indicator of the effects of air pollution upon human health are the *reports and complaints of the population* about e.g. stench, respiratory problems etc. Such reports are usually received by the urban air pollution control offices (DCMR, 1982). Another useful indicator of pollution damage to the population of the city is the population density combined with pollution concentrations. Mathematical models have been developed for the calculation of the so-called daily dosage population, based, among others, on population density and pollutant concentrations (see e.g. Finzi et al., 1977). For a visual correlation a superimposition of *population density* and pollution concentrations might yield interesting patterns.

5.3.1.6 The themes to-be-mapped.

As already mentioned in section 5.3.1 the themes to be mapped for the purposes of urban air pollution decision support and control are determined by two basic factors: **the physical elements** involved in urban air pollution and **the tasks and needs of the users** of the maps. The physical elements involved in urban air pollution and their interrelations in urban surroundings were the subject of the previous sections (5.3.1.1 to 5.3.1.5). An overview of them is given in Figure 5-2.

The main tasks of the urban air pollution office were introduced in section 4.8, in terms of air pollution control. The tasks and needs which can be supported by cartographic (visual) means are given in Figure 5-3.

Controls on emissions from air polluting sources and on fuel usage are tasks in which urban planners are also involved. The main interest of urban planners with respect to air pollution is to evaluate the effects which the various planning solutions will have upon the urban air quality in order to select the optimum solution. Many of these planning solutions rely on land-use zoning such as the separation of industrial and residential areas (Chandler, 1976). Since, however, the effects of air polluting emissions upon air quality are determined, as already seen, by more factors (i.e. meteorology, topography etc.) land-use zoning is applied in combination with local topographic and meteorological factors such as terrain anomalies, wind and temperature inversions (Frenkiel, 1956; see also section 5.3.1.2). In that way the influence of turbulent eddies generated by terrain variations (e.g. the bringing down of industrial plumes) or the trapping of air pollution in an inversion layer is lessened. Similarly, the effects from traffic emissions are not only controlled by the control of emissions themselves (in the fuel of exhaust systems of cars) as is the task of mainly the pollution office of the city, but also by suitable planning of the location, orientation and width of streets and of the height of buildings (street canyons). From section 5.3.1.3, for instance, it can be concluded that narrow streets with tall buildings should be oriented along the prevailing wind direction; streets which are oriented at rather right angles to the wind direction should be broad enough to be cleaned by the generated turbulent eddies.

Apart from planning for new urban settlements and/or new industrial developments the effects upon air quality of modifications in the structure and functions of the city are also of interest to urban planners.

The reports and complaints of the population (section 5.3.1.5) which are an interesting indicator of possible health effects of air pollution concern both urban planners and pollution office.

For the information of the general public the overall and/or local distribution of air pollutant concentrations is of main interest; a daily pollution report on TV (similar e.g. to the weather report) and public displays e.g. on monitors in the city's CBD are among the possibilities.

Such displays are of particular importance for the urban population during pollution episodes.

The tasks and needs discussed in the previous are summarized in Figure 5-3.

POLLUTION OFFICE	URBAN PLANNERS	PUBLIC
- overview of distribution	- overview of distribution and sources	- overview of distribution
- overview of sources and their contribution	- asses effects of urban development pans	- public display e.g. at shops in CBD; on TV (such as weather report)
- locate monitoring network stations	- asses effects of modifying city structure	- inform about 'hot spots'
- monitor local influence of sources	- assess local effects from projected developments	
- traffic control : instruct drivers along arteries or in a ring of roads	- assess impact of modifying neighborhood structure	
- take control actions	- monitor significant spots	
- inform about 'hot spots'	- inform about effects on population	
- inform about effects on population		

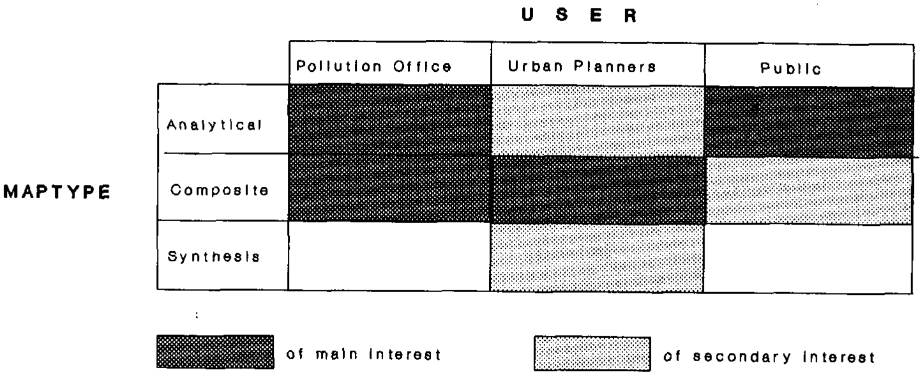
Figure 5-3. The tasks and needs of the users.

For the purposes of the cartographic representation (visualization) of the physical elements involved in urban air pollution the main points of interest emerging from the previous discussion could be summarized as follows:

The influence of the involved physical elements upon each other can be observed in both the whole urban area as well as locally . For instance the form of the terrain influences the overall appearance of the wind field and other meteorological factors which, in turn, influence air pollution: a city located inside a basin is more likely to witness critical air quality conditions than one on flat terrain. Local features such as hills change the wind field locally and buildings contribute to the development of turbulent eddies which influence the pollutant concentrations in their neighborhood. By its nature, therefore, the urban air pollution problem implies the concept of scale , since inside an urban area it is influenced by factors of varying spatial significance and, therefore, it develops over areas of varying spatial extent. Furthermore, man-made elements such as sources have overall as well as local influence upon the pattern of emissions and concentrations (see section 5.3.1.4). Consequently, the visualization of the air quality status can concern the whole area, but also certain municipalities or neighborhoods (industrial areas, areas with busy traffic, the CBD) and specific points of interest (archaeological spots, monuments). Even scales outside the urban range (e.g. regional) might be useful for visualizing other factors related to the urban air pollution problem (such as, for instance, migration).

Because of the combined influence of the considered physical elements upon the air quality status and, in general, upon each other it is obvious that apart from displaying their status separately they also should be visually combined on more complex maps, allowing for visual correlations. In general, the maps which are useful for the purposes of monitoring and controlling urban air pollution and generally enhancing the decision support process, are, first of all, series of **analytical** maps i.e. maps presenting only one characteristic. From these series **inventory** maps can be derived, which present more characteristics by superposition or juxtaposition of the original analytical maps; another useful sort of map, especially for planning purposes, is the so-called **synthesis** or **communication** map which results from the combination and simplification (i.e. structural/conceptual generalization) of exhaustive analytical maps (Pape, 1980; ICA, 1984). For urban air pollution purposes, in particular, analytical maps showing elements such as air pollutant concentrations, the industries emitting the pollutants, the inhabited areas affected by them are of interest for planners (Pape, 1973). Composite maps combining the above with more information (particularly on urban settlements and population) such as the residential density, the professional structure of the inhabitants, the types and age of the concerned urban settlements,. the kind of industries, would also be valuable for planning purposes, since connections between these factors exist (op.cit.; see also, sections 5.3.1.1 to 5.3.1.5). Planners actually prefer to combine all these elements -and possibly even more- on a single map (see e.g. Pape, 1973). This is a common "planners' trend" which, however, is not acceptable from the cartographic point of view (overloaded maps, possibility to answer questions only at the elementary reading level which, is not sufficient for a general overview, such as the one a planner actually requires). Instead, either selective (i.e. relatively simple) inventory maps or synthesis maps have to be produced, although the latter are highly generalized, resulting in a considerable loss of information.

The interests of the air pollution office comprise the visualization of all elements involved in the urban air pollution problem, since the pollution office is the main authority concerned with them. Series of exhaustive analytical maps showing the air pollutant concentrations of a number of air pollutants over the area are, of course, of primary importance. Emission maps are also required (see e.g. Hammerle, 1976). Composite maps combining the air quality and emissions distributions with meteorological, topographic and urban factors are also very useful. Synthesis maps are not really necessary for the tasks that the APO is concerned with, mainly because of their high degree of generalization: as already mentioned they are more suitable for communicating gross information.



		USER		
		Pollution Office	Urban Planners	Public
MAPTYPE	Analytical	▓	░	▓
	Composite	▓	▓	░
	Synthesis		░	

▓ of main interest

░ of secondary interest

Figure 5-4. The generic types of maps and their interest for the users.

Finally, a number of maps created mainly for the pollution authority and the urban planners can be selected for the information of the general public i.e. mostly analytical maps displaying the distribution of the most important air pollutants, or simple inventory maps showing additional information such as e.g. wind or traffic densities.

The generic types of maps (analytical, composite, synthesis) and their interest for each user group are shown in Figure 5-4.

Another interesting point with respect to the cartographic representation of the air pollution elements is their **3-D spatial** as well as **temporal** aspect. In Chapter 1 (Introduction) the increasing consideration of these aspects in cartography and, in general, in GISs (from both the production and the theoretical point of view) has been given.

As already seen (e.g. section 5.3.1.1) the three dimensional space of the urban area is involved in the generation of air pollution. It would be useful, therefore, to display the elements involved in the 3-D space, either on ordinary 2-D maps (e.g. slices on different heights or at different vertical planes) or -for more comprehensive visualizations- to display aspects of the area (e.g. terrain, urban profile or even their combination) in three dimensions. Furthermore, another possibility is the combination (superposition) of three dimensional maps with two-dimensional ones (e.g. 2-D layers containing thematic information). The latter could actually be considered as another 3-D sort of inventory map visualizing multiple information relevant to air pollution.

In Chapter 4 the dynamic nature of the air pollution phenomenon was described. The visualization of air pollution dynamics is of interest for all user groups. Most important for all users are the changes in the air quality status; changes in the meteorological conditions and traffic emissions are also useful, especially for the APO. Such changes are to be displayed either on series of static maps or on dynamic (i.e. animated) maps. They could be reflecting either the real situation (measured or simulated) or possible developments in the air quality status, resulting from different control or planning scenarios ("what if"). The topic of dynamic maps is treated in more detail in the beginning of Chapter 7.

The next possible step is the combination of 3-D and dynamic maps for the purpose of more realistic and comprehensive visualizations. Although theoretically (and practically) possible it has not been implemented here due to pragmatic (computer) limitations (see Chapter 6).

On the basis of all the characteristics discussed so far (i.e. the elements involved in air pollution and their interrelations, the needs of the users for, mostly, analytical and inventory maps and the spatio-temporal characteristics of the involved elements) the most important themes proposed to be mapped for the purposes of urban air pollution monitoring and control are summarized in Figure 5-5. At this point it should be noted that the generation of synthesis maps is not considered here, mainly because what should be selected generalized/clustered and displayed on such maps is highly depended on specific planning needs and approaches. Nevertheless, the display algorithms are identical with the ones used for composite maps (overlays).

5.3.2 The space involved.

5.3.2.1 The scales of the maps.

As seen in section 4.2.1 the horizontal dimension of the air pollution problem is that of the diameter of the urbanized area, which usually extends up to some tens of kilometers. This horizontal extent of the area of concern determines the "maximum window" to be viewed and, consequently, -depending on the physical dimensions of the final map- the minimum map scale. On a map of this scale a synoptic overview of the distribution of air pollution over the whole area can be displayed. In order, however, to view the situation at certain parts of the city or at

		overlayed elements				
		terrain & topographical	meteorological	urban	sources and emissions	air quality
base map elements	terrain & topographical	11 · 3-D form of terrain · 3-D terrain & selected topographic elements (urban, industrial etc. land-use) · topography	· 3-D form of terrain with superimposed layers of meteorological information · 3-D terrain & atmospheric layers (e.g. inversion) · topography and wind - static - animated	· 3-D terrain with superimposed layers of land-use information (as in 33)	· 3D terrain & superimposed layers with source & emission information (e.g. industries, traffic) · on the *same* 3-D surface - 3-D terrain and industries - 3-D terrain and traffic emissions	· 3D terrain & superimposed layers with concentrations (e.g. concentrations at different heights) · 3-D terrain & monitoring stations · green *and* concentrations · buildings & concentrations · buildings & monitoring stations
	meteorological		22 · windfield - static - animated · windroses · temperature ↕ horiz. & vertically · radiation · moisture · wind & temperature	· land-use & wind · land-use & wind & building heights · land-use & temperature · land-use & precipitation · green and temperature	· wind and industries (sort, site and emissions) · wind and traffic emissions	· wind and concentrations · wind and alarm concentrat. · windroses & monit. stations · temperature & concentrat. (for secondary pollut.) · temper. & monit. stations · radiation & concentrations (for secondary pollut.) · moisture & concentrations · visibility & concentr.
	urban			33 · traffic density (static and animated) · migration · city expansion · changes in land-use · population density · population increase · land coverage · age of buildings · city profile (2-D & 3-D)	· land-use and industries (sort and site) · land-use and traffic density · land-use & traf. density & building heights · land-use & C.H. *emissions* · building heights & traffic density & wind	· land-use & concentrations · land-use & monitoring stations · traffic density and concentrations · traffic density and monitoring stations · population density and concentrations and wind
	sources and emissions				44 · industries - sites - sort - emissions · road network - emissions linear - emissions areal · central heating emissions (areal)	· industries (sites, sort, emissions) & concentrations · traffic emissions & concentrations · C.H. emissions & concentr. · sites of *industries* & monitoring stations · industrial emissions & monitoring stations · traffic network & emissions & monitoring stations
	air quality					55 · concentrations - static - animated · alarm conditions - at monitoring stations - overall · traffic control (car in city) · population reports · concentr. & monit. stations · concentr. & popul. reports

Figure 5-5. The subjects of the proposed maps.

☐ composite maps

▨ analytical maps

specific neighborhoods of interest, larger map scales, where more elements of the topography become apparent are also necessary. The choice of a "minimum window" and therefore of the largest scale to be used depends on particular characteristics having to do with the air pollution situation in the area, such as the spatial resolution of the input of the emission inventory, the distribution of the monitoring stations and/or the meteorological stations etc.

The borders between the categories of the air pollution problem (section 4.2.1) cannot be precisely defined and when they are (Fig. 4-4), they are rather indicative. In general it could be said that the average minimum extent when dealing with urban air pollution is that of a neighbourhood (e.g. approximately between 0.5-5.0 km). [Stern et al. (1984), for instance, list a number of so-called "spatial scales" (not to be confused with the cartographic scale) for the establishment of a (stationary) monitoring network. The "neighborhood scale" extends from 0.5 - 5.0 km and the "urban scale" from 5.0 - 50 km].

The physical dimensions of the final map will determine the range of scales to be used. It will be:

$$sc_{min} = \frac{s_m}{maxwin} \qquad \text{(eq. 5-1)}$$

$$sc_{max} = \frac{s_m}{minwin} \qquad \text{(eq. 5-2)}$$

where:

sc_{min}: the minimum map-scale
sc_{max}: the maximum map-scale
maxwin: the maximum window i.e. the maximum geographical area to be viewed.
minwin: the minimum window i.e. the minimum geographical area to be viewed.
s_m: the shortest map side.

It might be argued that this traditional concept of scale which derives from topographic two-dimensional paper maps is irrelevant when the output maps are displayed on CRT, as is the case here, since the user has the possibility to "zoom-in" and "zoom-out" and therefore generate displays in practically any scale and not only in the limited range utilized for topographic maps. However, since the geometric input is usually obtained from general use topographic maps it is there where the concept of map scale refers to (i.e. the source map to be digitized). Furthermore, the possibility to zoom-in and -out and, therefore, to generate map displays at any scale doesn't mean that the content of these maps is truly "in scale". Suitable generalization algorithms are necessary for this purpose; such a task constitutes a large field of cartographic research by itself and is, in any way, beyond the scope of the present work. (see also section 5.4.2). Here, therefore, the base maps have been derived by digitizing topographic maps at five different scales. Whenever the user will select a window which generates an intermediate scale the scale selection program will choose the closest scale available for the display of the map.

The value of s_m (i.e. a function of the physical screen dimensions and the selected layout) for the maps produced here is 14 cm. For the calculation of the smallest scale sc_{min} (eq. 5-1) a value of 35 km was used for maxwin (this is the approximate extent of the Greater Athens area, which constitutes the sample area in this work). For sc_{max} (eq. 5-2) a value of minwin = 2km was chosen, mainly because the extent of the area sources for the emission inventory in Athens is 1km x 1km , a cell size which happens to be very common in practice (Hammerle, 1976; NTUA, 1986). It wouldn't make much sense then to look for variations in pollutant concentrations within this area, at least for the simulated concentrations. For the measured concentrations the spatial distribution of the stations can suggest the minimum window to be used. For the center of Athens the average distance among the (automatic) monitoring stations is approximately 2.5 km. A minimum window of 2km x 2km seems therefore to be satisfactory since this size is also found within the lowest half of the neighborhood limits (i.e. 0.5 to 5.0 km). Consequently, the map-scales used here for the display of urban air pollution elements range from 1 : 10000 to 1 : 250000. A map of Greece at smaller scale (approximately 1 : 4000000).is also used for the display of internal migration to the capital of the country from the post-war years onwards. Needless to say, these scales refer to the 2-D maps. The scales of the 3-D maps are not defined precisely; the maps can be interactively manipulated before their display (zoomed-in and -out). Furthermore, on 3-D maps the vertical scale is larger than the horizontal (vertical exaggeration) so that the characteristic features of the area are emphasized for better spatial recognition.

5.3.2.2 The map projection.

The projection which is used for the proposed maps is the Universal Transverse Mercator projection (UTM). The reasons which have lead to its utilization are the following:

1. The linear and areal deformations which result from its utilization in the whole area of interest are small (practically negligible, especially when compared with the accuracy of the thematic content of the

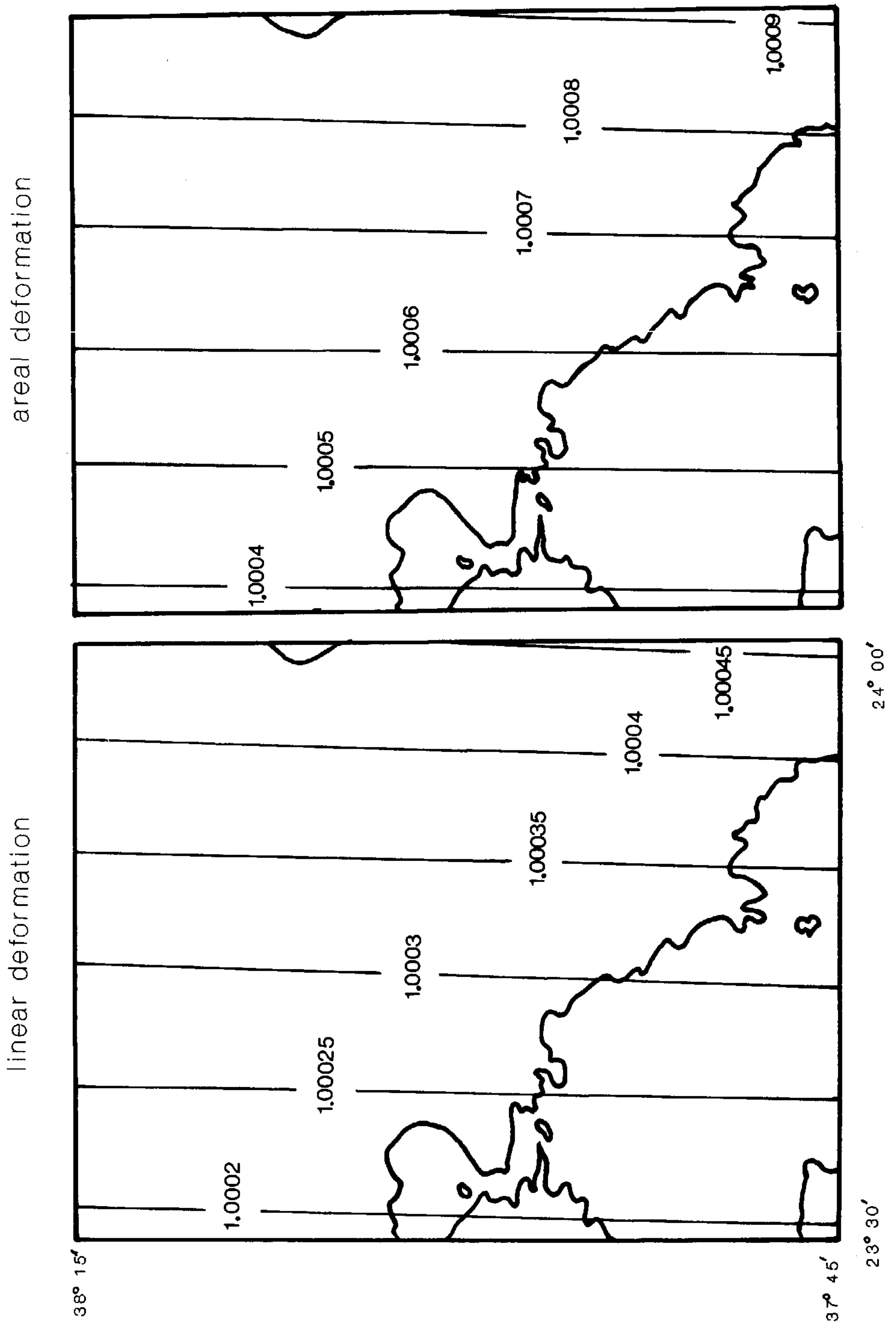


Figure 5-6. The linear and areal deformations introduced by the UTM projection over GAA.

maps; see also section 5.4.3). Figure 5-6 displays the pattern of these deformations over GAA.

2. The projection is also used on the topographic maps of the area (with the exception of those at scale 1:10000).

3. The projection is widely used not only for topographic mapping but also for the spatial registration of thematic characteristics, such as the contents of environmental data banks (Ouelette et al., 1975) and of emission inventories (Hammerle, 1976). The advantages of its utilization for environmental purposes stem from the facts that the UTM grids are continuous and they are not influenced by political subdivisions, that the projection is used worldwide and that the UTM system is becoming "the base depository" for growing technical information (op. cit.).

Here it should be mentioned that in Greece a uniform projection system for the topographic maps of the country does not exist. A variety of projection systems, ellipsoids, datums, sheet divisions and grids is in use. In Figure 5-7 the characteristics of the topographic maps for the scales used here are given. As seen, for the scales 1:25000 to 1:250000 the projection used is the UTM (with zones of 6°) but the used grid has been derived from the Hatt projection. The Hatt projection is an ellipsoidal variation of the oblique aspect of the azimuthal equidistant projection developed by the French Philippe Hatt at the end of the 19th century; apart from Greece it is also used by the French for coastal and hydrographic maps (Snyder, 1987; Reignier, 1957). The Hatt projection is also used for topographic maps at scale 1:5000 while e.g. city maps issued by the Ministry of Environment, Planning and Public Works at scales 1:1000 and 1:2000 have been made in a variation of the UTM (zone of 3° instead of 6°). Topographic maps at scale 1:500000 are utilizing the Lambert conic projection. In general, there is a large variety in the maps produced by the different state mapping services, with respect to projection system ellipsoid and map sheet division; this results in problems for their use. For instance the maps are difficult to connect, the cartesian coordinates of concrete objects or thematic entities refer to different grids and therefore are not consistent etc. It is also not rare that, because of the variety of their characteristics (e.g. projection, datum, grid system) and the lack of standards for their construction some of these characteristics are not registered at all and become difficult to trace back (especially for the non-topographic maps which are produced, distributed and exchanged among the mapping divisions of the ministries). The result is that the user is confronted with various maps which register thematic information but on which there is no information about projection, grid system etc. This variety has stimulated studies and proposals for the implementation of a commonly accepted system (see e.g. Boutoura, 1987).

For the above reasons it often becomes necessary to transform map coordinates from one grid to another without knowing the projection characteristics of the maps and, therefore, without computing, as an intermediate step, the geographical coordinates. Many methods are in use for the transformation of (cartesian) map coordinates (for an overview see Brandenberger, 1985; see also Katsambalos, 1983; Koussoulakou et al., 1983; Paraschakis and Fotiou, 1988; Spiess and Brandenberger, 1986).

scale	projection	ellipsoid	datum	grid
1:10000	Hatt	Bessel	GR-D (Athens)	Hatt
1:25000 to 1:250000	UTM (6)	Hayford	ED50	Hatt

Figure 5-7. The projection characteristics for the scales used.

For the purposes of the present work an algorithm for coordinate transformation is given, for the general case that the projection characteristics of the original thematic maps from which information is selected, are unknown. The algorithm gives the possibility to select among a number of different transformation functions (namely: affine, bilinear polynomial and power series). In order to illustrate the principle the affine transformation (eqs. 5-3 and 5-4) is used here as an example.

Let us suppose that x, y are the cartesian coordinates of the final map and x^*, y^* are the coordinates of the source map, which have to be transformed. Then it will be:

$$x = a_1 x^* + b_1 y^* + c_1 \qquad \text{(eq. 5-3)}$$

$$y = a_2 x^* + b_2 y^* + c_2 \qquad \text{(eq. 5-4)}$$

or, in matrix notation :

$$[\,x\ \ y\,] = [\,x^*\ \ y^*\ \ 1\,] \begin{bmatrix} a_1 & a_2 \\ b_1 & b_2 \\ c_1 & c_2 \end{bmatrix} \tag{eq. 5-5}$$

a_1, a_2, b_1 and b_2 produce scaling, shearing and rotation, c_1 and c_2 produce translation

If (eq. 5-5) is applied for a number n of points common on the two maps (i.e. the nodes of the geographic graticule, street intersections or any other recognizable identical points) we have:

$$\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \cdot & \\ \cdot & \\ \cdot & \\ x_n & y_n \end{bmatrix} = \begin{bmatrix} x_1^* & y_1^* & 1 \\ x_2^* & y_2^* & 1 \\ \cdot & & \\ \cdot & & \\ \vdots & & \\ x_n^* & y_n^* & 1 \end{bmatrix} \begin{bmatrix} a_1 & a_2 \\ b_1 & b_2 \\ c_1 & c_2 \end{bmatrix} \tag{eq. 5-6}$$

where:

x_1, y_1, ... , x_n, y_n : the cartesian coordinates of the selected points on the final map.
x_1^*, y_1^*, ... , x_n^*, y_n^* : the cartesian coordinates of the selected points on the original (source) map.

Equation 5-6 can also be written:

$$\mathbf{X} = \mathbf{X}^* \mathbf{M} \tag{eq. 5-7}$$

where:

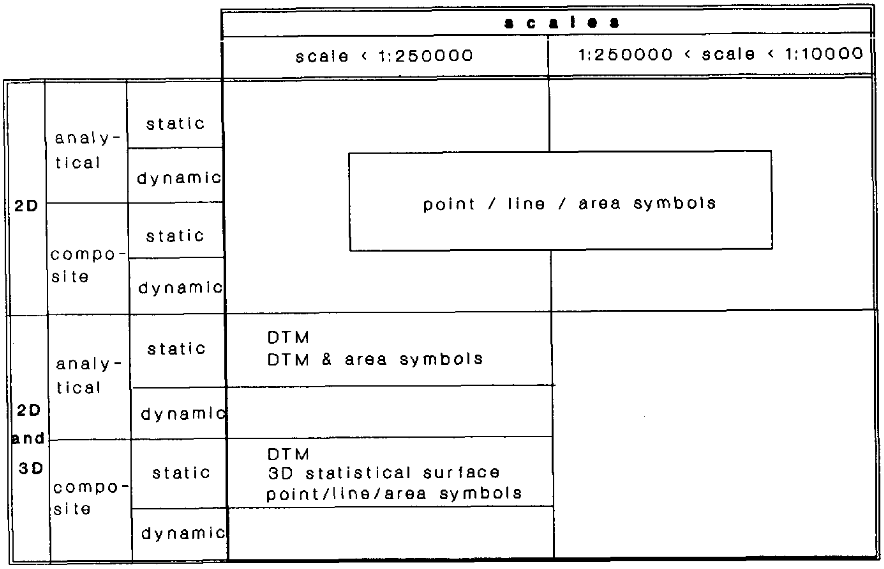
X : a n x 2 matrix of the final coordinates.
X* : a n x 3 matrix of the original coordinates.
M : a 3 x 2 matrix of the transformation parameters.

For the solution of (eq. 5-7) the method of least squares can be used.

5.4. Internal identification.

5.4.1 Cartographic representation

The types of cartographic representation used for the mapped themes are shown in Figure 5-8 (see also: Koussoulakou, 1988a).



			scales	
			scale < 1:250000	1:250000 < scale < 1:10000
2D	analytical	static		
		dynamic	point / line / area symbols	
	composite	static		
		dynamic		
2D and 3D	analytical	static	DTM DTM & area symbols	
		dynamic		
	composite	static	DTM 3D statistical surface point/line/area symbols	
		dynamic		

Figure 5-8. Cartographic representation of the mapped themes.

For the two-dimensional analytical and inventory maps, point, line and area symbols and combinations of them (especially for the inventory maps where multiple themes are overlayed) are used.

Apart from static displays attempts to map changes are also made. In order to capture the course of air pollution over the area animated maps are created; on such maps the results of interactive manipulations (e.g. the prediction of the air quality status for the next day) can be seen as a smooth sequence of changing pollution distributions. If past data are available presentation of historical development on air quality is also possible in this way. The occurrence of emergency cases when established air quality limits are exceeded is another example of dynamic map display which utilizes flashing symbols or changing colours to indicate the dangerous pollution levels. Apart from changes in the urban air quality status, dynamic maps are also used to display changes in the meteorological parameters (i.e. the wind field, the temperature etc.).

Moving or/and changing point and area symbols are used for this purpose. In order to show general patterns of changes in urban characteristics e.g. expansion or contraction of a certain land use type, changing areal symbols are utilized. For the display of regional trends such as internal migration proceeding line symbols give an impression of the followed directions. Changes in traffic densities (or emissions) are also utilizing lines the width of which changes with time according to the amount of the displayed quantity. Moving point symbols are used for simple traffic control maps intended to give a realistic impression of car navigation through the city.

Combinations of two- and three-dimensional surfaces intend to give more realistic overviews of the situation. A digital terrain model of the area is created to provide an easily recognizable geographic basis for the display of pollution concentrations depicted by a statistical surface overlayed on the modelled terrain. The statistical surface can be given either by a 3-D (volumetric) representation or by a 2-D thematic overlay (such as e.g. isarithms) viewed in perspective. A perspective view of a 2-D surface can also be used for the geographic base , in case the topography has to be kept simple, in order to focus upon particular selected features (e.g. the traffic network) and correlate visually their pattern with distribution of pollution. Combination of 3-D and 2-D surfaces can be used for visualizing not only the pollution concentrations but also other meteorological and/or urban elements. Any point of view can be selected interactively by the user for viewing the surfaces; it is also possible to display multiple windows for a simultaneous view of the maps from different points.

Examples of the produced map types are shown in Chapter 6.

5.4.2 Generalization

As already mentioned in section 5.3.2.1 the topic of generalization is not considered in the present work. The topograpic elements which are involved in air pollution, as described in section 5.3.1.1 (i.e. hypsometric contour lines water, green buildings), as well as the traffic network are simply selected and digitized from the topographic maps of the area.

5.4.3 Accuracy.

In the present section an attempt to describe the factors which influence the quantitative accuracy of the final products of the prototype (i.e. the thematic maps) is made.

The final accuracy of a map can be considered as the combined result of the transformations which take place during the map creation process (see section 3.4; see also Muller, 1987).

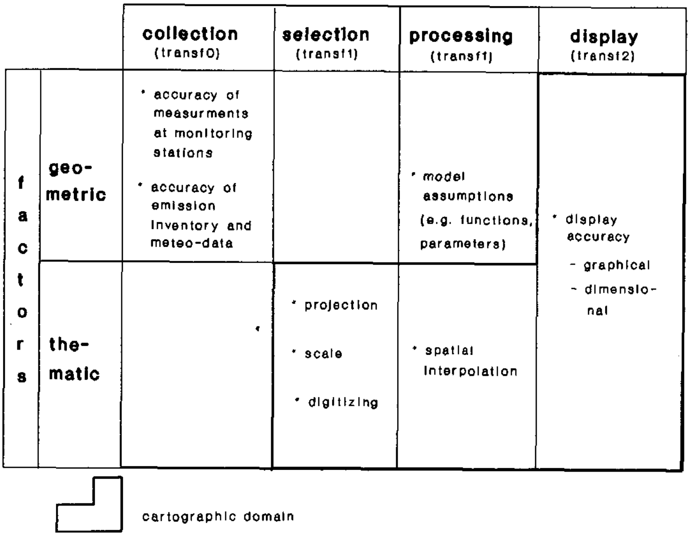
Figure 5-9 summarizes the factors which introduce errors during the map creation process and, therefore, influence the accuracy of the final product (compare with Figure 2-4 in Chapter 2). The factors involved in the collection and processing of the thematic content are not controlled by the cartographer; they purely depend on the urban air pollution authorities of the city. Their influence, therefore, is out of the scope of the present work. An example of such factors as applied for the Athens case is given in Chapter 6.

