AN ABSTRACT OF THE THESIS OF

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Abstract approved ________________
W. P. Lowry

A mathematical model of the atmosphere in an airshed is developed, which relates pollutant source distributions and intensities to the volume of air available for dispersion and to pollutant concentrations or air quality standards. It can be used as a tool for obtaining an answer to an air resource management question such as, "With a given air quality standard, what is the optimal distribution of sources which will minimize the likelihood that pollutant concentrations will exceed that standard in an airshed with a given climate?"

In contrast to diffusion models which operate on plumes expanding under the influence of turbulent eddies, the airshed-episode model involves the transport and accumulation of pollutants within an entire airshed during types of episodes which are characteristically associated with maximum observed concentrations. An airshed is treated as a set of discrete sub-volumes and a basic assumption is that mechanisms exist which will, during the course of an episode, effect

complete mixing resulting in a uniform distribution of pollutants within each sub-volume. By continuity considerations, it is possible to relate emissions within each volume to final concentrations everywhere in the airshed. The model can be applied "backward" using dynamic programming so as to optimize the allocation of emission rates in the various parts of an airshed in order that specified air quality standards not be violated.

The airshed-episode model has been evaluated in the conventional configuration, in which it yields estimates of concentrations resulting from particular source distributions, using realistic source and meteorological data for the Willamette Valley of western Oregon. The calculated patterns of concentration are qualitatively quite similar to patterns observed in the valley during the annual period of field burning. In the inverse configuration, the model has been used to allocate optimal emission rates which would yield a uniform concentration everywhere in the airshed during episodes, and also to illustrate the optimal allocation of emission rates in an airshed with an "industrial area" superimposed upon an otherwise uniform air quality standard. The latter case illustrates the limitations, in the form of emission standards, which must be imposed on industrial zones in order that excessive emissions there not result in degradation of air quality far beyond their areal limits.

Construction and Evaluation of an Airshed-Episode Model for Air Resource Management

by

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Associate Professor of Biometeorology
in charge of major

Redacted for privacy

Head of Department of General Science

Redacted for privacy

Dean of Graduate School

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TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

APPENDIX FIGURES

Figure		Page

CONSTRUCTION AND EVALUATION OF AN AIRSHED-EPISODE MODEL FOR AIR RESOURCE MANAGEMENT

I. INTRODUCTION

Air pollution is a regional problem; when sources and receptors share a given air mass for some period of time, the pollutants released by the sources become more and more concentrated within the region and often become a serious burden to the receptors. As population density increases, it generally represents an increased density not only of receptors, but also of sources, so that the atmospheric environment tends to be degraded. Awareness of air pollution as a serious problem has led to increasing efforts to control it, and increasingly often control activities are being undertaken on a regional scale. The logic of this is simple; in order to maintain acceptable quality of the air in a given place, it is clearly desirable to control the emissions from all sources which contribute pollutants to the air mass over that place. Often this means that rather widely separated sources and receptors must be considered as occupying the same region, which is sometimes referred to as an airshed.

Efforts are being made to establish air quality standards which can then serve as guides to the amounts of pollutant emissions which would be tolerable in a particular airshed. This of course requires that methods be available for relating pollutant emissions to pollutant concentrations in the various parts of the region. Often, the problem is expressed in the form of a question such as, "With a given distribution of sources, what concentration patterns are likely to occur and where, or how often, will concentrations exceed a given standard?" For application in air resource management, more useful information might be found in an answer to the alternative question, "With a given air quality standard, what is the optimal distribution of sources which will minimize the likelihood that concentrations will exceed that standard in an airshed with a given climate?" The purpose of this thesis is to construct and evaluate a mathematical model of the atmosphere for application in that context of zoning for land use and traffic patterns to meet air quality standards.

Earlier work in the area of atmospheric models for estimating pollutant concentrations and relating distributions of sources to pollutant concentration patterns has been reviewed recently by Wanta (1968) who outlined some of the best known diffusion models which have been proposed. Modern diffusion models are based on the assumption that the diffusing material is distributed normally across the width and through the depth of a plume which expands downstream, with time, under the influence of turbulent eddies. Solution of the equations upon which those models are based generally requires an assumption that meteorological conditions are unchanging and that the underlying terrain is homogeneous. For the purpose for which the equations were originally developed, namely the estimation of concentrations in the vicinity of a source, these assumptions are not unduly restrictive. Diffusion models are often relatively successful when used for the prediction of concentrations within a few kilometers of a source. Essentially, they relate current concentrations to current emissions, and this approach will probably always be the most fruitful way to analyze emissions from particular, well defined sources in order to determine the peak or average concentrations to be expected at a specific location in their vicinity.

Several experimental programs have been undertaken to develop prediction techniques applicable to particular kinds of major sources at some of the Atomic Energy Commission facilities and the missile test ranges (e.g. Fuquay, Simpson and Hinds, 1964; Haugen and Fuquay, 1963; Islitzer and Dumbauld, 1963; Taylor, 1965). In general, they have contributed to the empirical evaluation and refinement of diffusion theory. In addition, a number of prediction equations developed by multiple regression analysis have resulted, which in some cases permit valid predictions beyond the scales of time and distance which usually limit the application of theory. For example, Fuquay et al. found that observations of wind fluctuations and thermal stability in the lower atmosphere permitted estimation of diffusion to distances of about 25 kilometers. The multiple regression technique of prediction of course limits the use of the prediction equation to the experimental site, or to sites which are strictly comparable.

In problems having larger scales of space and time, or when meteorological conditions are known to vary during the travel time of the pollutants from source to point of interest, conventional diffusion models based on probability theory cannot be expected to give reliable estimates. In particular, under stagnant conditions when the atmospheric motion consists largely of local circulations due to terrain or diurnal heating and cooling effects, the statistical distribution assumption becomes dubious and the concepts of classical diffusion theory cannot be applied. (Pasquill, 1962).

The classical conditions under which air pollution is most likely to become serious due to prolonged accumulation often occur when a large mass of air, extending from the surface to heights of several kilometers, becomes stagnant. In that deep layer, the air aloft tends to sink, warming by compression, thereby containing pollutants relatively close to the ground. Until very large scale circulation patterns act to move such a stagnating air mass, it can remain essentially stationary except for locally derived motion for considerable periods of time. The local circulation often is not sufficient to remove pollutants from their source region. Material emitted into such an air mass becomes so thoroughly mixed after a few days that diffusion is no longer an important consideration and the concentration might best be described in terms of mass transfer of material uniformly distributed within some discrete geometrical volume.

Hewson (1955) described the ground level concentration of pollutants which might be expected to occur under those conditions when high concentrations are stirred abruptly into the layer of air immediately above ground level, in terms of the volume of a wedge-shaped section of the atmosphere with its apex at the source. Smith (1961) illustrated the progressive deterioration of air quality, as city size increases or wind speed decreases, by describing a rectangular box over a city and discussing the motion of air through it. Hewson and Olsson (1967) have presented a qualitative description of situations in which an air mass might be trapped either physically or dynamically for several days, or even weeks. They pointed out that urban heat islands and terrain induced circulations, as well as lake or sea breezes, can lead to development of essentially closed cellular circulations. In time, the distribution of pollutants within such cells would become uniform.

At least two models have been reported recently which illustrate another approach to the large-area or airshed problem. Bowne (1968) has presented a model which makes explicit allowance for varying meteorological conditions by solving the problem in steps with provision for altering the meteorological variables at predetermined intervals. In his model, the concentration at any point of interest is determined by following trajectories upstream and accumulating the contributions from upwind sources. The model requires specification of the wind field as the large scale meteorological parameter, empirical values of the standard deviations of pollutant concentrations as an indication of small scale diffusive motion, and the pollutant source configuration. Bowne has used the model with wind and source data covering the state of Connecticut and although verification is incomplete, preliminary results are promising.

Slade (1967) developed a model to demonstrate pollutant concentration patterns that might be expected in the Washington, D. C. - Boston megalopolitan corridor. He assumed a specific distribution and intensity of sources and investigated the patterns which would result from a continuous wind flow along the Washington-Boston axis and from an annual wind direction distribution. In the first case, he calculated concentrations at various downwind distances from each source with the commonly used Gaussian distribution function (Gifford, 1960). Average annual concentration patterns were obtained by integrating the diffusion equation in the vertical then dividing by the mean depth of the mixed layer. The contribution of each source to each point of interest was determined, and the total contribution at those points obtained. He included a decay term to allow for various scavenging mechanisms which might affect concentrations of some pollutants during their travel.

Slade pointed out that the diffusion equations he used are intended for use over distances up to a few kilometers. This and other simplifications, such as ignoring diurnal and terrain effects, probably have some effect on the derived patterns. However, he considered the inadequate knowledge of source locations and intensities to be more serious.

Both Bowne's and Slade's models lend themselves, by iterative solutions, to the examination of the concentration patterns which would result from a variety of source configurations. Both require explicit source information, either real or assumed, as input data. It would, of course, be possible to solve them backward, from a specific pollutant concentration distribution pattern, to determine a source distribution which would yield that concentration pattern. This does not appear to have been done as yet, and would be a very large computational task because of the treatment of expanding plumes which is inherent in diffusion models. Any model which yields estimates of concentrations through the accumulation of contributions from many diffusing plumes would be very difficult to employ in the optimum allocation of sources which would correspond to a particular air quality standard. The reason for this is that each plume source represents a decision variable, and as a rule of thumb, the amount of computation to arrive at optimal solutions increases exponentially with the number of variables (Nemhauser, 1966).

In contrast, the prime purpose of the present model is to optimize source allocations to meet air quality standards in an airshed; and its application in the "conventional" sense, to relate known sources to resulting concentration patterns, is primarily useful for checking the conceptual validity of the model.

II. DIMENSIONS OF THE MODEL

A. Spatial Dimensions

The notion of an airshed as a space analogous to a watershed has become more and more popular as a way of defining the boundaries of the particular air mass of interest to a given community or region. Several ways of specifying these boundaries have been suggested; each appears to have its merits and its drawbacks.

Kneese (1966, 1967) has presented the economist's view that an airshed should be large enough to assure that the effects of pollutants released within the airshed will be borne by receptors in the same airshed. In this way, a realistic cost-benefit analysis should be possible, which in turn would lead to equitable controls. In many cases, this approach would involve very large and sometimes diverse regions in the same airshed. The main difficulty, however, would be the identification of effects specifically enough to permit attributing them to specific sources. In general, there simply are not enough data available to identify all effects.

Currently, the National Air Pollution Control Administration is engaged in designating "Air Quality Control Regions" (Gaulding, 1968) which might be thought of as pseudo airsheds. These will be based primarily on jurisdictional boundaries, urban-industrial concentrations, and other factors necessary to provide adequate implementation of air quality standards. There are, of course, several regional control jurisdictions in existence which are based largely on political boundaries. Examples include the Bay Area Air Pollution Control District comprised of seven counties around San Francisco Bay, the Puget Sound Air Pollution Control Agency made up of the three most populous counties on the east side of Puget Sound, and the Mid-Willamette Valley Air Pollution Authority which includes five western Oregon counties with a total area of some 5600 square miles. Many such districts came into being with no attempt having been made to include all of the sources which contribute to the pollutant load in the main population centers or, conversely, to include all of the area which receives pollutants from sources within the jurisdiction.

Neiberger (1966) recommended that the limits of an airshed should be based on the rate of dilution of pollutants from a given source or group of sources such as a metropolitan area. He suggested that the diameter of a control region should be three times the largest dimension of the fully developed metropolitan area. In the case of a megalopolitan strip oriented along the wind, a single control district might then need to be many hundreds of miles long. The natural variability of the weather is such that under some circumstances much more than three times the diameter of the metropolis would be inadequate to permit dilution to acceptable levels. Another technique for defining an airshed is due to Calvert (1967) in which the boundary for each pollutant is shifted based on knowledge of where the concentration reaches some threshold or air quality standard. This scheme leads to many overlapping areas around a given metropolitan region because of different thresholds assigned to each pollutant and to different emission rates of different pollutants.

In many practical situations, topography and meteorology often dictate to a certain extent the limits of a distinct airshed. When there is large-scale stagnation of the atmosphere, as occurs under essentially stationary high pressure areas, and when vertical motion of the atmosphere is constrained, as is often the case under such quasi-stationary high pressure areas due to subsidence of air from higher levels, then terrain barriers further serve to restrict horizontal motion in the low levels and the air is effectively contained within a distinct basin or trough. The Los Angeles basin, the San Francisco Bay area, the Willamette Valley, and the Puget Sound basin are all examples of the kind of topography which lends itself to this kind of trapping. The climatology of stagnating high pressure areas has been established (Holzworth, 1962; Korshover, 1967) and the coincidence of preferred locations of stagnation and topographically defined basins can be used to develop a first estimate of such naturally defined airsheds.

For the purpose of this thesis, the Willamette Valley is the specified airshed (Figure 1). However, the model under consideration

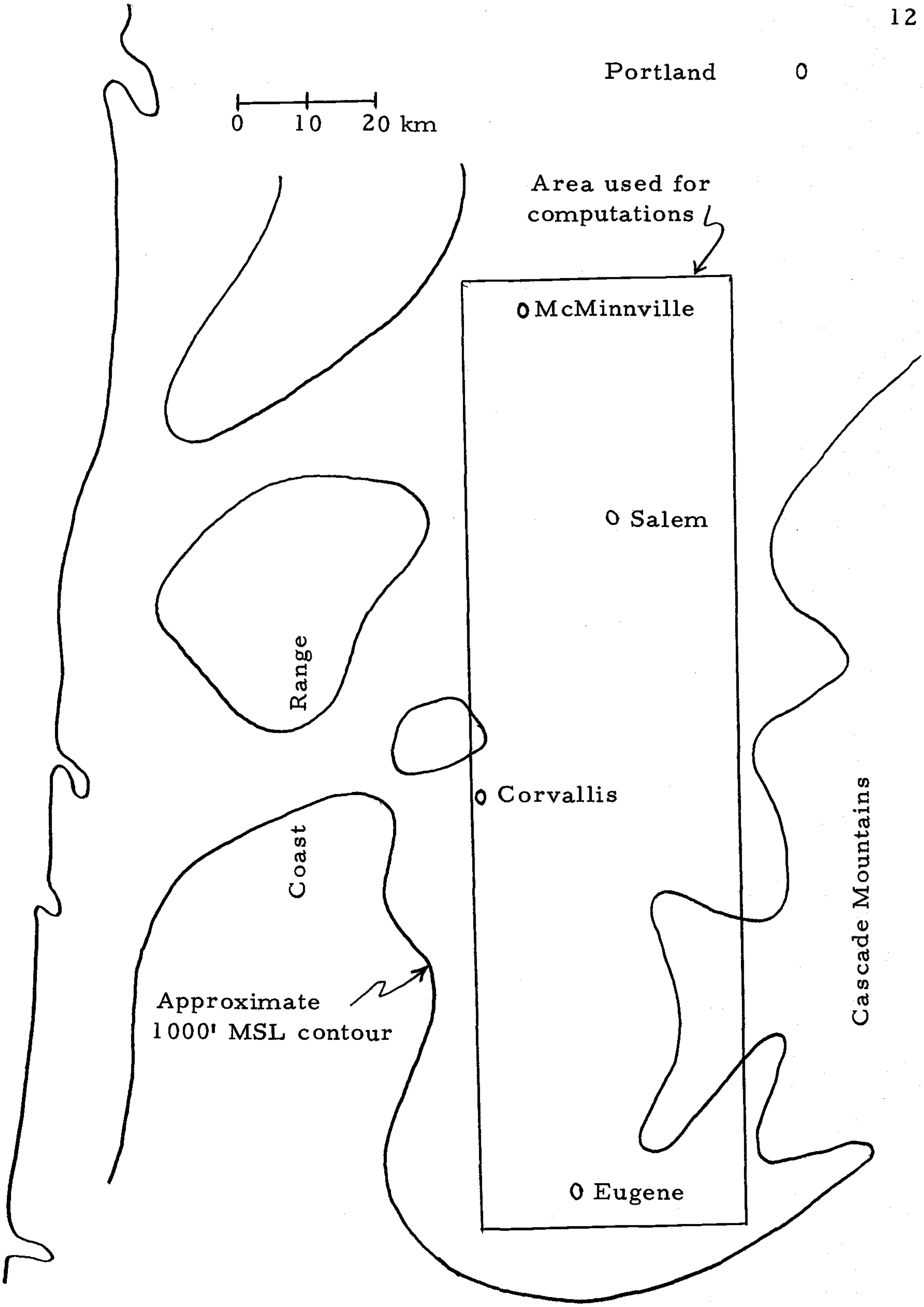


Figure 1. Willamette Valley airshed.

should be applicable elsewhere as well. Possible means of application in other airsheds will be suggested in Chapter IV. C.

The depth of the volume of interest is simply the depth of the layer of air into which the pollutants are emitted and within which they eventually become uniformly distributed. Most emissions occur at or near the surface, but the depth of the layer into which they are stirred varies in both space and time. A concept which has come into wide usage is that of maximum mixing depth which is the height above the surface where the adiabatic lapse rate from the surface maximum temperature intersects the observed vertical temperature profile (Holzworth, 1962). Of course if direct measurements of pollutant distribution with height are available, during the time of day when maximum convective vertical motion is occurring, the maximum mixing depth is available directly.