The factors which fall within the cartographic domain concern:

1. The **selection** of the geometric map content. The errors introduced are, basically, due to the digitization process of the selected topographic features for the base map, which is mainly determined by the scale of the map. The projection used is also introducing certain deformations.
2. The **processing** of the geometric and thematic map content. As already mentioned, the processing of the thematic information per se (i.e. here the assumptions of the used mathematic simulation model) are not of cartographic concern. The output of the model, however, as well as the measurements performed in the stations of the monitoring network (i.e. the discrete information at points) have also to be processed before being displayed in the form of a continuous statistical surface. This processing is done via methods of spatial interpolation. (Because the information is spatially referenced, the step is described as "geometric" rather than "thematic" processing in Figure 5-9, although it concerns the processing of the thematic map content). The processing errors in such a case depend on the interpolation method which will be used. For topographic maps (maps of geometric content) such errors influence the positional (i.e. horizontal) and elevation (vertical) accuracy of the contour lines. But while for topographic maps standards exist, which give the allowable position and elevation errors according to the steepness of the terrain and the map scale (see e.g. Imhof, 1982; Yoeli,1984) for the thematic accuracy there are absolutely no norms whatsoever; this is due to a number of reasons, the most important being the fact that topographic maps have cartometric purposes and for this reason higher accuracy demands and standards than thematic maps. Thematic map accuracy, on the other hand, focusses rather on relative geographic positioning and statistical accuracy rather than on absolute positional or vertical accuracy (Muller, 1987). Furthermore, thematic maps are concerned with the display of a variety of themes each one of them being of a different nature, which, also, often happens to be non-tangible or abstract and therefore not easy or possible to measure directly. It would not, therefore, be easy and maybe even not recommended to establish common accuracy standards. Nevertheless, it would be useful to display together with the statistical surface portraying the spatial

distribution of a phenomenon, the errors contained in this distribution (i.e. the error surface). In this way the user gets the feeling of "what's in a map"

3. The display accuracy, which can be further distinguished in graphic (graphic error, graphic precision), dimensional and relational (Bertin, 1983). The graphic precision of a traditional paper drawn map is 0.2 - 0.1 mm. Dimensional accuracy is "the metric meaning of graphic precision" (op.cit.) and it is directly linked to scale. It can be determined when scale and graphic precision are known (e.g. on a scale 1:10000 with graphic precision 0.2mm the graphic accuracy is 2m). On a raster image the graphical precision is determined by the pixel size and therefore the dimensional accuracy can be calculated from the scale and the pixel size (or the screen resolution and the image dimensions). For the screens used here the pixel size varies between 0.25 - 0.3 mm). The relational accuracy denotes the relation between the used symbols and the map scale; it does not involve a metric evaluation but offers the means to discern and compare the elements of the graphic information so that they constitute a recognizable reference system (op. cit.).



		collection (transf0)	selection (transf1)	processing (transf1)	display (transf2)
factors	geo-metric	• accuracy of measurments at monitoring stations • accuracy of emission inventory and meteo-data		• model assumptions (e.g. functions, parameters)	• display accuracy - graphical - dimensional
	the-matic		• projection • scale • digitizing	• spatial interpolation	

Figure 5-9. Factors influencing the accuracy of the final maps (compare with Figure 2-4).

The errors introduced in the selection and display steps are therefore, directly associated with the input and output media and are possible to minimize (by selecting e.g. the projection, by accurate digitizing and/or adjusting the digitizing errors, by displaying on high resolution screen etc.). From the previous it can be seen that their influence for non-cartometric thematic maps is negligible. What is more important for such maps are the errors introduced by processing and, in particular, by spatial interpolation. For this reason a brief review of the topic is given in the following section.

5.4.3.1 Spatial interpolation

Spatial interpolation can be described as the procedure of estimating the value of a property at any point (point interpolation) or for any area (areal interpolation) on the basis of a given set of spatial data referring to discrete points or subareas respectively; the estimation is performed via a function which best represents the whole (statistical or concrete) surface (Lam, 1983; Burrough, 1986;). Point interpolation is used to perform contour (i.e. isarithmic) mapping; area interpolation is used for purposes such as isopleth mapping or for obtaining values for a set of areal units from another set of areal units which boundaries do not coincide (Lam,

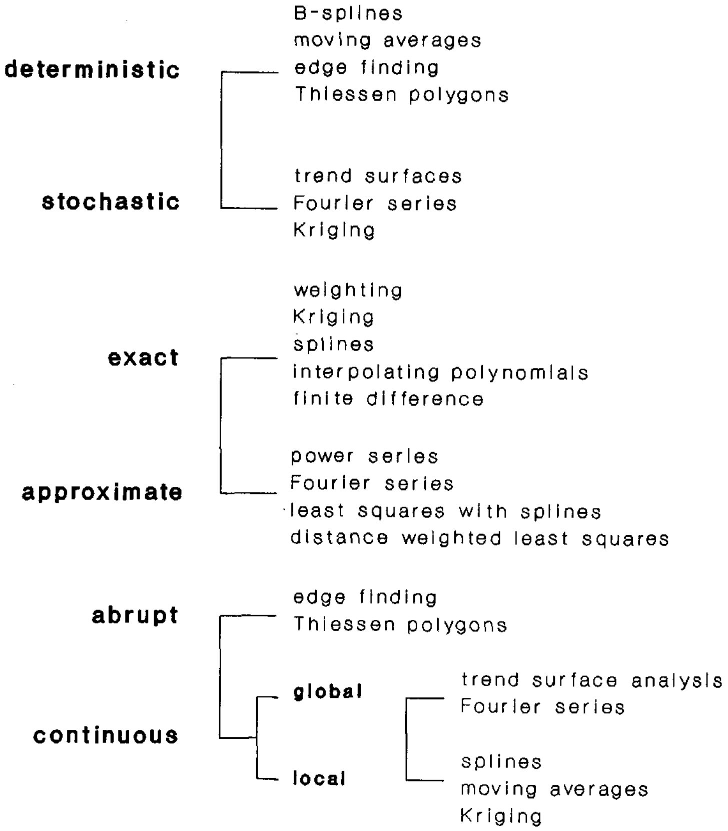


Figure 5-10. Various classifications of point interpolation methods.

from another set of areal units which boundaries do not coincide (Lam, 1983; Green, 1990). Area interpolation will not be further considered here. Spatial interpolation is a topic of major interest to cartography and in general to Geosciences with a vast field of literature and applications.

Major reviews of spatial interpolation methods are to be found in e.g. Ripley (1981), Lam (1983), Burrough (1986), Crain (1970). Various subdivisions of point interpolation methods exist according to the nature of each method. Thus, point interpolation methods can be distinguished in **deterministic** and **stochastic**; in **exact** and **approximate**, according to whether they preserve or not the original sample point values; in **abrupt** and **continuous**, according to the model of spatial change they assume. Continuous methods are further subdivided in **global** and **local** fitting techniques: the former estimate values from all observations, the latter only from the neighboring points. An example of the various subdivisions is given in Figure 5-10 for some common point interpolation methods.
The spatial variation of most natural properties and phenomena is quite erratic in a way that no simple mathematical expression can describe it (Oliver and Webster, 1990). Nevertheless, most interpolation methods usually assume spatial dependence since these properties are continuous i.e. the values of points which are close together in space are expected to be more similar than the values of points far apart from each other. The form of the spatial dependence (i.e. the spatial variation) is, however, important.

A method which follows a stochastic approach in order to take the spatial aspects of properties in account is the method of optimal interpolation, also known as kriging (from the name of the mining engineer D.G. Krige who was, together with the mathematician Matheron, the co-founder of its theory). The basic principle of the theory is that the spatial variation of any property is too irregular to be modelled by a mathematical function (such as e.g. moving averages); a stochastic surface is more appropriate for its description (Burrough, 1986). The spatial properties are also known as "regionalized variables"; the basis of optimal (kriging) interpolation is contained in the so-called regionalized variable theory. The theory of regionalized variables and Kriging is described in detail in: Matheron, 1965 and 1971; Delfiner and Delhomme, 1975; Dagbert and David, 1976; Haas and Viallix, 1976; Davis and David, 1978; Royle et al.,1981; Blais, 1982; Lam, 1983; Carr et al, 1985; Burrough, 1986.

Apart from the stochastic approach to spatial properties the interesting aspect of kriging from the point of view of thematic map accuracy is that it provides estimates of the errors of the interpolated values, while most of the other interpolation methods do not.

Kriging includes various sets of interpolation methods such as simple kriging (or point kriging), ordinary kriging (or block kriging) co-kriging, universal kriging and disjunctive kriging (Lam, 1983; Burrough, 1986;

Oliver and Webster, 1990). In this work simple and ordinary kriging are used for interpolation. Since, however, the method requires some computational effort a simpler interpolation algorithm is also used for a fast, preliminary overview of results (see Chapter 6).

Summarizing from the previous it could be said that the geometric i.e. positional map accuracy is expressed here in terms of ground resolution determined by scale and screen resolution determined by pixel size (program SCASE, see section 6.4) as well as projection deformation (program DEFORUTM). For evaluating the accuracy of the simulated values simple comparisons or correlations are carried out (programs COMPRI and CORREL resp.); in this case, however, it has to be assumed that the measured values are error free. The (kriging) interpolation accuracy is expressed in terms of kriging estimation errors (program GEOEAS). The values to be interpolated, however, are either measured (assumed error free) or simulated i.e. carrying collection and processing errors which are difficult if not impossible to trace; the elimination of these errors is, however, a task of air pollution engineering specialists rather than a cartographic or GIS task, as already mentioned in the previous.

5.5 The map creation process

In this section an overview of the components of the map creation process described earlier in this chapter is given. The main tasks to be carried out are shown by means of a flowchart and the main software modules developed/used to perform them are briefly described.

In Figure 5-11 the general flow of the map creation process (collection/ selection, processing and display) is given for the geometric (topographic) and the thematic (sources/emissions and meteorology) elements involved. In Figure 5-12 the algorithms for the processing of the topographic and thematic data are given in more detail together with a short description of the task they perform. The graphic algorithms for the display of the maps are given in Figure 5-13. A more detailed description of the way the software programs based on the above algorithms work is to be found in Chapter 6.

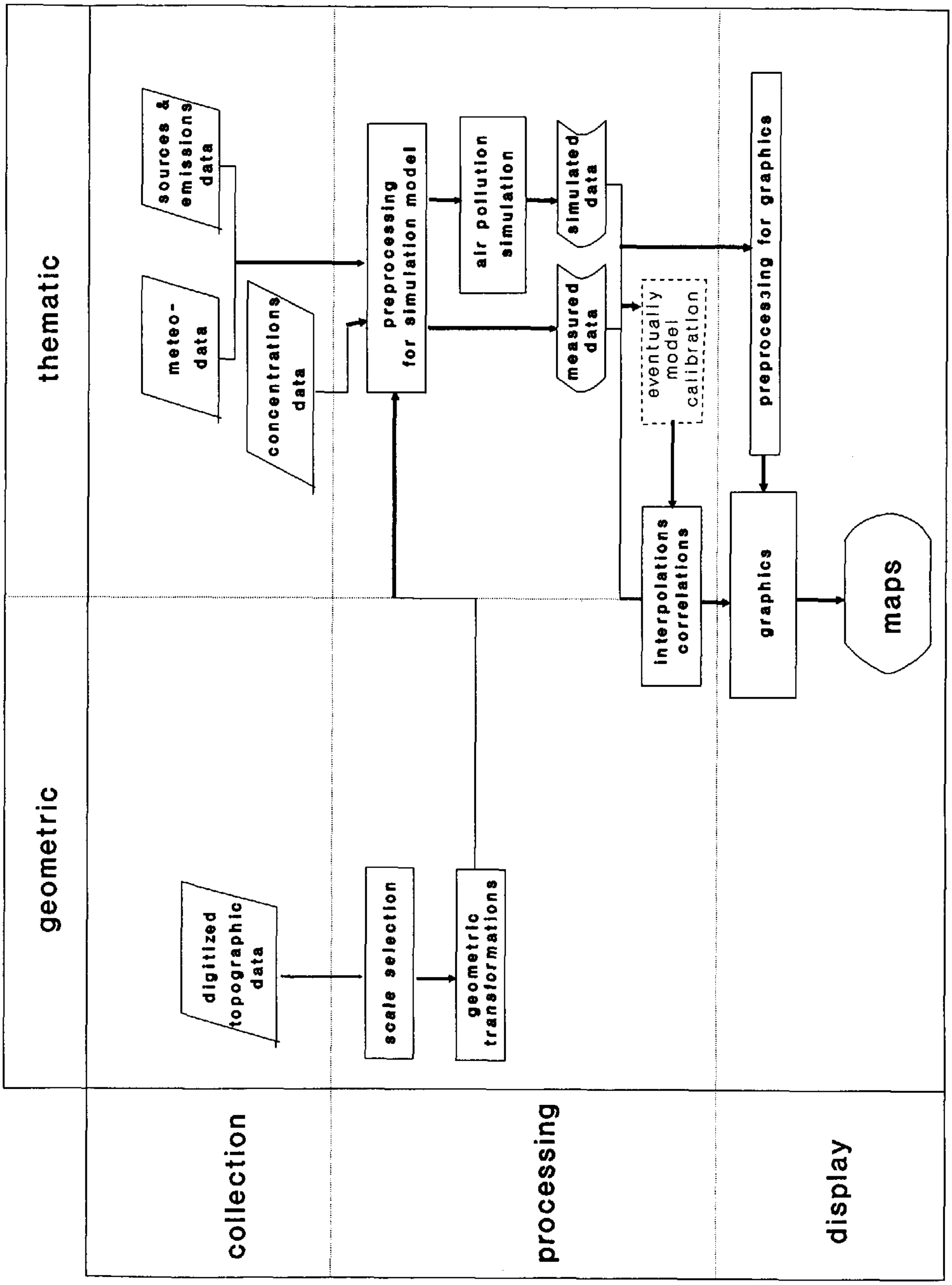


Figure 5-11. The map creation process.

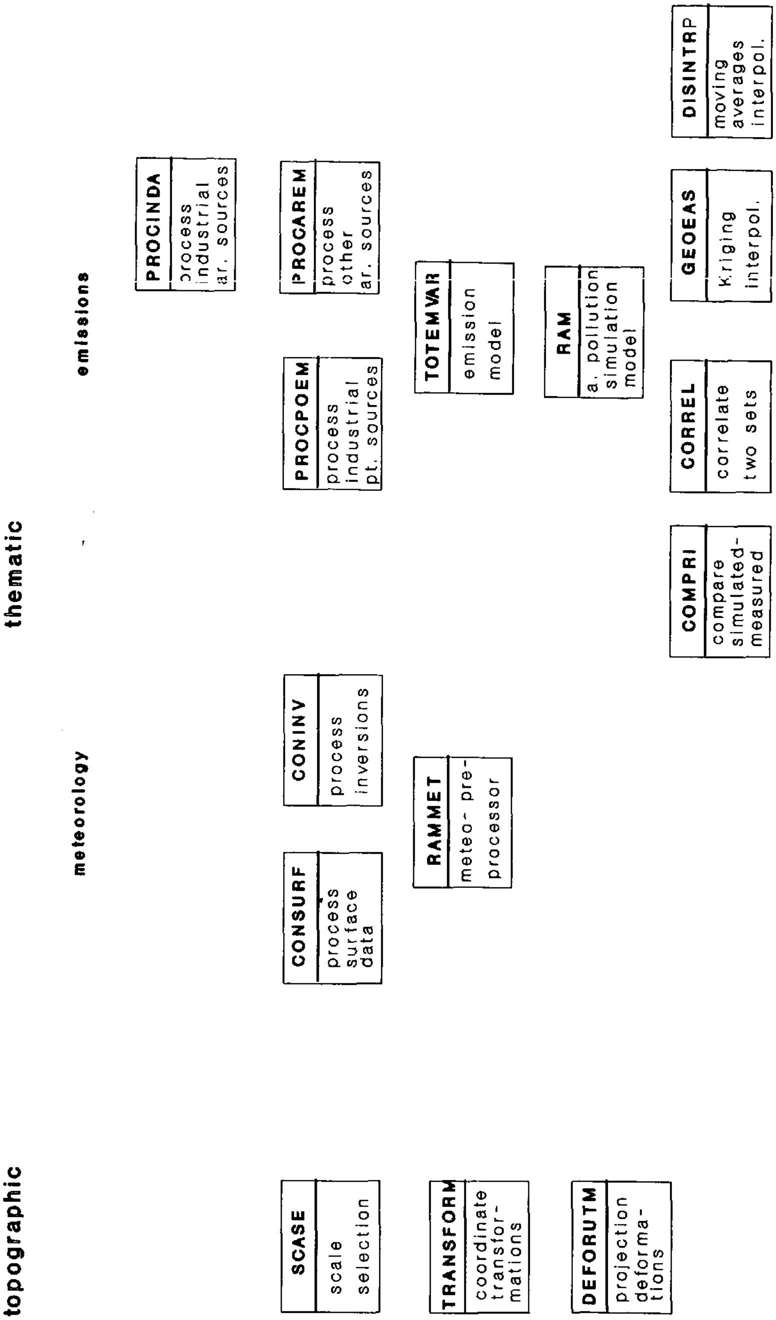


Figure 5-12. The data processing algorithms.

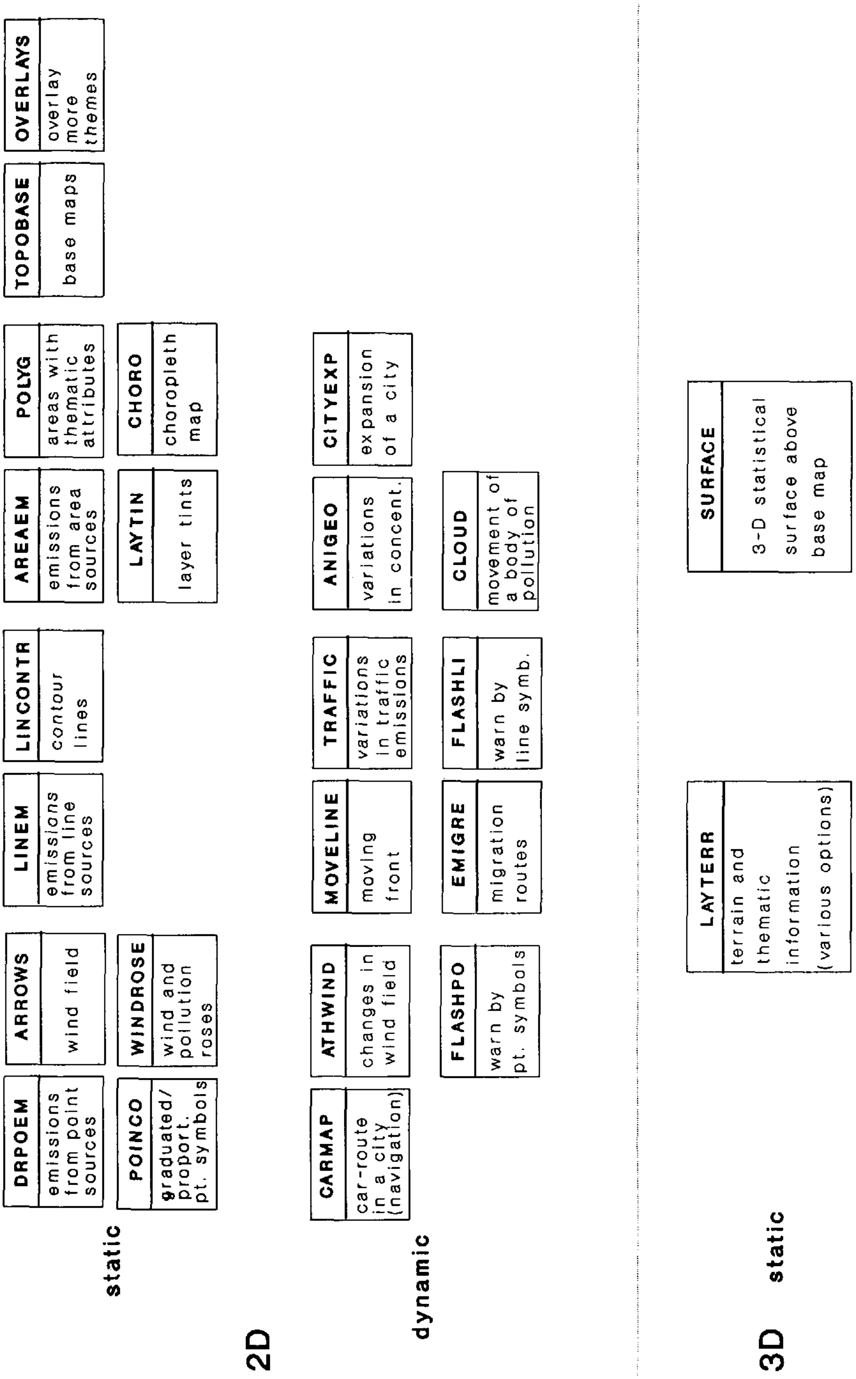


Figure 5-13. The display algorithms.

CHAPTER 6. SYNTHESIS AND IMPLEMENTATION OF THE PROTOTYPE.

6.1 Introduction.

In this Chapter the implementation of the prototype proposed for simulating and mapping urban air pollution is described. The prototype was built using the urban and industrial area of Athens as a case study. Initially (section 6.2) the physical (i.e. natural and man-made) elements involved in air pollution (see previous Chapter) are given for the particular urban area of implementation. In the rest of the Chapter the implementation is described: section 6.3 describes the process of data gathering; in section 6.4 the functionality of the used / developed algorithms is given and finally, in section 6.5 examples of the produced maptypes are illustrated.

6.2 The physical elements involved in air pollution in the urban and industrial area of Athens.

The elements of the physical environment (natural and man-made) which are involved in the generation of air pollution over an urban area and the interrelations between them have been described in the previous Chapter. In the following sections (6.2.1 to 6.2.4) these elements and their effects with respect to air pollution will be given for the area of Athens, as an illustration to their general discussion in Chapter 5.

6.2.1 Terrain and topography.

The greater urban and industrial area of Athens (in the following it will be referred to as the Greater Athens Area [GAA]) has an extent of 35 km x 35 km approximately. GAA comprises the Athens basin and the Thriasson plain (Fig. 6-1). The Athens basin is formed by low mountain ranges: to the west a range of maximum height about 450 m separates it from the Thriassion plain; to the east and north higher mountain ranges of about 1000 m maximum height are found. The basin has a SSW direction with its south and southwest sides open to the sea. The plain to the west of the basin is also surrounded by mountains and has similarly a south-southwest access to the seacoast. Within the basin the cities of Athens and Piraeus are located, together with a major industrial zone between them and other industrial spots in the coast northwest from Piraeus. Within the plain smaller inhabited areas and many industrial locations are found. Within the basin lower hills exist, the highest of them being approximately 275 m high.

The whole GAA is, in general, a dry area. The two torrent-rivers flowing through the area are in most of their extent covered and dry. Green areas are also rather limited, especially in the center of the basin. Inside the city of Athens only a few major gardens and parks are to be found.

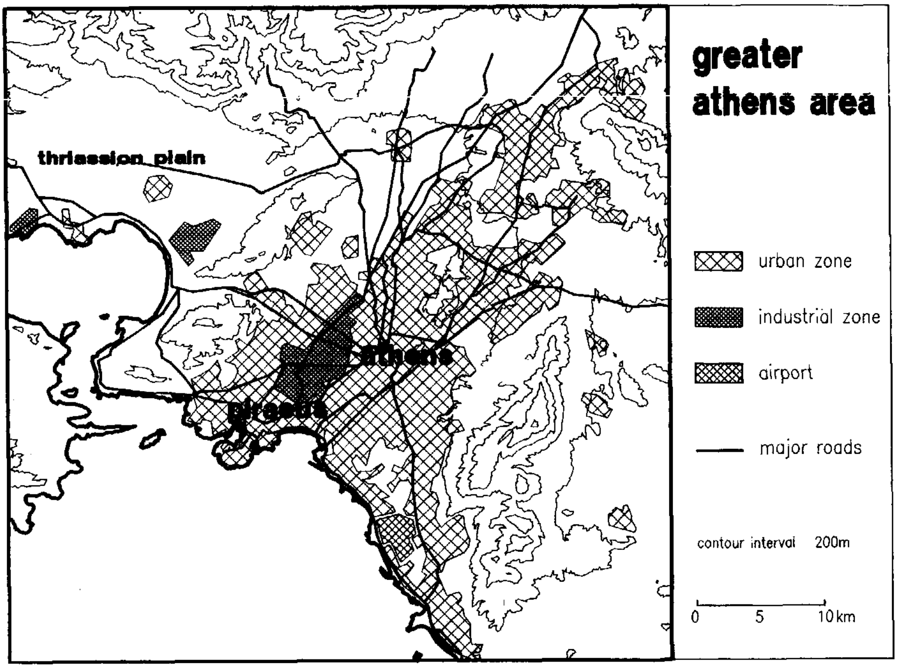


Figure 6-1. The Greater Athens Area.

Large building groups are rather exceptional in GAA. In general, the highest buildings are located in the central district of Athens; a few individual skyscrapers are to be found sporadically.

6.2.2 Meteorology.

As already mentioned in the previous, the two most critical meteorological factors with respect to the air pollution problem are wind and temperature inversion: the wind is responsible for the dilution (or, in case of calm conditions, the concentration) of air pollutants, while temperature inversions cause trapping of pollutants within the inversion layer and prevention of diffusion.

In the GAA the prevailing wind direction (during the whole year) is NNE

-i.e. along the direction of the basin formed between the mountain ranges- towards the coast. The second prevailing wind direction is SSW, due to general wind circulation during the period October-March on one side (deflection of the meridional circulation caused by the coriolis force) and local wind systems such as the sea-breeze which develops in a SSW direction during late spring and summer on the other side. The form and direction of the basin is also, of course, very critical for the direction of the wind.

The wind speed is, in general, low. The wind is considered as a cleaning atmospheric mechanism, because it causes the diffusion of pollutants; there are cases, however, where it can have the reverse effect, in combination with the topography of the area. In GAA both situations i.e. enhancing and preventing diffusion of pollutants occur. The former situation is observed in the case of trade winds which cause cooling and cleansing of the atmosphere; during the summer months when weak sea and land breezes occur very often the latter situation is more common (Lyroudias, 1980). The sea-breeze occurs two or three hours after sunset, has a SSW direction extends vertically up to a height of 300-500 m and at its strongest it can penetrate into GAA up to 12 ks from the coast (op.cit.). In the general case, therefore, a weak sea-breeze can be an additional obstacle along the coast, which is actually the only way through which the pollutants can escape, since in all other directions mountain ranges trap the polluted air. Under such conditions high concentrations of air pollutants have indeed been observed to occur in the basin, while during the period of trade winds the average pollutant concentrations are much lower (Ginis and Zambakas, 1976).

Temperature inversions often worsen the situation in GAA, since they form an additional obstacle vertically, which actually functions as a lid over the basin, preventing the vertical movements of polluted air masses. Such conditions result in unpleasant atmospheric stagnations over the GAA. During the whole year, however, temperature inversions fortunately occur at night and early morning hours rather than during the day, when emissions are generally higher.

6.2.3 Urban conditions.

The modern history of Athens starts in 1833, when the city was inaugurated as the capital of the young Greek state. There were very few things in common between the ancient and medieval past of the city and the small town of the early 19th century; its cultural inheritance, however, was one of the strongest reasons for its selection as the new capital.

Although the structure of the city was redesigned it was never planned for accommodating the immense growth which took place after the 2nd World War. While in 1834 the population was about 10.000, in 1981 it reached

3.000.000, corresponding to an average yearly growth of 4% and classifying Athens as a "mushroom city" (Project II.4, 1983)- let alone the fact that this growth was not smooth but occurred mostly after the war. At the end of the 19th century Athens could be described as resembling a colonial capital city; in the first decades of the 20th century the city was the intermediary between rural Greece and industrialized Europe, acquiring in the years of World War II its own industrial base (op. cit.). Since then it has become the centre of economic activity in Greece. The great expansion of the city started in the early 50s, due to a number of socio-political and economical reasons. By 1951 Athens had absorbed 18% of the total population of Greece; the percentage increased to 22% in 1961, 29% in 1971 and finally 31% according to the 1981 census; in the early 80s concentrated in the city were approximately: 42% of the industrial work force, 76% of the 100 largest industrial enterprises, 50% of the total investment, 64% income consumed by households (op. cit.).

This rapid urban and industrial growth in the area during the last four decades constitutes the main cause for a series of problems, air pollution being one of them. With respect to the air pollution the most important changes in the urban surroundings which have taken place could be distinguished in **changes in the man-made urban elements** and, consequently, increase, of air pollution sources, and **changes in the climatic factors** because of the urban growth and the consequent urban changes.

The most important types of air pollution sources in GAA (they will be discussed separately in section 6.2.4) can be attributed to :

1. the increasing industrial activity.
2. the expansion of residential space.
3. the increase of the car fleet.

Apart from directly generating air pollution sources and emissions, urban and population growth in the area is also responsible for the disturbance of a number of climatic factors, strongly related to the problem of air pollution, such as wind, temperature pattern, incoming solar radiation and rain.

It has been found that the wind speed over the city of Athens has considerably decreased in the period 1910-1970 (Ginis and Zambakas, 1976). The fact is mainly due to the changes in the city profile (increase of buildings) and to the generation of a heat island above Athens. The analysis of temperatures which refer to a period of 50 years (1931-1980) has indeed shown (Lyroudias, 1980) that a heat island appears over the center of the city during the post war decades, obviously due to the increase of population, buildings and general activity in the area. Other rather local changes in temperature are attributed to the decrease of green areas and the increase of nocturnal inversions.

The incoming solar radiation has been found to decrease over GAA because of atmospheric pollution; the decrease is 5.7 minutes per day per 10.5 $\mu gr/m^3$ of soot (Ginis and Zambakas, 1976).

Although influence of urban areas upon precipitation patterns has not been proved (see section 5.3.1.3) secondary effects such as floods tend to increase in urban areas, because mainly of deforestation and insufficient technical constructions which disturb the hydrological balance (Liakatas and Nianios, 1980). Such cases have indeed occurred in GAA during the last 10-15 years.

6.2.4 Sources, emissions and air quality.

Due to the enormous population influx in GAA after World War II there has been a pressing demand for houses which had to be constructed at minimum cost in the shortest possible time. A lot of buildings were constructed without thermal isolation and therefore the energy consumption is high. Furthermore the lack of long term planning (which could have promoted district heating or heating from natural gas) resulted in the wide use of central heating for each building using individual boilers and oil as the fuel (Project II.4, 1983). Pollution from central heating installations is assumed to be proportional to the population density. It is producing high concentrations locally, because of the relatively low height of emissions and eventually aerodynamic downwash* at the sides of high buildings. Although not significant for the overall GAA it is important for the center of Athens where many people work and live. Smoke and SO_2 are the pollutants commonly produced by central heating. The highest smoke concentrations usually appear during the morning hours (6.00 to 9.00 a.m.) because boilers and central heating furnaces start working around that time: the combustion is incomplete and relatively high smoke concentrations of smoke are generated. An additional reason is that low temperature inversions during winter months in the area usually occur around that time.

SO_2 and smoke were the pollutants of major concern during the 70s. However, abatement measures such as reduction of the sulfur in the used fuel (oil and diesel) used in space heating furnaces reduced SO_2 levels significantly; at the same time the replacement of fuel oil with diesel in central heating installations resulted in further lowering of SO_2 and smoke levels (Economopoulos, 1987).

The industrial sources existing in GAA are numerous middle and light plants, located mostly in the industrial zone between Athens and Thriassion and a few basis industries along the northwest coast and in Thriassion (see Fig. 4-12 for industrial source types and their emissions). Industrial emissions were the major source of air pollution in GAA about 15 years ago. Although abatement measurements have significantly reduced the contribution of industries to the overall air pollution problem, industry is still responsible for high dust concentrations and considerable smoke, SO_2, NOx and VOC emissions; it has been shown, however, that proper maintenance and inspection of industrial sources (boilers and nitrogen content in the used fuel) could decrease smoke and NOx emissions significantly (op. cit.).

Apart from the measurements taken for industrial emissions the increase of the number of vehicles during the last two decades in GAA is the reason that the air pollution problem is nowadays of a different nature than in the first years of its appearance. This fast increase is responsible for a respective increase in traffic emissions, consisting mainly of CO, HC and NOx. It could be said, therefore that in its early stages the air pollution problem in GAA could be described as of the "London type" (high concentrations of SO_2 and smoke); nowadays it resembles rather the "Los Angeles" type (photochemical pollution due to traffic emissions) especially because the topography (i.e. the form of the basin) and the climatic factors in the two areas have a lot in common.