B. Time Dimension

Aside from local problems, which may be severe or simply nuisances, most significant air pollution occurs on a time scale of several days. Pollutants accumulate in a particular airshed during the course of stagnation periods which are sometimes called episodes. During these periods, there is not enough horizontal motion of the air to provide adequate ventilation of the airshed, nor enough vertical motion to mix the pollutants into a sufficiently deep layer to maintain air quality at acceptable levels. The longer such stagnation persists, the more concentrated the pollutants become throughout the airshed.

During episodes lasting several days, it is unlikely that meteorological conditions ever approximate the steady state, and diffusion theory thus would become exceedingly complicated. On the other hand, local and diurnal circulations within the airshed might reasonably be expected to effect rather complete mixing. To be useful in terms of a mass budget and mass transfer computations for an airshed, the time scale of episodes needs to be defined so that the beginning and end of each stagnation period can be identified.

In some areas, air pollution episodes are specified when the concentration of certain pollutants equals or exceeds some predefined threshold or standard. For example, Maga (1967) has pointed out that certain cities in the Central Valley of California have found the state air quality standards particularly valuable in assessing the frequency of occurrence of photochemical air pollution episodes. He goes on to say, however, that there is a lack of satisfactory data upon which standards can be based.

A regional warning system has been described by Glenn (1966) which employes air quality standards for air pollution alerts in the New York-New Jersey Co-operative district. Lieber (1968) has evaluated and criticized this approach; although it did not accomplish its primary purpose of region-wide action, it did identify clearly the major episode which occurred in the region during November of 1966.

The primary drawback to such a scheme would appear to be, as Maga pointed out, that unless adequate data are available on which to base standards, they are essentially meaningless. This would, of course, be especially true for any region where preventive measures were to be undertaken before the problem reached serious proportions. In such an airshed, the potential for air pollution episodes would be of greatest interest.

Studies supported by the National Center for Air Pollution Control have led to the regular preparation of air pollution potential forecasts for the contiguous United States. Current procedures used in the preparation of these forecasts have been described by Stackpole (1967). Essentially, they are based on work reported by Niemeyer (1960) which described the meteorological conditions for high air pollution potential over large areas. The system has the merit of being a potential which can exist regardless of the presence of sources and can be identified solely on the basis of meteorological conditions, such as those characterized by stagnating high pressure areas, which are conducive to the accumulation of pollutants. This very large scale potential prediction is, however, too gross to be applicable to particular communities ore regions. The procedures specify that the affected area must be no smaller than an area equivalent to a four-degree latitude-longitude square. In addition, there are other criteria which tend to be sufficiently stringent that it is not unusual for even relatively large areas to experience substantial accumulations of pollutants without an air pollution potential advisory having been issued. The reasoning is clear; the Weather Bureau forecasters prefer to be conservative enough that when a potential is predicted the conditions will be met. They would rather miss what they consider to be marginal cases than to forecast a high potential when none occurs, according to Stackpole.

Lowry and Reiquam (1968) have developed a pollution potential index which lends itself to identification of episodes within regions on the scale of airsheds. It consists of an expression of the stability of the low-level atmosphere and can be summed to reflect the persistence of vertical stagnation. Criteria have been suggested by which the summation can be stopped when there is sufficient precipitation to indicate large-scale vertical motion or washout of pollutants, or when there is sufficient horizontal ventilation to accomplish large-scale mechanical mixing or to carry pollutants outside the airshed.

The basic index is obtained very simply from routine radiosonde data:

$$I = 14 + (T_{9,m} - T_{s,m}) + (T_{9,a} - T_{s,a})$$

where T refers to temperature in degrees Celcius, subscript 9 refers to the 900 millibar level and s to the surface level, and subscripts m and a refer to morning and afternoon radiosonde observations. The 14 is included as a threshold, or baseline, to account for the fact that some accumulation occurs with moderate lapse rates. This pollution potential index is used by the Mid-Willamette Valley Air Pollution Authority to identify routinely those periods in which air quality is especially likely to deteriorate. The 900 millibar level is used because it is near the elevation of the major terrain barriers which bound the Willamette Valley. Individual episodes are ended by one or more of three criteria:

Instability (vertical ventilation): $I \leq 0$,

Precipitation: amounts ≥ 0.05 inch per day,

Wind (horizontal ventilation: resultant vector with length greater than the appropriate airshed dimension.

In the present study, this index has been used an an aid in selecting relevant periods for analysis.

III. CONSTRUCTION OF THE MODEL

A. General

As indicated earlier, an airshed is considered here to be a basin or valley in which the atmosphere stagnates during episodes which can be identified by regional pollution potential criteria. Such an airshed can be subdivided into any number of discrete volumes of regular shape which lend themselves to analysis by continuity of mass considerations. The surface area of the individual sub-volumes can be chosen arbitrarily; a reasonable choice will, of course, depend on data availability. The vertical dimension must be the depth of the mixed layer, and this will vary in both time and space.

The model consists of an array of boxes oriented along the longest airshed axis which will generally coincide, approximately, with the episode-resultant wind. Net motion through the boxes is determined from episode-resultant vectors of the wind; the upper limit on the mixed layer, represented by the tops of the boxes, can be an isentropic surface identified by the intersection of the adiabatic lapse rate from the afternoon maximum temperature with the temperature profile, or if data are available, the level above which aerosol concentrations decline abruptly.

In perhaps its simplest form, the model can be visualized as it appears in Figure 2, with the concentration uniform within each box, but varying among boxes.

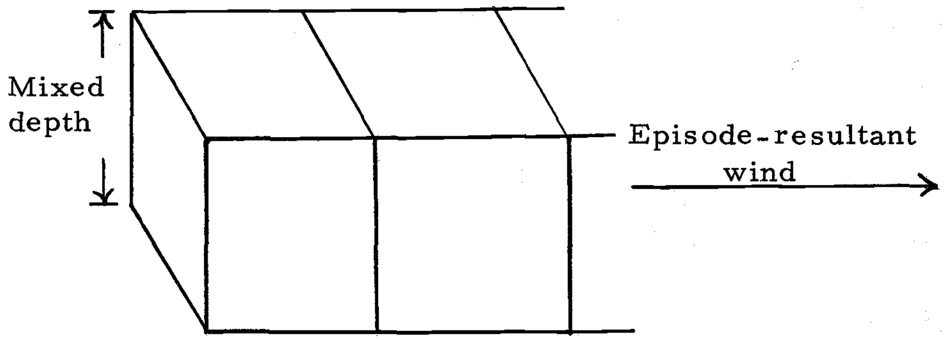


Figure 2. Schematic diagram of the model.

B. Assumptions

The rationale for the details of the present model which is based entirely on the assumption that there is homogeneity within each of the sub-volumes or boxes but heterogeneity among them, is that mechanisms exist which will, in the course of an episode, accomplish complete mixing within each box. Among the mechanisms which will act toward this end are the generally accepted diffusion processes, local diurnal wind regimes which include mountain and valley winds and often a modified sea breeze circulation, diurnal variations in mixing depth due to radiative processes and local differential heating of the surface, as well as mechanical mixing as the air is forced to rise over irregularities of terrain.

The material to be considered might be either gas molecules or aerosols; it is assumed that no significant settling occurs and that secondary reactions are negligible so that no scavenging or other removal mechanisms need be considered. This is not a critical assumption because it would be possible to add a decay term to account for these processes if they were known to be significant and could be specified.

The grid underlying the airshed is assumed to be rectangular; the base of each box is taken to be a square. If sufficiently detailed data were available, it would be an advantage to consider boxes with small surface areas in order to enhance the validity of the assumption about uniform distribution within each box. During the episodes which are considered to be typical, the horizontal wind is light and tends to be constrained by terrain barriers so that the resultant wind, both daily and episode-resultant, essentially parallels the longest airshed axis.

For simplicity, it is desirable to assume no advection of pollutants into the airshed. That is, either the airshed boundaries might be considered impervious to pollutants or it might be assumed that no significant sources occur near enough to the boundaries to contribute to the burden in the airshed. In practical situations, this is no doubt an unrealistic assumption so one of the inputs to the model should be the contribution to the airshed load at the upwind boundary either by assumption or by source inventory.

The pollutants advected into the airshed and carried from box to box within it are assumed to be transported by the episode-resultant wind. If sufficient data were available to construct detailed trajectories, they could be traced to determine the path traveled by emissions from particular sources, but that meandering path is considered to be part of the mechanism for accomplishing the complete mixing within each box so it is reasonable to consider the net travel of the wind as the transport device.

The advected material is further assumed to be distributed uniformly in time through the episodes. An alternative would be to distinguish between day and night motion, for example, or to limit the advection from a given area to those periods when sources are active in that area. However, all sources are presently assumed to emit uniformly in time as well. This assumption could be avoided by considering shorter periods, such as individual days, and then summing over the episodes. That approach might tend to violate the uniform distribution assumption which requires some considerable period of time to accomplish the mixing, but will be discussed further in Chapter IV. C.

The principle of area emissions uniformly distributed over the surface area of each box, as opposed to point sources, is used here for two reasons. No source inventory is available which would permit identification of point sources and the times during which they are active in the Willamette Valley airshed; and also, for zoning purposes, area emissions are appropriate because they can be taken to represent either a single relatively large source or several smaller ones, either stationary or mobile.

C. Conventional Configuration

By conventional configuration is meant the expression of the model in a form which would be useful for relating specific source distributions and intensities to their resulting pollutant concentration patterns. In this sense, it is conventional because that is the commonly used application of atmospheric models in air pollution problems. In its present form, this model is not intended to provide detailed predictions and has been kept simple deliberately. The main value of the conventional configuration of the airshed-episode model is its usefulness for providing a check on the general validity of the concepts employed.

In the conventional configuration, the model provides an approximate functional relationship describing the homogeneous concentration of pollutants in each box:

Concentration = f (episode length; box volume; rate at which material is transported into the box; emission rate within the box; residual of transported and emitted material which remains in the box.)

That functional expression can be written, for box n, in equation form.

$$C_n = \frac{P}{V_n}[r_n q_n + R_n Q_n] \tag{1}$$

where

C_n = concentration in box n at the end of an episode,

P = period of interest = episode length,

V_n = volume of box n at the end of P,

q_n = rate at which pollutants are advected into box n,

Q_n = emission rate in box n,

r_n = residual of q_n remaining in box n at the end of P,

and R_n = residual of Q_n remaining in box n at the end of P.

When the streamlines of the resultant wind parallel the X axis of the grid underlying the airshed, and it is assumed that q_n is a uniform rate of transport across the upwind boundary of box n during P, and that Q_n is a uniform rate of emission during P and is also uniformly distributed over the area of box n, the residuals r_n and R_n can be found as functions of the motion through the box.

Let T_n = net travel through box n. If $T_n \leq X$,

$$r_n = 1 \tag{2a}$$

because none of the material advected into the box would be removed by the end of the period. If $T_n > X$, the residual of the advection term will be the ratio of the volume of the box to the volume into which the advected material becomes mixed during the episode. If, for this purpose, we assume that depth Z varies little in the distance T_n,

$$r_n = \frac{XYZ}{T_n YZ} \cong \frac{X}{T_n} \quad . \tag{2b}$$

The residual of the emissions in box n also will be the ratio of the box volume to total volume, but because emissions occur over the entire surface area,

$$R_n = \frac{XYZ}{(X+T_n)YZ} \cong \frac{X}{X+T_n} \quad . \tag{2c}$$

More generally, streamlines will not exactly parallel the grid and there will be transport of material from one row of boxes to the adjacent row, as in Figure 3a. The residuals for each box with a component of crosswind will then be reduced. The net rate of gain to a particular box may be the same due to the q term from a second box, but both r and R would be reduced.

The case of square boxes is considered here. Let θ_n = angle, averaged over the area of box n, between the streamlines and the X axis. Dropping Z from Equations (2), the residuals can be taken as ratios of areas.

In Figure 3b,

$$r_n = \frac{\text{hatched area}}{YT_n} \quad .$$

When $\theta \leq \frac{\pi}{4}$ radians; if $T_n > X$,

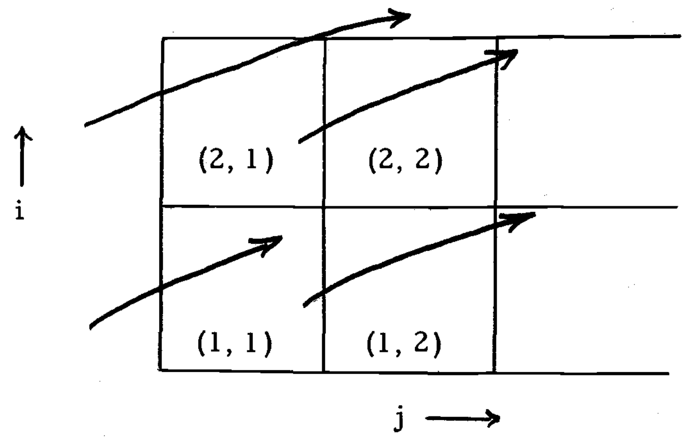


Figure 3a. Transport by cross-wind.

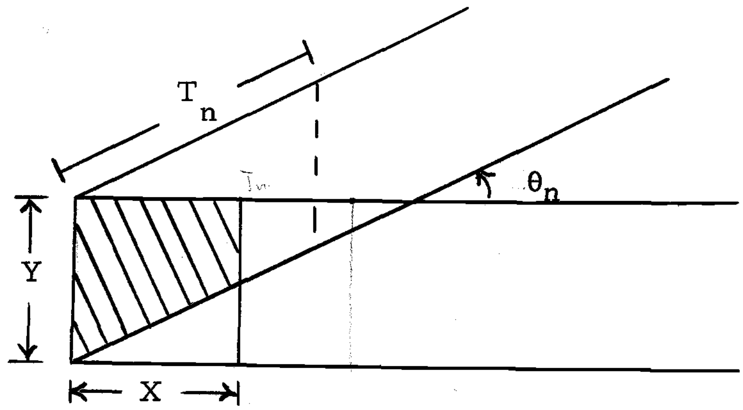


Figure 3b. Geometry of the relationship between resultant wind and transport residual.

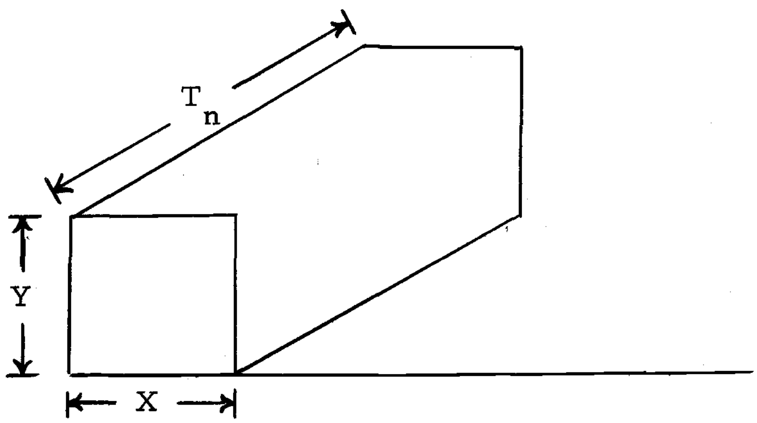


Figure 3c. Geometry of the relationship between resultant wind and emission residual.

$$r_n = \frac{XY - \frac{X^2}{2}\tan\theta_n}{YT_n} \qquad (3a)$$

and if $T_n \leq X$,

$$r_n = 1 - \frac{T_n^2}{2}\cos\theta_n \sin\theta_n . \qquad (3b)$$

When $\theta > \frac{\pi}{4}$,

$$r_n = \frac{Y^2/2 \tan\theta_n}{YT_n} = \frac{Y}{2T_n \tan\theta_n} . \qquad (3c)$$

Similarly, in Figure 3c,

$$R_n = \frac{\text{box area}}{\text{total area}} ;$$

$$R_n = \frac{XY}{(XY)+T_n(X^2+Y^2)^{1/2}} . \qquad (3d)$$

Then, for example, if box notation and streamline orientation are as illustrated in Figure 3a, $q(2, 2)$ = material transported into box (2, 2) will be the sum of contributions from boxes (2, 1) and (1, 2). In general,

$$q(i, j) = \{[1-r(i, j-1)]q(i, j-1)+[1-R(i, j-1)]Q(i, j-1)\}\{\frac{Y}{Y+X\tan\theta(i, j-1)}\}$$

$$+ \{[1-r(i-1, j)]q(i-1, j)+[1-R(i-1, j)]Q(i-1, j)\}\{\frac{X\tan\theta(i-1, j)}{Y+X\tan\theta(i-1, j)}\} \qquad (4)$$

where parentheses are used to indicate subscripts in the Fortran convention, as (i, j), and brackets and braces, [ ], { }, are used to indicate multiplication.

D. Inverse Configuration

The main value of the airshed-episode model is intended to be found in its application to airshed zoning. This application is through the inverse configuration, because the functional relationship given in Chapter III. C. is "inverted" to yield an expression for the emissions related to a particular concentration which might be an air quality standard. That is,

Emission rate = f (episode length; rate at which material is transported into the box; residual of transported and emitted material which remains in the box; box volume; limiting concentration.)