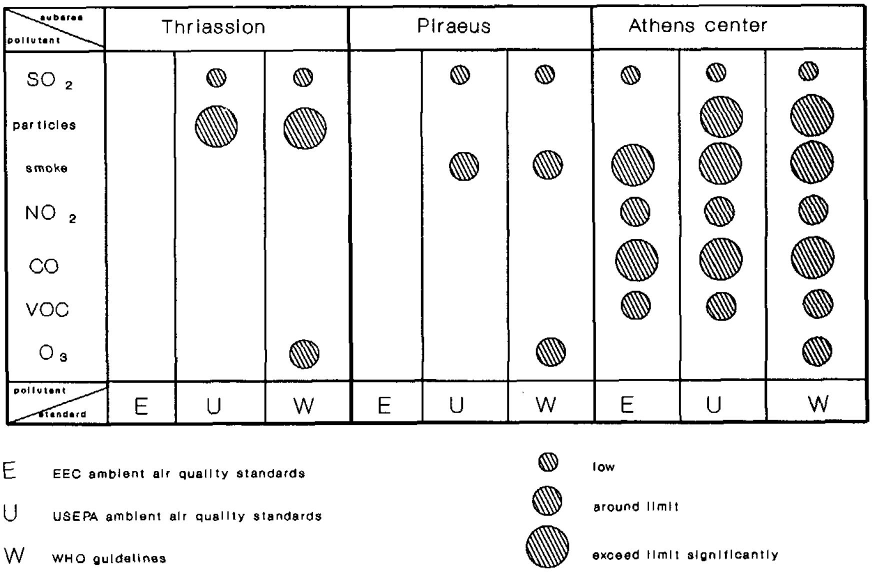


Figure 6-2. The air quality status in GAA.
(data from: Economopoulos, 1987)

Figure 6-2 summarizes visually the air quality status in GAA by displaying concentrations of the most important air pollutants to be found in the three major urban / industrial subareas (Athens' center, Pireaus and

Thriassion plain).

As it was seen from section 4.8 long term air pollution control strategies are basically concerned with either the control of sources by means of imposing emission standards or the control of air pollutant concentrations by means of imposing air quality standards. For short term (i.e. tactic) control, apart from the control of sources, other targets are the elimination of pollution episodes or/and elimination of "hot spots" which are achieved by the sort term monitoring of air quality levels.

In Athens both types of control are implemented. For the purposes of strategic control the control of sources and their emissions was considered appropriate for the city (Economopoulos, 1987). For the short term control the APO of the city maintains a monitoring network consisting of 18 stations, approximately half of which is fully automatic and the rest semiautomatic. Qualitative estimations of the overall status of air pollution are made on the basis of meteorological data obtained from the meteorological service on a daily basis. During the last years, however, an effort is made to organize the development and/or implementation of air pollution simulation models for GAA.

6.2.5 Synthesis

The GAA has been used in this work as a case study area for the implementation of the proposed prototype for simulating and mapping air pollution. An operational system based on the proposed prototype can assist in air pollution control in an urban area, in monitoring air quality levels, in evaluating the elements involved in air pollution and projecting their potential impacts. In Chapter 4 the natural elements and their interrelations were discussed in order to understand their nature, functions and interrelations and consequently their spatial and temporal behaviour in the context of urban air pollution. In the previous Chapter the spatial aspects of both natural and man made-elements involved in air pollution in an urban environment were discussed in more detail and an effort was made to list the most important among them and their influences upon each other (see e.g. the matrix in Fig. 5-2). On the basis of this matrix concept and the fundamental functions of an urban air pollution control service the themes to be mapped were derived (see e.g. the matrix of maps in Fig. 5-5) and the rest of the cartographic elements were also identified. In the rest of this Chapter the software modules developed and/or used for implementing what has been proposed in the previous will be described. The software can be considered as performing two main functions: preparation and processing of the information and map production. Although occasionally application-dependent, the software modules are meant to be used for the purposes of urban air pollution simulation and mapping purposes in general.

A short description of the data collected for implementing the prototype will precede. The description of the functionality of the main algorithms and some examples of produced maptypes will follow.

6.3 Data collection

The collected input emission and meteorological data and their sources are shown in Figure 6-3. For the point source emissions (i.e. the emissions from industrial sources the data of emission inventory of the APO of the city of Athens were used (Koussoulakou, 1988b). In the APO files those data existed in the form of hand written questionnaires from which the necessary parameters had to be selected and registered. For some industries, however, not all the required parameters were available; in such cases the industries were considered as area sources or assumptions regarding the missing parameters were made (about e.g. the emission height or the stack gas temeprature etc.). Additional information on

			input data	source
emissions	point	industry	source coordinates emission rate stack height stack volume flow stack temperature	APO
	area	industry traffic central heating	SW corner coordinates source length emission rate' source height	APO NTUA Proj.II.4
meteorology		surface	wind direction wind speed air temperature cloud cover cloud ceiling	NMS
		upper air	mixing height	NMS

Figure 6-3. Input data and their sources.

industrial boilers, which was not contained in the APO files was obtained from Final report no.4.2 (1984) and also from personal communications. Emissions from traffic and central heating were considered as areal emissions; the necessary input parameters were obtained from NTUA (1986) for traffic and from Project II.4 (1983) for central heating emissions. The emissions of the seven most important air pollutants were included in the created files, namely SO_2, particulates, smoke, NOx, CO, VOC and Pb.

Meteorological data were obtained from the National Meteorological Service (NMS). Surface data (i.e. wind direction, wind speed, air temperature, cloud cover and cloud ceiling) were given on standard (meteorological) format on magnetic tape. Upper air data (i.e. mixing heights), however, were not directly available and they, therefore, had to be exctracted from special diagrams for recording radiosonde information (the so-called tephigrams), which were available at NMS. It should be noted that this information is obtained from radiosonde balloons which are released at the area of the airport; consequently the estimated inversion heights are possibly not representative for the whole GAA.

Finally, topographic information was obtained from topographic maps of the Hellenic Geographic Army Service at the scales mentioned in Chapter 5 (i.e. 1:10000 - 1:250000).

As mentioned in the beginning of the previous section (6.2.5) the particular area of application (GAA) was used as a case study area for the development and implementation of a prototype for simulating and mapping air pollution. From the previous discussions, however, it has become clear that the assumptions in the input data on one side and the simplified form of the RAM simulation algorithm (see e.g. section 4.7.2) on the other, pose restrictions for the implementation of the developed prototype on an operational basis. With respect to the RAM simulation model, in particular, it should be mentioned at this point that despite its simplistic assumptions (with respect e.g. to terrain or wind field) the model was utilized for a number of pragmatic reasons:

- a more advanced algorithm especially developed to suit GAA was not available.
- even if such an algorithm had existed, serious shortcomings in the input data would still be a drawback (e.g. information about the wind field over the whole area was not available; information about inversions was very limited etc. It seems, however, that given the magnitude of the problem in the area, such studies are under development).
- on this basis the available algorithm - although not the most suitable one - was used as a mere tool for proceeding with the development of the prototype. It could be very easily substituted by another one, in case a more suitable model for GAA becomes available.

6.4 The software modules

The algorithms described in the following were developed for the purposes of the present study, with the exception of two software packages (namely RAM/RAMMET and GEOEAS) which both are public domain software developed by the United States Environmental Protection Agency.

For the data processing algorithms FORTRAN was used as the programming language. For the map display algorithms FORTRAN was also used, in combination with standard graphics subroutine packages such as GKS (Graphical Kernel Standard) and graPHIGS (IBM version of PHIGS: Programmer's Hierarchical Interactive Graphical Standard). graPHIGS was used in addition to GKS because of its 3D options and the possibilities it offers for animation (although not actually designed for such a purpose). Occasionally, an additional graphics subroutine package having concepts almost similar to these of GKS was used (HALO Graphics Kernel System), because it offered the possibility to create "transparent" overlays (XOR drawing) with FORTRAN calls, something which was not possible for GKS.

In the rest of this section the functionality of the algorithms shown in Figures 5-12 and 5-13 is given.

SCASE: the program selects the scale of the map after the user chooses interactively two points on a small-scale map of the area presented initially on the screen. The selection is made among five possible scales (1:10000, 1:25000, 1:50000, 1:100000 and 1:250000); the program actually picks the scale closest to one of the above and draws the selected area in this scale, starting from the lower left corner of the map. It also gives information about the positional accuracy, according to scale and map display.

TRANSFORM: the program performs coordinate transformations in order e.g. to convert the cartesian coordinates of points on a map with an unknown projection to another grid coordinate system, or to correct digitizing errors etc. After common (i.e. identical) points are selected on the two maps a transformation is applied to convert the coordinates of the original map to these on the final map. The user can choose among an affine, a bilinear polynomial and a power series transformation, depending on the nature of the application. The values of the transformation parameters which are determined by applying the method of least squares are used to convert the initial data set.

DEFORUTM: the program calculates the linear and areal deformations of the UTM projection for the area of application.

CONSURF: the program converts the original surface meteorological data in order to be further processed by RAMMET.

CONINV: conversion of upper air data from millibars to meters in order to obtain the inversion heights.

RAMMET: the program uses the hourly surface meteorological observations prepared by CONSURF and mixing height (inversions) information prepared by CONINV to calculate atmospheric stability classes and randomized flow vector and writes hourly meteorological data arrays in daily records. Data for a whole year have been used here.

PROCINDA: the program processes industrial areal emissions. It calculates the total emission rates for each area source on the basis of yearly emission parameters of each industry, their seasonal, weekly and daily variations and the geographic location of industries.

PROCPOEM: conversion and processing similar to PROCINDA, but for point industrial sources.

PROCAREM: conversion and processing of the rest of the areal sources (traffic, central heating)

TOTEMVAR: This program actually implements an emission model by calculating hourly variations of emissions for a selected time. The user is initially asked if he/she wants to consider time variations of emissions for the implementation of the model. If not, the yearly average emissions will be used for the simulation. If yes, the user is asked to give the year, the day, the month, the day of the week and the hour. The hourly emissions are then calculated on the basis of the emission variation factors given in the input files of this program. It is possible to store emissions for maximum one day (i.e. 24 hours).

RAM: This is the air quality simulation program which implements the algorithm described in Chapter 4. The program accepts input for sources and emissions from program TOTEMVAR and for meteorology from RAMMET and calculates concentrations of the pollutants which have been selected by the user (among 7 possible choises, namely SO_2, particulates, smoke, NOx, CO, VOC, Pb) at selected (by the user) locations. Various options are offered such as consideration of stack downwash, specification of significant sources, calculation only for a selected type of sources (i.e. area, point), generation of additional receptors downwind of significant sources or generation of a denser array of receptors to cover a specific area, or generation of a polar coordinate receptor array etc.

COMPRI: The program creates printouts for comparison between the concentrations which have been calculated by the model for the locations of the monitoring network stations and the respective measured concentrations at the stations of the network.

CORREL: The program correlates two sets of data (here the simulated and measured concentration values) by computing correlation coefficients. It can also be used to compare other sets of thematic and/or spatial data.

GEOEAS: This is the kriging interpolation program. It computes descriptive statistics, produces statistical diagrams (such as scatter diagrams, histograms, probability plots) examines the spatial correlation structure of the data and represents this structure with a variogram model (chosen among a set of options). This model is then used to interpolate a grid of kriged estimates, using either ordinary or simple kriging. The computed kriging estimates and the respective estimation errors can be viewed graphically by means of contour plots.

DISINTRP: This is the moving average interpolation program. Since kriging requires some computational effort this program can be used for a fast preview of results (simulated and/or measured).

DRPOEM: The program displays the emissions of industrial (point) sources with the help of proportional or graduated point symbols (circles, pies). Initially all the industrial point sources of GAA are displayed classified in four types (basis, heavy, middle, light industries). Then the user is asked to select interactively one or more type(s) of sources of which the emissions will be viewed and also to select the pollutant(s) to be viewed. The selected combination is then displayed; the user can go back to the main menu and make another selection or exit the program.

ARROWS: The program uses point symbols (arrows) of varying magnitude and direction to display the wind field above an area.

POINCO: An array of graduated or proportional point symbols is used for the display of concentrations.

WINDROSE: Point symbols in the form of wind and pollution roses for the display of long term meteorological conditions and air quality levels.

LINEM: Emissions from line sources (e.g. roads) are displayed with the help of line symbols of varying thickness.

LINCONTR: Contouring algorithm to generate and display isarithms from a set of values interpolated or calculated on the nodes of a regular grid.

AREAEM: The program displays the emissions from area sources (square cells) using values of a color to show the various emission levels. The emission overlay is transparent i.e. the topographic features are visible.

LAYTIN: The program generates layer tints from contour lines in order to give a better visual impression of a distribution. The layer can be transparent or the important topographic features can be superimposed.

POLYG: Display of areas (polygons) having various thematic attributes.

CHORO: Choropleth mapping.

TOPOBASE: Topographic base at the five selected scales.

CARMAP: Animated display of a point symbol (representing a vehicle) following a predefined route (path) in a city.

ATHWIND: Same type of display as arrows, but animated i.e. the magnitude/direction changes with time, indicated by an analog clock.

FLASHPO: Flashing point symbols indicate exceeded air quality standard at certain locations (e.g. monitoring stations).

MOVELINE: A moving pollution front.

TRAFFIC: Variations in traffic emissions. Display same as in LINEM, but animated e.g. the line thickness of the segments forming the street network changes in the course of time.

EMIGRE: Proceeding arrows display routes of regional migration in Greece.

FLASHLI: Flashing line symbols indicate exceeded air quality standards over GAA.

ANIGEO: Change of air pollution concentrations simulated by RAM above GAA in the course of a day (can also be of measured concentrations). The concentration levels are displayed with the help of transparent layer tints which evolve in the course of time (indicated by a digital and analog clock). An example of non-real time (precalculated) animation (see Fig. 7-). The maptype was produced in cooperation with the Delft Hydraulics laboratory (see: WL, 1990).

CITYEXP: Expansion of the city of Athens during the post-war years.

CLOUD: Movement of a body of pollution. The display is similar to ANIGEO but simpler: the cloud is visualizing the concentrations above a certain level but the different concentration levels are not distinguished. The program is useful for a quick preview of changes in air quality, especially since ANIGEO requires considerable time for generating an animated display.

OVERLAYS: Program which combines thematic data files for the purposes of visual correlation of elements involved in air pollution.

LAYTERR: 3D (solid) display of the terrain and topography of GAA. The program offers various options such as to view the terrain only, or to combine it with thematic information (land-use); to view the 3-D terrain with one or two superimposed 2D layers displayed in perspective and containing thematic information such as pollution concentrations, wind field etc.; to display multiple views of the terrain from different viewpoints in different windows on the screen; to visualize the mixing layer and the inversion layer and combine them with the terrain in a 3D display.

SURFACE: The program draws a 3D (solid) statistical surface over a 2D layer of the topography of GAA viewed in perspective.

6.5 Examples of produced maptypes

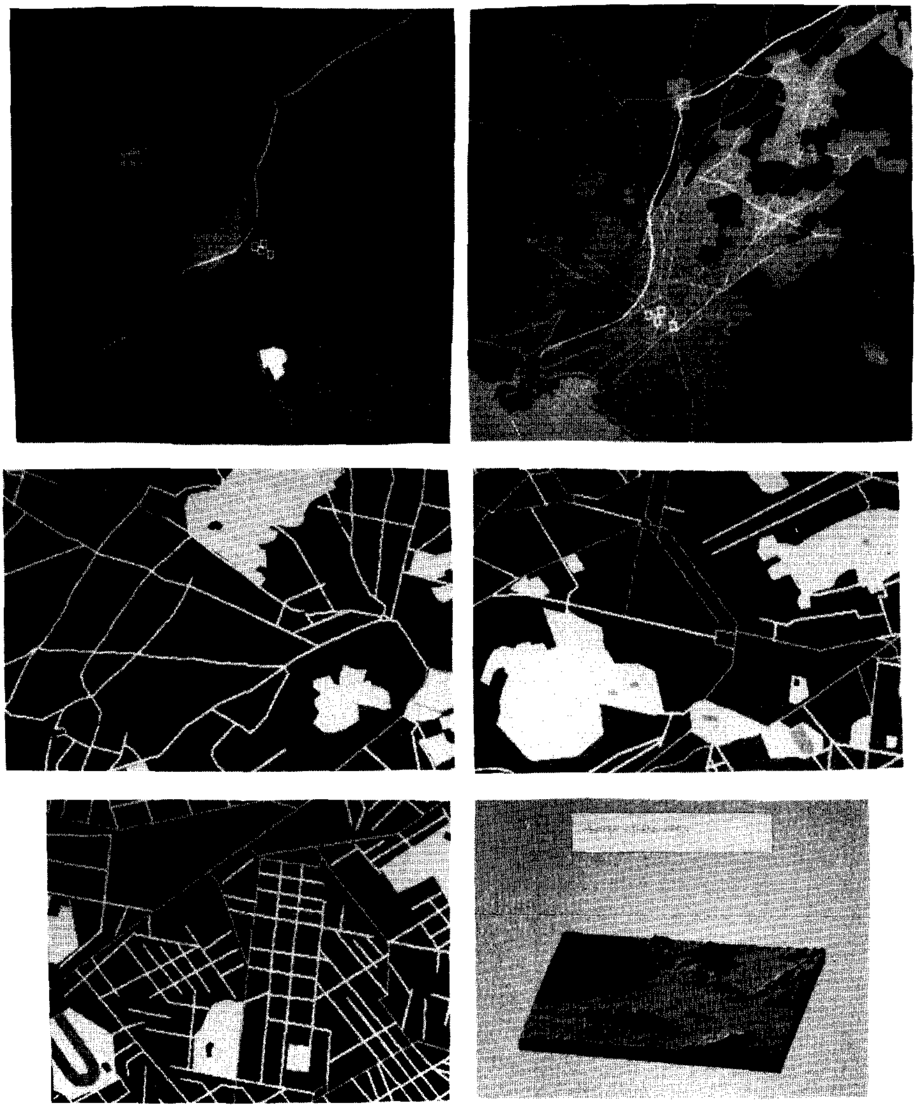


Figure 6-4
(1). Base map at scale 1:250 000
(2). Base map at scale 1:100 000
(3). Base map at scale 1: 50 000
(4). Base map at scale 1: 25 000
(5). Base map at scale 1: 10 000
(6). 3-D form of the terrain

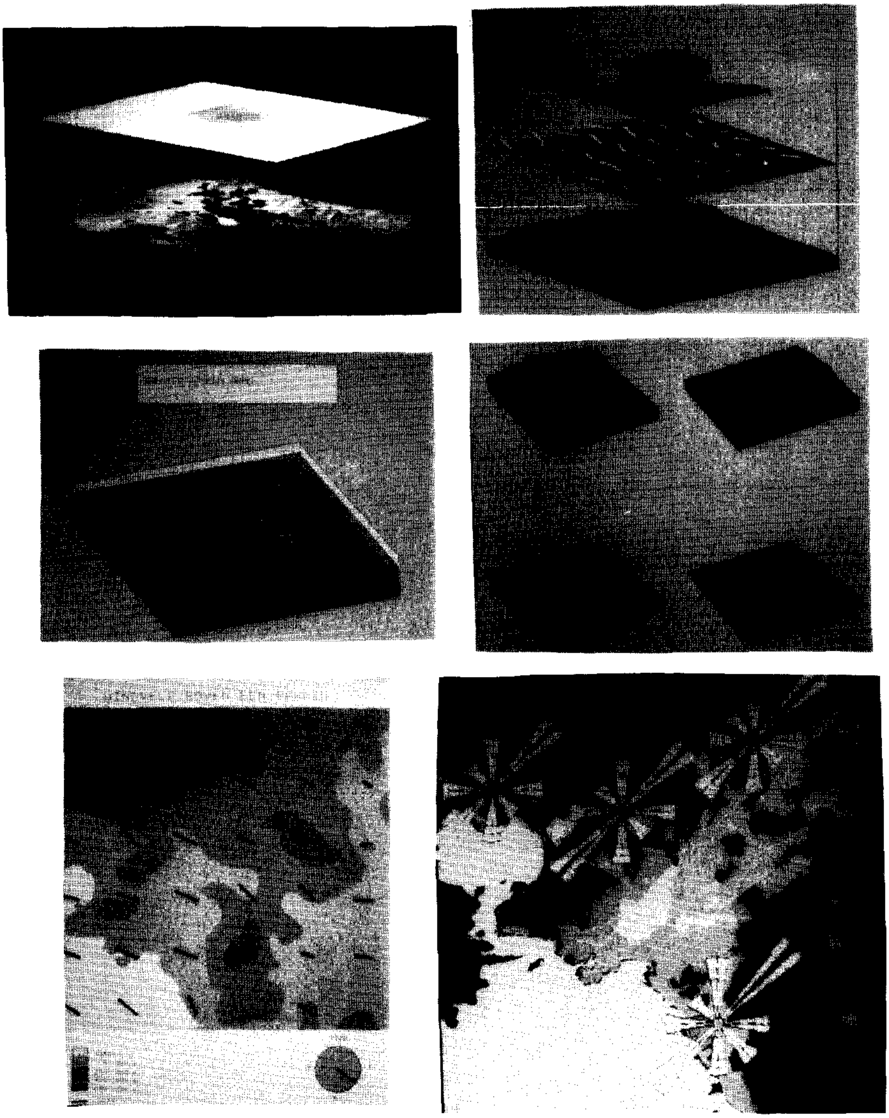


Figure 6-5
(1). 3-D terrain with landuse and superimposed layer (pollution).
(2). 3-D terrain and superimposed layers (pollution and wind)
(3). 3-D terrain with mixing layer and inversion layer
(4). 3-D terrain viewed from four points
(5). Windfield (animated)
(6). Windroses

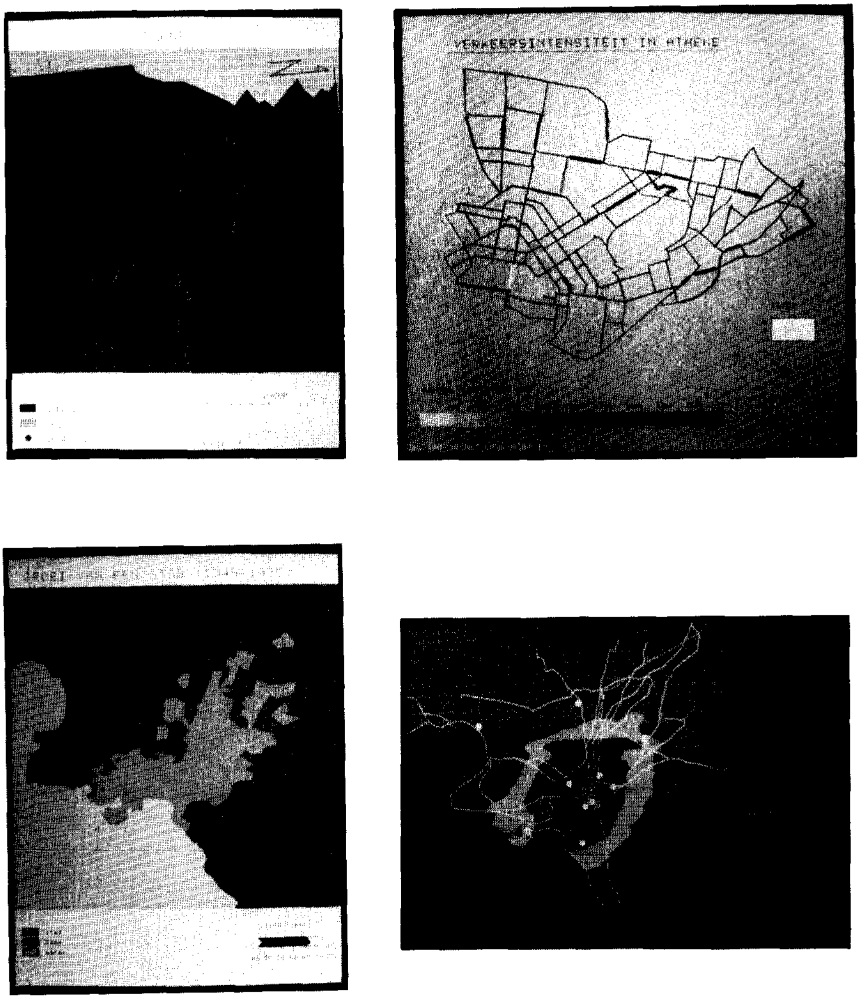


Figure 6-6
(1). Car route in city (animated)
(2). Traffic density (animated)
(3). City expansion (animated)
(4). Concentrations displayed with layer tints

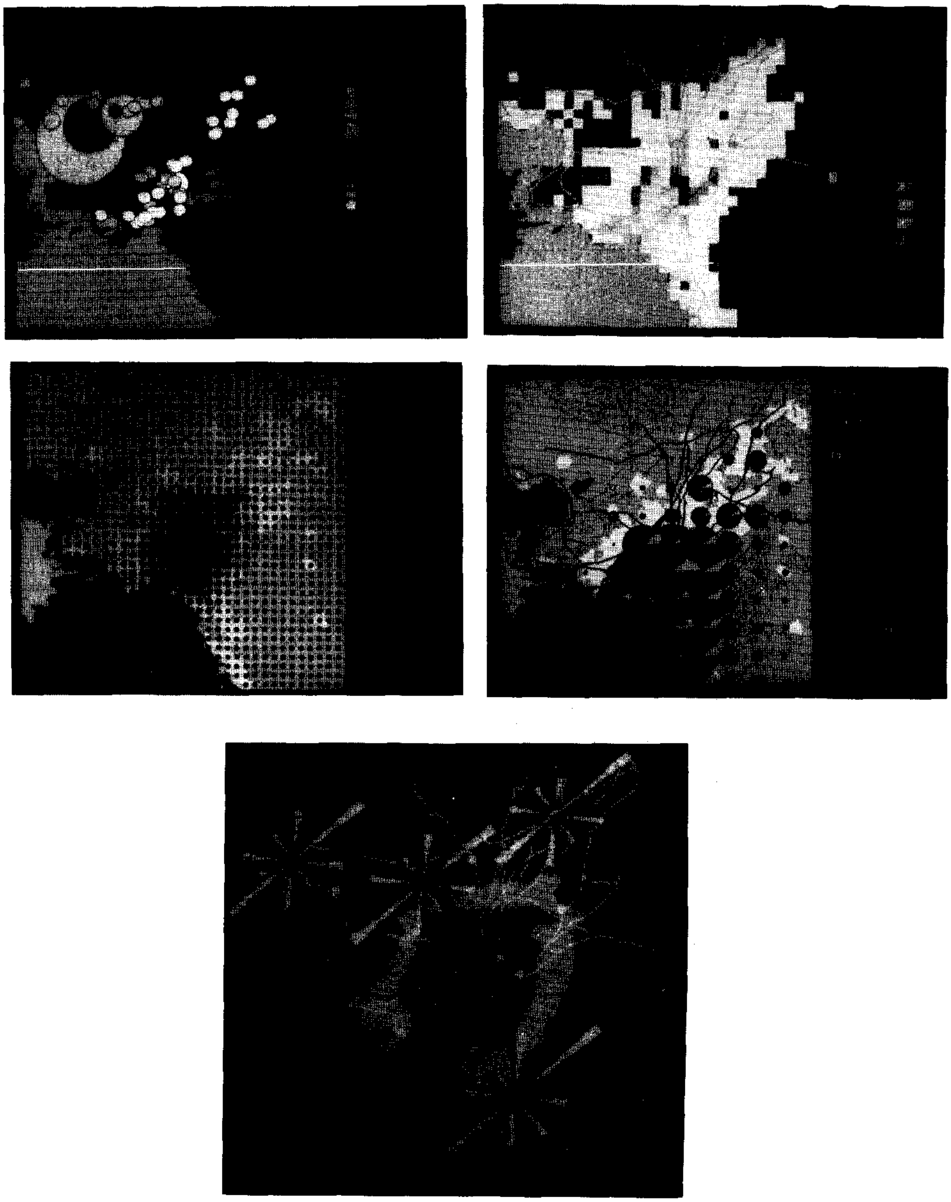


Figure 6-7
(1). Industrial emissions
(2). Traffic emissions
(4). Concentrations of one pollutant displayed with point symbols
(3). Concentrations of more pollutants displayed with point symbols
(5). Overlay: Concentrations and windroses and monitoring network

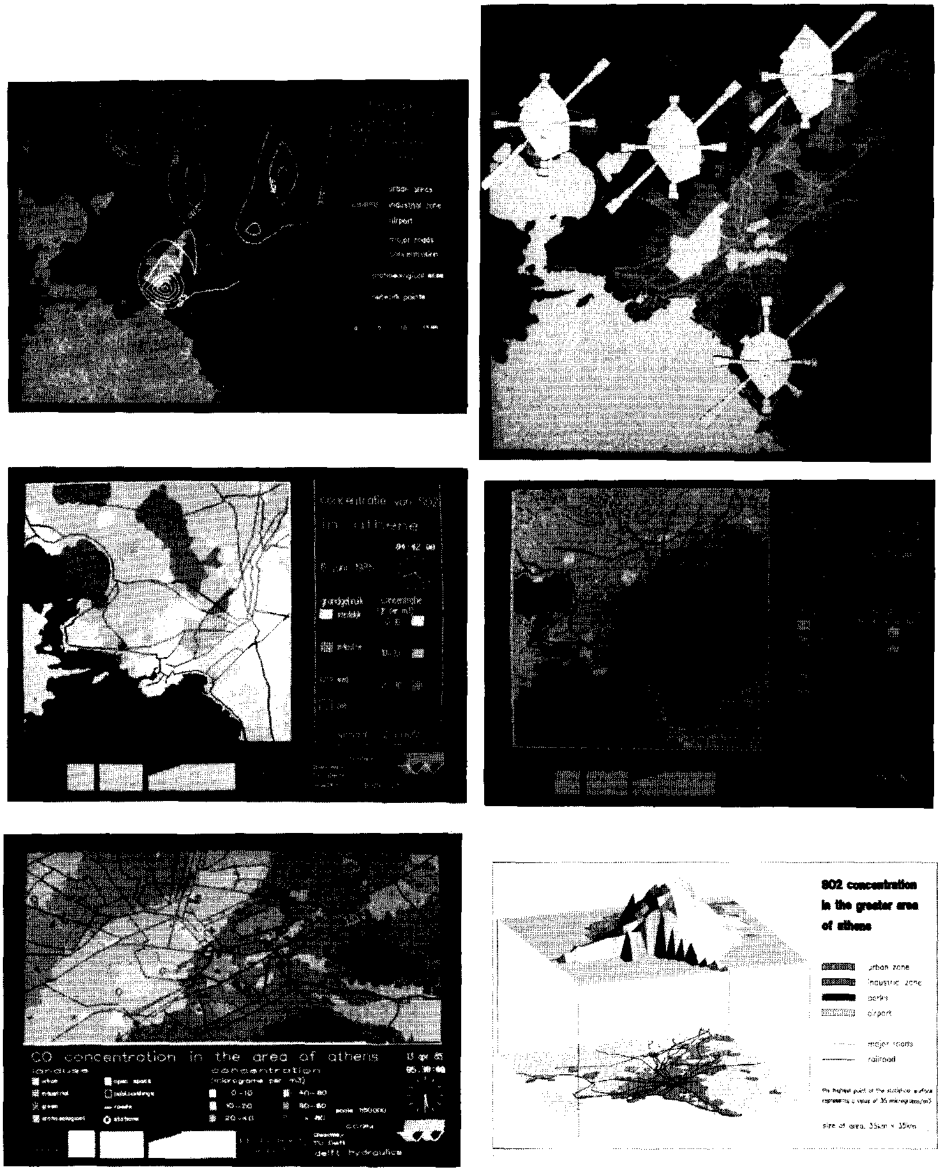


Figure 6-8
(1). Concentrations displayed with isarithms
(2). Pollution roses
(3). Concentrations of SO_2 *(animated)*
(4). Concentrations of CO (animated)
(5). Concentrations of CO in the city center (animated)
(6). Concentrations displayed with 3-D statistical surface

CHAPTER 7. A MAP-USER TEST FOR ANIMATED MAPS

7.1 Introduction

This Chapter is concerned with the map-user test which was carried out in order to conduct a preliminary assessment of the performance of some dynamic map displays. In section 7.2 the context and the purpose of the test are discussed. In section 7.3 the procedure which was followed for carrying out the test is described i.e. the maps, the questions, the test environment. The discussion of the results and the conclusions drawn are given in the last section of the Chapter (7.4).

7.2 The context and purpose of the test

As it has already been seen in the introductory Chapter the main purpose of cartography and GISs is to accept, organize, process (e.g. analyze, transform, compare, combine etc.) and, finally, display spatial information for the users. Within this wide scope of applications there is a growing trend for visualizing spatial processes having a strong temporal component. The monitoring and mapping of time based changes (physical or social, real or projected) provide a tool which has a potential for scientific, engineering and educational applications, but can also be very useful for decision-makers at various levels (planners, administrators, politicians).

Some examples of possible dynamic mapping products have been given throughout this work, with an emphasis on environmental applications. The scope of dynamic mapping applications seems to be growing and one of the reasons this is happening has to do with the fact that the study of the dynamics of physical phenomena and the assessment of impacts is in favour (hence the already mentioned increasing utilization of prediction models and the study of spatio-temporal patterns). Consequently, there comes a demand for a dynamic presentation of time based changes. Since the computer facilities of nowadays have made such displays possible to generate, dynamic (animated) maps are becoming more and more commonly used.