For zoning purposes, the primary goal is to determine the rate of emissions at various locations which, during air pollution episodes, will result in concentrations no greater than a pre-selected limit. In order to be useful, however, any zoning guidelines need to be constructed in such a way that they avoid penalizing one portion of an airshed for excessive emissions elsewhere, while at the same time not unduly penalizing any one part of the airshed for the geophysical features which tend to cause an accumulation of pollutants. That is, the aim might be expressed as an effort to maximize the emissions in each part of an airshed in such a way that the concentration in each part will not exceed some limit. It is an effort to optimize the allocation of sources within an airshed making allowance for transport and accumulation during those periods which characteristically are associated with maximum observed concentrations.

Nemhauser (1966) describes dynamic programming as an efficient approach to solving optimization problems. Basically, dynamic programming is a technique for converting a sequential or multistage decision process containing many interdependent variables into a series of single-stage problems, each containing only a few variables. The transformation is based on the intuitively obvious "optimality principle:" an optimal set of decisions has the property that whatever the first decision is, the remaining decisions must be optimal with respect to the outcome which results from the first decision.

Although allocations are generally made simultaneously, the use of sequential allocation as a mathematical artifact allows the decisions to be made one at a time.

From Hillier and Lieberman (1967), Kaufman (1967), and Nemhauser (1966), certain basic features which characterize dynamic programming problems emerge.

An appropriate mathematical model must exist which permits dividing the problem into stages, with some decision to be made in each stage. The policy decision in each stage determines the state variables in the next stage, and once they are available optimal decisions in remaining stages are independent of the decisions made in previous stages. The solution procedure uses a recursive relationship, moving backward stage by stage from the last stage of the problem, until the optimal policy when starting at the initial stage is found.

Dynamic programming is generally applied to problems with global objective functions in which an over-all measure of effectiveness depends upon the optimal decisions made in each stage. The measures of effectiveness of such global objective functions might be, for example, maximum profit or minimum deviation from a trajectory.

In the present work, however, the choice has been made to find local optima, rather than a global optimum. That is, the objective is chosen to be the maximum emission rate in each sub-volume of an airshed, subject to certain constraints, where the sub-volumes constitute the stages of the problem. In each stage, the input is the transport rate out of that stage, the decision to be made is the emission rate within that stage, and the output is the transport rate into that stage.

With these features in mind, an airshed comprised of an array of boxes might be visualized as shown in Figure 4 where

$$C_n = \frac{P}{V_n} [r_n q_n + R_n Q_n] \qquad (1)$$

and

Q_n = (the total emission rate which would "saturate" the first n boxes)

- (the rate of transport into the upstream end of the airshed, q_N)

- (the sum of emission rates allocated to the first n-1 boxes)

= the emission rate allocated to box n.

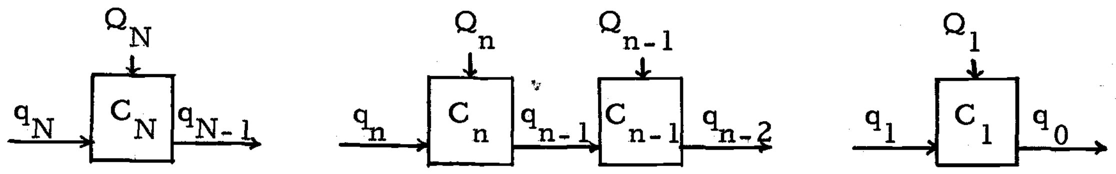


Figure 4. Block diagram of an airshed model.

The device of reversing the order of the subscripts on the boxes from the conventional configuration of the model is simply a convenience for the dynamic programming solution of this inverse configuration.

For zoning purposes, the "best" set of Q's, the emission rates allocated to each box, will be taken as those which strike a balance between penalizing the downstream end for excesses committed upstream, and unduly penalizing the upstream end for the physical constraints which tend to collect the bulk of the airshed emissions in the downstream end. That is, the optimum Q_n might be expressed as the maximum emission rate in box n which will, together with q_n transported in from upstream, result in concentration C_n = limit L such that q_{n-1}, the contribution from box n to all boxes downstream, will result in $C_i \leq L$, $i = 1, \ldots, n-1$.

For box k, Equation (1) can be written

$$\frac{C_k V_k}{P} = r_k q_k + R_k Q_k \tag{5}$$

or

$$\frac{C_k V_k}{P} = q_k + Q_k - q_{k-1}. \tag{6}$$

It is therefore possible to eliminate q_k and obtain an expression for the emission rate in box k which depends on downstream transport rates, but not on upstream rates.

$$Q_k = \left[\frac{1-r_k}{R_k - r_k}\right] \frac{C_k V_k}{P} - \left[\frac{r_k}{R_k - r_k}\right] q_{k-1}. \tag{7}$$

An optimal solution is then the maximum value of Q_k from Equation (7) subject to the constraints that $C_k \leq$ standard, or an upper limit, and that $Q_k \geq 0$, or a lower limit.

That is, the optimal emission rate in box k is the maximum which will, together with the pollutants transported in from upstream, avoid an excessive concentration in box k and at the same time yield a small enough transport rate to box $k-1$ so that those pollutants, together with the Q_{k-1} already determined, will not produce an excessive concentration there.

IV. EVALUATION OF THE MODEL

A. Conventional Configuration

For present purposes, the model has been examined in the conventional configuration as a means of checking its general validity. It would therefore be desirable to choose a situation with distinctive sources in a well defined airshed during clearcut episodes. The field burning season in the Willamette Valley ordinarily represents such a situation. During late summer and early fall each year, some 150, 000 acres of grass seed land and 50, 000 acres or more of grain stubble are burned after harvest. The suspended particulate matter due to these fires constitutes the most pronounced air pollutant in the airshed; all other routine sources are completely overpowered.

In 1968, plans were made to mount the necessary observation program, but the season was sufficiently anomolous to destroy certain of the fundamental assumptions required by that program. Record setting amounts of rainfall during August delayed the harvest and prevented the burning of those fields already harvested until after regrowth had begun. This actively growing plant material, with the overburden of damp and sometimes rotting straw, produced quantities of smoke somewhat greater than usual. It is not possible to estimate accurately the production rate of the suspended particulate matter from those fires. In addition, although the atmosphere was relatively stagnant on several individual days, the prolonged heavy rain and accompanying high wind meant that there were no significant stagnation episodes until very late in the season. By that time, re-growth made burning very difficult and smoke production was obviously abnormal.

It therefore became necessary to construct, on the basis of fragmentary data from several seasons, a coherent set of data to simulate observations which might reasonably be expected to apply to a single season.

Meland and Boubel (1966) found that the grass field wastes normally represent a fuel load which can be approximated very closely by the constant 2.5 tons per acre. In addition, Boubel and Darley (1968) have determined that the amount of suspended particulate matter in the atmosphere resulting from the combustion of these agricultural wastes, under typical conditions, amounts to approximately 15.6 pounds per ton of fuel. Thus the aerosol emissions from field burning can ordinarily be taken as 17.8 kilograms per acre. This generalized source factor was applied in this evaluation.

The Oregon State Sanitary Authority assembled an approximate inventory of acreage burned by county and by week during the 1967 season and this was used as a basis for estimating a set of source distributions. Due to the limitations in the emission inventory data, the surface area of individual boxes in the array representing the airshed has been taken as 400 km^2 in spite of the fact that such a large area weakens the assumption that suspended particulate matter is uniformly distributed within each box.

A first estimate of reasonable episode lengths was determined from the regional pollution potential described in Chapter II. B.

The mechanism for transporting the pollutants from one box to another is assumed to be the net travel as determined from the resultant wind field during an episode. For accuracy, the net travel should be determined from a network of vertical wind profiles, but in the airshed under study, there are available only four such profiles each day taken at four different times and at two different locations. Therefore, a further simplification is made by assuming that surface wind observations describe the flow through the depth of the mixed layer. This is not a very damaging simplification, however, because during what appear to have been typical episodes an examination of the rawinsonde profiles from Salem shows that the wind aloft up to the top of the mixed layer tends to agree very closely, both in speed and direction, with the surface wind. At the top of the mixed layer, of course, there is often a discontinuity in both speed and direction.

The residual terms r and R which appear in Equation (1) used to calculate the concentration in a given box at the end of an episode must be evaluated from Equations (3). Because some of the advected and the emitted material arrives in a given box early in the episode and some of it late in the episode, care is required to find the appropriate residuals. In order to reduce the amount of computation and to maintain a small requirement for input data, the choice was made here to calculate r and R as though net travel were distributed uniformly in time. That is, if T_{ep} is total net travel during an episode of length P, the travel each day is assumed to be T_{ep}/P. The residuals of the material which arrives in a given box on the last day of an episode are functions of the net travel on that day only, T_{ep}/P. On the other hand, the residuals of the material which arrives on the first day of the episode are functions of the net travel during the entire episode, T_{ep}. The overall residuals can be thought of as means, over the episode, of the various daily residuals; and these have been calculated from Equations (3) by replacing net travel T in those equations with $\overline{T}$, the simple average of T_{ep} and T_{ep}/P.

The approximate acreage of grass lands in the airshed is indicated in each of the boxes comprising the airshed, and in two additional boxes, in Figure 5. The two boxes indicated by broken lines are assumed to contribute to the pollutant burden in the airshed by advection. From these data, various combinations of field burning activity have been chosen arbitrarily.

During the summer of 1966, data were available from six wind observation stations in the Willamette Valley on a somewhat irregular basis. In 1968, the network has been improved so that at least eight

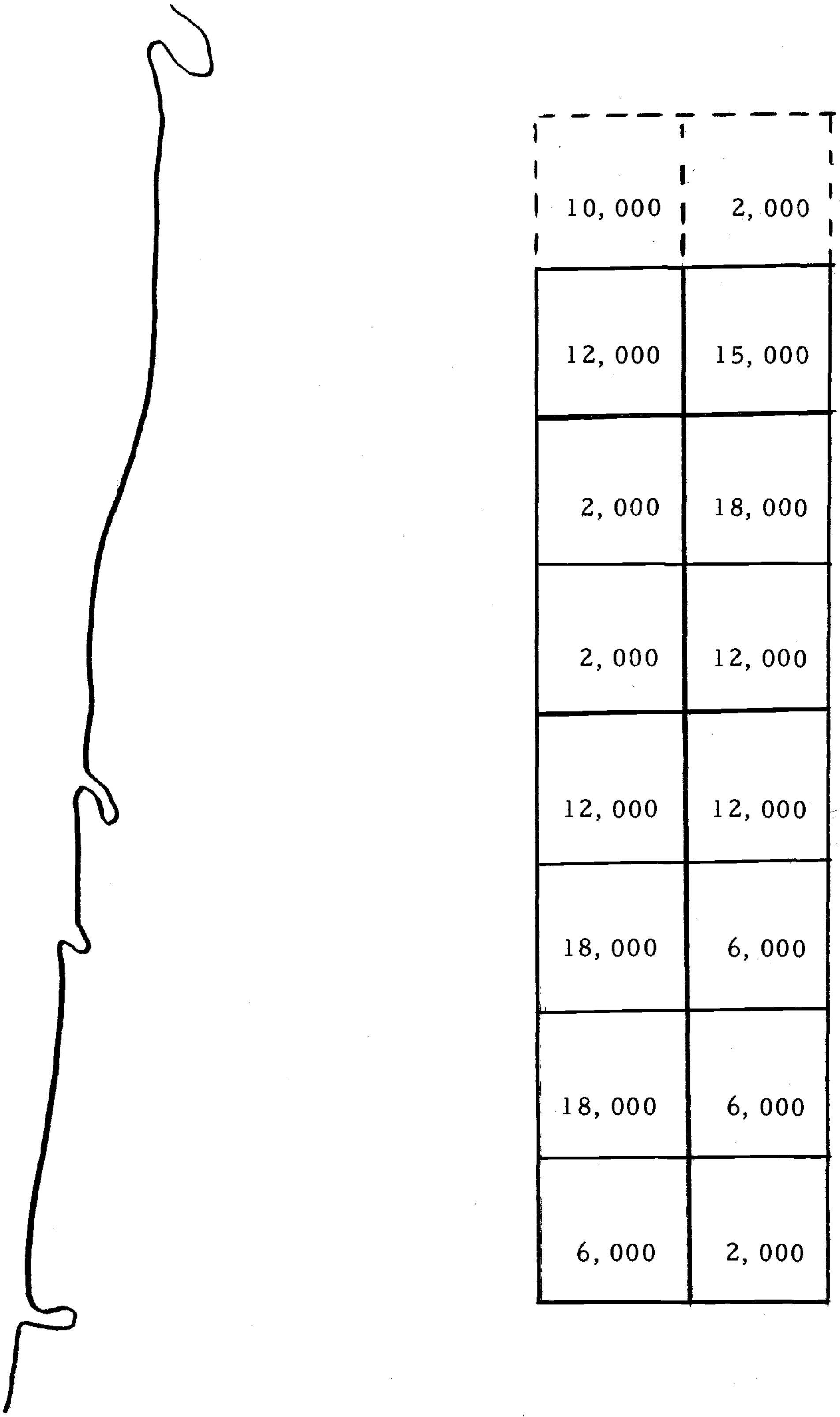


Figure 5. Approximate distribution of grass acreage in the airshed.

stations were generally available. For each station, resultant wind vectors have been drawn for each of the days which appeared to be part of an episode as identified by the regional pollution potential. These vectors were examined qualitatively to determine whether or not the local short-term circulations which are required to accomplish complete mixing were present, and to verify that total travel was not sufficient to carry pollutants beyond the airshed boundaries "overnight." The daily vectors were then summed over several days to obtain episode-resultant vectors for each station. From these, maps of episode streamlines and net travel within the airshed were constructed. Data were taken at selected grid points from these maps in the form of net travel in kilometers during an episode, and deviation of the streamlines from the north-south axis of the airshed in radians.

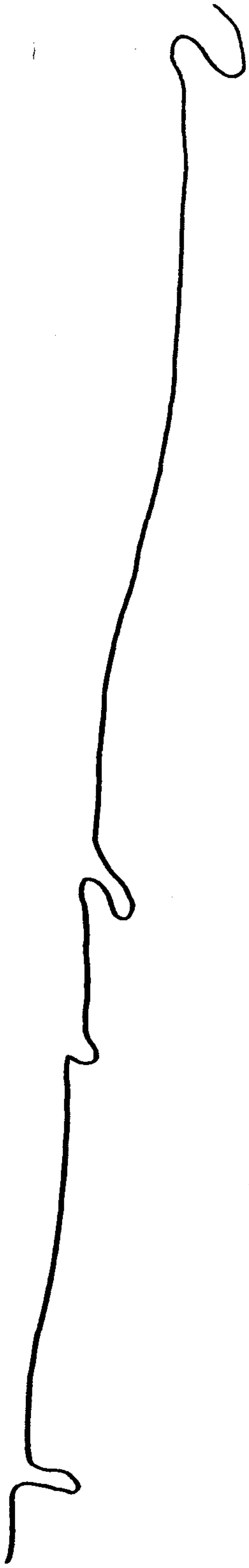
The depth of the mixed layer, of course, varies from place to place within the airshed as well as with time of day and from day to day within episodes. Twice daily radiosonde observations taken at Salem by the U. S. Weather Bureau were examined and the "maximum mixing depth" defined by Holzworth was determined as a guide to the approximate location of the top of the airshed mixed layer each day. During the 1968 season, an instrumented aircraft flew selected patterns throughout the airshed. Temperature profiles were obtained with a fast-response portable temperature probe using a precision bead thermistor manufactured by E. Bollay Associates, Inc. The unit is self-contained and is powered by rechargeable batteries. The temperature data were continuously recorded on a Rustrak recorder inside the aircraft. Simultaneous measurements of Aitken nuclei concentrations were made with a Gardner Associates, Inc. Small Particle Detector, Type CN. The supersaturation in these instruments, produced by adiabatic expansion of moist air, is relatively high. The density of the fog produced by expansion is measured by the extinction of a light beam passing through the expansion chamber to a selenium photocell with the extinction coefficient precalibrated. There is sufficient supersaturation to activate almost all naturally occurring condensation nuclei; and the counter, although operated manually, permits counts of aerosols at approximately 30-second intervals. By adjusting the rate of climb, therefore, the counts could be obtained at arbitrarily small intervals of altitude. These data afford a direct check on the assumption that pollutants are mixed uniformly with depth and provide a more direct measure of the altitude of the top of the layer than does the temperature profile. On the initial climb, during each flight, the top of the layer was noted and then the observer in the aircraft directed the pilot to porpoise through a layer approximately 1000 feet deep bracketing the top of the mixed layer. In this way, fixes on the top of the layer were obtained at several locations in the airshed; and when a temperature discontinuity accompanied the abrupt drop in nuclei count, the two different measurements provided checks on each other. On most flights, at least four profiles were obtained from 500-1000 feet above terrain to altitudes at least 1000 feet above the top of the mixed layer. These data were taken in mid-afternoon, near the time of maximum surface temperature, when it is assumed that convective activity was at its maximum. Therefore, the data provide measurements of the maximum height to which pollutants would be uniformly mixed on the days of the flights. Mixed depth was analyzed as contour maps of the airshed, and for days chosen to represent the last day of an episode for analysis in the model the depth in kilometers was selected at the same grid points used for the wind data.