Actually, since their early stages of development computers have been successfully used for numerical modelling and simulation of complex physical phenomena. The visual display of the numeric solutions, however, was made possible much later, after significant advances in computer graphics technology. During the last few years, in particular, the advances in computer hardware and software have promoted the utilization of more sophisticated graphic tools such as computer animation.

Apart from its wide use in arts and advertising computer animation is nowadays becoming popular for the visualization and evaluation of results in scientific and engineering applications. Its great power lies in the possibilities it offers to look at things in unusual ways. Some of its applications in various disciplinary fields are illustrated here by means of a few examples:

Astronomy: position and movements of planets and stars in space.

Geodynamics: display of the continental drift i.e. the movements of tectonic plates; display of movements/deformations of control points/networks because of e.g. earthquakes; display of tides.

Space and military applications: visualization of targets, orbits and relative positions of objects.

Meteorology: weather and storm displays for meteorologists, pilots, general public.

Architectural design: move inside and/or around buildings (e.g. to evaluate visibility); "travel" inside a city ("the movie map").

Building construction: display impacts of earthquakes on buildings.

Accident simulation: scenarios for reconstructing and displaying e.g. what might have happened during a plane crash, on the basis of the available recorded data.

Medicine: geometric modelling and viewing of body objects and their functions.

Education: visualization of principles of mathematics (e.g. calculus), physics (mechanics, theory of relativity).

This Chapter concentrates on certain cartographic aspects of computer animation. Before a general discussion on computer animation within the context of Computer Assisted cartography, some fundamental concepts and techniques will be given in the following section.

7.2.1 General concepts in computer animation

Animation is the process of designing and producing images which create the illusion of motion (to "animate" means literally to "infuse life"). Animation, however, is more than merely showing the real motion of a real scene: apart from that it can also generate imaginary, impossible, abstract or unobservable actions. Because of its potential to reveal the nature of not only real events but also of events which are impossible to happen in the real world -or at least impossible to photograph- animation constitutes a very powerful means of visual communication.

The basic principle of animation is to break down the continuous reality into a series of similar (while not completely identical) pictures (commonly known as frames) which, when viewed rapidly in succession produce the illusion of motion. The traditional way of producing animation is by either drawing an individual picture for each frame or by photographing a flexible model in successive positions (i.e. frames).

Since this process very often requires repetitious and time-consuming jobs and since for that kind of task computers are perfectly adept, most of the steps of a conventional animation process are nowadays computerized.

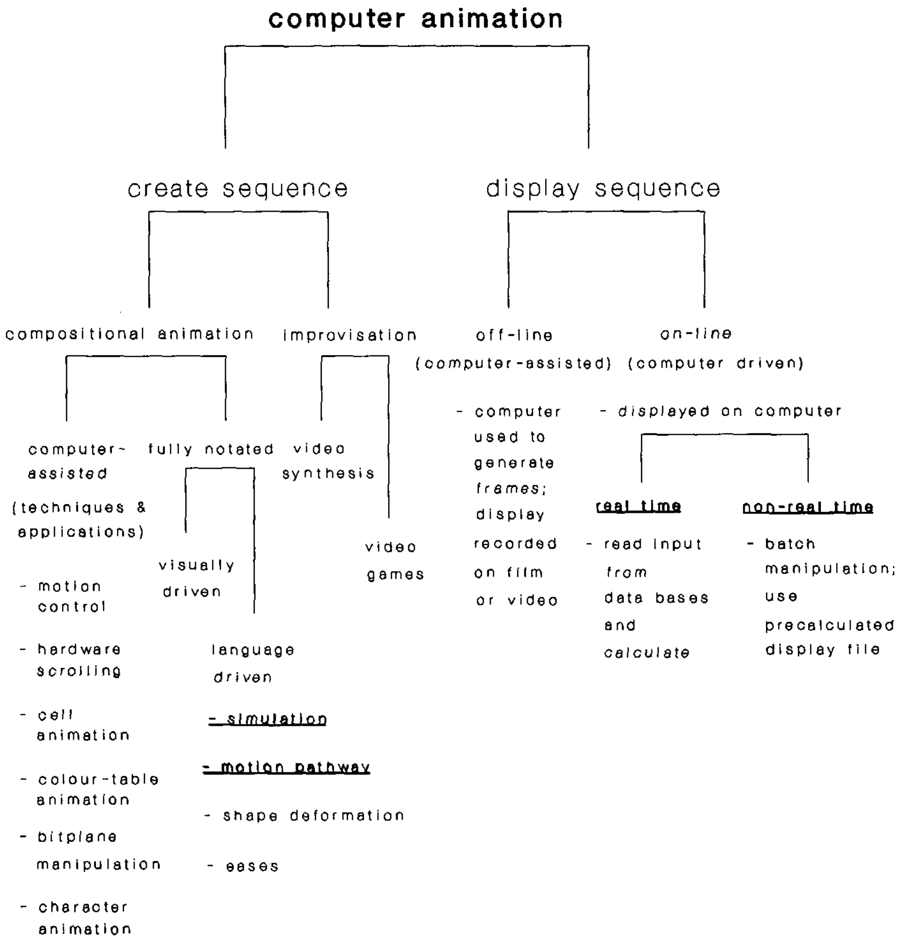


Figure 7-1. Overview of computer animation.
(the methods highlighted have been used for the production of animated maps in the present work).

In Figure 7-1 a general overview of the computer animation process is given. As seen, the whole process can be considered of consisting of two major parts, namely the creation (generation) of the animation sequence and the consequent display of this sequence.

The **creation** of animation sequences can be done by either **compositional** or **improvisational** media (Rosebush, 1985). The latter comprise media such as video synthesis and video games; they will not be of further concern here. Applications of compositional animation fall into two groups: **computer assisted** and **fully notated.**

The first group contains techniques which assist rather than perform the process of creating an animation sequence. These techniques are briefly reviewed here.
The main characteristic of computerized **motion control** is the employment of physical cameras and artwork which are equipped with computer controlled motors. The computer focusses and moves the cameras and positions the artwork to be photographed.
Hardware scrolling is a technique which allows the computer to get the sequential images by looking into a different part of the screen memory for each frame. The screen functions like a moving window over the whole image stored in a sequential manner in the computer's memory.
Computer assisted **cell animation** is the utilization of computer hard- and software facilities for the steps of a traditional cell (i.e. cartoon) animation process. These include e.g. scripting (word-processing), storyboarding (illustration graphics systems), composing the various layers (spreadsheets), drawing (illustration graphics systems), in-betweening (interpolation methods), inking and painting the layers (scan conversion).
Colourtable animation is a way to produce (limited) animation on a static display. It creates action by sequentially illuminating areas that are already predefined positionally (like the light bulbs in a theater marquee). An object is assigned a colour number which corresponds to a colour in a colour table. The different positions of the object in the successive frames are assigned successive numbers, pointing to different colours. When the colour look-up table is modified by changing the colour in the different positions an illusion of motion or change is created.
Bitplane manipulation involves the separation (splitting) of the bit planes of the screen memory so that it can be considered as consisting of separate layers. Two separate bit planes, for instance, can create an animation effect when switched on and off: during the time the first is on, the second is updated, then the first is turned off (i.e. made invisible) and the second displayed; during this time the first updates in order to be displayed again and so on.
Character animation involves objects (characters) which are drawn and animated separately from their background. the simplest method of achieving character animation is to draw separately the different frames of the object in the same position by making use of the computer's character set (a sort of drawing on a matrix of pixels). Each new frame erases the previous one; the illusion of motion can be created by sequentially cycling through a number of defined frames.

Within the second group of compositional animation (i.e. fully notated) all objects to be animated are described using numerical data bases stored in the computer's memory. The animation is either **language** or **visually driven**. In the first case a programming language is used to model shapes, to move objects and to generate the motion. In the second case the animation program is interactive and picture driven. The positions of the objects are selected in real time, stored in a data base as key frames and finally interpolated to form the animation. The interactive approach is better for achieving natural motions; the language approach is best when the movement has to be algorithmically derived or when a physical process has to be simulated via mathematical description.

The methods used most commonly in language driven animation are:
Eases i.e. rates of change which define acceleration or deceleration;
Motion pathways which define the successive positions of an object;
Shape deformations which define geometrically changes in the shape of objects (i.e. stretch, squash, interpolated frames between the successive key frames etc.);
Simulation which models the physical laws that affect objects.

The **display** of animated sequences can be either **off-line** or **on-line**. In the first case cine or video techniques are used to record the animation sequence the separated steps of which were created with the assistance of the computer. In the second case the animation sequence is displayed on the computer itself. There are two main kinds of (on-line) display programs to be distinguished: **a.** those which perform the calculations real-time i.e. each time the program runs it reads the input information about the animation sequence from a data base and calculates in real time before it displays the output. **b.** those which compute the animation sequence in batch time and store the result in a display file: each time the program runs it is this precalculated file which is actually displayed on the screen.

7.2.2 Animation in cartography.

Attempts to display on maps, with the help of animation methods and techniques, the temporal dimension of spatial phenomena or to utilize animation techniques for better visualization of thematic distributions are not new to cartography (see e.g. Thrower, 1961; Cornell and Robinson, 1966; Tobler, 1970; Moellering 1980a and 1980b; Mounsey 1982a and 1982b; Taylor 1984a; Olson, 1984) In most of the cases, however, the display of animated maps was done off-line (i.e. utilizing cine film, video film or video disks). It was not until a few years ago that - thanks to computer advances- on-line animated maps became easier and cheaper to produce and, therefore, started to appear more often in cartographic applications (see e.g. Sena, 1989; Sena 1990; Pfitzer, 1990).

Animated maps are concerned with the display of dynamic spatial phenomena. Conventional static map displays ,however, can also be utilized for the same purpose. In the general case a map will be considered as dynamic when it displays temporal aspects of a dynamic phenomenon. A dynamic map might therefore make use of either a conventional (i.e static) or an animated display (Fig. 7-2).

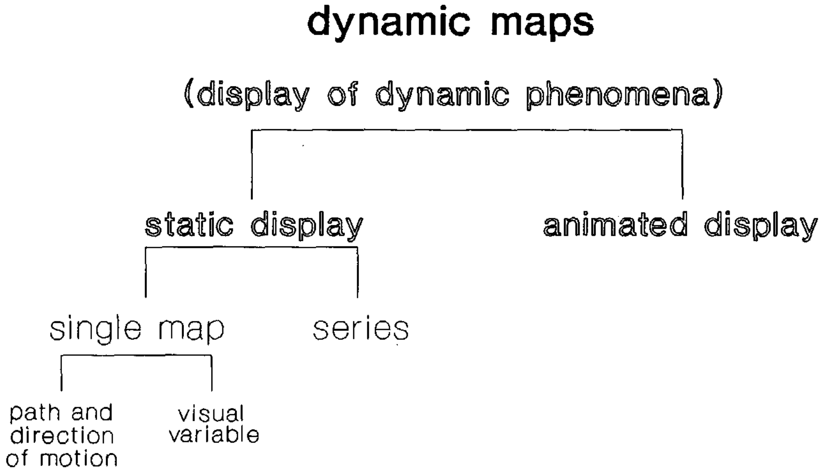


Figure 7-2. Types of dynamic maps.

Maps which display processes of dynamic phenomena introduce an additional component i.e. the time component, which could in the first place be considered as a thematic component. Depending on the way the subject of the map is displayed, however, this temporal component can be transcribed graphically in basically three ways (Bertin, 1986; see Fig. 7-2):

1a. on a single static map: the temporal component is transcribed graphically by means of the **visual variables** that the graphic sign system has at its disposal.

1b. on a series of static maps: **no visual variables** are utilized to depict the time component *per se*; the variations introduced by this component are perceived by the succession of the individual maps depicting the situation at certain time moments. It could be said that the temporal sequence is represented by a spatial sequence, which the user has to follow, in order to perceive the temporal variation. The number of images is, however, limited since it is difficult to follow long series.

2. on an animated map: here the variations introduced by the temporal component are furnished to the user on a single image. The similarity with case 1b is that no visual variables are utilized for the temporal component per se; the difference is that the variations introduced by this component have not to be deduced from a spatial sequence but from **a real movement** on the map itself.

For the case of dynamic maps it could therefore be said that while for the geometric component the graphic transcription is always done by

			component		
			geographic	thematic	temporal
map display	static	single	plane	visual variable	visual variable
		series	plane	visual variable	"spatial" deduction
	animated		plane	visual variable	memory deduction

Figure 7-3. Graphic transcription and perception of the geometric, thematic and temporal components of dynamic maps.

utilizing the dimensions of the plane and for the thematic component always by utilizing visual variables, for the temporal component three different ways are possible (Fig. 7-3)

The temporal component is therefore, in the general case not regarded as an additional thematic component but rather as an additional dimension (in the spatial sense).

7.3 A map-user test for animated maps.

The growing interest about temporal aspects of spatial phenomena is increasing the utilization of various animation techniques for cartographic and GIS applications. It seems that the use of animated map displays as informative, educational, research and planning tools will further increase, not only because there is a growing demand but also because computer hardware and software developments make such displays easier and cheaper to produce.

From the cartographic point of view it is interesting not only to produce such animated map displays (map creation process), but also to assess the performance of these new products i.e. to examine how the map-user will interpret the information furnished by them (map-use process). As mentioned in Chapter 2 cartographers should try to make the original information I extracted from the real world and displayed on a map coincide as much as possible with the information I' extracted from the map by the map-user. In order to do this an evaluation of I' has to be made; then a feed-back to I has to be done in order to improve the necessary elements in the map creation process. The evaluation of I' is the task of map user tests in general;
the evaluation of I' extracted from animated map displays is the purpose of the map-user test carried out here.

As seen in the previous section dynamic processes can always be displayed on conventional static maps (although sometimes with inevitable loss of information). The first question which, therefore, arises is whether the dynamic nature of spatial processes justifies their animated cartographic representation; in other words do animated maps help the user extract the correct information more accurately than the representative static maps which depict the same subject ?. The purpose of animated maps is to display activities, processes and trends of spatio-temporal phenomena in the course of time. Having in mind that maps are always meant to save time, the question which then follows is whether, indeed, an animated map succeeds in making the user perceive the evolution and trends of a phenomenon not only more clearly (i.e. correctly, accurately), but also faster than a conventional static map.

The map-user test carried out in the present work was an attempt to obtain some concrete evidence about the response of users to both animated map displays and the respective static ones depicting the same subjects. In this way some first indications about the suitability of animated map displays could possibly be derived.

At this point it should be noted that the test by no means attempts to be comprehensive and draw general conclusions about animated maps. It was performed on a limited number of maptypes, asking selected types of questions to a certain group of users; its purpose was to carry out a preliminary assessment and provide indications rather than draw conclusions. These indications, however, could possibly stimulate further research on the subject.

The test was carried out in an entirely interactive, computer-driven environment (see also: Kraak, 1988). The creation and display of the maps as well as the display of the questions was performed by a software program written for this purpose. The answers given by each user as well as the respective response times were registered in an separate (for each user) data file, which was consequently used as input to the program for the statistical processing of the results.

7.3.1 The maps

Very often map user tests concentrate on the assessment of particular elements on the map (such as the location and identification of a specific feature) or measure the effectiveness of individual cartographic symbols (such as squares, circles, cubes etc.) rather than the effectiveness of the whole map display (the individual thematic symbols viewed against their background). The complexity of real maps is a major reason for doing so: there are so many factors involved in a map that it is difficult to draw detailed conclusions; in order to do so one should differentiate between all sorts of factors on the map and test them separately. On the other hand when thematic symbols are no longer regarded in their context but are tested separately, one cannot know if the results are still valid for the map as a whole.

In the present map-user test the thematic symbols used for the display of temporal changes were viewed within their map context. It has been tried, however, to keep the maps as simple as possible in order to avoid confusion and allow the user to focus his/her attention on the changing thematic phenomenon. Most of the map types used in the test were produced for the purposes of the urban air pollution mapping system described in the previous Chapters. Here these same software programs were used with different data sets to generate additional maps for the purposes of the user test.

Figure 7-4 shows the subjects of the maps used for the purposes of the test. Since the original maps were created for the display of elements involved in a (man-caused) environmental problem (i.e. urban air pollution) all the maps created for the test were kept within the context of environmental cartography, displaying natural or man-caused environmental phenomena. Three different types of symbols were used to display the thematic phenomenon which was changing with the course of time i.e. point, line and area symbols.

On the dynamic maps the point symbols were arrows whose magnitude and direction was changing with time. Line symbols were distinguished in two types: **a.** a trajectory which was seen to proceed in the course

	symbol			
	point	**linear**		**areal**
		a. proceeding	b. displacing	
group1	wind field over Athens	trajectories of radio-active cloud from Chernobyl	pollution front above the Netherlands	diurnal variation of CO levels in Athens
group2	wind field over the Netherlands	trajectories of tropical cyclones in SE Asia	pollution front above a city	diurnal variation of SO_2 levels in Athens

Figure 7-4. The themes of the maps used for the test (see also Appendix III)

of time and **b.** a single line (representing a front) which was changing location and shape in the course of time. Areal symbols (layer tints) were also changing in shape and location with time. Time was indicated with either a clock (analog or analog and digital) or a time bar. The respective static maps were either a series of (smaller) maps displaying the situation at different time moments and viewed altogether in a "comics" manner, or a single static map utilizing different visual variables than the respective dynamic in order to depict the different time moments. Series of smaller maps were used for the point and area thematic symbols; a different visual variable (value in this case) was used for the line symbols.

7.3.2 The questions

In section 2.4.1 where the map reading process was briefly described it was mentioned that a map user reads a map by actually questioning it. Within a certain question (i.e. a question concerning a certain component of the information) reading occurs in three distinct levels: the elementary, the intermediate and the overall level. These reading levels introduce the respective questions, an example of which was given in the same section. In section 7.2.2 the temporal component introduced by dynamic maps was discussed. It was argued that in the general case the temporal component cannot be regarded as an additional thematic component; it should rather be considered as another "dimension" in the spatial sense, which, however, cannot be directly transcribed on the plane (i.e. the geographic space). In this sense the concept of the three reading levels can be utilized for the temporal component in the same manner it is done for the geographical component. Consequently, when viewing a dynamic map a user asks questions concerning the temporal component in an elementary level (i.e. for a certain moment in time), at an intermediate level (i.e. during a certain period of time) and at an overall level (i.e. during the whole time questioning the temporal trend of the process).

time	**overall**	**III** when do the maximum (minimum) values occur at location l ?	**IV** what is the trend ? i.e. over the area during the whole time
	local	**I** what is the value at time t at location l ?	**II** where are the minima (maxima) found at time t ?
component	reading level	**local**	**overall**
	component	**geographical**	

Figure 7-5. The general types of questions asked for each map of the test

It was decided to restrict the questions asked in the test at the elementary and overall level for both the geographic and temporal component. This was done for a number of pragmatic and substantial reasons: for the user it would not only be boring to view the same map many times but it would bias the results since after many repetitions he/she would remember the display and answer more easily. The selection of the two "extreme" levels (i.e. local and overall) was also done in order to see if animated maps were more suitable for viewing trends and static maps more suitable for answering questions at the local level.

The general types of questions (I,II,III,IV) asked for each map of the test are shown in Figure 7-5. All the questions asked are given, together with the respective maps, in Appendix III.

7.3.3 The users

It is anticipated that, in the general case, users of dynamic maps will be not only people concerned with study and research on spatio-temporal processes, but also further users of that kind of information such as planners or decision makers. Although all groups concerned have a familiarity with cartographic displays the degree of familiarity varies for each group. It is therefore not easy to obtain a representative opinion for all users; for a single test a certain homogeneous group has to be selected instead. In the present case a group of (thirty-nine in total) subjects from the academic environment was selected. The group consisted of Geodesy students but also researchers working with spatial information, all of them being quite familiar with computer maps.

7.3.4 The test procedure

Since the test was entirely computer-driven it was carried out in a computer terminal room. The part of the room which was used for this purpose was isolated with temporary walls, so that the users could concentrate and work quietly.

The computer hardware used for the test is shown in Fig. 7-6. The alphanumeric terminal in the middle (t_m) was used for giving information and instructions to the users; the keyboard in the middle (k_m) was used for interaction with the map display. The screen to the right (s_r) was the medium where most of the maps (i.e. the maps created with PHIGS graphics routines using FORTRAN as a programming language) were displayed. The questions were always displayed at the top right corner of s_r; the user was interactively picking the answer -among three possible choices- with the cursor shown in Fig. 7-5. All the above hardware components belong to the same system (mainframe computer). The screen and keyboard at the left of Fig. 7-5 (s_l and k_l respectively) are actually a second computer system (personal computer) which was used to display the maps created with the ANIGEO program (see Chapter 6). There was no direct communication between the two systems; the user was instructed to respond to or invoke the appropriate map display on the personal computer system via the main program running on the mainframe. The messages instructing the user how to proceed were always appearing at the top right corner of s_r.

Figure 7-6. The computer hardware used in the test.

Since all this hardware had to be used an effort was made to create simple, clear and easy to follow instructions so that the user would not be scared by all the equipment he/she had to deal with and also would not be confused by the messages. Indeed, the whole interactive test procedure ran very smoothly with only very few minor problems (such as e.g. when a user was responding without being asked to do so, or by accident etc.) which would have been avoided if the main test program was 100% "fool proof". Even when such mistakes were made they had no serious consequences for the rest of the test; the program would just block, with a simple intervention it would continue normally. Occasionally, however, this would influence the response time: in such a case the response times were rejected (i.e. not used further for the statistical calculations). Such cases, were very few, however.

Before commencing the test some general oral information and instructions were given to each user. In the beginning of the test the user also got information about the content and purpose of the test, the nature of the displayed maps and the general procedure to be followed. This information appeared on t_m. Consequently the maps and the questions appeared on s_r. First the question appeared, then the map. The first two maps in the test (an animated and a static one) were used as introductory maps, in order to accustom the user to what would follow. The answers and the response time to the questions concerning these two maps were registered but not considered further (i.e. in the statistical processing). For the static maps the response time was starting to count after the map had been displayed on the screen; in the case of animated maps the time was starting to count after the movement was completed. In case the map was created on the personal computer system the user was prompted (in s_r) to enter the suitable command (in k_l). After the map display was completed (on s_l) the answer was given (on s_r). The answers and the respective response times were registered in data-files (separate for each user) on the mainframe system; these data-files were then used for the statistical processing of the results. The duration of the test was approximately 45-50 min.

7.4 The test results

A visual summary of descriptive statistics concerning the results of the test is given in Figures 7-7 (correct answers) and 7-8 (response time).

From Fig. 7-7 it is seen that, in general, the percentage of correct answers is high for both static and animated maps, with the exception of some type I questions for maps K_5, K_6 and K_8. Since in the case of map K_8 this happens for both the animated and the static display it should rather be attributed to a difficult question which the users just failed to answer. In the case of map K_5 the number of correct answers is much smaller for the static display, while in the case of map K_6 the correct answers to the same type of question were given for the static and not the animated map.

In Figure 7-8 the average response times and their standard deviations are given for each question. At this point it should be mentioned that for some questions (namely: no. 64: IV, K_7, static; no. 23: II,K_1,animated, no. 16: I,K_5,animated, no.48: III,K_5,animated, no. 11: II,K_6,animated and no. 46: III,K_8,animated) some extremely high values of answer times occured. It was decided to discard these response times as non-representative. It is of course difficult to decide whether to consider such a value as representative or not when the sample group is limited; on the other hand descriptive statistics concerning a small sample group will be biased by an individual extreme value while for a larger sample the influence will be definitely less. In order to illustrate the above cases the scatter diagrams of the resonse times to the respective questions are given in Appendix IV.

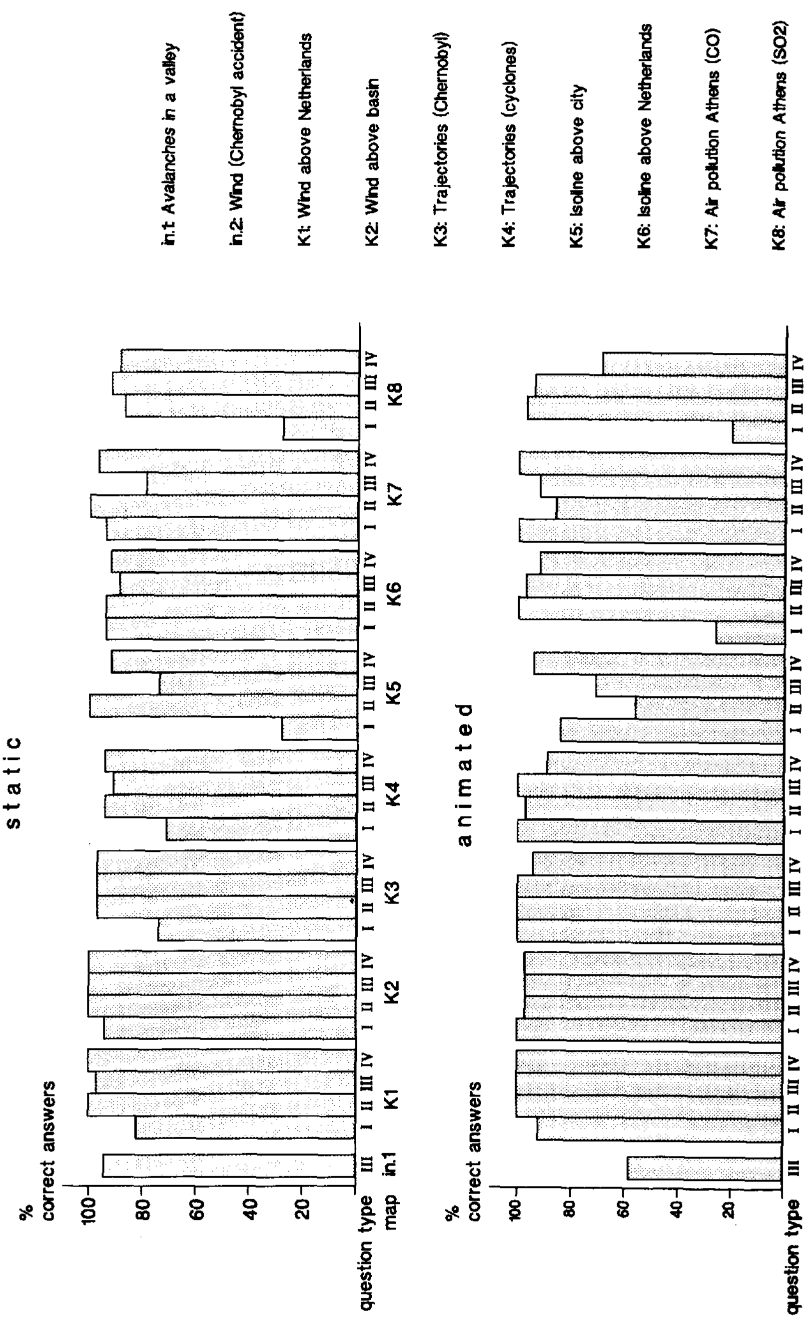


Figure 7-7. Percentage of correct answers.

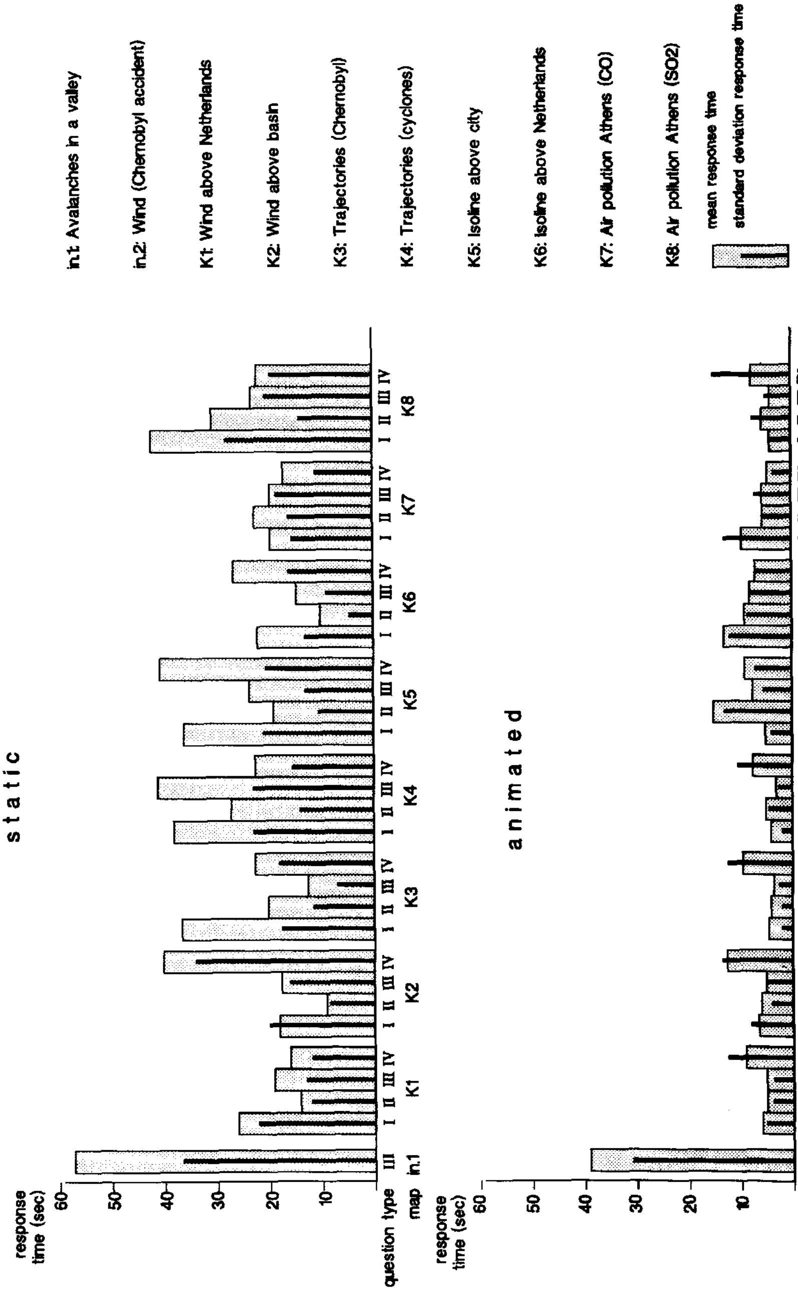


Figure 7-8. Average response times and their standard deviations.

From Fig. 7-8 it is seen that there is an obvious difference in the response times of the static and the respective animated maps for all types of questions. What is also remarkable is that the values of the standard deviation are in the case of animated maps mostly large (which is usually not the case for the static). This can be probably attributed to a different degree of familiarity of the users with animated displays, while static maps are quite familiar to everybody.

	correctness				response time			
map type / read. level	point	line (a)	line (b)	area	point	line (a)	line (b)	area
I	Z = 0.17 A	Z = 0.08 A	Z = 4.88 R	Z = 0.39 A	df = 86 t = -4.26 R	df = 79 t = -6.34 R	df = 109 t = -3.92 R	df = 103 t = -4.71 R
II	Z = 0.07 A	Z = 0.00 A	Z = 1.52 A	Z = 0.71 A	df = 100 t = -3.14 R	df = 83 t = -5.39 R	df = 142 t = -2.61 R	df = 94 t = -5.74 R
III	Z = 0.14 A	Z = 0.14 A	Z = 0.37 A	Z = 0.30 A	df = 87 t = -4.80 R	df = 93 t = -4.53 R	df = 111 t = -4.07 R	df = 92 t = -4.05 R
IV	Z = -0.02 A	Z = 0.07 A	Z = 0.07 A	Z = 0.71 A	df = 150 t = -1.99 R	df = 102 t = -3.42 R	df = 87 t = -5.76 R	df = 130 t = -3.10 R

Z: *Z statistic*
t: t statistic
df: degrees of freedom

A null hypothesis accepted
R null hypothesis rejected

Figure 7-9. Results of the tests of significance.

In order to assess the significance of the above results two tests of significance were carried out: the two-sample two-tailed t test for comparing the mean response times of static and animated maps and the Mann-Whitney two-tailed U test for comparing the quality of answers of static and animated maps. In both cases the purpose is to test the null hypothesis that there is no difference between the two samples. The hypothesis is rejected if the statistics **t** and **Z** (calculated for the two samples in comparison) do not fit the 95% confidence interval (a very commonly used confidence interval for significance tests). Figurea AIV-8 and AIV-9 at the and of Appendix IV were used for checking the results. A significant difference between the two samples is assumed, in case the null hypothesis is rejected; in case it is accepted it is regarded as possible but not necessarily correct (Kraak, 1988).

The results of the statistical analysis for the four reading levels and each maptype are given in Figure 7-9. As seen, the null hypothesis is rejected for all samples in the case of response times: this means that the difference in response times (as shown in Fig. 7-7) is statistically significant. For the quality of the answers, however, the null hypothesis is accepted (with only one exception); this means that there is probably no significant difference between the two samples.

This could be an indication that, for giving information to the user, a well designed static map displaying dynamic processess, functions just as well as an animated one; however, the user perceives faster when the representation of the dynamic phenomenon is an "imitation" of the real process (i.e. a movement) than an utilization of the two dimensions of the plane for representing an essentially non-spatial process.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

This Chapter summarizes the work of the present thesis and gives some suggestions for possible improvements and extensions.