For control data with which to compare the concentration patterns calculated with the model, some suspended particulate matter observations taken with high-volume samplers are available. These unpublished data were taken for a special study on the effects of field burning on air quality in the Willamette Valley by the Mid-Willamette Valley Air Pollution Authority in 1966. The observations indicate the mean mass loading of the air near ground level over 24 hour periods.

Sets of data constructed to represent conditions during realistic episodes have been assembled as inputs to the conventional configuration of the model. Data in the boxes indicated by dashed lines in the following figures are used to determine rates of transport of pollutants into the airshed proper, which is the rectangle indicated on Figure 1, page 12.

Input CC-1, shown in Figures 6a-6d, was used to calculate homogeneous concentrations by box at the end of a five day episode. The distribution of emission rates, Figure 6a, represents the burning of approximately five percent of the grass field acreage in each box per day. The emission rates indicated in the northernmost pair of boxes represent the boundary conditions which give an amount of material to be advected into the airshed proper. Net travel during the episode and episode-resultant streamlines, Figures 6b and 6c, are idealized patterns which approximate the patterns suggested by fragmentary wind data collected in both 1966 and 1968. The contour map of the top of the mixed layer on the fifth day of the hypothetical episode, Figure 6d, is based on measurements of Aitken nuclei concentrations made on 12 August, 1968. The top of the layer appeared quite clearly that day as the altitude above which the nuclei count dropped abruptly from several thousand to a few hundred per cubic centimeter.

Net travel from Figure 6b, deviation of the streamlines from the north-south axis from Figure 6c, and depth of the mixed layer from Figure 6d, were each read at the corners of each 20-kilometer square. The four values of each variable were averaged to obtain single values to describe conditions in each box. Appropriate residuals were then calculated for each box from Equations (3), and



8,900	1,780
10,700	13,400
1,780	16,000
1,780	10,700
10,700	10,700
16,000	5,350
16,000	5,350
5,350	1,780

Figure 6a. Distribution of emissions, CC-1.
(kg day^{-1}/20-km square)

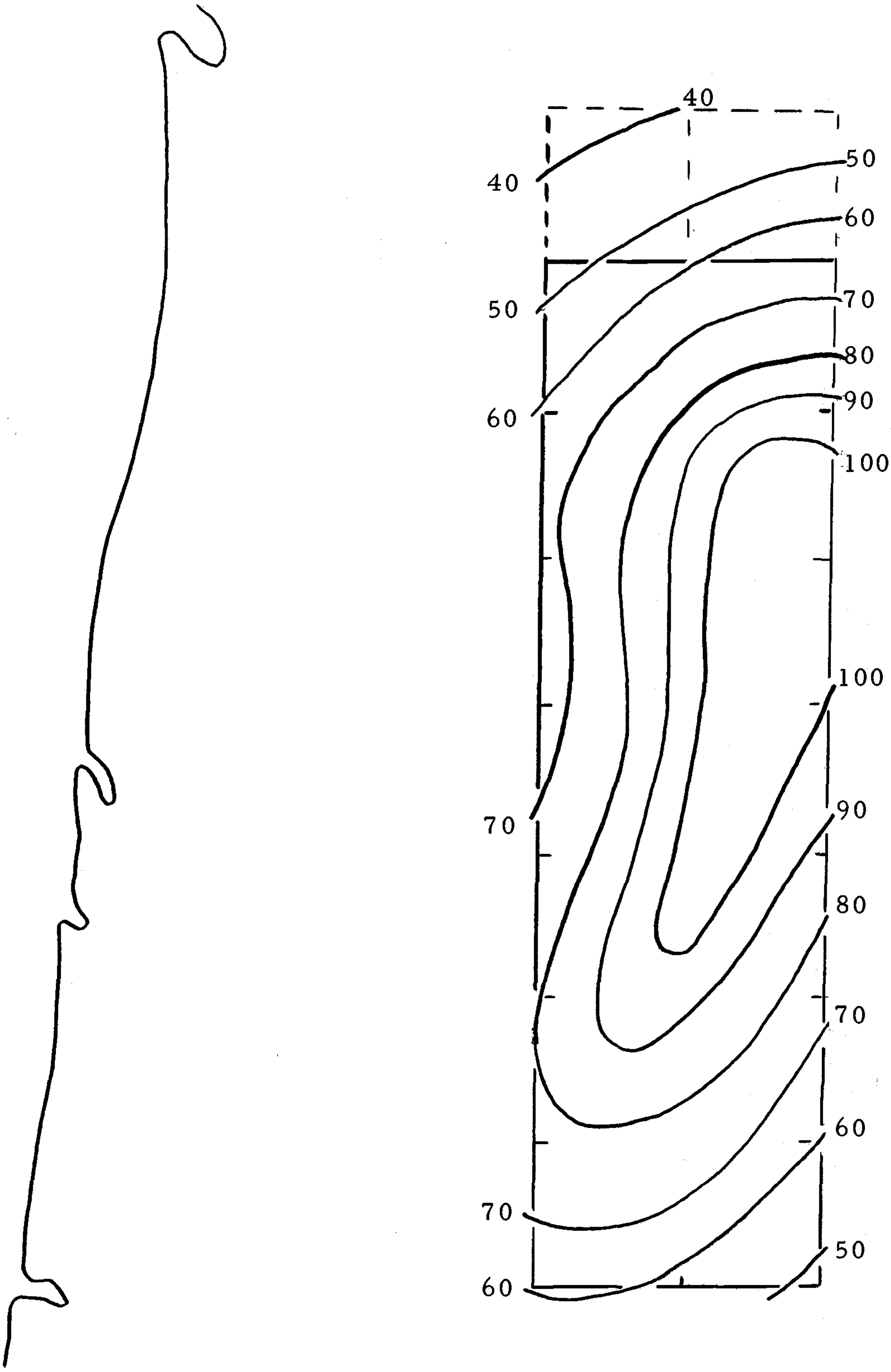


Figure 6b. Net travel during episode, CC-1. (km)

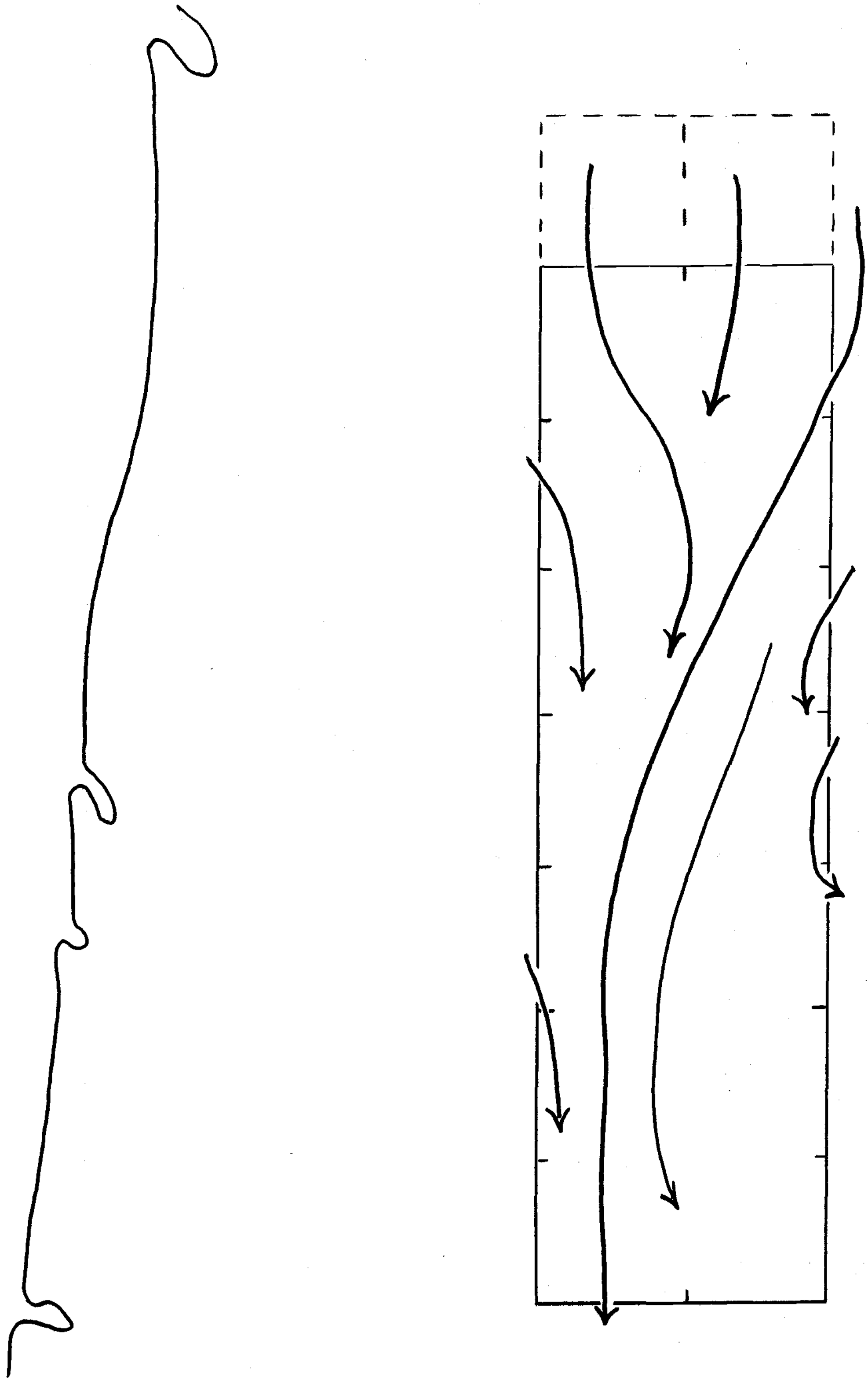


Figure 6c. Episode-resultant streamlines, CC-1.

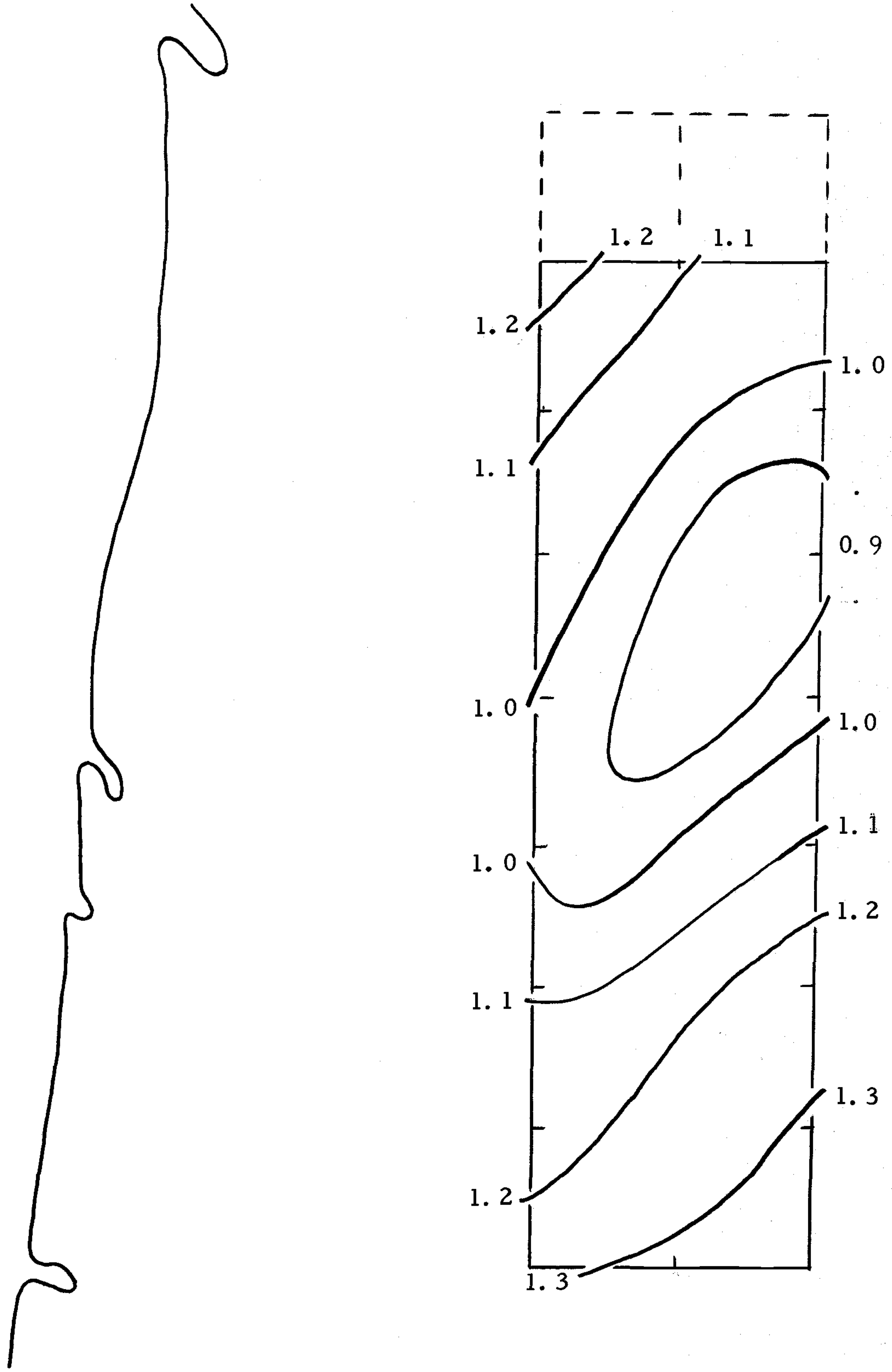


Figure 6d. Depth of the mixed layer, CC-1. (km)

beginning with the emission rates in the two northernmost boxes from Figure 6a, the concentration in each box was calculated from Equation (1). As the calculation proceeded downstream, the rate of transport into successive boxes was determined from Equation (4).

The uniform concentration of suspended particulate matter in each 20-kilometer box calculated from input CC-1 is shown in Figure 7 as isopleths of concentration. That calculated pattern can be compared with observed patterns from the 1966 field burning season which are shown in Figures 8-11. It is only reasonable, of course, that the general patterns should be similar because of the distribution of grass field acreage. The control data themselves are relatively sparse so the details of those patterns may be somewhat distorted although the positions of the maxima are fairly certain. The pattern on 24 August, 1966, Figure 11, probably reflects decreased burning activity in the northern part of the airshed where it appeared to be completed earlier than in the southern part that year.

Three other sets of input data constructed to illustrate a variety of emission rates and degrees of stagnation, together with the resulting concentration patterns calculated with Equation (1) and discussion of these results are included in Appendix I.

Concentration calculated with the model is "above background," which itself may vary from place to place within the airshed due to the locations of other large sources or concentrations of many small

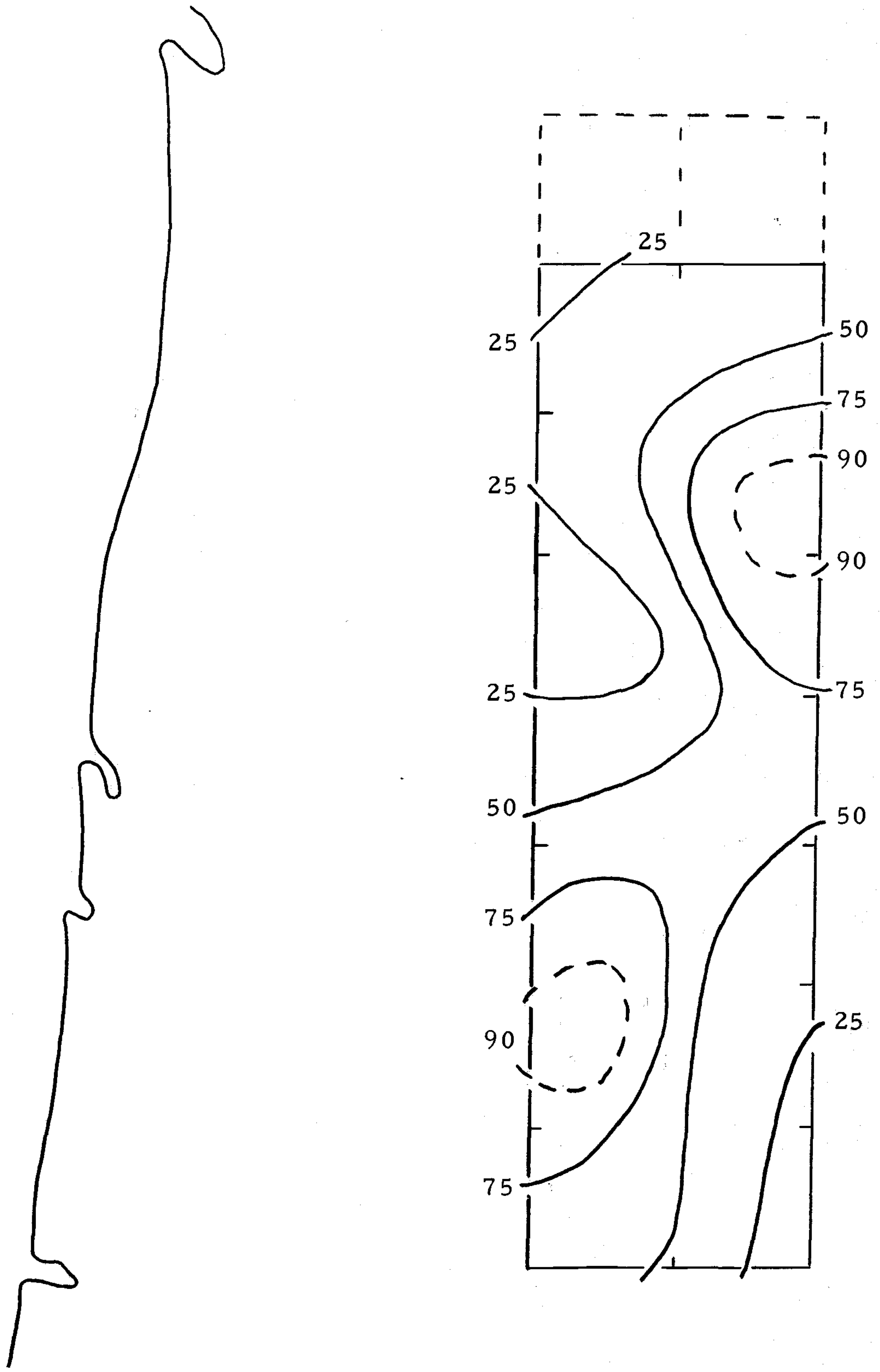


Figure 7. Concentration pattern, CC-1, calculated with the model. ($\mu g\ m^{-3}$)