The main objective of the work has been the proposal and development of a prototype, which can assist decisions concerning air pollution in an urban environment. The developed prototype combines methods of urban air pollution simulation modelling with computer-assisted cartographic methods for the evaluation (and eventually prediction) of urban air pollution levels on one side, and for the cartographic visualization of both spatial and temporal aspects of the involved elements, on the other.

The value of utilizing a simulation model lies not only in the advantages offered by models, in general, (Chapter 4) but also in the fact that the quantitative descriptions furnished by a model give a good insight into the natural and man-made elements involved in the problem and their interrelations. This fact facilitates the cartographic information analysis: understanding the nature, functions and interactions of these elements means understanding their spatial and temporal behaviour. The themes to be mapped and, consequently, the map types proposed here as well as the rest of the elements of map identification have been derived in this way i.e. by considering the elements involved and by examining the relations of each one of them with the rest of the others; the various needs of the users have also been considered. A number of software modules have been developed in order to assist the map creation process i.e. the processing of the collected data and the production of the proposed map types.

An emphasis has been put on visualization aspects, not only because they offer a powerful tool for control and decision support, but also because despite the above fact, their use in practice is very limited. Even in cases where well developed, sophisticated systems are used for urban air pollution data collection and processing, the utilization of maps is rather restricted; the utilization of computer maps, in particular, is even less implemented. The visualization of spatial data is not the strongest point of GISs, either. The methods and techniques for visualization of spatial and temporal information offered by computer-assisted cartography, could, therefore, contribute at that stage by offering a useful tool having direct practical applications.

The output of this work can, therefore, be considered as a compilation of modules which could constitute a part of a GIS having an enhanced functionality with respect to environmental issues.

The last part of the work is basically a theoretical issue concerned with map-use aspects of animated map displays; nevertheless, the subject is also of practical interest because of the growing attention which spatio-temporal phenomena are getting recently and the consequent confrontation of various GIS and map users with animated maps. As already mentioned in the respective Chapter (Chapt. 7) the test carried out for comparing static and animated maps does not intend to draw conclusions but only to make a preliminary assessment, giving mere indications about the user response.

Further conclusions and suggestions concerning both the general subject of map creation for urban air pollution decision support and the specific aspect of animated maps -which constitutes part of the main subject- are as follows.

The collection of all kinds of information related to the environment and the consequent creation of environmental data bases in urban, regional and continental level has increased during the last years. Some of the most common uses of data retrieved from such data bases are the generation of environmental reports, the qualitative assessment of environmental impacts by combining data from various sources or the quantitative estimation of impacts by utilizing simulation models. As already mentioned, the development and use of models for environmental purposes has been promoted during the last years; nowadays there seems to be a trend for developing models and/or integrating data from a broader context i.e. not only from the physical but also from the social environment in order e.g. to link health effects and environmental quality levels, or to make long term projections of environmental quality on a continental level on the basis of the current environmental and economical status etc. Although each case of application involves a different spatial and temporal scale, the primary problem common in all is the access to the data needed and, in a second step, the compatibility of data gathered from the various sources.

For urban air pollution studies, such as the one carried out as part of this thesis, the above problem is still encountered in practice, despite the fact that urban air pollution is one of the most common air pollution cases with a relatively long practical experience in monitoring and control methods. Data accessibility is, in general, no problem when air quality data are collected directly from monitoring stations. Most of the times such networks are fully automated, with on-line communication facilities and the recorded data are available on request. If, however, detailed emission data -necessary for simulation modelling- are needed it is not always possible to obtain them (industrial emissions, in particular). This is, of course, understandable, if the possible misuses of such data at various financial/political levels are considered; this should not, however, constitute an obstacle for conducting research.

Another point of interest related to the collection of data is their spatial reference. The compatibility of data with respect to their spatial reference i.e. the consistency of the coordinate system(s) to which the various data files refer, depends, in general, on the consistency, coordination and standardization of the topographic mapping activities among the various mapping services in a country. The use of a consistent coordinate system on the different base maps used for the reference of the various (point, line and area) elements involved in urban air pollution avoids the expensive processes of coordinate conversion and, occasionally, area interpolation (e.g. for administrative or area units and the respective thematic data). Since, however, consistency in the spatial (topographic) reference of environmental data is not guaranteed, an environmental GIS should offer options for coordinate conversion (preferably without involving intermediate calculation of geographic coordinates -latitude and longitude- for the general case that a map projection is unknown). An example of an algorithm for this purpose has been given here. Algorithms for area interpolation should also be part of such a GIS.

A point which needs a great deal of attention is the quality of the final results displayed on thematic maps. As already mentioned, this quality is determined primarily by the quality of the data input to the model and by the accuracy of the predictions furnished by the model itself. Although both of these tasks (i.e. the collection of emission data, the built up of emission inventories and the associated emission models on one side, and the development of air quality simulation models on the other) do not constitute real cartographic or GIS tasks, their results or/and methods are implemented as part of cartographic or GIS applications. It is not without use, therefore, to point out the need for accurate emission data, improvement of emission models (e.g. for derivation of emissions from measured traffic quantities) and of course for the development of a representative air quality simulation model for the specific area studied. An assessment of the achieved accuracy can be made by correlating simulated results and the respective measured air quality data. The subject can be considered as part of the general problem of error propagation within GISs, which constitutes a large area of current research (see e.g. Heuvelink et al., 1989).

Assuming that the predicted data -or the measurements of the air quality network- are error free, (or have a certain accuracy) the next step with respect to the accuracy of the thematic results is to assess the accuracy of the spatial interpolation method used. The possibilities offered by the geostatistical approach with respect to that point are well known from literature; the method has also been used here.

For the visualization of results the map types proposed here (and the developed algorithms for their production), although not exhaustive, cover most of the elements involved in the problem. Nevertheless, the possibility of new or additional products always exists. Three-dimensional visualizations, in particular, are of use not only because they achieve "dramatic" or attractive views, but also because they offer better insight into the elements involved in the problem. Some examples of further possible products are:

- 3D large scale urban maps combined with the (3D) wind field: such a display can give insight to local air pollution problems
- combination in 3D of building heights and of the form of the terrain: apart from giving a realistic view of the city profile, the map can be useful for the study of traffic emissions and their diffusion along the streets, for anticipating driving modes and the consequent emission levels (as an example, the cars will operate on a low gear while driving up on slopes and, therefore, generate more harmful emissions) and, in general, for traffic planning within the city
- 3D visualization of the body of plumes generated from industrial chimneys, in combination with the 3D terrain: useful for industrial emission control and for designing future industrial plants
- visualization of a pollution cloud as a 3D body (iso-surface) and display of its different densities i.e. the different concentration levels in the three dimensions

The consideration of the dynamics of spatial phenomena is, as seen, an area which tends to attract increased attention during the last years. Some aspects of cartographic visualization of dynamic phenomena through time have been addressed in this study; namely, the creation of some types of animated map displays (primarily for the purposes of the urban air pollution cartographic prototype) and the consequent utilization of the main software modules for the production of more maps (for the purposes of the map-user test).

The visualization of spatio-temporal phenomena is a new area offering interesting possibilities for cartographic applications. It is anticipated that new cartographic methods for visualization of temporal dynamics will be devised, implemented and applied, especially for planning and spatial decision support purposes. Possibilities for incorporating computer-driven or video animation facilities into GISs seem to attract growing interest. In order to improve the efficiency of such new products more research in map users' reactions to animated maps should be carried out to evaluate the functionality of the various map elements. Nevertheless, options such as good user interfaces which allow interaction of the user with the displayed process are undoubtfully improving the map efficiency, especially if practical applications are concerned.

For the specific area of urban air pollution considered here, some examples of further possible dynamic map production could be:

- the animated display of congestion patterns in urban road/highway networks, which would be useful not only for the evaluation of respective emission patterns, but also for traffic planning purposes
- the combination of dynamic and 3D maps

The cartographic system proposed here for the purposes of decision support in urban air pollution cases has been developed as a prototype, which, as already mentioned, could constitute part of an environmental GIS. On a fully operational level and in order to make the user access easier and the whole system user friendly some possible additions, improvements and extensions could, for example be:

- the creation of good user interfaces (by means of e.g. graphic toolbox software) with graphics screens and menus
- the coupling with a data-base package for more efficient data storage, retrieval and manipulation
- interface to a GIS package, the functions of which could offer further possibilities for analysis, overlaying, buffer-zoning etc. For instance, the production of synthesis maps for planning purposes, mentioned in Chapter 5 would be facilitated a lot in such a way.

CHAPTER 9. SUMMARY / SAMENVATTING

Computer-assisted cartography for monitoring spatio-temporal aspects of urban air pollution.

The technological achievements of the last decades and, in particular, the fast developments in the fields of computer hard- and software had a tremendous impact on Cartography. Although initially computers were introduced in order to enhance and speed up the map drafting process, automation was soon introduced to other steps of the map creation process, such as data elaboration (spatial interpolation, generalization, smoothing etc.). Nowadays almost all cartographic tasks are carried out with the help of computers; computer-assistance is the case rather than the exception in Cartography.

The progress made during the last years in the fields of computer hard- and software has resulted in a number of further cartographic developments. The various tasks of the map creation process (collection, storing and retrieval, processing and cartographic display of spatial data) are nowadays carried out in an integrated way by means of the tools provided by Geographical Information Systems.

The growing needs for handling spatial information and the computer hard- and software possibilities for applications in this area have promoted the creation of various GIS software packages and the establishment of a growing market for computerized spatial data processing. These commercial packages are nowadays enormously popular and are used for a variety of applications related to spatial data. The situation offers a great potential for Cartography and GISs. A growing number of users is familiarized with spatial data concepts and methods for their processing and display. This fact opens more fields for Cartographic applications and/or new developments within the field. The Cartographic/GIS tasks tend to incorporate knowledge and methods of various disciplinary fields for their applications. A prominent example of this trend, which has been made very clear in (GIS/LIS, Cartographic, Spatial Data Handling) Conferences of the last 2-3 years is the coupling of spatial data with simulation models, developed originally within the fields and for the purposes of the relative disciplines.

Another rather recent trend, manifested also in Conferences of the last years is the consideration of spatio-temporal aspects. Both past (i.e. historical) data as well as future projections (e.g. predictions furnished by a simulation model) can be useful for decision support purposes. The interest can be focussed on two major areas: the storage and retrieval of spatio-temporal data (the design of temporal data bases) and their animated display (dynamic maps).

The present work addresses some of these points, namely simulation modelling and the display of spatio-temporal phenomena, and attempts to integrate them in a decision support tool. More specifically, the cartographic aspects of an environmental problem, namely the air pollution problem in an urban area are considered. The problem is examined in terms of the natural and man-made elements involved. These elements and their interrelations are discussed in order to understand their nature, functions and interrelations and consequently their spatial and temporal behaviour. An attempt is made to list the most important among them and their influences upon each other. On the basis of this concept and by considering the fundamental functions of an urban air pollution control service the themes to be mapped are derived and the rest of the cartographic elements are also identified.
The objective of the work is the development of a prototype of a software system for the simulation, cartographic processing and visualization of the causes and results of urban air pollution.

An emphasis is put on visualization aspects, not only because they offer a powerful tool for control and decision support, but also because despite the above fact their use in practice is very limited. Even in cases where well developed, sophisticated systems are used for urban air pollution data collection and processing, the utilization of maps is rather restricted; the utilization of computer maps in particular is even less implemented. The visualization of spatial data is not the strongest point of GISs, either. Cartography could, therefore, contribute at that stage by offering a useful tool having a direct practical application.
Apart from the spatial aspects of the subject temporal aspects are also considered and types of maps to be produced for the most important purposes of urban air pollution decision support are proposed.

The greater urban and industrial area of Athens has been used in this work as a case study area for the implementation of the prototype. An operational system based on the proposed prototype can assist in air pollution control in an urban area, in monitoring air quality levels, in evaluating the elements involved in air pollution and projecting their potential impacts.

A further point of interest is the theoretical issue arising from the introduction among the proposed maptypes of a relatively new cartographic product, namely the dynamic map. Since the need and demand for this kind of map displays is continuously growing, as already mentioned, it was considered worthwhile investigating the respond of users to such map displays.

Chapter 2 gives the theoretical cartographic background. The most prominent schools of cartographic thought are described in brief and the one which is followed here is presented. This approach combines the principles of cartographic communication and graphic semiology; according to it the two main components of the cartographic process are map creation and map use. Map creation consists of collection, processing and display of the information to be mapped; these tasks form the subject of the following four chapters (i.e. 3-6) for the specific theme treated here. Map use aspects are considered in Chapter 7.

The link between cartography and the specific application is made in Chapter 3, where a general framework of the environmental problem is presented and the contribution of cartography to environmental science is discussed and illustrated.

Chapter 4 is concerned with the problem of urban air pollution. The physical mechanisms involved in the problem are described and the topics of air pollution simulation modelling and urban air pollution control are treated. Finally the spatial aspects of a system for urban air pollution control and decision support are introduced.

In Chapter 5 the elements of the cartographic prototype proposed here are given. The cartographic products are identified externally (i.e. the elements to be mapped and their relations, the space involved) and internally (their cartographic representation, their accuracy). Computer aspects of the proposed prototype are introduced at that stage.

Chapter 6 forms the synthesis and implementation of what has been discussed in the previous.

Chapter 7 is concerned with the more specific subject of map use aspects of dynamic maps. After the general principles of dynamic map production aspects are given, a preliminary map-user test is carried out in order to assess the performance of a number of dynamic maps. This assessment is performed by comparing the answers given to questions concerning dynamic phenomena, displayed on both animated and static maps. The results indicate that the degree of correctness of answers is the same for both animated and static maps; in the case of animated maps, however, answers are given faster.

Possible extensions and improvements concerning the visualization, processing and collection of urban air pollution information are discussed in the final Chapter, where conclusions and proposals for user research on animated maps are also given.

Computer-ondersteunde kartografie voor de bewaking van tijd-ruimte aspecten van luchtvervuiling in stedelijke gebieden.

De technologische prestaties van de laatste decennia, in het bijzonder de snelle ontwikkelingen op het gebied van computer hard- en software, hadden een grote invloed op de kartografie. Hoewel in het begin computers geïntroduceerd werden om het kaartvervaardigingsproces te vergroten en te versnellen werd de automatisering als snel ingevoerd bij andere onderdelen van kaartvervaardiging, zoals gegevensverwerking (ruimtelijke interpolatie, generalisatie, vereffening, etc.). Tegenwoordig worden vrijwel alle kartografische taken uitgevoerd met behulp van computers. Computerondersteuning is eerder regel dan uitzondering in de kartografie.

De vooruitgang, die de laatste jaren is gemaakt op het gebied van hard- en software, heeft geresulteerd in nog een aantal kartografische ontwikkelingen. De diverse taken op het gebied van kaartvervaardiging (verzamelen, opslaan en oproepen, verwerken en kartografische weergave van ruimtelijke gegevens) worden tegenwoordig op een geïntegreerde manier uitgevoerd door middel van de door geografische informatiesystemen verschafte hulpmiddelen.

De toenemende behoefte om ruimtelijke informatie te verwerken en de mogelijkheden die computer hard- en software bieden voor toepassing op dit gebied hebben de ontwikkeling van diverse GIS softwarepakketten en het ontstaan van een groeiende markt voor gecomputeriseerde ruimtelijke gegevensverwerking bevorderd. Deze commerciële pakketten zijn tegenwoordig enorm populair en worden gebruikt voor een diversiteit aan toepassingen op het gebied van ruimtelijke gegevensverwerking. Deze situatie biedt een groot potentieel voor kartografie en geografische informatiesystemen. Een groeiend aantal gebruikers is bekend met ruimtelijke gegevensconcepten en methoden voor verwerking en weergave. Dit gegeven opent meer kartografische toepassingsmogelijkheden en/of nieuwe ontwikkelingen binnen het veld. De kartografie/GIS taken hebben de neiging om kennis en werkwijze uit verschillende disciplines voor hun toepassingen over te nemen. Een uitzonderlijk voorbeeld van deze trend, die erg duidelijk is geworden op (GIS/LIS, kartografische, ruimtelijke gegevensverwerking) conferenties gedurende de laatste twee drie jaar, is het koppelen van ruimtelijke gegevens met simulatiemodellen, die oorspronkelijk ontwikkeld zijn binnen de velden en voor de doeleinden van de onderscheiden disciplines.

Een andere, nogal recente ontwikkeling, die ook op de voorgrond trad in conferenties gedurende de laatste jaren, is het in ogenschouw nemen van ruimte/tijd aspecten. Zowel gegevens uit het verleden (historische) als toekomstige projecties (voorspellingen geleverd door een simulatiemodel) kunnen nuttig zijn voor het ondersteunen van de besluitvorming. Het belang kan gericht worden op twee belangrijke gebieden: het opslaan en oproepen van ruimte/tijd gegevens (het ontwikkelen van voorlopige databases) en hun weergave in animatievorm (dynamische kaarten).

Het huidige werk richt zich op sommige van deze punten, namelijk simulatiemodellen en de weergave van ruimte/tijd fenomenen, en probeert hen de integreren in een systeem ten behoeve van de ondersteuning van de besluitvorming. Specifieker worden de kartografische aspecten van een milieu-probleem, namelijk het luchtverontreinigingsprobleem in een stedelijk gebied, in ogenschouw genomen. Het probleem wordt onderzocht in termen van de natuurlijke en door de mens gemaakte elementen die er bij betrokken zijn.
Deze elementen en hun relaties worden besproken om hun karakter, functies en relaties en vervolgens hun gedrag in ruimte en tijd. Een poging is ondernomen om de meest belangrijke daaronder en hun onderlinge beïnvloeding te catalogiseren. Op basis van dit concept en het in ogenschouw nemen van de fundamentele functies van een stedelijke luchtverontreinigingscontroledienst, worden de thema's die in kaart moeten worden gebracht, afgeleid en de rest van de kartografische elementen geïdentificeerd. Het doel van de studie is de ontwikkeling van een prototype van een software-systeem voor simulatie, kartografische verwerking en visualisatie van de oorzaken en gevolgen van stedelijke luchtverontreiniging.

De nadruk is gelegd op visualisatie-aspecten, niet alleen omdat zij een krachtig hulpmiddel voor controle en besluitvorming zijn, maar ook omdat, ondanks het hierboven vermelde feit, hun gebruik in de praktijk zeer beperkt is. Zelfs in zaken waar goed ontwikkelde, hoogstaande systemen worden gebruikt voor het verzamelen en verwerken van gegevens betreffende stedelijke luchtverontreiniging, is het gebruik van kaarten nogal beperkt; in het bijzonder het gebruik van computerkaarten komt nog minder voor. Het visualiseren van ruimtelijke gegevens is ook niet het sterkste punt van een gis. Kartografie zou daarom een bijdrage kunnen leveren op dat punt door een bruikbaar stuk gereedschap aan te reiken met een directe praktische toepassing. Met uitzondering van de ruimtelijke aspecten van het onderwerp worden tijdelijke aspecten ook bekeken en nog te produceren kaarttypen voor de belangrijkste doeleinden voor het ondersteunen van beslissingen op het gebied van stedelijke luchtverontreiniging voorgesteld.

Het grote stedelijke en industriële gebied Athene is in dit werk gebruikt als een casestudygebied voor toepassing van het prototype. Een operationeel systeem, gebaseerd op het voorgestelde prototype, kan assisteren in de luchtverontreinigingscontrole in een stedelijk gebied, in het volgen van luchtkwaliteitniveaus, in het evalueren van de elementen die betrokken zijn bij luchtverontreiniging en het projecteren van hun potentiële invloed.

Verder van belang is het theoretische punt van het opkomen van een betrekkelijk nieuw kartografisch produkt tussen de voorgestelde kaarttypen, namelijk de dynamische kaart. Vanwege het feit dat de behoefte en vraag voor dit type kaartweergave voortdurend groeiende is, zoals reeds gemeld, was het de moeite waard om te onderzoeken hoe gebruikers reageerden op deze vorm van kaartweergave.

Hoofdstuk 2 geeft de theoretische, kartografische achtergrond. De scholen met het meeste aanzien op het gebied van de kartografische denkwijze, worden in het kort beschreven en degene die hier gevolgd wordt wordt voorgesteld. Deze benadering combineert de principes van kartografische communicatie en grafische semiologie; volgens deze zijn de twee belangrijkste onderdelen van het kartografisch proces kaartvervaardiging en kaartgebruik. Kaartvervaardiging bestaat uit verzamelen, verwerken en weergave van de informatie die op de kaart moet worden weergegeven; deze taken vormen het onderwerp van de volgende vier hoofdstukken (3 tot en met 6) betreffende het specifieke thema dat hier wordt behandeld. De aspecten van kaartgebruik worden in hoofdstuk 7 behandeld.

De koppeling tussen kartografie en de specifieke toepassing is gemaakt in hoofdstuk 3, waar een algemeen kader van het milieuprobleem wordt gepresenteerd en de bijdrage van de kartografie op het gebied van milieuwetenschap wordt besproken en geïllustreerd.

Hoofdstuk 4 gaat over het probleem van stedelijke luchtverontreiniging. De fysische mechanismen binnen dit probleem worden beschreven en de hoofdpunten van luchtverontreinigingssimulatiemodellen en stedelijke luchtverontreinigingscontrole worden behandeld. Uiteindelijk worden de ruimtelijke aspecten van een systeem voor stedelijke luchtverontreinigingscontrole en ondersteuning van de besluitvorming geïntroduceerd.

In hoofdstuk 5 worden de elementen van het hier voorgestelde kartografische prototype gegeven. De kartografische produkten worden van buitenaf (d.w.z. elementen die in kaart moeten worden gebracht, hun relaties en de ruimte waarop het betrekking heeft) en van binnenaf (hun kartografische weergave en hun nauwkeurigheid) geïdentificeerd. Computeraspecten van het voorgestelde prototype worden hier geïntroduceerd.

Hoofdstuk 6 vormt de synthese en implementatie van het in het voorafgaande besprokene.

Hoofdstuk 7 betreft het meer specifieke onderwerp van aspecten van kaartgebruik van dynamische kaarten. Na bespreking van de algemene principes op het gebied van het vervaardigen van dynamische kaarten, wordt een voorlopige kaartgebruikerstest uitgevoerd om de prestaties in kaart te brengen van een aantal dynamische kaarten. Dit in kaart brengen wordt gedaan door de antwoorden die gegeven zijn betreffende dynamische fenomenen, weergegeven op zowel statische kaarten als kaartanimaties, te vergelijken. De resultaten geven aan dat de mate van juistheid van antwoorden hetzelfde is voor zowel statische kaarten als kaartanimaties; als het kaartanimaties betreft worden de antwoorden echter sneller gegeven.

Mogelijke uitbreidingen en verbeteringen betreffende de visualisatie, verwerking en verzameling van informatie inzake stedelijke luchtverontreiniging, worden besproken in het laatste hoofdstuk, waar bovendien conclusies en voorstellen voor gebruikersonderzoek betreffende kaartanimaties worden gegeven.

REFERENCES

ARNOLD G. and E. EDGERLEY, **Urban develpment in air pollution basins -an appeal to the planners for help.** Journal of the air Pollution Control Association, 17, 1967, pp. 235-237.

BERTIN J., **Sémiologie graphique.** Paris, Mouton, 1967.

BERTIN J., **Semiology of graphics.** Madison, The university of Wisconsin Press, 1983

BLAIS J.A.R., **Synthesis of kriging estimation methods.** Manuscripta Geodaetica vol. 7 (1982), pp. 325-352.

BLAKEMORE H., **From lineprinter maps to geographic information systems: a retrospective on digital mapping.** SUC Bulletin vol. 19 (1985) no. 2, pp. 65-70.

BOARD C., **Maps as models.** In: R.J. Chorley and P. Hagget "Models in Geography". London, Methuen, 1967.

BOARD C., **Cartographic Communication and Standardization.** International Yearbook of Cartography, 1973, pp. 229-236.

BOERSEMA J.J., COPIUS PEERBOOM J.W. and W.T. DE GROOT, **Basisboek Milieukunde.** Boom-Meppel, Amsterdam, 1986.

BORNSTEIN R.D., **Observation of the Urban heat-island effect in New York City.** Journal of Applied Meteorology, 7, 1968, pp. 575-582.

DE GROTE BOSATLAS. Wolters-Noordhoff, Groningen, 1988.

BOUTOURA C., **Computer assisted base map 1:5000-1:10000; original and derived cartographic processes and norms.** Dissertation, School of Rural and Surveying Engineering, Faculty of Engineering, University of Thessaloniki, 1987 (in Greek).

BOUWER K. and J.C.M. KLAVER, **Milieuproblemen in geografisch perspectief.** Van Gorcum Assen/Maastricht, 1987.

BRANDENBERGER C.G., **Koordinatentransformation fur Digitale Kartographische Daten mit Lagrange- und Spline-Interpolation.** Herausgegeben vom Institut fur Kartgraphie, Eid genossische Technische Hochschule Zurich, 1985.

BRIGGS G.A., **Plume rise predictions.** In: lectures on air pollution and environmental impact analyses, Workshop proceed. Boston, 1975, American Meteorological Society.

BURROUGH P.A., **Principles of Geographical Information Systems for Land Resources Assessment.** Clarendon Press, Oxford, 1986.

CARR J.R., MYERS D.E. and C.E. GLASS, **Co-kriging- a computer program.** Computers and Geosciences vol. 11, no.2, 1985, pp.111-127.

CHANDLER T.J., **The climate of London.** Hutchinson, London, 1965.

CHANDLER, T.J., **Night time temperatures in relation to Leicester's urban form.** Meteorologigal Magazine, 96, 1967, pp. 244-250.

CHANDLER T.J., **Urban Climatology and its relevance to urban design.** World Meteorological Organization, Technical note no. 149, Geneva, 1976.

CHEREMISINOFF P.N. and A.C. MORESSI, **Environmental Assessment and Impact Statement Handbook.** Ann Arbor Science Publishers, 1977.

CLARKE J.F. and T.J. PETERSON, **The effect of regional climate and land use on the nocturnal heat island.** In: Preprints, Conference on Urban Environment and Second Conference of Biometeorology, American Meteorologic Society, Philadelphia, 1972, pp. 147-152.

CORNELL B. and A. H. ROBINSON, **Possibilities for computer animated films in Cartography.** The Cartographic Journal, 3, pp.79-82, 1966.

CRAIN I.K., **Computer interpolation and contouring of two-dimension data: a review.** Geoexploration, 8 (1970), pp. 71-86.

DAGBERT M. and M. DAVID, **Universal kriging for ore-reserve estimation -Conceptual background and application to the Navan deposit.** CIM bulletin, vol. 69, no. 766, 1976, pp. 80-92

DAVIS M.W.D. and M. DAVID, **Automatic kriging and contouring in the presence of trends (universal kriging made simple).** The Journal of Canadian petroleum technology, vol. 17, no.1, 1978, pp. 90-99.

D.C.M.R. (Dienst Centraal Milieubeheer Rijnmond), 1982: **Jaarverslag.**

DELFINER P. and J.P. DELHOMME, **Optimum interpolation by kriging.** In: Davis J.C. and M.J. McCullagh: "Display and Analysis of Spatial Data" pp. 96-114, John Wiley, 1975.

DENT B.D., **Principles of thematic map design.** Addison-Wesley, 1985.

DUTTWEILER D.W. and W.M. SANDERS, **Future environmental management using models.** In: Proceedings of the USEPA Conference on Environmental modelling and simulation, Cincinatti, 1976.

ECONOMOPOULOS A.P., **Development of the five-year air pollution abatement plan for the Greater Athens Area.** Journal of the Air Pollution Control Association, vol. 37, no. 8, 1987, pp. 889-897.

FINAL REPORT no. 4.2, **Technoeconomical study for the reduction of emissions of air pollutants from industrial boilers and furnaces in GAA.** Ministry of Physical Planning, Housing and Environment (now Ministry of Environment, Physical Planning and Public Works), Environmental Division PERPA, October 1984 (in Greek).

FINZI G., FRONZA G., RINALDI S. and P. ZANETTI, **Modelling and forecast of the dosage population product in Venice.** Proceedings Environmental System Planning, Design and Control, IFAC Symposium, Kyoto, Japan, 1, 1977, pp. 403-407.

FLOOR C., **Weerfoto als bodemkaart.** Zenith, januari 1989, pp.28-29.

FREITAG U., **Grundlagen, Aufbau and Zukünftige Aufgaben der Kartographische Wissenschaft.** In: H. BOSSE - Kartographische Aspekte der Zukunft. Karlsruhe, 1979.

FREITAG U., **Can communication theory form the basis of a general theory of Cartography?.** Nachrichten aus dem Karten und Vermessungswesen Reihe II no.3 1980.

FRENKIEL F.N., **Atmospheric pollution and zoning in an urban area.** Scientific Monthly 82 (4), 1956, pp. 194-203.

FRENKIEL F.N. and D.W. GOODALL, **Simulation Modelling of Environmental Problems.** John Wiley, 1975

FROHLICH C., **Deep earthquakes.** Scientific American, vol. 260, no.1, January 1989, pp.32-39.

GIFFORD F.A., **Turbulent diffusion- typing schemes: a review.** In consequences of effluent release, Nuclear Safety 17:68, 1976.

GINIS and ZAMBAKAS, **The influence of trade winds and sea breeze on the pollution of Athens.** Report, laboratory of Climatology, University of Athens, 1976.

GRAEDEL T.E. and P.J. CRUTZEN, **The changing atmosphere.** Scientific American, September 1989, pp. 28-36.

GREEN M., **Statistical models for areal interpolation.** Proceedings first European Conference on Geographical Information Systems, Amsterdam, 1990, vol. 1, pp.392-399.

GREGORY K.J. and D.E. WALLING, **Man and Environmental processes.** Buttleworths, 1981.

GUPTILL S.C. and L.E. STARR, **The future of Cartography in the information age.** In: Computer assisted Cartography research and development report. ICA Commission C (compiled by L.E. Starr) 1984, pp. 1-15.

HAAS A.G. and J.R. VIALLIX, **Krigeage applied to Geophysics -the answer to the problem of estimates and contouring.** Geophysical prospecting, vol. 24, 1976, pp. 4-69.

HAMMERLE J.R., **Emission inventory.** In: Stern A.C., Air Pollution (Vol. 3), 3rd edition, Academic Press, 1976.

HANNA S.R., **Review of Atmospheric Diffusion Models for Regulatory Applications.** Technical note no. 177, World Meteorological Organization, 1982.

HEATH D.C. (Publ.), **Physics.** D.C. Heath & Co., Boston, 1960.

HEUVELINK G.B.M., BURROUGH P.A. and A. STEIN, **Propagation of errors in spatial modelling with GIS.** International Journal of Geographical Information Systems, vol. 3, no. 4, 1989, pp. 303-322.

HILL A.C., **Vegetation: a sink for atmospheric pollutants.** Journal of Air Pollution Control Association, 21, 1971, pp. 341-346.

HÖHN R., **Wetter-Winde-Wolken.** Leipzig, 1955.

I.C.A., **Multilingual dictionary of technical terms in Cartography.** Wiesbaden: F. Steiner Verlag, 1973.

I.C.A., **Examples of environmental maps.** Madrid, Instituto Geografico Nacional, 1980.

I.C.A, **Basic Cartography for students and technicians,** Vol. 1, 1984.

IMHOF E., **Cartographic relief representation.** Walter de Gruyter, 1982.

KADMON N., **Photographic, Polyfocal and Polar-Diagrammatic Mapping of Atmospheric Pollution.** The Cartographic Journal, vol. 20, no. 2, 1983 pp. 121-126.

KATSAMBALOS K., **Fast coordinate transformations from one projection to another using complex numbers.** Quaterniones Geodaesiae, vol., 4, no.3, pp. 169-186, 1983 (in Greek).

KEDDIE A.W.C., ROBERTS, G.H. and F.P. WILLIAMS, **The application of numarical modelling to air pollution in the Forth Valley.** In: "Mathematical models for environmental problems", London, Pentech Press, 1975.

KINSMAN B., **Wind waves.** Dover publications, 1984.

KOEMAN C., **The principle of communication in cartography,** International Yearbook of Cartography, 1971, pp. 169-176.

KOLACNY A., **Cartographic information, a fundamental concept and term in modern Cartography.** Praha, 1968.

KOUSSOULAKOU A., LIVIERATOS E. and D. ROSSIKOPOULOS, **Deformation analysis of historical maps.** Quaterniones Geodaesiae, vol. 4, no. 2, pp. 127-148 , 1983, (in Greek).

KOUSSOULAKOU A., **Simulation and dynamic mapping of air pollution for the area of Athens, Greece.** Proceedings Eurocarto 7, Enschede, 1988a.

KOUSSOULAKOU A., **Computer simulation and thematic mapping of air pollution for the area of Athens.** Centre for Computer Graphics and Mapping (CCGM) report, Delft, 1988b.

KRAAK M.J., **Computer-assisted cartographical three dimensional imaging techniques.** Delft: Delft University Press, 1988.

KRETSCHMER I., **Theoretical Cartography: position and tasks.** International Yearbook of Cartography 1980, pp. 142-155.