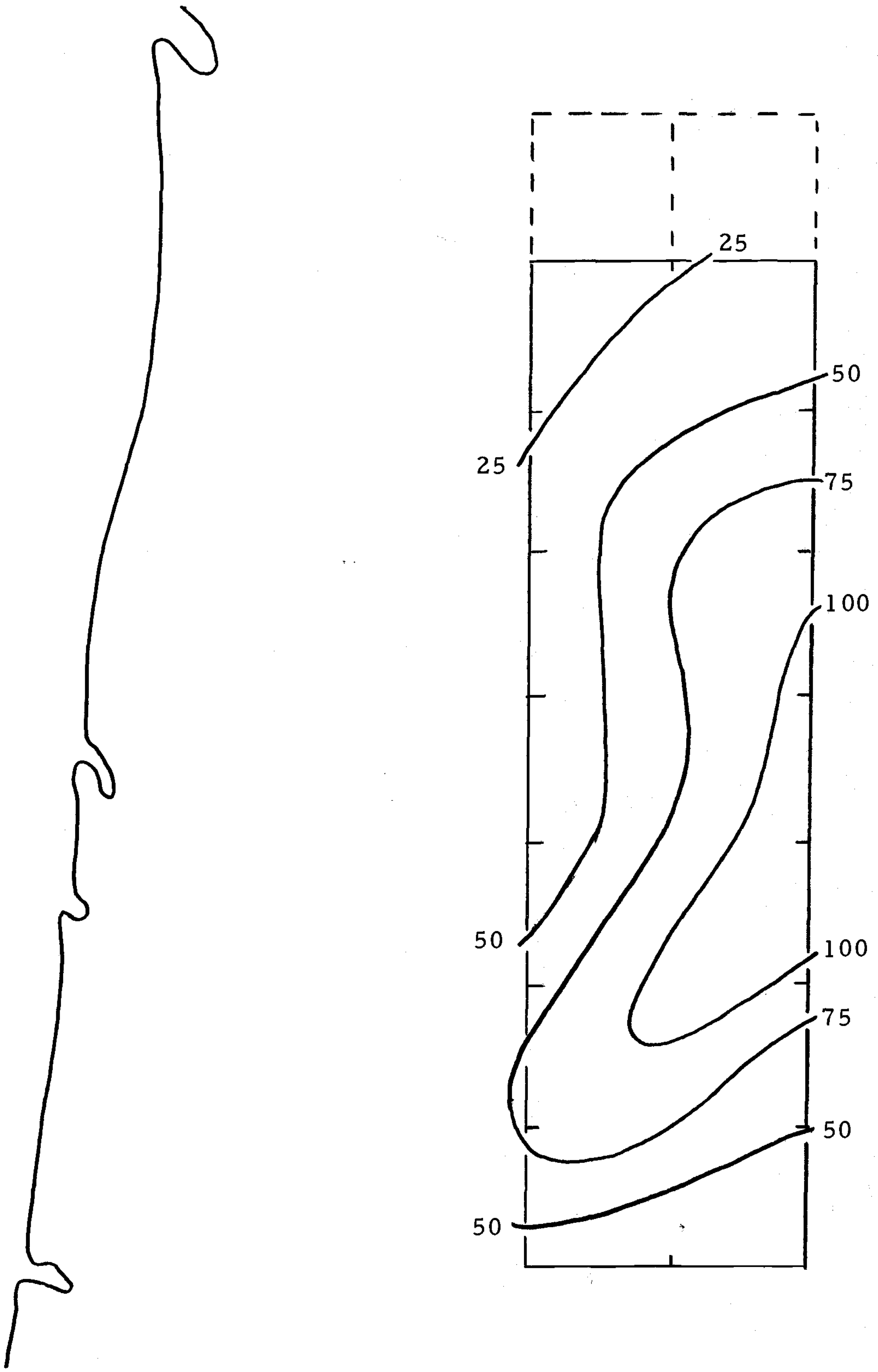


Figure 8. Suspended particulate matter concentration pattern observed 10 August, 1966. ($\mu g\ m^{-3}$)

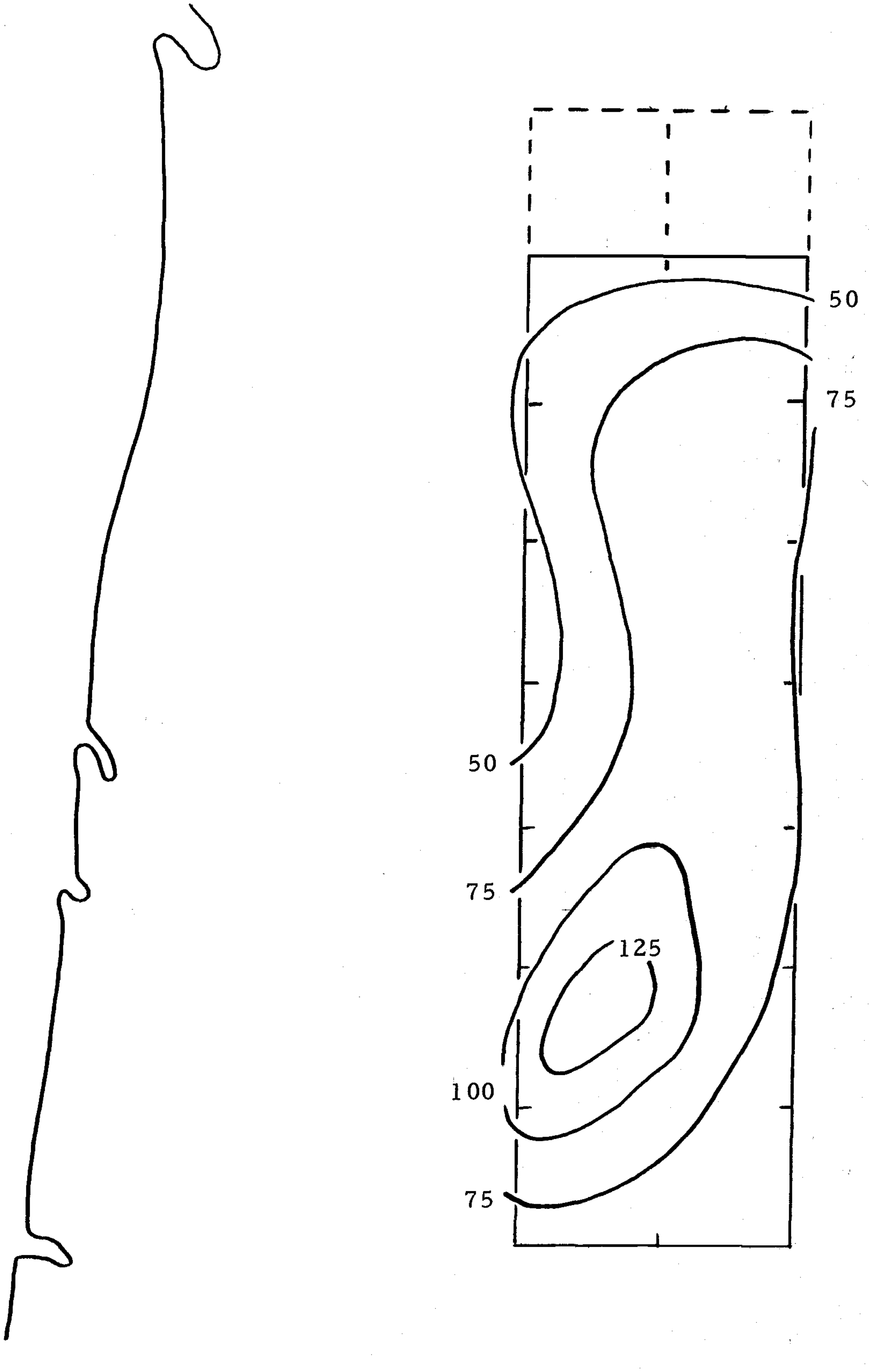


Figure 9. Suspended particulate matter concentration pattern observed 12 August, 1966. ($\mu g\ m^{-3}$)

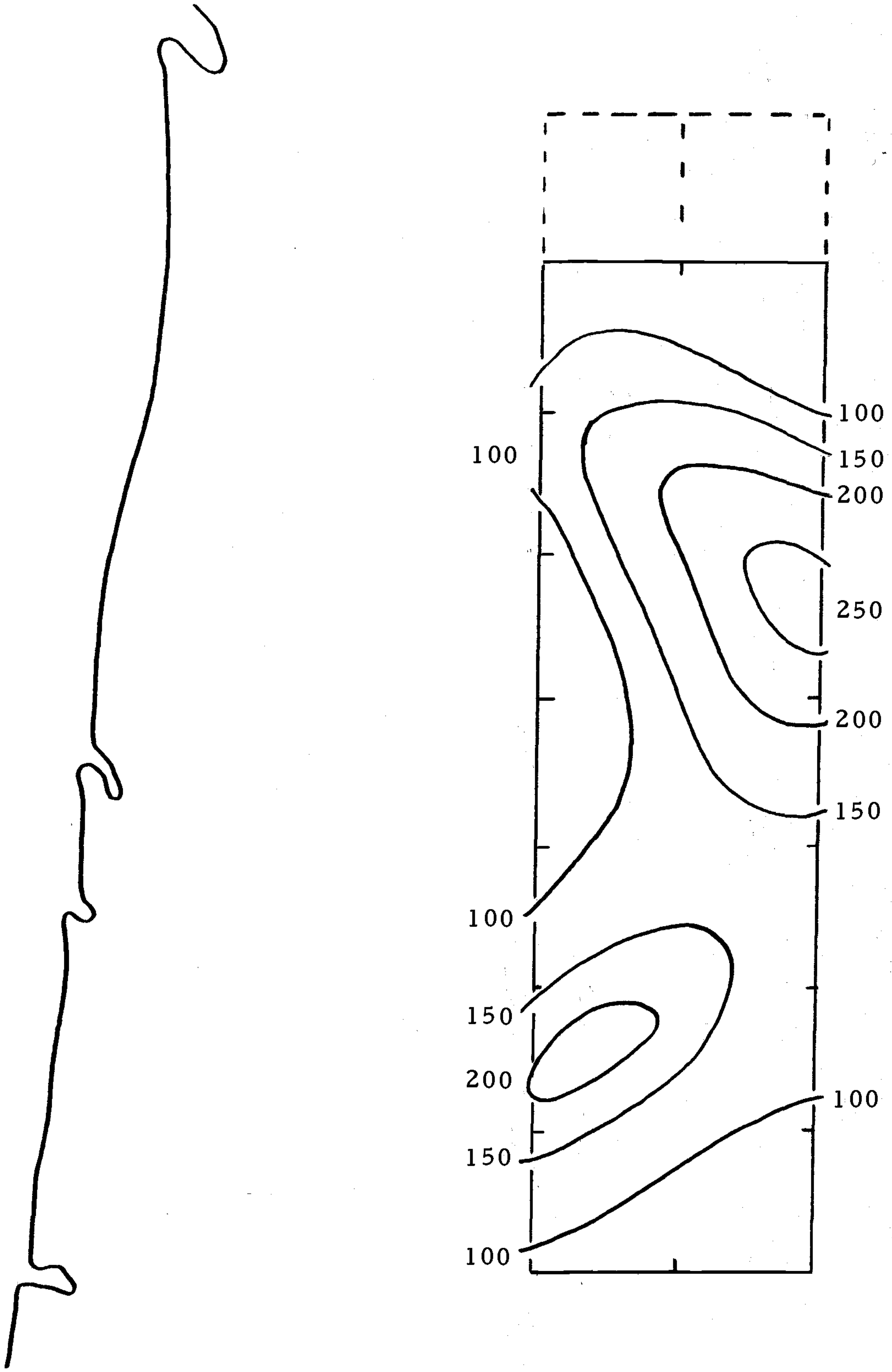


Figure 10. Suspended particulate matter concentration pattern observed 16 August, 1966. ($\mu g\ m^{-3}$)

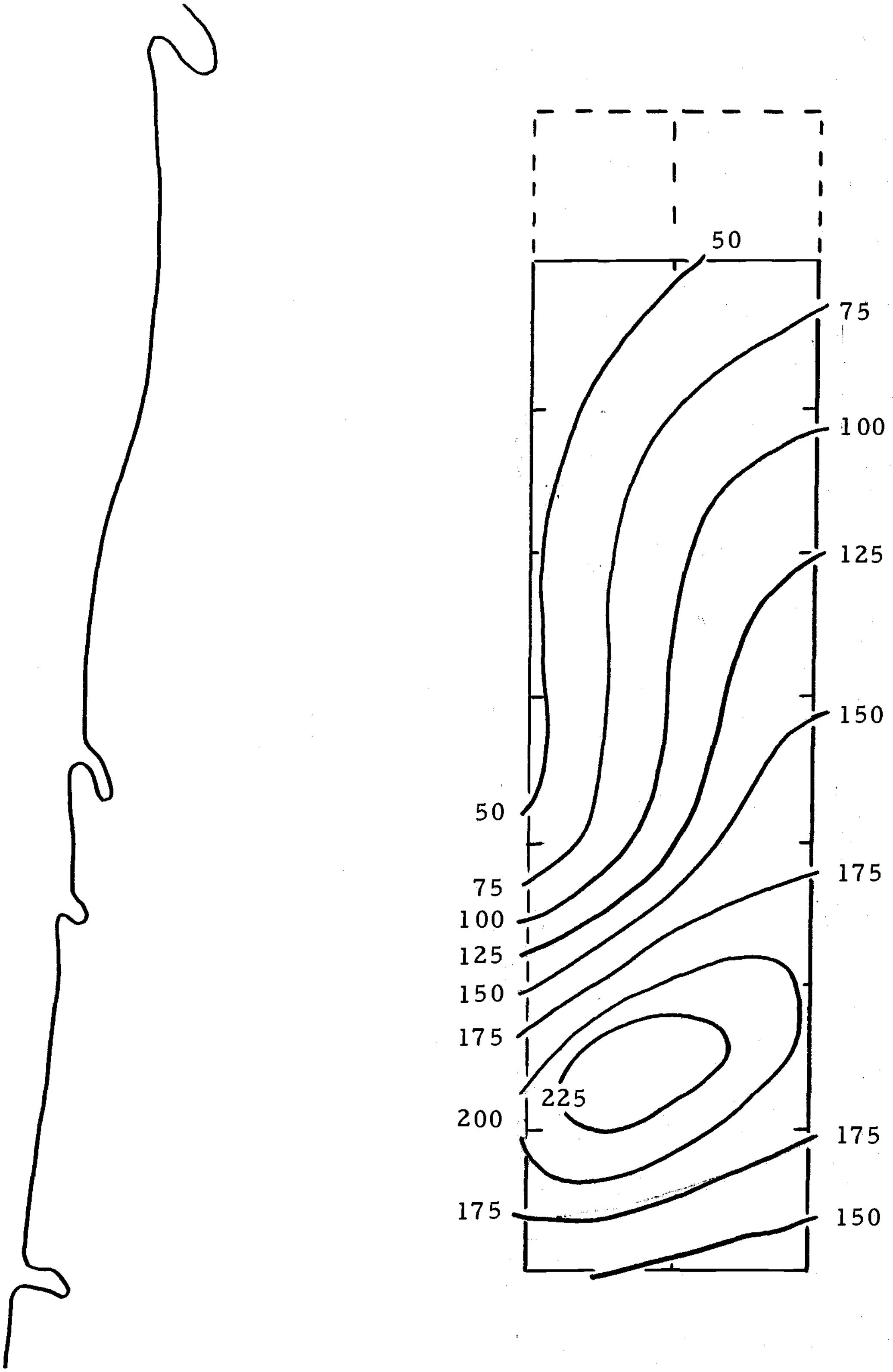


Figure 11. Suspended particulate matter concentration pattern observed 24 August, 1966. ($\mu g\ m^{-3}$)

sources. In any case, there appears to be sufficient similarity between the calculated and the observed patterns to instill some confidence in the concepts employed in constructing the model.

B. Inverse Configuration

Because the utility of the airshed-episode model is intended to be in the inverse configuration, it has been kept as simple as possible in order that it not suffer from overpowering data requirements in this application. It is felt that, at least until the optimization technique has had an adequate trial, oversimplification is preferable to excessive detail.