LAM N.S.N., **Spatial interpolation methods: a review.** The American Cartographer, vol. 10, no. 2, 1983, pp. 129-149.

LANDSBERG H.E., **The climate of towns.** In: Man's role in changing the face of the Earth. (ed. W.L. Thomas), University of Chicago Press, 1956.

LEE N. and C. WOOD, **Methods of environmental impact assessment for use in project appraisal and physical planning.** Department of town and country planning, University of Manchester, Paper no. 7, 1980.

LEOPOLD L.B., CLARK F.E., HANSHAW B.B. and BALSLEY J.R., **A procedure for evaluating environmental impact.** U.S. Geological Survey

Circular 645, Washington, 1971.

LIAKATAS and NIANIOS, Communication to the 2nd Greek Hydrological Seminar, Athens 1980.

LUDWIG, F.L and J.H.S. KEALOHA, **Urban Climatological studies.** Final report, Stanford Research Institute, Menlo Park, California, 1968.

LYROUDIAS P., **Urban pollution and microclimate.** Case study, Faculty of Architecture, National Technical University of Athens, 1980.

MAAS F.M., **Town and Country Planning. Consideration for Air Pollution and Location of Industry.** Frankfurt, 1972.

MANAHAN S., **Environmental Chemistry.** PSW Publishers, 1982.

MATHERON G., **Les variables régionalisées et leur estimation.** Masson et Cie, Paris, 1965.

MATHERON G., **The theory of regionalized variables and its applications.** Les cahiers du centre de morphologie mathematique de Fontainebleu. Ecole Nationale Superiere des Mines de Paris, 1971.

McCORMICK R.A., **Air pollution in the locality of buildings.** Philosophical Transactions of the Royal Society of London, Series A, 269, 1971, pp. 515-526.

McCUEN R.H., **The anatomy of the modelling process.** In: "Mathematical models for environmental problems". Proceedings of the International Conference held at the University of Southampton, (edited by C.A. Brebbia), Pentech Press, 1975.

McINTOSH D.H. and A.S. THOM, **Essentials of Meteorology.** Wykeham publications, London, 1969.

MDNR (Maryland Department of Natural Resources), **Environmental Atlas Potomak Estuary** Annapolis, 1979.

MEETHAM A.R., **Atmospheric Pollution in Leicester.** D.S.I.R. Technical paper no.1, H.M.S.O., London, 1945.

MEINE K.H., **Certain aspects of cartographic communication in a system of Cartography as a science.** International Yearbook of Cartography 1978, pp. 102-117.

MELLI P. and A. SPIRITO, **I modelli matematici della diffusione atmosferica: un conciso stato dell' arte.** Note di Informatica, IBM Italia, 1982, pp. 7- 28.

MOELLERING H., **The real time animation of three-dimensional maps.** The American Cartographer, vol.7, no.1, pp. 67-75, 1980a.

MOELLERING H., **Strategies of real-time Cartography.** The Cartographic Journal vol. 17, no. 1, pp. 12-15, June 1980b

MORRISON J.L., **Computer technology and cartographic change.** In: "The computer in contemporary Cartography" (ed. by D.R.F. Taylor). John Wiley & Sons, 1980.

MORRISON J.L., **Cartography: a milestone and its future.** Proceedings AUTOCARTO London, 1986, vol. 1, pp. 1-12.

MOST P.F.J. van der, **Emission inventory and its applications in the Netherlands.** In Proceedings of the Seminar "Teaching Cartography for Environmental Information Management", ICA Commission on Education and Training, Enschede, 1989.

MOTTO H.L., **Lead in soils and plants: its relationship to traffic volume and proximity to highways.** Environmental Science and Technology, 4(3), 1970, pp. 231-251.

MOUNSEY H., **The cartography of time-changing phenomena -the animated map.** PhD Thesis, University of Durham, 1982a.

MOUNSEY H., **Mapping population change through time by computer and cine-film.** Computers in Cartography, British Cartographic Society special publication no. 2, pp. 127-132, 1982b.

MUEHRCKE P.C., **Maps in Geography.** Cartographica vol 18 (1981) no.2, pp.1-41.

MUEHRCKE P.C., **Map Use.** Madison: JP Publications, 1983.

MULLER J.-C., **The concept of error in Cartography.** Cartographica, vol. 24, no. 2, 1987, pp. 1-15.

MUNN R.E., **Airflow in urban areas.** In: Urban climates, Technical note no. 108, World Meteorological Organization, Geneva, 1970, pp. 15-39.

NICHOLSON S.E., **A pollution model for street level air.** Atmospheric Environment Vol. 9, pp. 19-31, Pergamon Press, 1975.

NOVAK J.H. and D.B. TURNER, **An efficient Gaussian-plume multiple-source air quality algorithm.** Journal of the Air Pollution Control Association, vol. 26, no.6, June 1976 pp. 54-59

NOVAK J.H. and D.B. TURNER, **Users guide for RAM.** Environmental Sciences research Laboratory, U.S.E.P.A., 1978.

NTUA (National Technical University of Athens): **Development of an emission pattern for traffic (linear sources). Implementation for the Athens basin.** Processes and Systems Analysis, Planning and Development Department. Faculty of Chemical Engineering, National Technical University of Athens, 1986 (in Greek).

O'CALLAGHAN J.F., R.B. STANTON & C.J. BARTER, **Problems in automated Cartography.** Cartography 7 (1971), pp. 93-101.

OKE T.R. and C. EAST, **The urban boundary layer in Montreal.** Boundary Layer Meteorology, 1, 1971, pp. 411-437.

OLIVER M.A. and R. WEBSTER, **Kriging: a method of interpolation for geographical information systems.** International Journal of Geographical Information Systems, vol. 4, no. 3, 1990, pp. 313-332.

OLSON J.M., **Future research directions in cartographic communication and design.** In: "Graphic Communication and Design in Contemporary Cartography" (ed. by D.R.F. Taylor). John Wiley & Sons, 1983.

OLSON J.M., **Video disks and map design.** Technical papers of the 12th Conference of the I.C.A. Perth, Australia, vol.1, pp.509-518, 1984.

ORMELING F.J., **Richtingen in de theorie van de Kartografie.** Kartografisch Tijdschrift vol. 8 (1982) no. 4, pp. 38-43.

ORMELING F.J., **Environmental Mapping in transition.** In Proceedings of the Seminar "Teaching Cartography for Environmental Information Management", ICA Commission on Education and Training, Enschede, 1989.

ORMELING F.J. & M.J. KRAAK, **Kartografie.** Delft, Delftse Universitaire Pers, 1990.

OUELETTE R.P., GREELEY R.S. and J.W. OVERBEY II, **Computer techniques in Environmental Science.** New York, Petrocelli/Charter, 1975.

PAPE H., **Urban Cartography - Town Planning.** International Yearbook of Cartography, 1973, pp.191-199.

PAPE H., **Planning restriction area maps in town planning.** Nachrichten aus dem Karten und Vermessungswesen, Reihe II, nr.38, 1980, pp.61-67.

PARASCHAKIS I. and A. FOTIOU, **Problems of coordinate transformations in digitization of maps.** Eratosthenes, 22, 1988, pp. 125-

156 (in Greek).

PASQUILL F., **The estimation of the dispersion of windborne material.** Meteorological Magazine, 90, 1961, pp. 33-49.

PETCHENIK B.B., **The futures of Cartography.** Cartographica vol. 19 (1982) no 3 & 4, pp. 109-114.

PETERSON J.T., **The climate of cities: a survey of recent literature.** U.S. Department of Health, Education and Welfare, National Air Pollution Control Administration, Rayleigh, N.C., 1969.

PFITZER G., **Forecast graphics.** Computer Graphics World, pp.80-84, January 1990.

PRANDTL L. and O.G. TIETJENS, **Fundamentals of Hydro- and Aeromechanics.** Dover publications, 1957.

PROJECT II.4, **Technoeconomical study of the means for reducing the emissions from Central Heating.** Thermodynamics and Transport Phenomena laboratory / Heat Engines and Steam Boilers laboratory, National Technical University of Athens. Final report, Ministry of Physical Planning, Housing and Environment (now Ministry of Environment, Physical Planning and Public Works), Environmental division PERPA and EEC DGXI, Dec. 1983 (in English and Greek).

RAMAGE C.S., **El Niño.** Scientific American, vol. 254, no. 6, June 1986, pp.55G-61

RATAJSKI L., **The research structure of theoretical Cartography.** International Yearbook of Cartography 1973, pp. 217-227.

REED L.E., **Vehicle exhausts in relation to public health.** The Royal Society of Health Journal, 86, 231, 1966.

REIGNIER F., **Les systemes de projection et leurs applications,** tome I. Paris, 1957.

RIPLEY B.D., **Spatial statistics,** John Wiley, 1981.

ROBINSON A.H. & B.B. PETCHENIK, **The Nature of Maps.** Chicago: The University of Chicago Press, 1976.

ROBINSON A.H., R.D. SALE, J.L. MORRISON & P.C. MUEHRCKE, **Elements of Cartography.** John Wiley & Sons, 1984.

ROSEBUSH J., **Basic principles of Computer Animation.** In: Proceedings SIGGRAPH Advanced Animation Tutorial. San Francisco, 1985.

ROYLE A.G., CLAUSEN F.L. and P. FREDERIKSEN, **Practical universal kriging and automatic contouring.** Geo-Processing 1 (1981), pp. 377-394.

SALICHTCHEV K.A., **Cartographic Communication - its place in the theory of science.** The Canadian Cartographer, 15, 1978, pp. 93-99.

SAUNDERS P.J.W. and C.-M. WOOD, **Plants and air pollution.** Landscape Design, 105, 1974, pp.28-30.

SENA M.L., **Maps that move.** Computer Graphics World, Sept. 1989, pp. 101-106.

SENA M.L., **Computer-aided dispatching.** Computer Graphics World, May 1990, pp. 35-42.

SHANNON C.E. & W. WEAVER, **The mathematical theory of communication.** Urbana: University of Illinois Press, 1949.

SINGER T.A. and M.E. SMITH, **A summary of the recommended guide for the prediction of the dispersion of air-borne effluents.** In: Urban Climates, Technical note no. 108, World Meteorological Organization, Geneva, 1970, pp. 306-324.

SMITH D.G. and B.A. EGAN, **Design of monitoring networks to meet multiple criteria.** In: Quality assurance in air pollution measurement. (E.D. Frederick, ed.) Air Pollution Control Association, Pittsburg, 1979, pp. 181-187.

SNYDER J.P., **Map projections: a working manual.** Geological Survey professional paper 1395. U.S. Government Printing Office, Washington, 1987.

SPIESS E. and C. BRANDENBERGER, **Transformation of digital and analogue map data by interpolation methods - an important tool in small-scale map compilation.** International Yearbook of Cartography, 1986, pp. 149-173.

STERN A.C. (editor), **Air Pollution.** Vol. 1, (2nd edition), Academic Press, 1968.

STERN A.C., BOUBEL R.W., TURNER D.B. and D.L. FOX, **Fundamentals of Air Pollution.** (2nd edition), Academic Press, 1984.

STOLARSKI R., **The Antarctic Ozone Hole.** Scientific American, vol. 258, no.1, January 1988, pp.20-26.

TAYLOR D.R.F., **The creation and design of maps for Videotex systems.** Technical papers of the Austra CartoOne Seminar. Perth, Australia, 1984a, vol.1, pp. 277-290.

TAYLOR D.R.F., **Computer assisted Cartography, new communication technologies and cartographic design: the need for a "New Cartography".** Technical papers of the 12th Conference of the I.C.A. Perth, Australia Aug. 1984b, vol. I, pp. 457-467.

THROWER N., **Animated Cartography in the United States.** International Yearbook of Cartography 1961, pp. 20-28.

TOBLER W.R., **A computer movie: simulation of population change in the Detroit region.** Economic Geography, 46(2) pp 234-240, 1970.

TURNER, D.B., **Atmospheric dispersion modelling: a critical review.** Journal of the Air Pollution Control Association, Vol. 29, no.5, 1979, pp. 502-519.

U.S.E.P.A. (United States Environmental Protection Agency), 1973: **Compilation of Air Pollutant Emission Factors.** 2nd edition.

U.S.E.P.A., **The World's Air Quality Management Standards.** Volume I, 1974.

VISVALINGAM M., **Cartography, GIS and Maps in Perspective.** The Cartographic Journal vol. 26 June 1989, pp. 26-32.

WL (Waterloopkundig Laboratorium), **Gebruikers handleiding computeranimatie programmatuur,** 1990.

YOELI P., **Error bands of topographical contours with computer and plotter (program KOPPE).** Geo-Processing, 2 (1984), pp. 287-297.

ZOUMAKIS N.M., 1984: **A contribution to the study of the distribution of inert (or inert under conditions) gaseous pollutants in the Thessaloniki area.** Ph.D. Thesis, University of Thessaloniki (in Greek).

APPENDIX I. GLOSSARY OF TERMS.

The terms to be found in this Appendix are not only those indicated by asterisks in the main text but also some additional ones which were considered useful to include (most of the definitions have been extracted from: Webster's dictionary, ed. 1983).

absorb: to drink in; to receive or take up by chemical or molecular action

adiabatic process: of or denoting change in volume or pressure without loss or gain of heat

adsorb: to collect (a gas, liquid, or dissolved substance) in condensed form on a surface

advection: the transference of heat by horizontal currents of air

acid rain: rain with ahigh concentration of acids produced by sulfur dioxide, nitrogen oxide etc.; it has a destructive effect on plant and aquatic life, buildings etc.

air: the mixture of invisible odorless tasteless gases which surrounds the earth.

atmosphere: a. a gaseous mass envelopping a celestial body (as a planet) b. the whole mass of air surrounding the earth.

atom: the smallest particle of an element that can exist either alone or in combination.

breeze: a light gentle wind; a wind of 4-31 miles/hour, caused by differential heating between land and water surfaces.
sea breeze: in the daytime heating occurs more quickly over land than over sea, causing air (sea breeze) to rise over the land
land breeze: at night cooling occurs more quickly over the land, causing air (land breeze) to rise from land to water.

buoyancy: a. the tendency of a body to float or to rise when submerged in a fluid. b: the power of a fluid to exert an upward force on a body placed in it.

burn: to consume with fire; to reduce to ashes by the action of fire; to expel the volatile parts and reduce to charcoal; in chemistry to calcine, to make undergo combustion.

calcine: to burn to ashes or powder, to reduce to calx (i.e. lime or chalk) or powder by the action of heat; to oxidize as a metal.

charcoal: a black form of carbon made by charring (i.e. burning partially, scorching, burning slightly) wood or another organic matter by a process of smothered combustion (i.e. by preventing the presence of air) in order to exclude air; it is used as afuel, filter, gas absorbent etc.

combustion: the rapid union of a substance with oxygen accompanied by the evolution of light and heat. The act or process of burning; rapid oxidation generating heat or both light and heat; also slow oxidation accompanied by relatively little heat and no light.

ambient pollution/ ambient concentration: frequently used terms, intending to distinguish pollution of the air outdoors (ambient air pollution) by e.g. wind transport and diffusion from condamination of the air indoors.
background concentration: pollutant concentrations to be found permanently in the atmosphere.

Dobson units: units for measuring ozone levels in the atmosphere: one unit is a hundrendth of a millimeter and refers to the thickness of the layer that would result if the ozone in a slice of the atmosphere were collected at standard temperature and pressure.

diffusion: the process whreby particles of liquids, gases or solids intermingle as the result of their spontaneous movement caused by thermal agitation and in dissolved substances move from a region of higher to one of lower concentrations.

disperse: a. to scatter; to cause to become spread widely; to cause to evaporate or vanish. b. to spread or distribute from a fixed or constant source; to distribute (as fine particles) more or less evenly throughout a medium.
dispersoid: finely divided particles of one substance dispersed in another.

downwash: the air that an airplane wing pushes downward while moving through the air; stack-downwash and building-downwash are terms used in air pollution terminology to denote movement of masses of (polluted) air due to air currents generated by large obstacles.

downwind: in the direction that the wind is blowin

eddy reflection: the movement away ("reflection") of circular eddies of air from the earth's surface since they cannot penetrate the surface. [S]

element: any of more than 100 fundamental substances that consist of atoms of only one kind and that singly or in combination constitute all matter.

emission model: a method for obtaining emission rates of pollutants on the basis of raw data such as type and quantity of fuel consumed

fume: smoke.

gas: a. a fluid (as air) that has neither independent shape nor volume but tends to expand indefinitely.

hydrocarbon: any compound containing only hydrogen and carbon (such as e.g. benzene and methane)

incineration: to burn to ashes, to consume, to cremate.

inversion: situation where atmospheric temperature incerases with height above ground, which is the inverse of the more usual case of temperature decrease with height.

mixing layer: the layer of the atmosphere where vertical movements of air masses occur causing mixing.

molecule: [fr. L. molecula] the smallest particle of a substance that retains the properties of the substance and is composed of one or more atoms.

organic: (in chemistry) designating or of any chemical compound containing carbon; some of the simple compounds of carbon are frequently classified as inorganic compounds. Designating or of the branch of chemistry dealing with carbon compounds.

particle: one of the minute subdivisions of matter (as an atom or molecule.
elementary particle: any of the submicroscopic(i.e. too small to be seen in an ordinary light microscope) constituents of matter and energy (as the electron, proton or photon) whise existence has not been attributed to the combination of other more fundamental entities.

photochemical reaction: one of the two types of atmospheric chemical reactions (the other is thermal). Photochemical reactions are the interactions of photons with species which result in new products.

plume: a pollutant body exiting from an industrial stack.

pollutant: any substance which appears in concentrations higher than the ones usually occuring.

pollutant half-life: the time required to lose by removal mechanisms 50% of the pollutant.
secondary pollutant: pollutant formulated by chemical reactions after its release into the atmosphere

pollution episode: Case where pollution concentration reaches critical limits.

radiosonde information: package of meteorological instruments and a radio transmitter carried aloft by a balloon and measuring/transmitting to the ground temperature, pressure and humidity data by means of radio signals.

runoff: something (that runs off) in excess of the amount absorbed e.g. by the ground.

smoke: the vaporous matter arising from something burning and made visible by minute particles of carbon suspended in it.

stagnation: situation where, due to a very stable atmosphere, pollution concentrations built up in the air over a region as if it were covered by a box having as its top the inversion ceiling.

substance: a physical material from which something is made or which has discrete existance; matter of particular or definite chemical constitution.

suspend: to keep from falling or sinking by some invisible support (as buoyancy)
suspended particles: particles held in suspension in the atmosphere.

turbulence: the quality or state of being turbulent as: wild commotion; irregular atmospheric motion especially when characterized by up and down currents; departure in a fluid from a smooth flow.

vapor: diffused matter (as smoke or fog) suspended floating in the air and impairing its transparency; a substance in the gaseous state as distinguished from the liquid or solid state, a substance (as gasoline, alcohol, mercury or benzoin) vaporized for industrial, therapeutic or military uses, also a mixture (as the explosive mixture in an internal combustion engine) of such a vapor with air.

venturi effect: effect created in the so-called "venturi-tube", where the velocity of the passing fluid incerases and its pressure is lowered.

volatile: flying; having the power of fly; evaporating rapidly; diffusing more or less freely in the atmosphere.

APPENDIX II. MATHEMATICAL DERIVATION OF THE GAUSSIAN AND THE GRADIENT TRANSPORT MODEL.

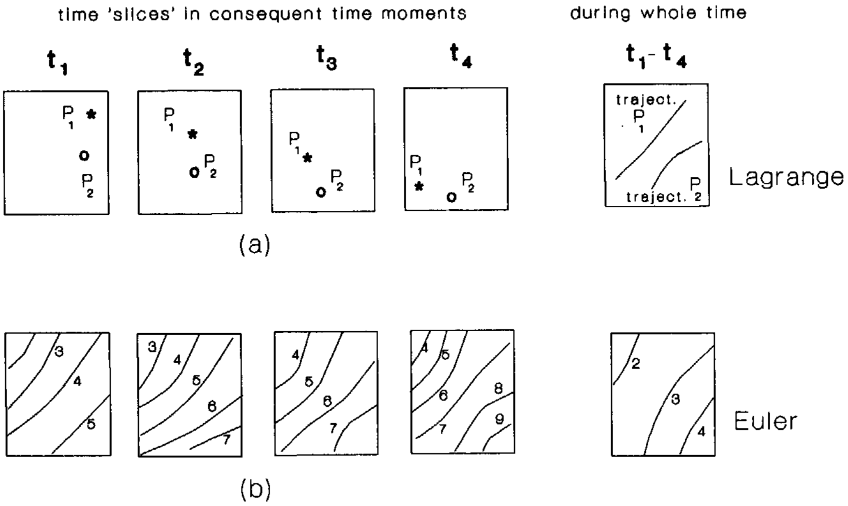
For the description of the movements of a fluid two methods have been devised (Prandtl and Tietjens, 1957):

- one method is concerned with **what happens to the individual fluid particles**: what paths they describe in the course of time, what velocities or/and accelerations they have during this time etc. This is the so called Langrangian method, since mostly Langrange has worked out its calculation.
- the other method is concerned with **what happens at a fixed point** (i.e. a location) in the space filled with the fluid: e.g. what is the velocity, acceleration etc. at this point (and how does it change with time); also how is the situation at the different points in this space. This is the so called Eulerian method (after Euler).

Therefore, the Lagrangian method gives information about the paths of the individual particles of the fluid as a function of time by describing the **path lines** or **trajectories** that the particles follow. The Eulerian method on the other hand can be thought of as a series of instantaneous photographs of the state of the motion given by **streamline** diagrams. These streamlines are actually generated from the information about the situation at the different points in space (at specific time moments or through the course of a certain time). It should be mentioned that there is no relation between the streamlines and the separate particles: in the general case the streamlines are generated by different fluid particles (op. cit.).

In order to clarify the concept of the two different approaches, which, however, describe the same phenomenon a simplified representation of each is given in Fig. AII-1. In Fig. AII-1(a) [Lagrangian case] the positions of two individual particles are shown at the consequent time moments t_1, t_2, t_3 and t_4. The situation during the whole time (i.e. t_1 till t_4) can be described by the trajectories which these two particles have followed. In Fig. AII-1(b) [Eulerian case] the streamlines (of e.g. particle velocities) at the consequent time moments are shown. The situation during the whole time can be described also by means of streamlines which actually depict the difference (in particle velocities) during the whole time (i.e. t_1 till t_4).

An illustration which depicts a more realistic situation (water flow in a sea wave) is shown in Figure AII-2.



(a)

(b)

Figure AII-1. A simplified representation of the concepts behind the Lagrangian and the Eulerian approach.

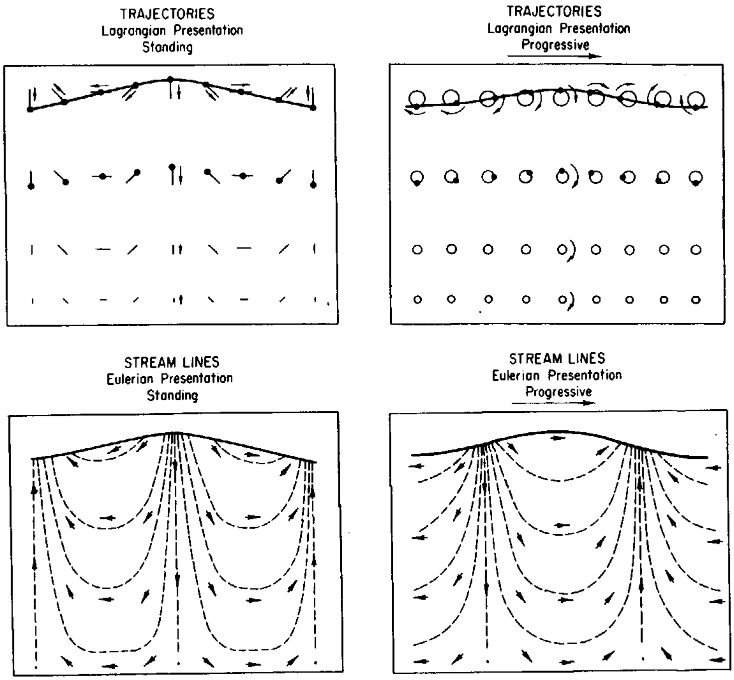


Figure AII-2. Particle paths [Lagrangian approach] and streamline [Eulerian approach] for a sea wave (from: Kinsman, 1984).

What we want to calculate is the concentration of a fluid (liquid or gas) **at specific location** for a period of time (e.g. t_o till t).
Following the Lagrangian approach the concentration at a point will be regarded as the result of transport of particles to this point during the above period of time (i.e. the concentration will be the "sum" of particles).
Following the Eulerian approach the concentration at a point is expressed in terms of its change during the period t_o till t at this point. A detailed example of each approach is given in the following.

Lagrangian approach - Gaussian model

The concentration C of a pollutant at a point **x**

$$\mathbf{x} = [\, x^1\ x^2\ x^3]^T \qquad \text{(eq. AII.1)}$$

where x^1, x^2, x^3 are the cartesian coordinates of the point

and at a certain time t, is a space-time function

$$C = C\,(\mathbf{x}\,,\, t) \qquad \text{(eq. AII.2)}$$

which is formed by a transport of particles.

It could be considered that before the transport of the particles of interest has created C, a partial concentration C_o was already existing at positions $\mathbf{x}_o$

$$\mathbf{x}_o = [\, x_o^{\,1}\ x_o^{\,2}\ x_o^{\,3}\ ]^T \qquad \text{(eq. AII.3)}$$

and at a time t_o, so that

$$C_o = C_o\,(\,\mathbf{x}_o,\, t_o\,) \qquad \text{(eq. AII.4)}$$

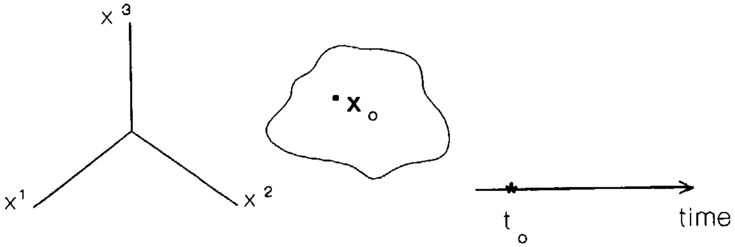


Figure AII-3. At time t_o the concentration C_o at position x_o is $C_o = C_o\,(\mathbf{x}_o,\, t_o\,)$

From time t_o until time t various pollutant emitting sources existing at positions $\mathbf{x}_s$

$$\mathbf{x}_s = [x_s^1\ x_s^2\ x_s^3]^T \qquad \text{(eq. AII.5)}$$

have emitted masses s of pollution at various times t_s, where:

$$t_o \leq t_s \leq t \qquad \text{(eq. AII.6)}$$

so that

$$s = s(\mathbf{x}_s, t_s) \qquad \text{(eq. AII.7)}$$

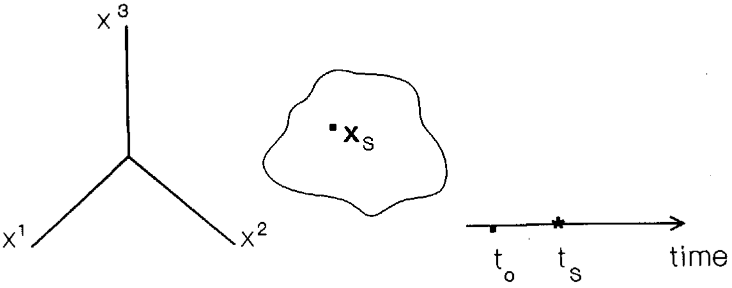


Figure AII-4. At time t_s the emitted quantity s of mass, at position $\mathbf{x}_s$ is $s = s(\mathbf{x}_s, t_s)$

Finally, at time t, where

$$t = t_o + \Delta t \qquad \text{(eq. AII.8)}$$

the concentration at positions $\mathbf{x}$ becomes $C = C(\mathbf{x}, t)$

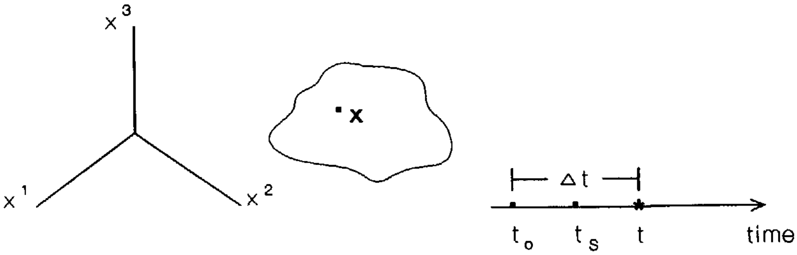


Figure AII-5. At time t the concentration C at position $\mathbf{x}$ is $C = C(\mathbf{x}, t)$

Thus, the concentration $C = C(\mathbf{x}, t)$ at point $\mathbf{x}$ at time t has been created (Fig. AII-6):

a. by transport of particles which were pre-existing at position $\mathbf{x}_o$ at time t_o;
b. by transport of particles which were emitted from sources at positions $\mathbf{x}_s$ at times t_s

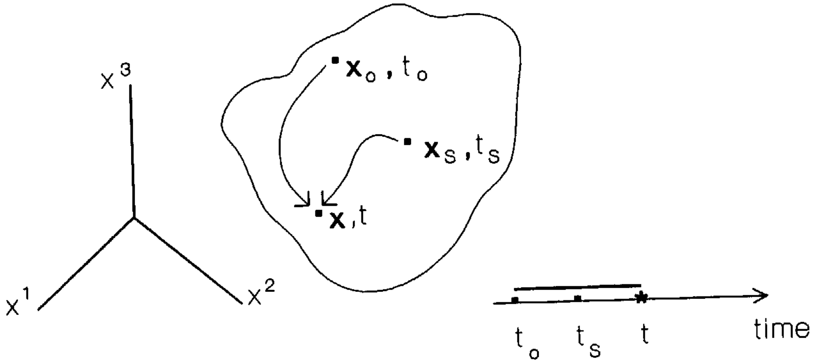


Figure AII-6. Transport of particles to position **x** from time t_o until time t

Let $\psi(\mathbf{x}, t)$ be the probability density function of a particle to exist, at time t, in an elementary volume dV, at point **x**.

From the definition of $\psi(\mathbf{x}, t)$ it is:

$$\int_V \psi(\mathbf{x}, t)\, dV = 1 \qquad \text{(eq. AII.9)}$$

The probability density to predict a particle at point **x** at time t can be expressed in the general case, as a function of the transition probability (reproducing Kernel) $Q(\mathbf{x}, t; \mathbf{x}_t, t_t)$

$$\text{where } \mathbf{x}_t = [\, x_t^1\; x_t^2\; x_t^3]^T \qquad \text{(eq. AII.10)}$$

$$t_t = t - \Delta t_t \qquad \text{(eq. AII.11)}$$

The transition probability $Q(\mathbf{x}, t; \mathbf{x}_t, t_t)$ expresses the probability of the transition of a particle from point $\mathbf{x}_t$ (at time t_t) to point **x** (at time t).

Consequently, the probability density function $\psi(\mathbf{x}, t)$ can be calculated from the total possible transitions of particles from all the points $\mathbf{x}_t$ at time t_t to point **x** at time t.

$$\psi(\mathbf{x}, t) = \int_V Q(\mathbf{x}, t; \mathbf{x}_t, t_t)\, \psi(\mathbf{x}_t, t_t)\, dV_t \qquad \text{(eq. AII.12)}$$

We have to consider, that in our case we have several sources at positions $\mathbf{x}_s$ emitting at various times t_s between initial time t_o and final time t.

Thus, the probability density function ψ_1 ($\mathbf{x}$, t) will be calculated from the total possible transitions of particles from all the points $\mathbf{x}_o$ at time t_o to point $\mathbf{x}$ at time t, and the probability density functions ψj ($\mathbf{x}$,t)
(j = 2,n) will be calculated from the total possible transitions of particles from all the points $\mathbf{x}_s$ to point $\mathbf{x}$, for a number n-1 of times t_{sj},
where $t_o \leq t_{sj} \leq t$

Because of the statistical nature of the phenomenon the average concentration C ($\mathbf{x}$, t) at point $\mathbf{x}$ at time t will be (Zoumakis, 1984):

$$C(\mathbf{x}, t) = \sum_{i=1}^{n} \psi_i (\mathbf{x}, t) \qquad \text{(eq. AII.13)}$$

$$C(\mathbf{x}, t) = \psi_1(\mathbf{x}, t) + \sum_{j=2}^{n} \psi_j (\mathbf{x}, t) \qquad \text{(eq. AII.14)}$$

or

$$C(\mathbf{x}, t) = \int_v Q(\mathbf{x}, t; x_o, t_o) < C(x_o, t_o) > dV_o + \qquad \text{(eq. AII.15)}$$

$$\int_{t_o}^{t} \int_{V} Q(\mathbf{x}, t; x_s, t_s)\ s(x_s, ts)\, dV_s\, dt_s$$

The first term of the second part in (eq. AII.15) represents the contribution to the final concentration C ($\mathbf{x}$, t) of those particles which were existing at time t_o at various positions $\mathbf{x}_o$ in space and which have a probability to arrive, at time t, at point $\mathbf{x}$.
The second term expresses the addition of particles emitted from the existing sources at various positions $\mathbf{x}_s$ and at various times t_s, between t_o and t.