For real zoning applications, a "new climatology" must be developed. It would not take the form of wind roses, frequency of occurrence of inversions, or mean maximum mixing depths derived from standard period climatology. Rather, because air pollution problems occur under essentially abnormal meteorological conditions, a climatology of episodes is required in which data on episode mixing depths and episode-resultant wind vectors would be provided. It is possible that a single characteristic set of such data would emerge for a given airshed. More likely, however, one would expect seasonal variations. For example, in the Willamette Valley, episodic climatology might reveal a typical summer episode with resultant vectors generally from the North and with airshed mixing depths on the order of a kilometer, while fall and winter episodes might be characterized by flow from the South within a mixing depth of only 400 to 800 meters.

For purposes of evaluating the inverse configuration of the model, transport of pollutants is considered to be along straight streamlines parallel with the longest axis of the airshed; net travel during episodes is considered only as simple patterns with one or two maxima. In fact, there is no justification for imposing patterns other than those in the Willamette Valley airshed because preliminary analyses of flow patterns suggest no straightforward or predictable deviations from this straight and parallel, simple pattern, assumption. The implication, when calculating optimum emissions for each sub-volume as though the flow were straight and parallel, is that the cross-valley components add to zero. The assumption that considerable cross-valley circulation exists during episodes in order to achieve such a uniform concentration is still employed. If for some reason these assumptions were unacceptable, the simplest alternative would be to vary the shapes of the sub-volumes in order to maintain the boundaries approximately parallel with the resultant flow.

As was the case in evaluating the conventional configuration of the model, the appropriate residuals to be used in the solution of the recursive equation for the inverse configuration, Equation (7), are overall episode residuals. Here, because the flow is assumed to parallel the airshed axis, the residuals can be found from Equations (2).

However, for material which enters a particular box on the last day of an episode,

$$R = \frac{X}{X+T_1} = \frac{PX}{PX+T_{ep}} \quad \text{and} \quad r = \frac{X}{T_1} = \frac{PX}{T_{ep}} \quad \text{if} \quad T_1 > X$$

so long as episode net travel is taken as P times daily net travel, $T_{ep} = PT_1$. The corresponding residuals for the material which enters on the first day of an episode are

$$R = \frac{X}{X+T_{ep}} \quad \text{and} \quad r = \frac{X}{T_{ep}} .$$

Continuing to employ the assumption that all emissions, as well as net travel, are uniformly distributed in time through the episodes, it is reasonable to use

$$\bar{R} = \frac{1}{2}\left[\frac{PX}{PX+T_{ep}} + \frac{X}{X+T_{ep}}\right] \tag{8a}$$

and

$$\bar{r} = \frac{1}{2}\left[\frac{X}{T_{ep}} + \frac{PX}{T_{ep}}\right] = \frac{1}{2}\left[\frac{X+PX}{T_{ep}}\right] . \tag{8b}$$

The implication is that the mean of the residuals for the first and the last days of an episode multiplied by episode length is equivalent to the sum of the individual daily residuals.

In Oregon, background concentration is often assumed to be 50 micrograms per cubic meter. There is some evidence (Mid-Willamette Valley Air Pollution Authority, 1966) that a real natural background for the region is nearer 25 $\mu g\ m^{-3}$. In addition, McCormick (1968) has presented analyses of suspended particulate matter data collected by National Air Sampling Network stations. There is a marked indication of seasonal variation; western Oregon mean concentration appears to range from about 30 $\mu g\ m^{-3}$ in summer to 60 $\mu g\ m^{-3}$, or more, in winter.

For the sake of illustration, background concentration is taken here to be 25 $\mu g\ m^{-3}$. One overall standard for the airshed has been chosen arbitrarily to be 50 $\mu g\ m^{-3}$. It is assumed that, in each box, the emission rate is sufficient to result in a concentration at least as great as the background by the end of any episode. The recursive Equation (7) and its contraints are then written

$$Q_k = \left[\frac{1-r_k}{R_k-r_k}\right]\frac{C_k V_k}{P} - \left[\frac{r_k}{R_k-r_k}\right]q_{k-1} \tag{7'}$$

subject to:

$$C_k \leq 50, \qquad \text{for all } k,$$

$$Q_k \geq \frac{25\, V_k}{R_k P}, \qquad \text{for all } k.$$

At the downwind boundary of the airshed, where solution of the recursive equation begins, it is further assumed that the advection rate is sufficient to raise the concentration from background to whatever concentration is chosen as the limit there. This leaves a very wide choice of boundary conditions available.

Emission rates have been allocated to each of 56 ten-kilometer square areas of the Willamette Valley airshed on this basis. Because of the total lack of episode climatology, a fictitious but presumably likely episode climate in the form of net travel distribution and a contour map of the top of the mixed layer has been selected as input data IC-1 for the model in the inverse configuration. The net travel applied here as a North resultant wind, is shown in Figure 12a. It is based on observations taken on nine days in August, 1966. The contours of mixed depth, Figure 12b, are based on temperature profile data collected on 5 September, 1968. The height of the isentropic surface corresponding to the maximum temperature at ground level was obtained from eight temperature profiles in the Willamette Valley. Episode length is nine days. In this configuration, data in the dashed boxes at the south end of the airshed are used to determine rates of transport of pollutants out of the airshed proper.

Again, single values of each variable were obtained to describe the conditions in each box and the residuals r and R were calculated with Equations (8). In the first stage of the solution of Equation (7), the transport rate q is assumed to be sufficient to raise the concentration from background to standard. Beyond that stage, each optimal emission rate Q_k which is found is used to calculate a

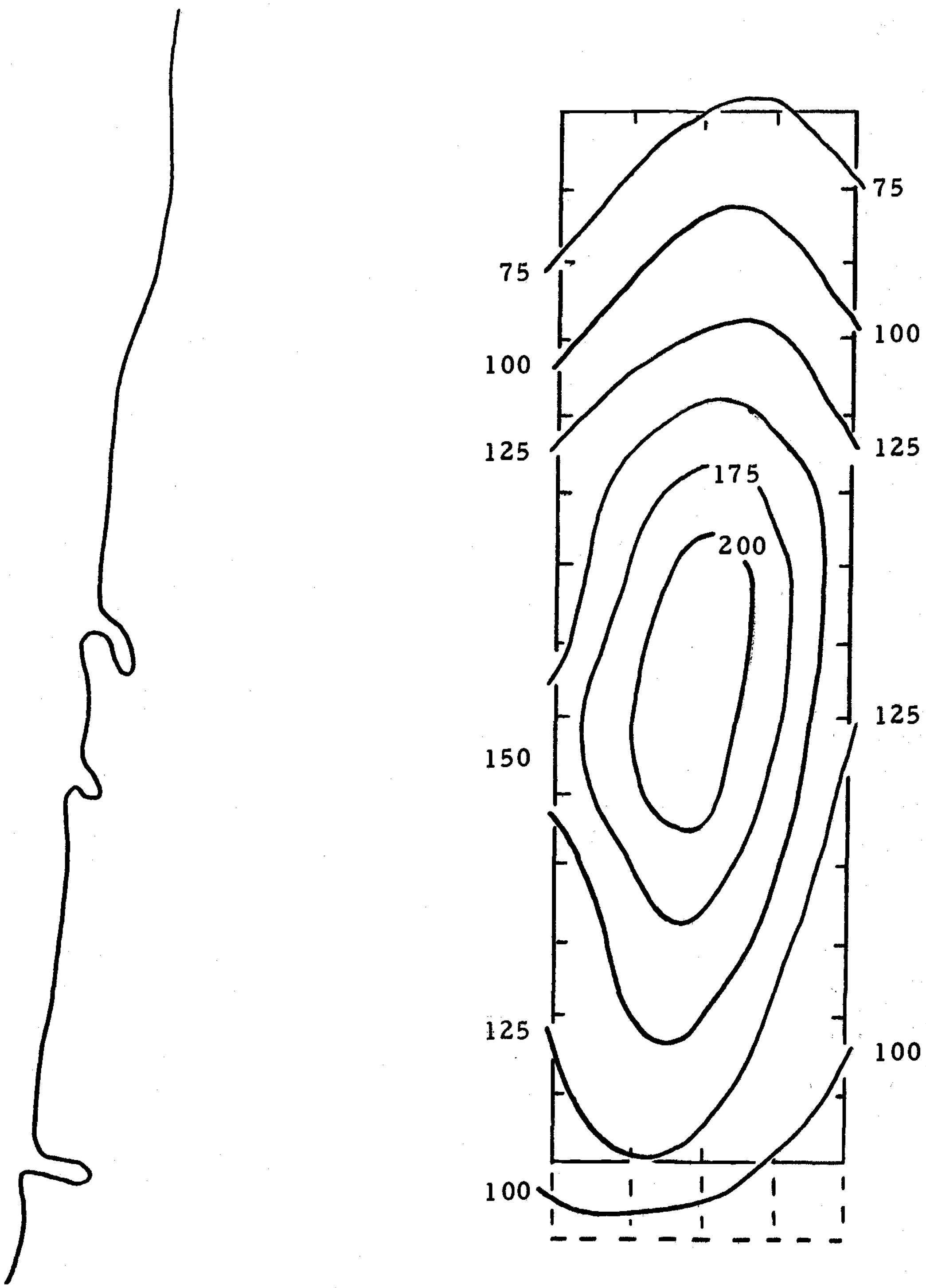


Figure 12a. Net travel during episode, IC-1. (km)

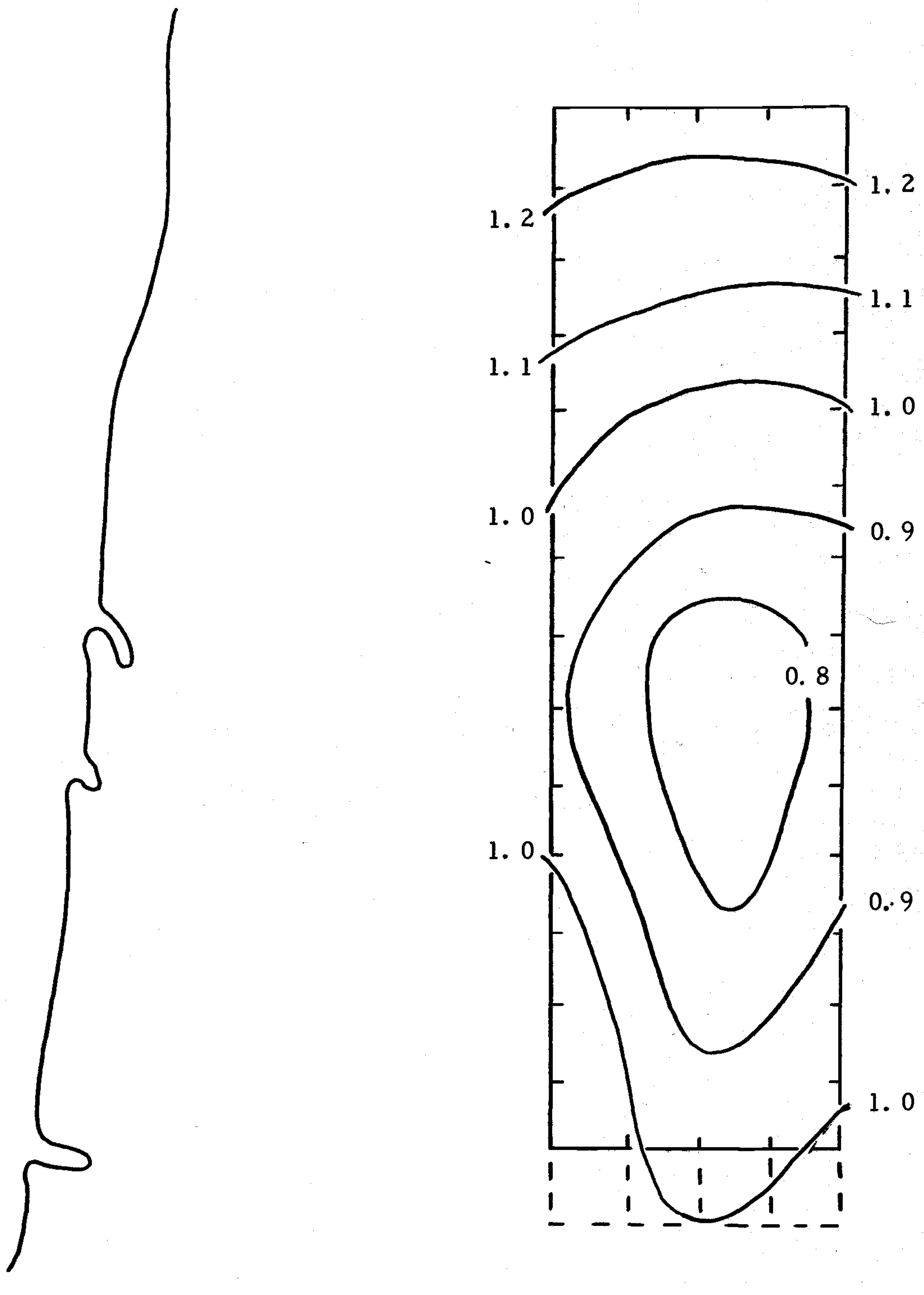


Figure 12b. Depth of mixed layer, IC-1. (km)

corresponding transport rate from Equation (5). This new q_k is then the q_{k-1} in the next stage and the solution proceeds stage by stage until optimal emission rates have been found for all boxes.

The pattern of optimal emission rates shown in Figure 13 is, as one might expect, very similar to the net travel and mixing depth patterns which are themselves similar in this case. Adequate climatology might show that net travel and/or mixed depth should be somewhat less than has been used here. If so, optimum emission rates would also be reduced.

This analysis is based on a uniform standard, or limiting concentration, of 50 $\mu g\ m^{-3}$ everywhere in the airshed. More generally, when standards are set they vary according to land use patterns in such a way that higher concentrations of pollutants are permitted; for example, in industrial areas.

The Oregon State Sanitary Authority has established general standards for the concentration of suspended particulate matter (Oregon Administrative Rules, 1962) as follows:

Standard for residential areas = 150 $\mu g\ m^{-3}$ + background,

Standard for industrial areas = 250 $\mu g\ m^{-3}$ + background.

Background concentration is not specified in the Rules; 25 $\mu g\ m^{-3}$ is used throughout this analysis.

To illustrate the effect of different standards, an "industrial area" has been inserted in the airshed with a buffer zone both upstream

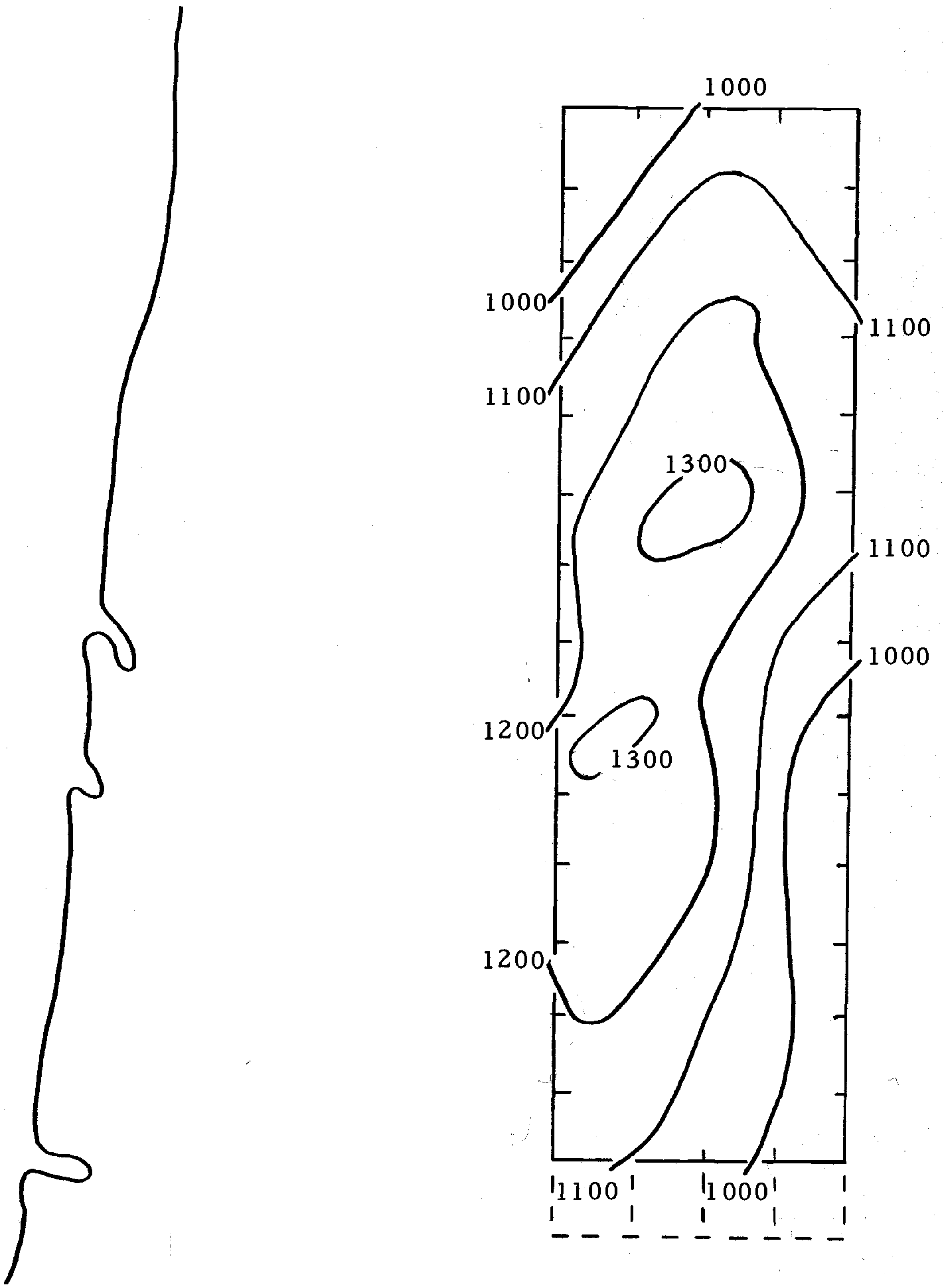


Figure 13. Optimal allocation of emission rates, IC-1. (kg day^{-1}/10-km square)

and downstream. The Oregon standards for industrial and residential areas have been used here. Figure 14 shows the limiting concentration allowed in the various parts of the airshed. The same 10-kilometer square boxes are used, but now the constraint on C_k in Equation (7') is no longer the same for all k. The optimal allocations which result from this analysis are shown in Figure 15. The industrial area has only a limited effect, which may be further limited here because of the assumption that emissions in every box are at least sufficient to result in background concentration of 25 $\mu g\ m^{-3}$. In a transport model such as this, it is not surprising that increased emission rates in a few boxes will result in higher concentrations downstream. Probably more important, is the fact that in this particular case, the excess emission rates are allocated to boxes outside the industrial area. In particular then, this figure illustrates the absurdity of establishing standards for industrial areas without regard for the transport of pollutants beyond the boundaries of those industrial areas. No emission rates within the industrial area are any greater than before, in order that downstream concentrations not exceed the limits there. That is, the standard is increased in twelve boxes, but three boxes further upstream are allocated an increased emission rate. Two additional cases, to illustrate other possible patterns and greater stagnation, are included in Appendix II. The results are similar in all cases; the effect of the same industrial area on emission