Equation (eq. AII.15) is the fundamental formula describing the dispersion of inert pollutants in a flow field, following the Lagrangian approach.

Thus, if we know the emitted mass quantities $s(\mathbf{x}_s, t_s)$ and the initial concentration C_o ($\mathbf{x}_o$, t_o), in order to calculate the concentration C ($\mathbf{x}$, t) at position $\mathbf{x}$ we need to know the transition probability Q to that position.

If turbulence is constant through time (i.e. its properties are time independent) and homogeneous in space (i.e. its properties do not depend on the position within the fluid field), then the transition probability Q follows a normal (Gaussian) distribution and depends on the transitions of the particles in space and in time and not on the position of a particle, or on the time (op. cit.) so that:

$$Q\ (\mathbf{x},\ t;\ \mathbf{x}_t,\ t_t) = Q\ (\mathbf{x} - \mathbf{x}_t\ ;\ t - t_t) \qquad \text{(eq. AII.16)}$$

If we have one source located at position $\mathbf{x}_s$, which emits instantaneously to the atmosphere a mass of pollutants s at time $t_s = 0$, then if **V** is the average wind speed :

$$\mathbf{V} = [\ u\ v\ w\ ]^T \qquad \text{(eq. AII.17)}$$

and we assume that **V** has the direction of the x_1 axis so that $v = 0$ and $w = 0$ (Fig. AII-7), then from the time t_s of the emission until the time t of interest the quantity s will be transported by the wind over a distance l along the x^1 axis so that:

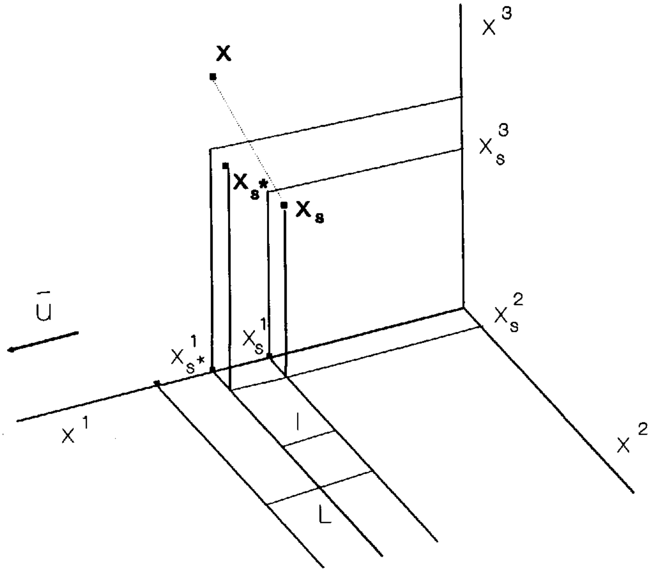


Figure AII-7. Transportation of s by wind $\bar{u}$ along the x^1 axis

$$l = \bar{u}\ (t - t_s) = \bar{u}\ t \qquad \text{(eq. AII.18)}$$

At time t, the quantity of mass s will arrive at a position $\mathbf{x}_{s*}$ (Fig. AII-5)

$$\mathbf{x}_{s*}\ [x_{s*}^1\ x_{s*}^2\ x_{s*}^3]^T \qquad \text{(eq. AII.19)}$$

where $x_{s*}^1 = x_s^1 + l = x_s^1 + \bar{u}\ t$ (eq. AII.20)

If the following assumptions are made :

a. The initial concentration $C(\mathbf{x}_o, t_o)$ is very small and it is neglected.
b. Obstacles such as buildings or rough terrain or atmospheric inversions do not exist.

then the solution of eq. (eq. AII.15) for the average concentration $C(\mathbf{x},\ t)$ of a pollutant which is assumed to be inert is

$$C(\mathbf{x}, t) = \frac{S}{\sqrt{(2\pi)^3}\ \sigma^1(t)\, \sigma^2(t)\, \sigma^3(t)} \exp\{- \tfrac{1}{2}\, \mathbf{d}^T\, \mathbf{W}\, \mathbf{d}\} \qquad \text{(eq. AII.21)}$$

where:

$$\mathbf{d} = \mathbf{x} - \mathbf{x}_s{}^* = [\ x^1 - x_{s*}^1 \quad x^2 - x_s^2 \quad x^3 - x_s^3\ ]^T \qquad \text{(eq. AII.22)}$$

$$\mathbf{W} = \begin{bmatrix} \frac{1}{\{\sigma^1(t)\}^2} & 0 & 0 \\ 0 & \frac{1}{\{\sigma^2(t)\}^2} & 0 \\ 0 & 0 & \frac{1}{\{\sigma^3(t)\}^2} \end{bmatrix} \qquad \text{(eq. AII.23)}$$

and **W** is the weight matrix with $\sigma^1(t)$, $\sigma^2(t)$, $\sigma^3(t)$ the standard deviations of the distribution of the concentrations along the cartesian coordinate axes x^1, x^2, x^3 respectively, expressed as functions of time t; (they are assumed uncorrelated, hence **W** diagonal).

If the previous source becomes a continuously emitting one, i.e. it emits with a constant emission rate S (e.g. S gr/sec) from time t_s until time t, then the concentration will be given by integrating the concentration of the instantaneous point source from time ts until time t.

Then we have (Zoumakis, 1984):

$$\bar{C}(\mathbf{x}) = \frac{S}{2\pi\, \sigma^2(L)\, \sigma^3(L)\, \bar{u}} \exp\left\{ - \tfrac{1}{2}\left[\left(\frac{x^2 - x_s^2}{\sigma^2(L)}\right)^2 + \left(\frac{x^3 - x_s^3}{\sigma^3(L)}\right)^2\right]\right\}$$

where $L = x^1 - x_s^1$ (Fig. AII-7) (eq. AII.25)

From (eq. AII.24) we see that for a continuously emitting source the distribution of the concentrations at various positions $\mathbf{x}$ is time independent and the standard deviations are expressed as functions of the distance of the position of interest $\mathbf{x}$, from the source along the x^1 axis (i.e. along the direction of the wind).

In reality pollution emitting sources cannot exist at whatever position in space, but they are located near the ground surface.

If H is the height of emission of the source above the ground, we can establish another coordinate system (x, y, z) with its origin located at $\mathbf{x}_G$

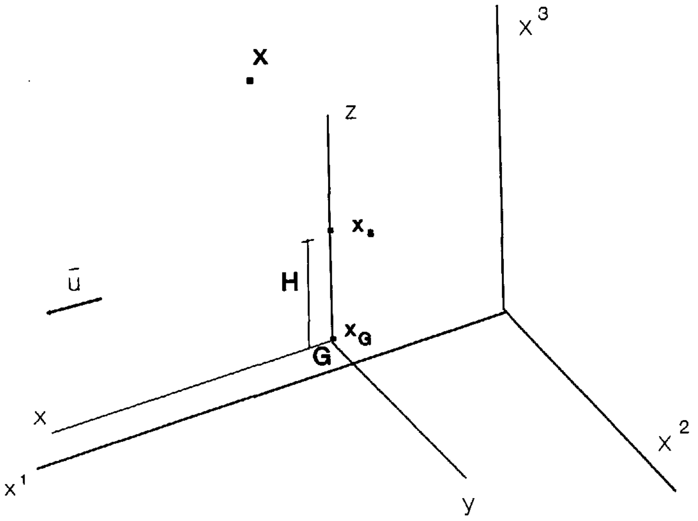


Figure AII-8. The coordinate system (x, y, z) has its origin in the location of the source on the ground $\mathbf{x}_G$.

where

$$\mathbf{x}_G = [\, x_s^1 - H \quad x_s^2 \quad x_s^3 \,]^T \qquad \text{(eq. AII.26)}$$

and we can express the concentration as $\bar{C} = \bar{C}(\mathbf{k})$

where

$$\mathbf{k} = [\,x \;\; y \;\; z\,]^T \qquad \text{(eq. AII.27)}$$

with respect to that system. (Fig. AII-6)

Then we have (op. cit.)

$$\bar{C}(k) = \frac{S}{2\pi\,\sigma_y\,\sigma_z\,\bar{u}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right\}$$

(eq. AII.28)

where

$$\sigma_y = \sigma_y(x) \qquad \text{(eq. AII.29)}$$
$$\sigma_z = \sigma_z(x) \qquad \text{(eq. AII.30)}$$

In eq. (eq. AII.28) it is assumed that the ground is a flat surface on which the pollutants are refracted.
In the theoretical case of an ideal refraction, thus, we would assume the exitance of a mirrored (imaginary) source P', so that over the point of refraction the concentration of the pollutants on the ground will be generated by the contribution of both sources (Fig. AII-9)

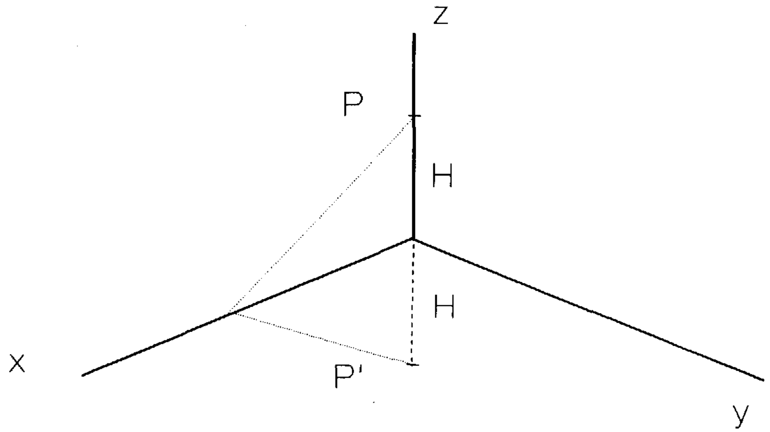


Figure AII-9. Contribution of real and imaginary source to pollution generation

In eq. (eq. AII.28) the factor (z-H) accounts for the contribution of the real source P, while the factor (z+H) accounts for the contribution of the imaginary P' (op. cit.).

Eulerian approach - Gradient-transport (K) model

Let us suppose that in a volume of air V_a there is a number n of pollutants i (i=1, 2, ..n)

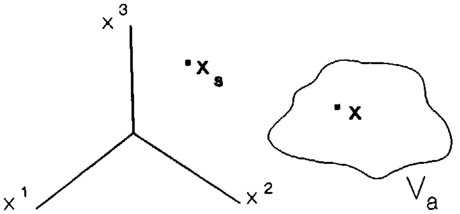


Figure AII-10. Source at $\mathbf{x}_s$ and receptor at **x**.

which were emitted from a source at position $\mathbf{x}_s$

$$\mathbf{x}_s = [x_s^1\ x_s^2\ x_s^3]^T \qquad \text{(eq. AII.31)}$$

and at time t_s

At a certain time t (t > t_s) and at a certain position **x**

$$\mathbf{x} = [\ x^1\ x^2\ x^3\ ]^T \qquad \text{(eq. AII.32)}$$

within the volume V_a the concentration C_i of a pollutant i is

$$C_i = C_i\ (\mathbf{x},\ t) \qquad \text{(eq. AII.33)}$$

Thus, if the space-time function $C_i = C_i\ (\mathbf{x}\ ,t)$ is known, we can calculate the concentration C_i of any air pollutant i, at any time t, at whatever position **x** within the volume of (polluted) air V_a.

From the continuity equation for fluids it is known that the change of the concentration C_i of a pollutant i with respect to time $\partial C_i/\partial t$ within a volume of air depends on the change of C_i within this volume because of;

a. transfer
b. molecular diffusion
c. possible existance of sources within that volume
d. possible chemical reactions within the volume which may increase or decrease the quantity of the pollutant i within the volume.

If **v** is the velocity of the wind, where

$$V = [\, u \;\; v \;\; w \,]^T \qquad \text{(eq. AII.34)}$$

D_i is the molecular diffusion coefficient of the pollutant i to the atmosphere

S_i is the emitted quantity of the pollutant i to the atmosphere from position **x** at time t

$$S_i = S_i(\mathbf{x}, t) \qquad \text{(eq. AII.35)}$$

R_i is a factor representing possible chemical reactions, and

$$T = T(\mathbf{x}, t) \qquad \text{(eq. AII.36)}$$

is the atmosphere temperature at time at position **x** the change of the concentration of a pollutant C_i with respect to time is (op. cit.)

$$\frac{\partial C_i}{\partial t} = -\nabla(C_i \bar{V}) + D_i \nabla^2 C_i + S_i + R_i \qquad \text{(eq. AII.37)}$$

where $-\nabla(C_i \bar{V})$ represents transfer
and $D_i \nabla^2 C_i$ represents molecular diffusion

Equation (AII.36) is written

$$\frac{\partial C_i}{\partial t} + tr\left(\frac{\partial V C_i}{\partial \mathbf{x}}\right) = D_i\, \mathbf{i}^T C_{i2} + R_i \{C_1, C_2, .. C_N, T\} + S_i (\mathbf{x}, t) \qquad \text{(eq. AII.38)}$$

where **i** is a unity vector

$$\mathbf{i} = [\, 1 \;\; 1 \;\; 1 \,]^T \qquad \text{(eq. AII.39)}$$

and C_{i2} is

$$C_{i2} = \left[\frac{\partial^2 C_i}{\partial (x^1)^2} \;\; \frac{\partial^2 C_i}{\partial (x^2)^2} \;\; \frac{\partial^2 C_i}{\partial (x^3)^2} \right]^T \qquad \text{(eq. AII.40)}$$

The solution of the differential equation (AII.38) gives a complete description of the behaviour of the gaseous pollutants.
In order to solve (eq. AII.38) the wind field must be known for every point **x** and for every time t.

However, in the boundary layer - which is the area of our concern - the flow is turbulent, in other words the components u, v, w of the wind velocity field are random variables at each point in space and time. Consequently the analytical solution of (eq. AII.38) is not possible. Thus, for the purpose of the statistical study of the properties of the boundary layer the concept of the turbulent flow is introduced.

Every physical parameter p of the turbulent flow field can be split in a mean value p and a disturbance dp (Fig. AII-11)

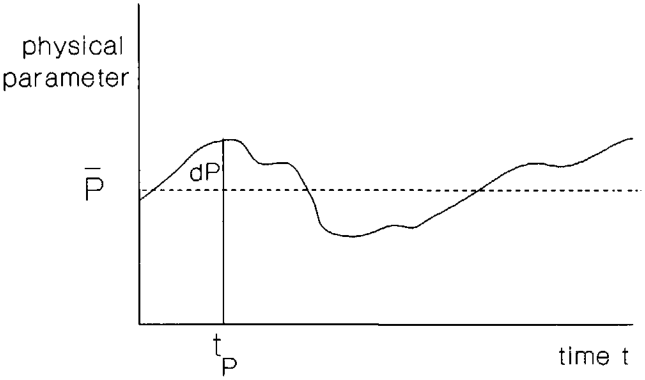


Figure AII-11. $p = \bar{p} + dp$, at t_p

Thus for the wind velocity field we have

$$V = \bar{V} + dV \qquad \text{(eq. AII.41)}$$

where

$$\bar{V} = [\ \bar{u}\ \ \bar{v}\ \ \bar{w}\ ]^T \qquad \text{(eq. AII.42)}$$

and

$$dV = [\ du\ \ dv\ \ dw\ ]^T \qquad \text{(eq. AII.43)}$$

and for the pollutant concentration C_i we have:

$$C_i = \bar{C}_i + dC_i \qquad \text{(eq. AII.44)}$$

As it was seen in Chapter 4 the magnitude l of the turbulent eddies in the turbulent boundary layer decreases downwards. In the lowest sublayer, where molecular diffusion appears we have l → 0, so that the influence of molecular diffusion in the dispersion of pollutants can practically be neglected, compared to the influence of eddy (i.e. turbulent) diffusion.

Thus (eq. AII.38) becomes, after substituting from (eq. AII.41) and omitting factor $D_i\, i^T\, C_{i2}$ and taking the mean value:

$$\frac{\partial \bar{C}_i}{\partial t} + tr\left(\frac{\partial \bar{V}\bar{C}_i}{\partial \mathbf{x}}\right) + tr\left(\frac{\partial\, dVdC_i}{\partial \mathbf{x}}\right) = \bar{R}_i\, (\bar{C}_i + dC_1,...,\bar{C}_n + dC_n, T) + S_i\, (\mathbf{x}, t) \qquad \text{(eq. AII.45)}$$

From the mixing length theory it is known that:

$$\overline{dV}\;\overline{dC}_i = -\mathbf{K}\frac{\partial \bar{C}_i}{\partial \mathbf{x}} \qquad \text{(eq. AII.46)}$$

where

$$\overline{dV} = [\; d\bar{u} \;\; d\bar{v} \;\; d\bar{w} \;]^T \qquad \text{(eq. AII.47)}$$

$$\mathbf{K} = \begin{bmatrix} K_{11} & 0 & 0 \\ 0 & K_{22} & 0 \\ 0 & 0 & K_{33} \end{bmatrix} \qquad \text{(eq. AII.48)}$$

$$\frac{\partial \bar{C}_i}{\partial \mathbf{x}} = \left[\; \frac{\partial \bar{C}_i}{\partial x^1} \;\; \frac{\partial \bar{C}_i}{\partial x^2} \;\; \frac{\partial \bar{C}_i}{\partial x^3} \;\right]^T \qquad \text{(eq. AII.49)}$$

$d\bar{u}$, $d\bar{v}$, $d\bar{w}$ are the mean values of the disturbances du, dv, dw along the x^1, x^2, x^3 axes respectively
$d\bar{C}_i$ is the mean value of dC_i
k_{11}, k_{22}, k_{33} are the eddy diffusivity coefficients along the x^1, x^2, x^3 axes respectively.

It is known (op. cit.) that:

$$\bar{R}_i\, \{\bar{C}_i + dC_i, ..., \bar{C}_n + dC_i, T\} \simeq R_i\, \{\bar{C}_i, ...\, \bar{C}_n, T\} \qquad \text{(eq. AII.50)}$$

Thus, finally we get:

$$\frac{\partial \bar{C}_i}{\partial t} + tr\left(\frac{\partial \bar{V}\bar{C}_i}{\partial \mathbf{x}}\right) = tr\left(\frac{\partial \left(\mathbf{K}\frac{\partial \bar{C}_i}{\partial \mathbf{x}}\right)}{\partial \mathbf{x}}\right) + R_i\, (\bar{C}_1, ...\, \bar{C}_n, T) + S_i\, (\mathbf{x}, t) \qquad \text{(eq. AII.51)}$$

Equation (AII.51) formulates the general expression of the so-called Gradient transport (K) model.

APPENDIX III. THE CONTENTS OF THE MAP-USER TEST

INTRODUCTORY PART.

1_i. **AVALANCHES IN A VALLEY** (static map).

Figure AIII_1i. Avalanches in a valley (static map).

1i. When did avalanches occur in the east of the lake ?

A. Between 1981 and 1985.
B. Between 1982 and 1984.
C. Between 1984 and 1986.

2_i. **WIND DURING THE CHERNOBYL ACCIDENT** (animated map)

Figure AIII_2i. Wind during Chernobyl accident (animated map).

2i. What is the wind direction above Scandinavia ?

A. First S, then E, then NW.
B. First SE, then SW, then W.
C. First SW, then NW, then N.

MAIN TEST.

1a. WIND ABOVE THE NETHERLANDS. (animated map)

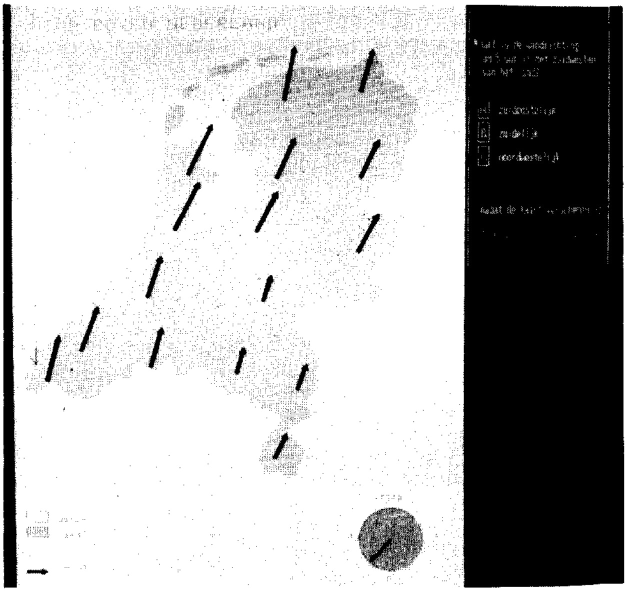


Figure AIII_1a. Wind above the Netherlands (animated map).

1a_I. What is the wind direction at 5 o'clock in the Southwest part of the country?
- A. Southeast.
- B. South.
- C. Northwest.

1a_II. Where did the minimum values occur at 4 o'clock?
- A. In the Western part.
- B. In the Northeastern part.
- C. In the Southeastern part.

1a_III. How much does the wind direction change in the middle of the Netherlands during the whole time?
- A. More than 10 degrees.
- B. Less than 10 degrees.
- C. There is no change.

1a_IV. What is the general change in wind direction?
- A. NW/ W/ NW.
- B. SE/ S/ SW.
- C. E / S/ NW.

1b. WIND ABOVE THE NETHERLANDS. (static map)

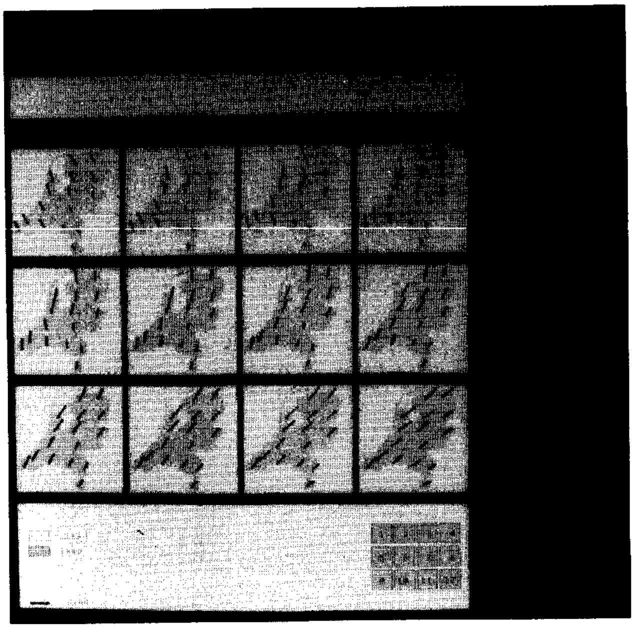


Figure AIII_1b. Wind above the Netherlands (static map).

1b_I. What is the wind direction at 5 o'clock in the Southwest part of the country?
  A. Southeast.
  B. South.
  C. Northwest.

1b_II. Where did the minimum values occur at 7 o'clock?
  A. In the Western part.
  B. In the Northeastern part.
  C. In the Southeastern part.

1b_III. How much does the wind direction change in the middle of the Netherlands during the whole time?
  A. More than 10 degrees.
  B. Less than 10 degrees.
  C. There is no change.

1b_IV. What is the general change in wind direction?
  A. NW/ W/ NW.
  B. SE/ S/ SW.
  C. E / S/ NW.

2a. WIND ABOVE A BASIN. (animated map)

Figure AIII_2a. Wind above a basin (animated map).

2a_I. What is the wind direction at 10 o'clock above the water?
- A. East.
- B. Southeast.
- C. North.

2a_II. Where did the minimum values occur at 11 o'clock?
- A. In the Northern part.
- B. In the Western part.
- C. In the Southeastern part.

2a_III. How much does the wind direction change in the middle of map during the whole time?
- A. More than 40 degrees.
- B. Less than 40 degrees.
- C. There is no change.

2a_IV. What is the general change in wind direction?
- A. SW/ NE/ SW.
- B. N / W/ S.
- C. NE/ S/ E.

2b. **WIND ABOVE A BASIN.** (static map)

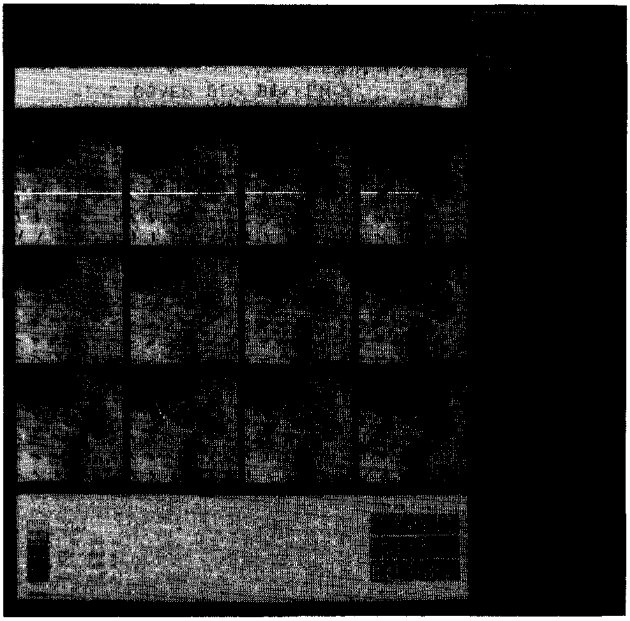


Figure AIII_2b. Wind above a basin (static map).

2b_I. What is the wind direction at 4 o'clock above the water?
- A. East.
- B. Southeast.
- C. North.

2b_II. Where did the minimum values occur at 2 o'clock?
- A. In the Northern part.
- B. In the Western part.
- C. In the Southeastern part.

2b_III. How much does the wind direction change in the middle of map during the whole time?
- A. More than 30 degrees.
- B. Less than 30 degrees.
- C. There is no change.

2b_IV. What is the general change in wind direction?
- A. SW/ NE/ SW.
- B. N / W/ S.
- C. NE/ S/ E.

3a. TRAJECTORIES OF RADIOACTIVE CLOUD: CHERNOBYL. (animated map)

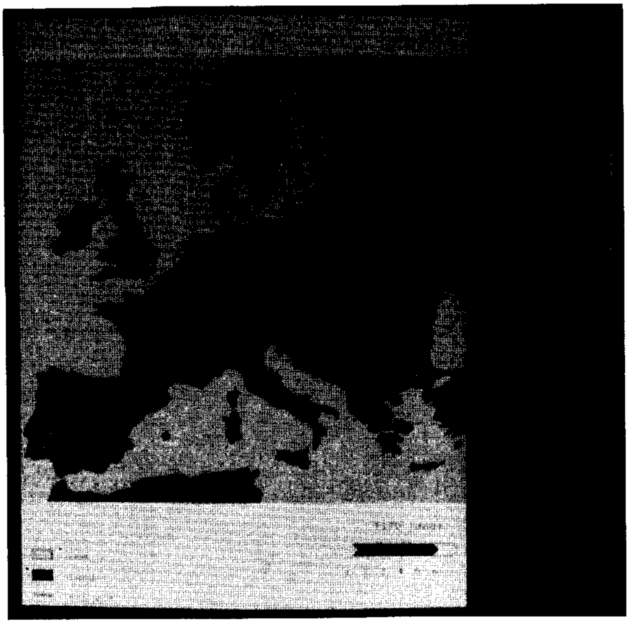


Figure AIII_3a. Trajectories of radioacive cloud from Chernobyl (animated map).

3a_I. What is the position of the radioactive cloud with respect to North Italy at day 3?
- A. Has already passed.
- B. Passes above.
- C. Has not yet reached.

3a_II. Where was the radioactive cloud at day 3?
- A. Above Northern Italy.
- B. Above Scandinavia.
- C. Above Belgium.

3a_III. During which day was the radioactive cloud above Belgium?
- A. During the fourth day.
- B. During the sixth day.
- C. During the third day.

3a_IV. What was the general direction of the trajectories?
- A. First NW, then S, then N.
- B. First NW, then SW, then N.
- C. First N, then SE, then W.

3b. TRAJECTORIES OF RADIOACTIVE CLOUD: CHERNOBYL. (static map)

Figure AIII_3b. Trajectories of radioacive cloud from Chernobyl (static map).

3b_I. What is the position of the radioactive cloud with respect to Austria at day 3?
A. Has already passed.
B. Passes above.
C. Has not yet reached.

3b_II. Where was the radioactive cloud at day 5?
A. Above Northern Italy.
B. Above Poland.
C. Above Belgium.

3b_III. During which day was the radioactive cloud above The Netherlands?
A. During the fifth day.
B. During the sixth day.
C. During the third day.

3b_IV. What was the general direction of the trajectories?
A. First NW, then S, then N.
B. First NW, then SW, then N.
C. First N, then SE, then W.

4a. TRAJECTORIES OF TROPICAL CYCLONES. (animated map)

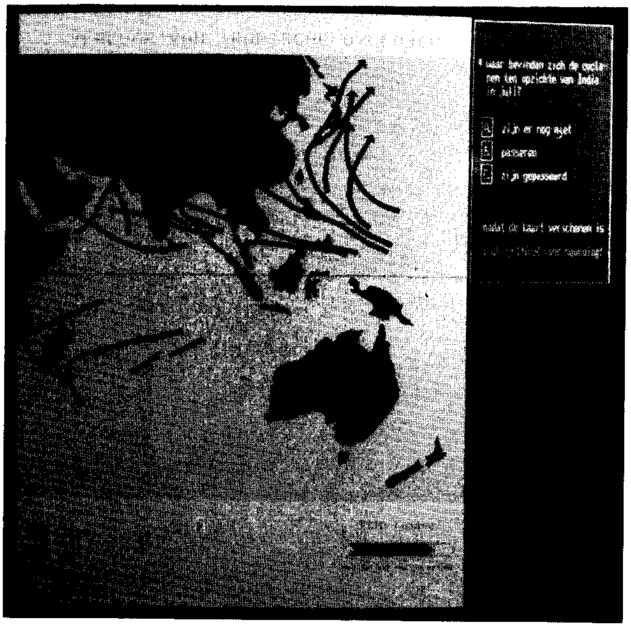


Figure AIII_4a. Trajectories of tropical cyclones (animated map).

4a_I. What is the position of the cyclones with respect to India in July?
- A. They have not reached yet.
- B. They pass above.
- C. They have already passed.

4a_II. Where are the cyclones during the period September-November?
- A. Above Saudi-Arabia.
- B. Above the Philippines.
- C. Above India.

4a_III. During which period do the cyclones appear over the area in the Southwest part of the map?
- A. From July to January.
- B. From May to September.
- C. From January to March.

4a_IV. What is the general direction of the cyclones' trajectories during the whole time?
- A. NW --> SE --> NE --> N.
- B. NE --> NW --> SW --> SE.
- C. SE --> SW --> NE --> NW.

4b. TRAJECTORIES OF TROPICAL CYCLONES. (static map)

Figure AIII_4b. Trajectories of tropical cyclones (static map).

4b_I. What is the position of the cyclones with respect to India in August?
A. They have not reached yet.
B. They pass above.
C. They have already passed.

4b_II. Where are the cyclones during July?
A. Above Saudi-Arabia.
B. Above New Zealand.
C. Above the Philippines.

4b_III. During which period do the cyclones appear over the area in the Southwest part of the map?
A. From July to January.
B. From May to September.
C. From January to March.

4b_IV. What is the general direction of the cyclones' trajectories during the whole time?
A. NW --> SE --> NE --> N.
B. NE --> NW --> SW --> SE.
C. SE --> SW --> NE --> NW.

5a. ISOLINE ABOVE A CITY. (animated map)

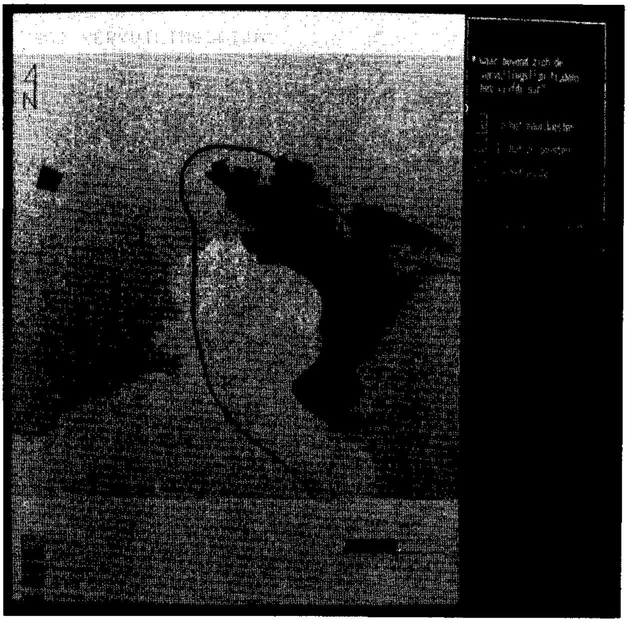


Figure AIII_5a. Isoline above a city (animated map).

5a_I. What is the position of the isoline with respect to the green area at 2 o'clock?

A. Far away.
B. Nearby.
C. Passes above.

5a_II. Where was the isoline during the fifth hour?

A. In the Northwest.
B. In the Southeast.
C. In the South.

5a_III. What is the status of the isoline with respect to the village in the Northwest?

A. It passes above it at 1 o'clock.
B. It passes above it at 5 o'clock.
C. It never passes above it.

5a_IV. What is the general directions along which the isoline moves?

A. East and Northwest.
B. North and South.
C. Northwest and Southeast.

5b. ISOLINE ABOVE A CITY. (static map)

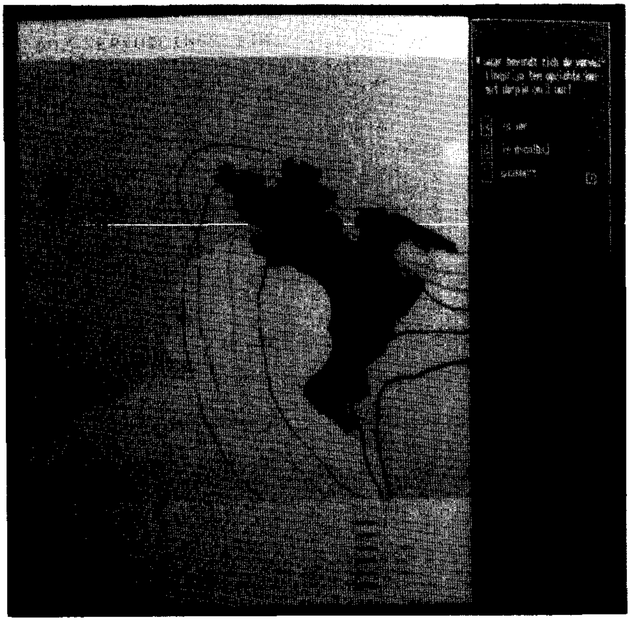


Figure AIII_5b. Isoline above a city (static map).

5b_I. What is the position of the isoline with respect to the village at 2 o'clock?
A. Far away.
B. Nearby.
C. Passes above.

5b_II. Where was the isoline during the fifth hour?
A. In the Northwest.
B. In the Southeast.
C. In the South.

5b_III. What is the status of the isoline with respect to the village in the Northwest?
A. It passes above it at 1 o'clock.
B. It passes above it at 5 o'clock.
C. It never passes above it.

5b_IV. What is the general directions along which the isoline moves?
A. East and Northwest.
B. North and South.
C. Northwest and Southeast.

6a. ISOLINE ABOVE THE NETHERLANDS. (animated map)

Figure AIII_6a. Isoline above The Netherlands (animated map).

6a_I. What is the position of the isoline with respect to the area of Limburg at 3 o'clock?
- A. Far away.
- B. Nearby.
- C. Passes above.

6a_II. From which part of The Netherlands passes the isoline during the first hour?
- A. The Southeast.
- B. The North.
- C. The Southwest.

6a_III. What is the status of the isoline with respect to the Southwest of The Netherlands?
- A. It passes above it at 2 o'clock.
- B. It passes above it at 5 o'clock.
- C. It never passes above it.

6a_IV. What is the general directions along which the isoline moves?
- A. West and North.
- B. West and South.
- C. South and East.

6b. ISOLINE ABOVE THE NETHERLANDS. (static map)

Figure AIII_6b. Isoline above The Netherlands (static map).

6b_I. What is the position of the isoline with respect to the islands at 3 o'clock?
A. Far away.
B. Nearby.
C. Passes above.

6b_II. From which part of The Netherlands passes the isoline during the first hour?
A. The Southeast.
B. The North.
C. The Southwest.

6b_III. What is the status of the isoline with respect to the Southwest of The Netherlands?
A. It passes above it at 2 o'clock.
B. It passes above it at 5 o'clock.
C. It never passes above it.

6b_IV. What is the general directions along which the isoline moves?
A. West and North.
B. West and South.
C. South and East.

7a. AIR POLLUTION IN ATHENS. (animated map)

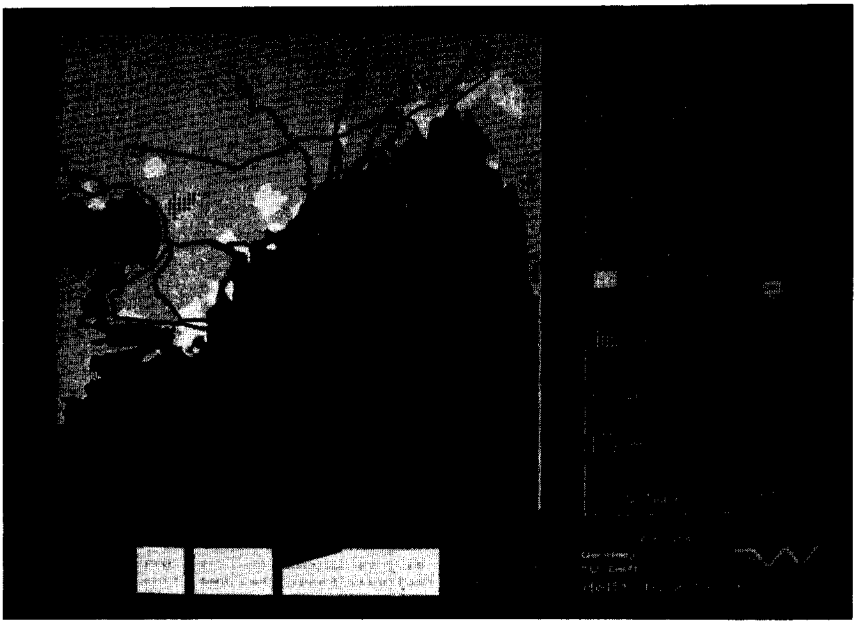


Figure AIII_7a.CO pollution above Athens (animated map).

7a_I. What is the situation at 3 o'clock at night above the city centre?
- A. high concentrations.
- B. low concentrations.
- C. no pollution.

7a_II. Where do the highest concentrations occur at 15 hours in the afternoon?
- A. In the North.
- B. In the Southwest.
- C. In the city center.

7a_III. What is the situation above the east part of the map in general?
- A. Always a lot of pollution.
- B. A lot of pollution during the night.
- C. No pollution.

7a_IV. What is the pollution trend?
- A. Decrease during the night.
- B. Increase during the night.
- C. Increase during the afternoon.

7b. AIR POLLUTION IN ATHENS. (static map)

Figure AIII_7b. CO pollution above Athens (static map).

7b_I. What is the situation at 3 o'clock at night above the city centre?
- A. high concentrations.
- B. low concentrations.
- C. no pollution.

7b_II. Where do the highest concentrations occur at 15 hours in the afternoon?
- A. In the North.
- B. In the Southwest.
- C. In the city center.

7b_III. What is the situation above the east part of the map in general?
- A. Always a lot of pollution.
- B. A lot of pollution during the night.
- C. No pollution.

7b_IV. What is the pollution trend?
- A. Decrease during the night.
- B. Increase during the night.
- C. Increase during the afternoon.

8a. AIR POLLUTION IN ATHENS. (animated map)

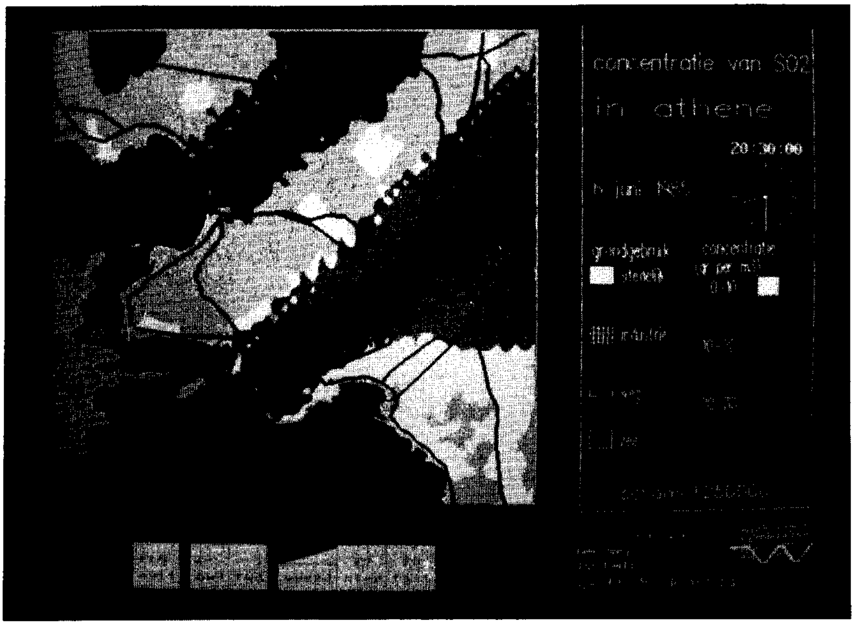


Figure AIII_8a. SO_2 pollution above Athens (animated map).

8a_I. What is the situation at 13 hours above industrial areas?
A. high concentrations.
B. low concentrations.
C. no pollution.

8a_II. Where do the highest concentrations occur at 21 hours?
A. Above industrial areas.
B. Along the coast.
C. In the Southeast.

8a_III. What is the situation above the north part of the map in general?
A. No pollution.
B. A lot of pollution during the night.
C. A lot of pollution during the afternoon.

8a_IV. What is the pollution trend?
A. Decrease during the night.
B. Increase during the night.
C. Increase during the afternoon.

8b. AIR POLLUTION IN ATHENS. (static map)

Figure AIII_8b. SO_2 pollution above Athens (static map).

8b_I. What is the situation at 13 hours above industrial areas?
A. high concentrations.
B. low concentrations.
C. no pollution.

8b_II. Where do the highest concentrations occur at 21 hours?
A. Above industrial areas.
B. Along the coast.
C. In the Southeast.

8b_III. What is the situation above the north part of the map in general?
A. No pollution.
B. A lot of pollution during the night.
C. A lot of pollution during the afternoon.

8b_IV. What is the pollution trend?
A. Decrease during the night.
B. Increase during the night.
C. Increase during the afternoon.

APPENDIX IV. SCATTER DIAGRAMS AND STATISTICAL TABLES.

In this Appendix the scatter diagrams of user response times are shown for a number of questions of the map user test. In the questions 11, 16, 23, 46, 48 and 64 the response times indicated by asterisks were regarded as non-representative and, therefore, they were not included in the statistical processing of the results. At the end of the Appendix the statistical tables used for the evaluation of the test results are given.

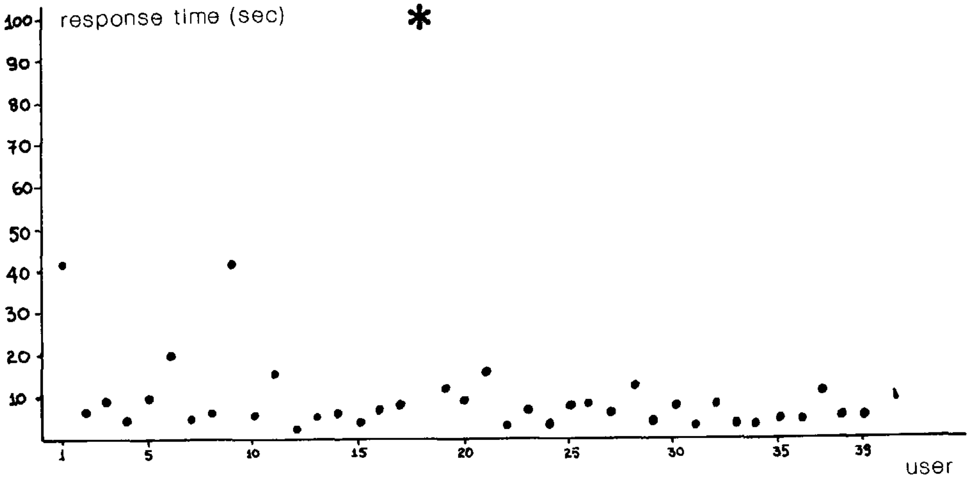


Figure AIV-1. Response times to question 11

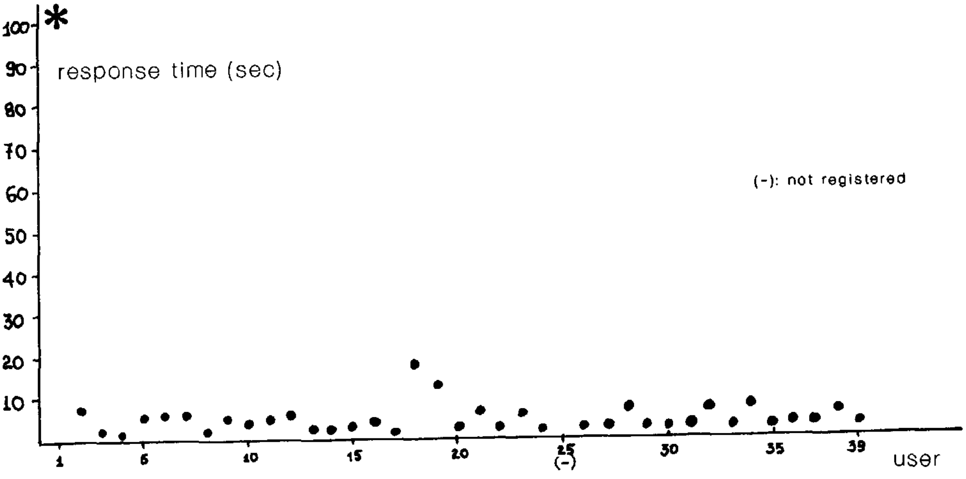


Figure AIV-2. Response times to question 16

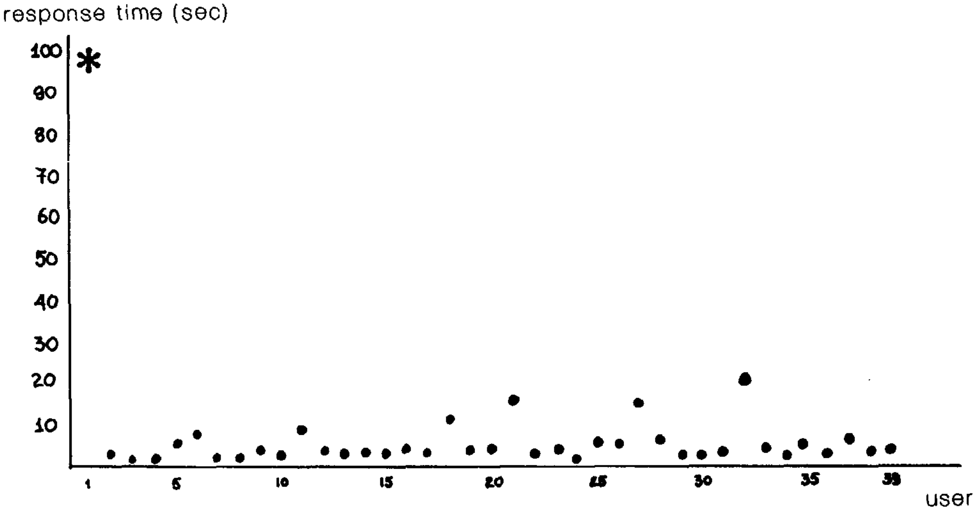


Figure AIV-3. Response times to question 23

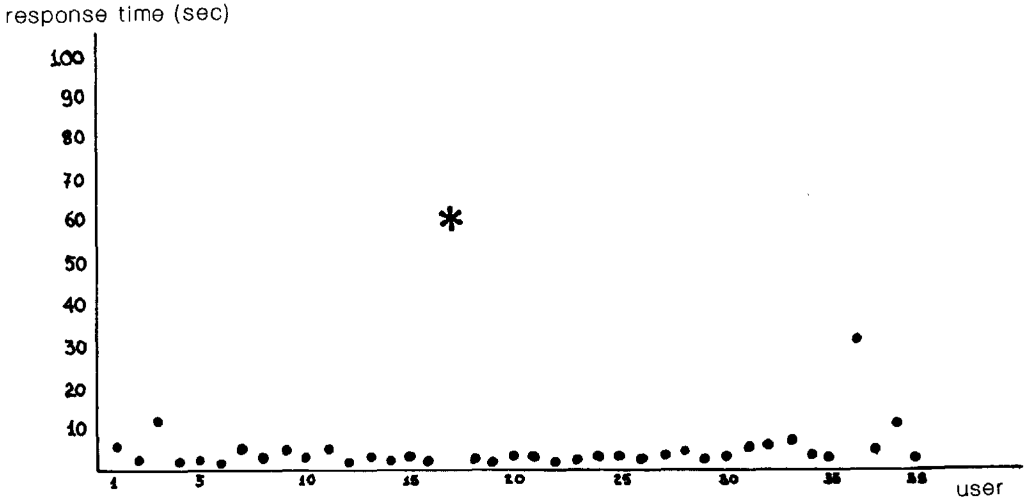


Figure AIV-4. Response times to question 46

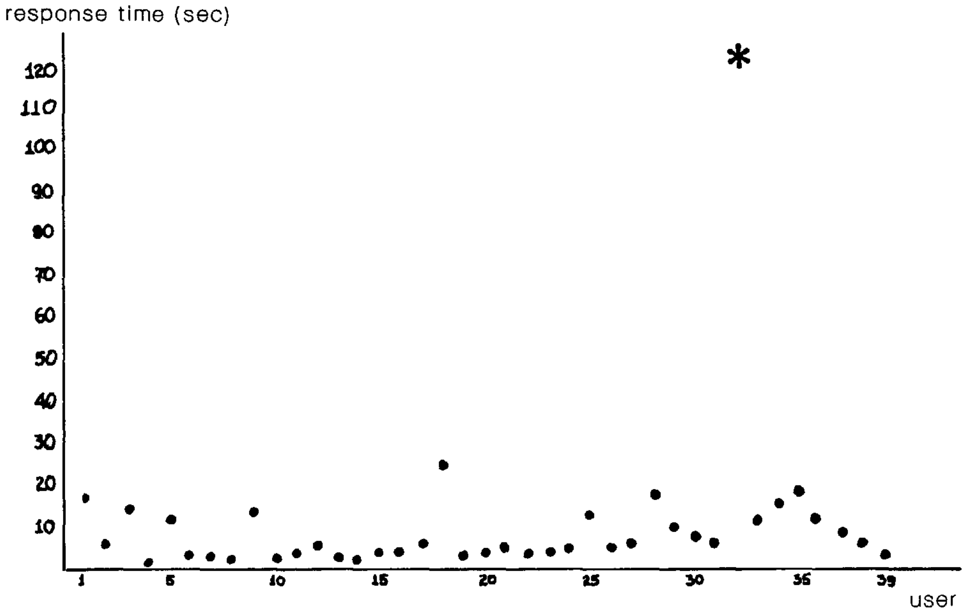


Figure AIV-5. Response times to question 48

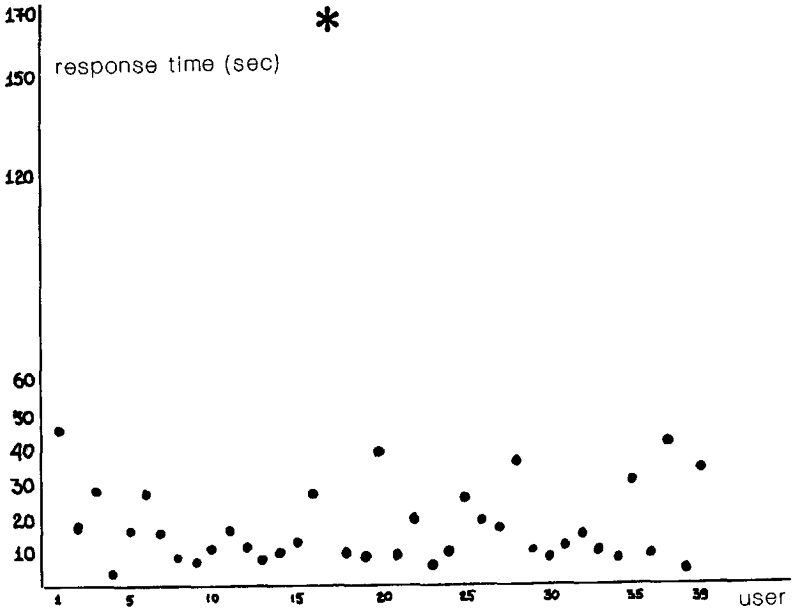


Figure AIV-6. Response times to question 64

TABLE E : VALUES OF t FOR SELECTED DEGREES OF FREEDOM (df) AND PROBABILITY P

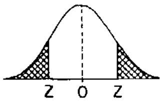
P df	.20	.10	.05	.02	.01	.002	.001	.0002	.0001	.00002	.00001	.000002	.000001	.0000002
1	3.078	6.314	12.706	31.821	63.657	318.309	636.619	3,183.099	6,366.198	31,830.989	63,661.977	318,309.886	636,619.772	3,183,098.862
2	1.886	2.920	4.303	6.965	9.925	22.327	31.598	70.700	99.992	223.603	316.225	707.106	999.999	2,236.068
3	1.638	2.353	3.182	4.541	5.841	10.214	12.924	22.204	28.000	47.928	60.397	103.299	130.155	222.572
4	1.533	2.132	2.776	3.747	4.604	7.173	8.610	13.034	15.544	23.332	27.771	41.578	49.459	73.986
5	1.476	2.015	2.571	3.365	4.032	5.893	6.869	9.678	11.178	15.547	17.897	24.771	28.477	39.340
6	1.440	1.943	2.447	3.143	3.707	5.208	5.959	8.025	9.082	12.032	13.555	17.830	20.047	26.286
7	1.415	1.895	2.365	2.998	3.499	4.785	5.408	7.063	7.885	10.103	11.215	14.241	15.764	19.932
8	1.397	1.860	2.306	2.896	3.355	4.501	5.041	6.442	7.120	8.907	9.782	12.110	13.257	16.320
9	1.383	1.833	2.262	2.821	3.250	4.297	4.781	6.010	6.594	8.102	8.827	10.720	11.637	14.041
10	1.372	1.812	2.228	2.764	3.169	4.144	4.587	5.694	6.211	7.527	8.150	9.752	10.516	12.492
11	1.363	1.796	2.201	2.718	3.106	4.025	4.437	5.453	5.921	7.098	7.648	9.043	9.702	11.381
12	1.356	1.782	2.179	2.681	3.055	3.930	4.318	5.263	5.694	6.756	7.261	8.504	9.085	10.551
13	1.350	1.771	2.160	2.650	3.012	3.852	4.221	5.111	5.513	6.501	6.955	8.082	8.604	9.909
14	1.345	1.761	2.145	2.624	2.977	3.787	4.140	4.985	5.363	6.287	6.706	7.743	8.218	9.400
15	1.341	1.753	2.131	2.602	2.947	3.733	4.073	4.880	5.239	6.109	6.502	7.465	7.903	8.986
16	1.337	1.746	2.120	2.583	2.921	3.686	4.015	4.791	5.134	5.960	6.330	7.233	7.642	8.645
17	1.333	1.740	2.110	2.567	2.898	3.646	3.965	4.714	5.044	5.832	6.184	7.037	7.421	8.358
18	1.330	1.734	2.101	2.552	2.878	3.610	3.922	4.648	4.966	5.722	6.059	6.869	7.232	8.115
19	1.328	1.729	2.093	2.539	2.861	3.579	3.883	4.590	4.897	5.627	5.949	6.723	7.069	7.905
20	1.325	1.725	2.086	2.528	2.845	3.552	3.850	4.539	4.837	5.543	5.854	6.597	6.927	7.723
21	1.323	1.721	2.080	2.518	2.831	3.527	3.819	4.493	4.784	5.469	5.769	6.485	6.802	7.564
22	1.321	1.717	2.074	2.508	2.819	3.505	3.792	4.452	4.736	5.402	5.694	6.386	6.692	7.423
23	1.319	1.714	2.069	2.500	2.807	3.485	3.768	4.415	4.693	5.343	5.627	6.297	6.593	7.298
24	1.318	1.711	2.064	2.492	2.797	3.467	3.745	4.382	4.654	5.290	5.566	6.218	6.504	7.185
25	1.316	1.708	2.060	2.485	2.787	3.450	3.725	4.352	4.619	5.241	5.511	6.146	6.424	7.085
26	1.315	1.706	2.056	2.479	2.779	3.435	3.707	4.324	4.587	5.197	5.461	6.081	6.352	6.993
27	1.314	1.703	2.052	2.473	2.771	3.421	3.690	4.299	4.558	5.157	5.415	6.021	6.286	6.910
28	1.313	1.701	2.048	2.467	2.763	3.408	3.674	4.275	4.530	5.120	5.373	5.967	6.225	6.835
29	1.311	1.699	2.045	2.462	2.756	3.396	3.659	4.254	4.506	5.086	5.335	5.917	6.170	6.765
30	1.310	1.697	2.042	2.457	2.750	3.385	3.646	4.234	4.482	5.054	5.299	5.871	6.119	6.701
35	1.306	1.690	2.030	2.438	2.724	3.340	3.591	4.153	4.389	4.927	5.156	5.687	5.915	6.447
40	1.303	1.684	2.021	2.423	2.704	3.307	3.551	4.094	4.321	4.835	5.053	5.554	5.768	6.266
45	1.301	1.679	2.014	2.412	2.690	3.281	3.520	4.049	4.269	4.766	4.975	5.454	5.659	6.130
50	1.299	1.676	2.009	2.403	2.678	3.261	3.496	4.014	4.228	4.711	4.914	5.377	5.573	6.025
55	1.297	1.673	2.004	2.396	2.668	3.245	3.476	3.986	4.196	4.667	4.865	5.315	5.505	5.942
60	1.296	1.671	2.000	2.390	2.660	3.232	3.460	3.962	4.169	4.631	4.825	5.264	5.449	5.873
70	1.294	1.667	1.994	2.381	2.648	3.211	3.435	3.926	4.127	4.576	4.763	5.185	5.363	5.768
80	1.292	1.664	1.990	2.374	2.639	3.195	3.416	3.899	4.096	4.535	4.717	5.128	5.300	5.691
90	1.291	1.662	1.987	2.368	2.632	3.183	3.402	3.878	4.072	4.503	4.682	5.084	5.252	5.633
100	1.290	1.660	1.984	2.364	2.626	3.174	3.390	3.862	4.053	4.478	4.654	5.049	5.214	5.587
200	1.286	1.652	1.972	2.345	2.601	3.131	3.340	3.789	3.970	4.369	4.533	4.897	5.048	5.387
500	1.283	1.648	1.965	2.334	2.586	3.107	3.310	3.747	3.922	4.306	4.463	4.810	4.953	5.273
1,000	1.282	1.646	1.962	2.330	2.581	3.098	3.300	3.733	3.906	4.285	4.440	4.781	4.922	5.236
2,000	1.282	1.645	1.961	2.328	2.578	3.094	3.295	3.726	3.898	4.275	4.428	4.767	4.907	5.218
10,000	1.282	1.645	1.960	2.327	2.576	3.091	3.292	3.720	3.892	4.267	4.419	4.756	4.895	5.203
∞	1.282	1.645	1.960	2.326	2.576	3.090	3.291	3.719	3.891	4.265	4.417	4.753	4.892	5.199

Values of P are for a two-tailed test. For a one-tailed test they should be halved.

Figure AIV-8. The t-table (from Williams, 1984)

TABLE B : AREAS UNDER THE NORMAL CURVE IN THE TWO TAILS

Entries in the body of the table refer to the shaded areas in the diagram. These areas are listed as proportions of the total area under the normal curve.



Second decimal place of Z

Z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	1.0000	.9920	.9840	.9761	.9681	.9601	.9522	.9442	.9362	.9283
0.1	.9203	.9124	.9045	.8966	.8887	.8808	.8729	.8650	.8572	.8493
0.2	.8415	.8337	.8259	.8181	.8103	.8026	.7949	.7872	.7795	.7718
0.3	.7642	.7566	.7490	.7414	.7339	.7263	.7188	.7114	.7039	.6965
0.4	.6892	.6818	.6745	.6672	.6599	.6527	.6455	.6384	.6312	.6241
0.5	.6171	.6101	.6031	.5961	.5892	.5823	.5755	.5687	.5619	.5552
0.6	.5485	.5419	.5353	.5287	.5222	.5157	.5093	.5029	.4965	.4902
0.7	.4839	.4777	.4715	.4654	.4593	.4533	.4473	.4413	.4354	.4295
0.8	.4237	.4179	.4122	.4065	.4009	.3953	.3898	.3843	.3789	.3735
0.9	.3681	.3628	.3576	.3524	.3472	.3421	.3371	.3320	.3271	.3222
1.0	.3173	.3125	.3077	.3030	.2983	.2937	.2891	.2846	.2801	.2757
1.1	.2713	.2670	.2627	.2585	.2543	.2501	.2460	.2420	.2380	.2340
1.2	.2301	.2263	.2225	.2187	.2150	.2113	.2077	.2041	.2005	.1971
1.3	.1936	.1902	.1868	.1835	.1802	.1770	.1738	.1707	.1676	.1645
1.4	.1615	.1585	.1556	.1527	.1499	.1471	.1443	.1416	.1389	.1362
1.5	.1336	.1310	.1285	.1260	.1236	.1211	.1188	.1164	.1141	.1118
1.6	.1096	.1074	.1052	.1031	.1010	.0989	.0969	.0949	.0930	.0910
1.7	.0891	.0873	.0854	.0836	.0819	.0801	.0784	.0767	.0751	.0735
1.8	.0719	.0703	.0688	.0672	.0658	.0643	.0629	.0615	.0601	.0588
1.9	.0574	.0561	.0549	.0536	.0524	.0512	.0500	.0488	.0477	.0466
2.0	.0455	.0444	.0434	.0424	.0414	.0404	.0394	.0385	.0375	.0366
2.1	.0357	.0349	.0340	.0332	.0324	.0316	.0308	.0300	.0293	.0285
2.2	.0278	.0271	.0264	.0257	.0251	.0244	.0238	.0232	.0226	.0220
2.3	.0214	.0209	.0203	.0198	.0193	.0188	.0183	.0178	.0173	.0168
2.4	.0164	.0160	.0155	.0151	.0147	.0143	.0139	.0135	.0131	.0128
2.5	.0124	.0121	.0117	.0114	.0111	.0108	.0105	.0102	.00988	.00960
2.6	.00932	.00905	.00879	.00854	.00829	.00805	.00781	.00759	.00736	.00715
2.7	.00693	.00673	.00653	.00633	.00614	.00596	.00578	.00561	.00544	.00527
2.8	.00511	.00495	.00480	.00465	.00451	.00437	.00424	.00410	.00398	.00385
2.9	.00373	.00361	.00350	.00339	.00328	.00318	.00308	.00298	.00288	.00279

First decimal place of Z

Z	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
3	.00270	.00194	.00137	$.0^{3}967$	$.0^{3}674$	$.0^{3}465$	$.0^{3}318$	$.0^{3}216$	$.0^{3}145$	$.0^{4}962$
4	$.0^{4}633$	$.0^{4}413$	$.0^{4}267$	$.0^{4}171$	$.0^{4}108$	$.0^{5}680$	$.0^{5}422$	$.0^{5}260$	$.0^{5}159$	$.0^{6}958$
5	$.0^{6}573$	$.0^{6}340$	$.0^{6}199$	$.0^{6}116$	$.0^{7}666$	$.0^{7}380$	$.0^{7}214$	$.0^{7}120$	$.0^{8}663$	$.0^{8}364$
6	$.0^{8}197$	$.0^{8}106$	$.0^{9}565$	$.0^{9}298$	$.0^{9}155$	$.0^{10}803$	$.0^{10}411$	$.0^{10}208$	$.0^{10}105$	$.0^{11}520$

Figure AIV-9. The Z-table (from Williams, 1984)

CURRICULUM VITAE

Alexandra Koussoulakou was born in 1959 in the town of Lamia, in Greece. She studied Geodesy and Surveying at the University of Thessaloniki, where she graduated with a diploma thesis on Cartography. She started her PhD at the Faculty of Geodesy of the Technical University of Delft with a fund provided by a Greek fellowship for post-graduate studies abroad. Later she worked as an AIO (Assistent in Opleiding) at the same Faculty. For a period of one year (1988) she worked in a joined Dutch-Greek project for mapping air pollution in Athens, which provided the data used for the case study of the present thesis.

Errata

1. In Fig. 4-43, p. 95: ug/m should be $\mu g/m^3$, mg/m should be mg/m^3

2. Eq. AII.15, p. 204 should be:

$$C\ (\mathbf{x},\ t) = \int_V Q\ (\mathbf{x},\ t;\ x_o,\ t_o) < C(x_o,\ t_o) > dV_o\ +$$

$$\int_{t_o}^{t} \int_V Q\ (\mathbf{x},\ t;\ x_s,\ t_s)\ \ s\ (x_s,\ ts)\ dV_s\ dt_s$$

3. Eq. AII.24, p. 206 should be:

$$\overline{C}\ (x) = \frac{S}{2\pi\ \sigma^2(L)\ \sigma^3(L)\ \bar{u}} \exp \left\{ -\ ½\left[\left(\frac{x^2 - x_s^{\ 2}}{\sigma^2(L)} \right)^2 + \left(\frac{x^3 - x_s^{\ 3}}{\sigma^3(L)} \right)^2\right]\right\}$$