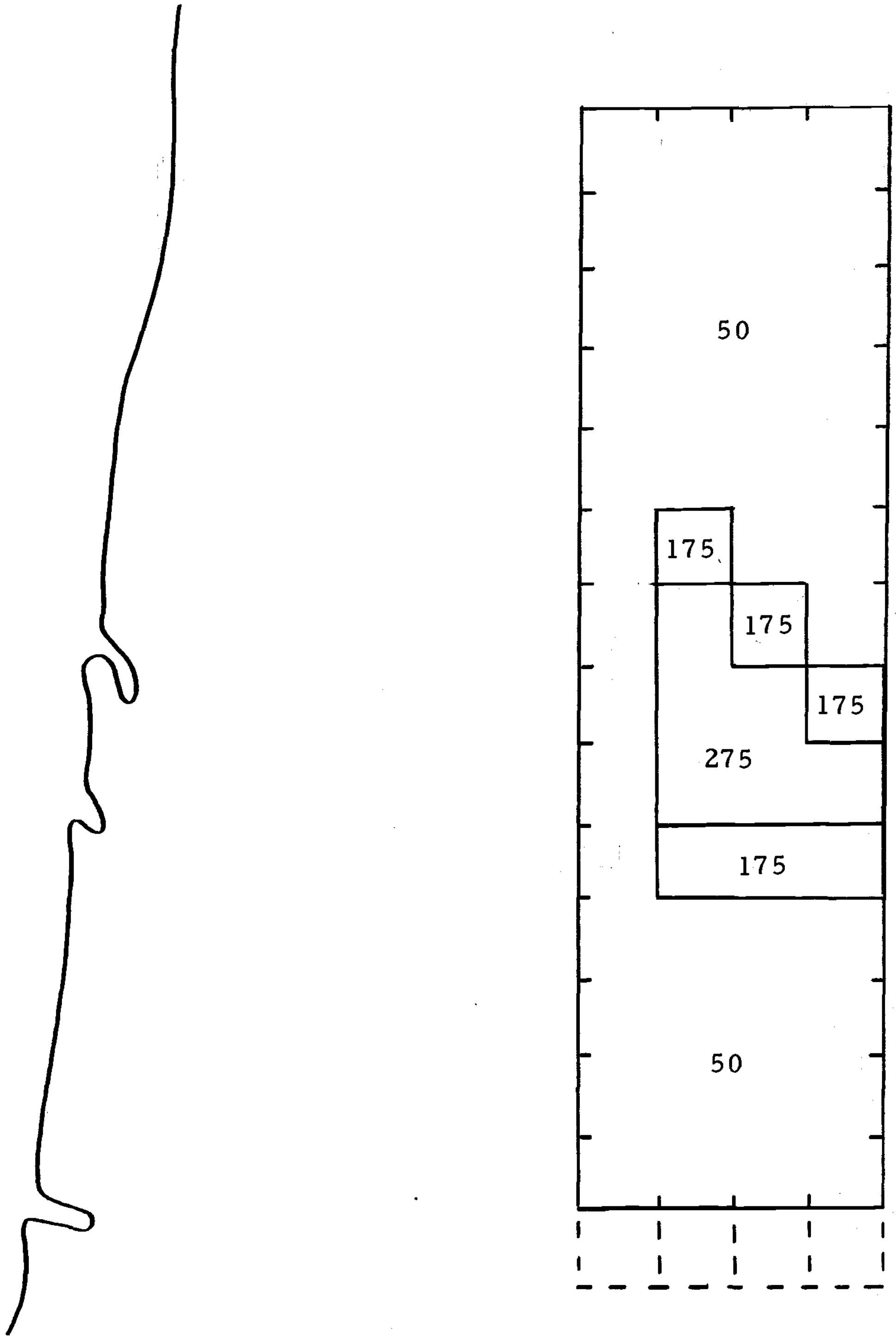


Figure 14. Concentration limits; industrial area and buffer zone in mid-airshed. ($\mu g\ m^{-3}$)

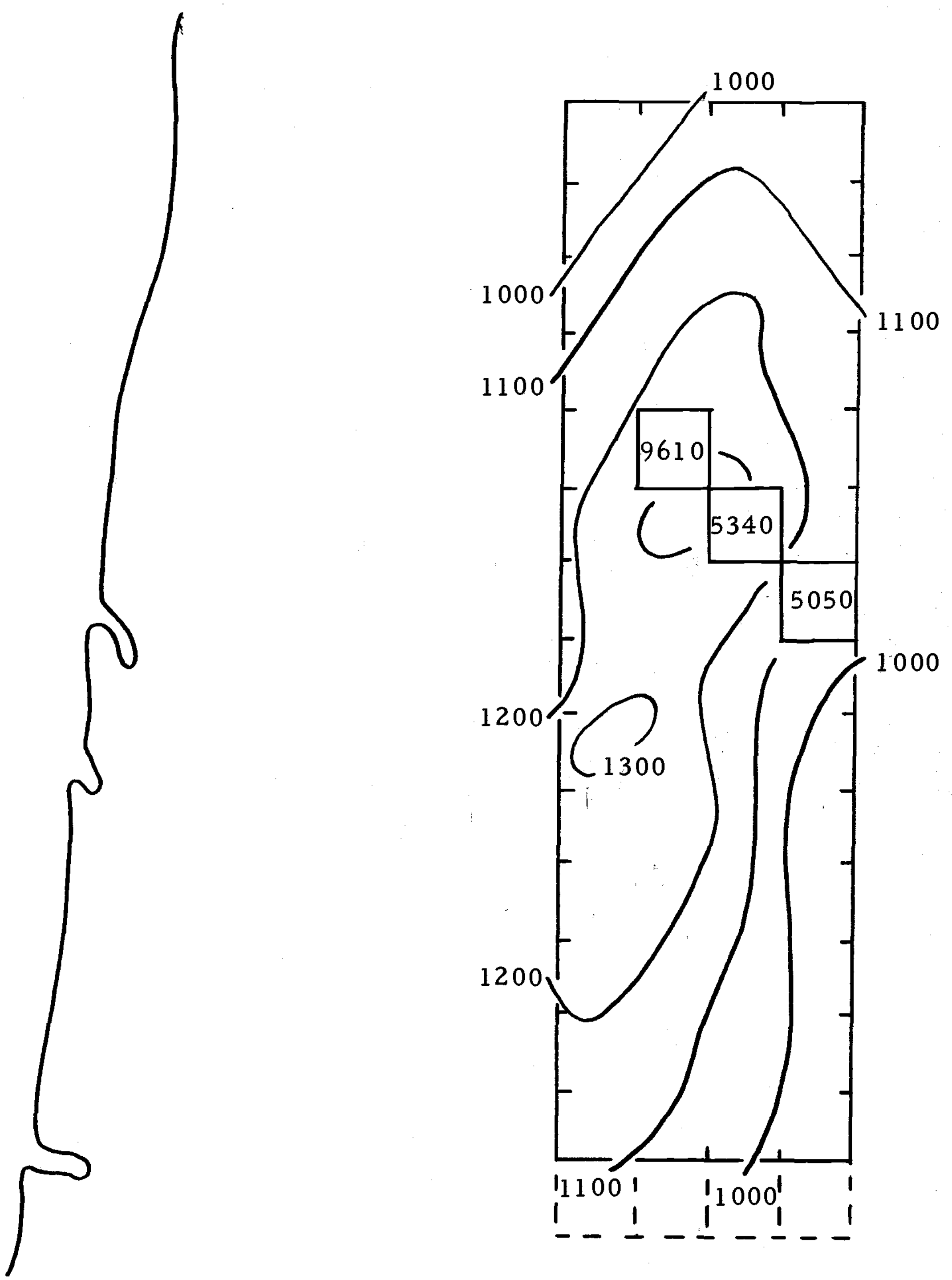


Figure 15. Optimal allocation of emission rates, IC-1'. (kg day^{-1}/10-km square)

rate allocations is more widespread in the more stagnant episodes. More boxes are permitted greater emission rates when stagnation is pronounced. Of course, greater stagnation results in greater restrictions on all emission rates.

Viewed another way, it might be said that when stagnation is not great so that the volume available for dispersion is relatively large, industrial area emissions need to be located far upwind if they are to be maximized in order to avoid excessive degradation of air quality downwind of the industrial zone. When ventilation is poorer, as when net travel is less during an episode, the effects of emissions are reflected in higher concentrations of pollutants nearer the sources; so industrial area emissions would have less effect on air quality outside their immediate vicinity.

C. Discussion

Although, as stated earlier, the airshed-episode model in its present form is deliberately simplistic and is therefore not intended to provide the kind of detailed, predictive results which are desirable when the interest is in examination of the pollutant concentration patterns which result from known source configurations, it does provide a realistic estimate with a modest requirement for input data. Therefore, when the amount of detail desired is not great it provides an easy way to obtain relatively quick results. In the conventional configuration, its explicit treatment of accumulation during episodes can sometimes be important.

The inverse configuration of the model provides a simple and realistic way to relate any selected air quality standard or limiting concentration, of either suspended particulate matter or gaseous pollutants, to zoning criteria or emission standards. By means of the optimization technique, it is possible to take implicit account of the economic value of utilizing the atmosphere as a waste disposal system through an equitable allocation of permissible pollutant emissions throughout the airshed. It also offers an illustration of the limitations which must be imposed on so-called industrial zones in order that excessive emissions there not result in degradation of air quality far beyond their areal limits.

Several ways to modify or extend this model and its application suggest themselves. Presently, it is unknown how much detail in input data would be desirable, or how small the sub-volumes of the airshed should be in order for the "uniform concentration" assumption to hold. It is planned to evaluate this assumption and to examine the question of optimum detail during 1969 at a well instrumented site in a Norwegian valley. Experimental application of the model in airsheds much smaller than the Willamette Valley would be possible if data were available on the proper scale. It is also possible that fine-scale data would permit use of the model in time periods of a day or less with uniform distribution assumed only within relatively small volumes. That would improve on the present assumption that the residuals, r and R, are simple means based on episode-resultant wind. If, for example, adequate daily data were available during episodes, it might be desirable to alter Equation (1) from its present form, dropping episode length P and making it a summation procedure from day to day. That would have the advantage of providing a more dynamic analysis in the conventional configuration. There is no assurance, however, that the locally derived motion in a period as short as a single day is sufficient to accomplish the uniform mixing which is required by the model.

In the inverse configuration, a parallel modification might be accomplished by using a slightly more complicated objective function. Episode length P would be dropped from Equation (7) and an accumulation rate term with a corresponding residual would be added. Solution of such a recursive equation would proceed from the downwind end of an airshed at the end of an episode, working "upstream" in both space and time. A major requirement would be to have available a suitable climatology of net travel and mixing layer depth which would permit taking such a dynamic approach.

There are many airsheds which are delineated with some clarity by terrain barriers. In addition to the Willamette Valley, the Central Valley of California and Puget Sound are easily recognized basins. It would seem reasonable that the airshed-episode model could be applied easily to many other areas of various size as well. For example, the horizontal extent of the air mass which stagnates over Los Angeles might be determined by constructing an envelope which contains the resultant wind vectors from wind observations representative of the basin. Because an active sea breeze is a major component of the diurnal flow pattern there, a three dimensional analysis might well be necessary. In that way, the volume of air involved in the diurnal motion due to the sea- and land-breezes could be determined with a fair degree of accuracy. Similarly, most megalopolitan regions could be defined as airsheds irrespective of terrain in this way; envelopes around appropriate resultant wind vectors could identify the relevant air mass boundaries. Alternatively, with the inverse configuration in particular, an analysis could be made of an arbitrarily large region so that the peripheral area sources could be assumed to be negligible.

Application in any airshed would be enhanced by explicit knowledge of the rate of exchange of air through the boundaries. The analysis here has been oversimplified, but with data in somewhat greater detail it would be possible to assess the "leakage" of air both into and out of the airshed. In the Willamette Valley, the sea breeze circulation often injects fresh marine air through the passes in the Coast Range and simple consideration of mass conservation requires that there be losses elsewhere. That exchange is allowed for to a certain extent in the conventional configuration, where the resultant streamlines are assumed to be curved, but until the exchange processes are understood in some detail, or at least can be described climatologically, no clear way to incorporate them into the inverse configuration appears. Perhaps a detailed analysis by means of tracer experiments during typical episodes would be the most direct way to obtain this kind of knowledge. The data collected to identify the top of the mixed layer, together with analyses of the horizontal wind, would lend themselves by way of the equation of continuity to calculations of the distribution of vertical velocity through the top of the mixed layer. Although of interest for its own sake, that component of the velocity is not required when direct observations of aerosol distribution with height are available.

A decay term to allow for removal of pollutants during episodes could easily be incorporated into the working equations as exponential factors to reduce the size of the residuals, r and R, as functions of the episode length P. The most likely removal mechanism to affect the concentrations of suspended particulate matter during episodes on the time scale considered here is simply fallout due to gravity. Typical terminal fall velocity for particles of 0.5 micron radius is on the order of 10^{-2} cm sec^{-1}. Junge (1963) has shown that if a homogeneous concentration of aerosols is assumed to be contained in a layer of depth Z, the mean aerosol residence time is $t = Z/v$ where v is the fall velocity. For illustration, it might be estimated that $Z = 500$ meters. Then, $t = 5 \cdot 10^6$ sec or 58 days. Clearly, in the present analysis, a correction for decay on that scale is not warranted in view of the fact that typical episodes are on the order of one tenth the residence time. However, allowance for decay is necessary in the case of reactive pollutants such as sulfur dioxide, or those which are readily absorbed such as carbon dioxide. It has been estimated that the "halflife" of some pollutant gases may range from a few hours to years (Junge, 1963; Slade, 1967; Turner, 1964).

Certain of the area emissions within an airshed might be constrained for various reasons outside the control of the users of this kind of optimization technique. For example, some major industrial sources might be exempt from zoning regulations. In addition, it is probable that for esthetic reasons it would never be desirable to maximize the emissions everywhere as a measure of an optimum. However, by varying the assumed background concentration and/or the limiting concentration in various parts of the airshed, it would be possible to examine the effects, under specific sets of meteorological conditions, of any combination of clean zones and residential or industrial areas.

A desirable extension of this model requires knowledge of the economic benefits which accrue from utilization of the atmosphere for waste disposal. The optimal solutions obtained with the present recursive equation could be weighted by economic criteria in such a way that uneconomic or convenience emissions would be the first to be reduced when an episode occurs. This would provide rational optimization criteria, alternative to the simple maximization of emission rates.

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APPENDICES

Appendix I.

Three additional analyses using the conventional configuration of the model are presented in this appendix. They are considered comparable to that shown in Chapter IV. A., but are intended to illustrate a variety of distributions of emission rates and degrees of stagnation.

The set of data used as input CC-2 is shown in Figures A-1a-A-1d. The emission rate distribution, Figure A-1a, is meant to illustrate the approximate rates at which suspended particulate matter is released during the height of the field burning season. Net travel during the episode, Figure A-1b, is the same pattern as input CC-1 but with much greater total travel. Episode-resultant streamlines, in Figure A-1c, are slightly different and are intended to show the distortion of the northerly flow around Coburg Ridge in the southeastern part of the airshed. That is the largest terrain feature which intrudes upon the otherwise nearly flat valley floor. Depth of the mixed layer, Figure A-1d, is the same as for input CC-1. These data were used, with an episode length of six days, to calculate the concentrations shown in Figure A-2. The pattern is very similar to Figure 7, page 46, and the differences mainly reflect the change in streamlines. Increased net travel apparently compensates for increased emission rates.

Figures A-3a-A-3d show the data used for input CC-3. Episode length is taken to be nine days; daily emission rates are shown in Figure A-3a. They are based on an approximate inventory taken by the Oregon State Sanitary Authority of acreage burned by week in 1967. Net travel and episode-resultant streamlines, Figures A-3b and A-3c, are based on the resultant wind observed with a rather sparse network of wind stations during a nine-day period in August, 1966. The net travel is the same as that used with the inverse configuration in Chapter IV. B. The top of the mixed layer shown in Figure A-3d was observed on 7 September, 1968. Figure A-4, the calculated concentration pattern, is also similar to Figure 7. The higher concentrations are due in part to the longer episode length and in part to the reduced net travel. The similarity to the pattern observed on 16 August, 1966, Figure 10, is remarkable.

The set of data used as input CC-4 includes emission rates the same as input CC-3, shown again in Figure A-5a. The pattern of net travel in Figure A-5b is imaginary, but is suggested by some observations. It was chosen to illustrate the effect of a double maximum and the short travel distances which might be observed with marked stagnation during a ten-day episode. In Figure A-5c, the streamlines are the same as those in input CC-1. Mixed depth on the tenth and last day of the episode, Figure A-5d, is the same as that used for input CC-3. Again, the calculated concentration pattern in Figure A-6 is similar in spite of the quite different net travel input.

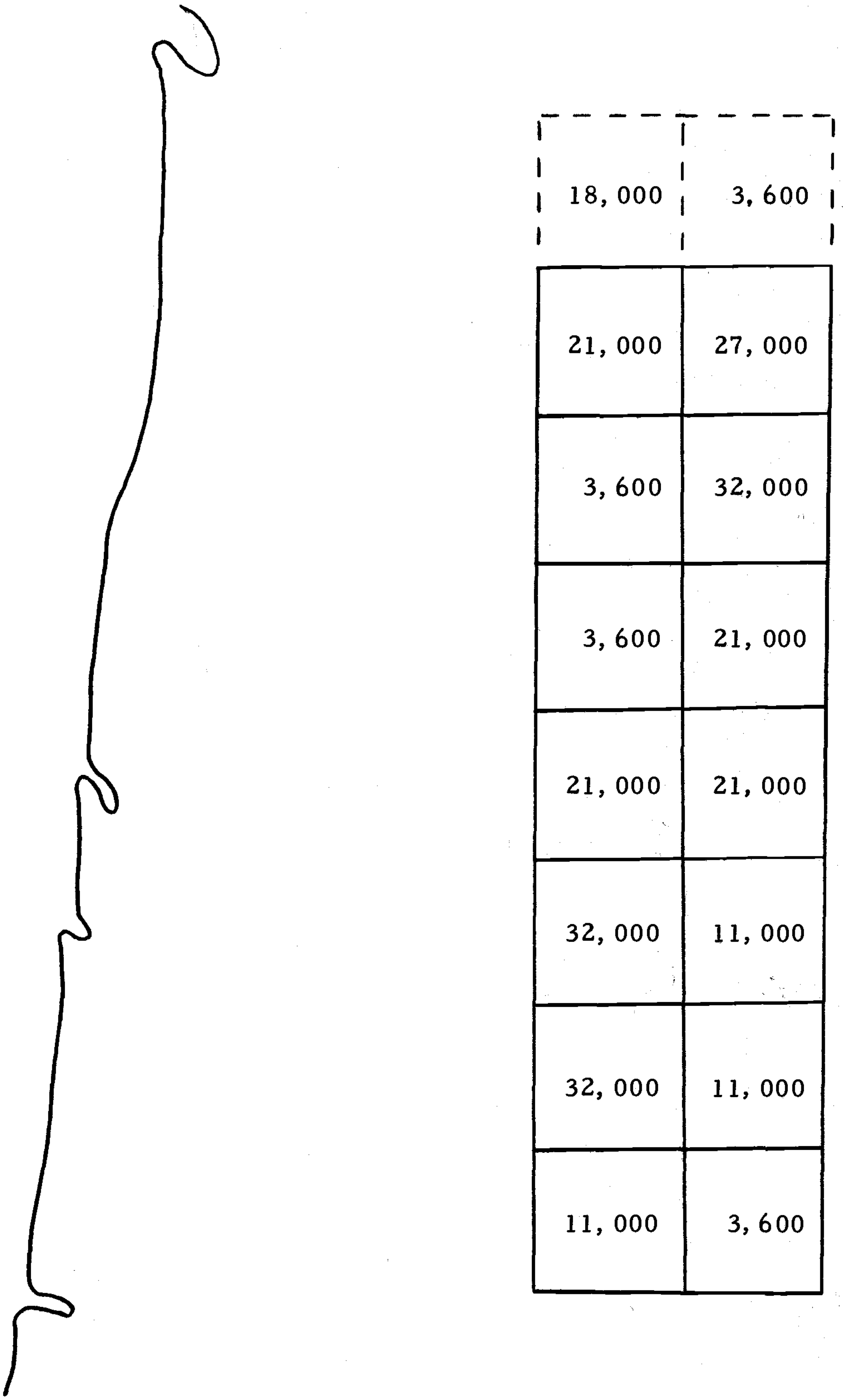


Figure A-1a. Distribution of emissions, CC-2.
(kg day^{-1}/20-km square)

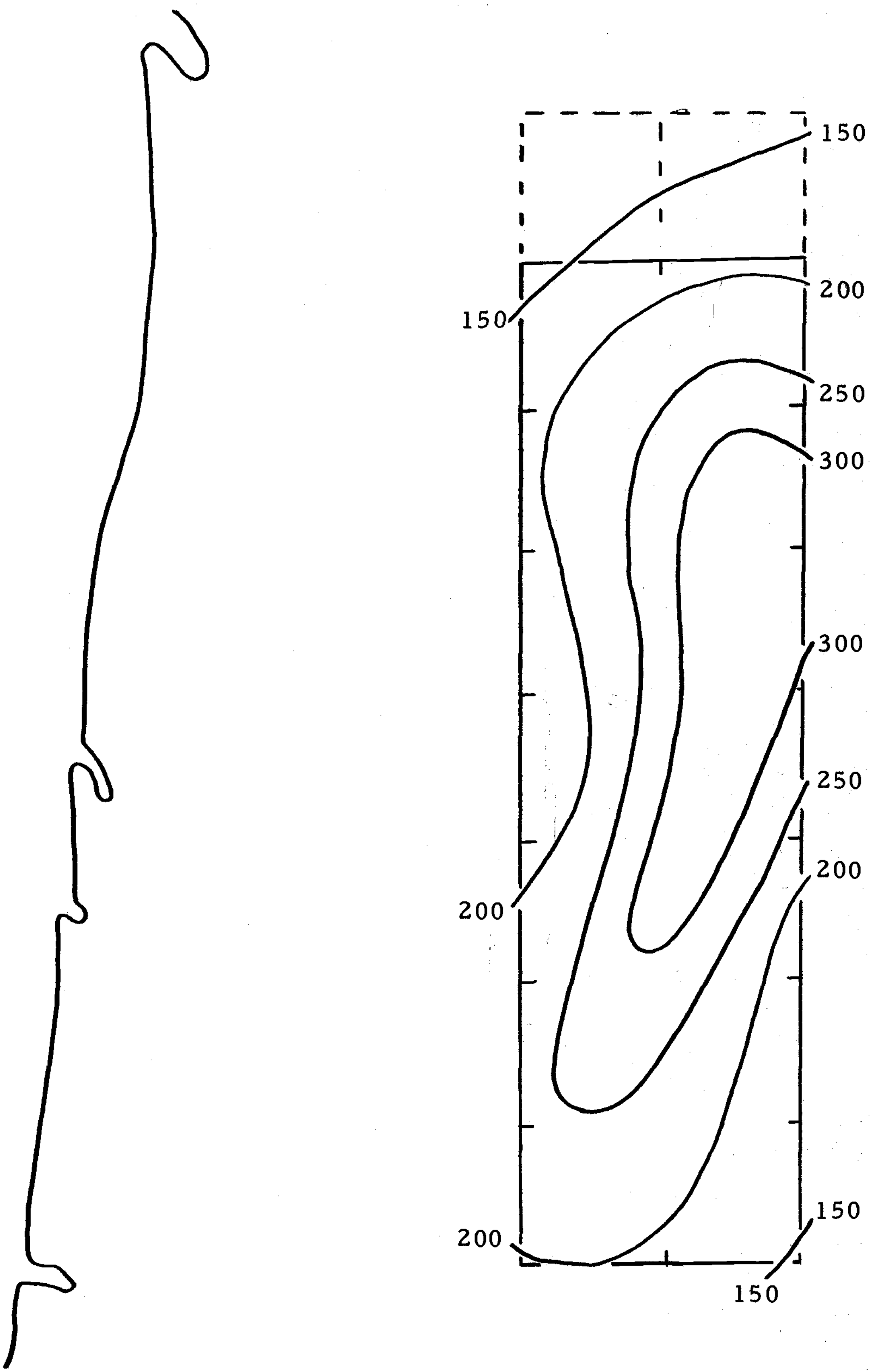


Figure A-1b. Net travel during episode, CC-2. (km).

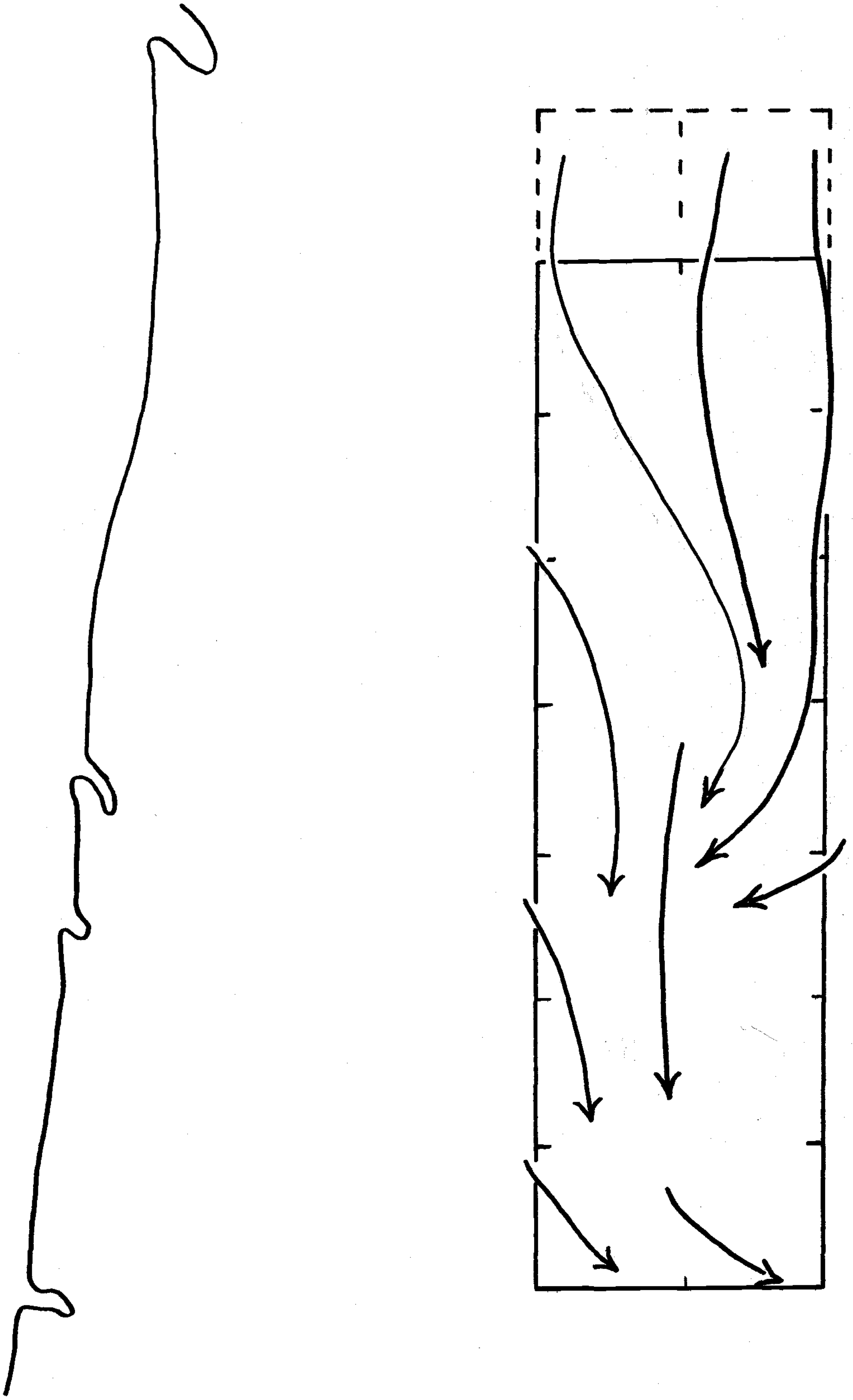


Figure A-1c. Episode-resultant streamlines, CC-2.

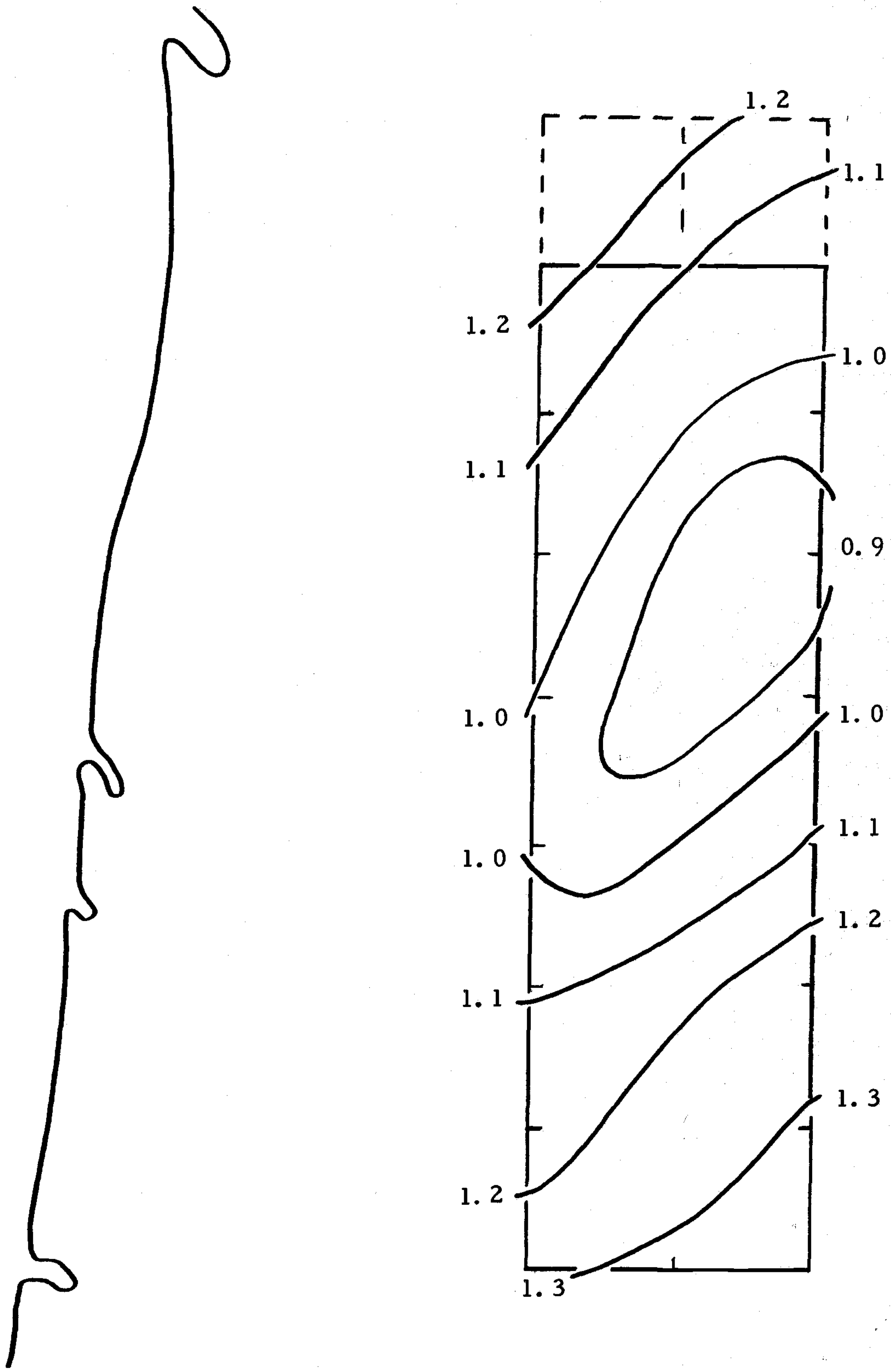


Figure A-1d. Depth of mixed layer, CC-2. (km)

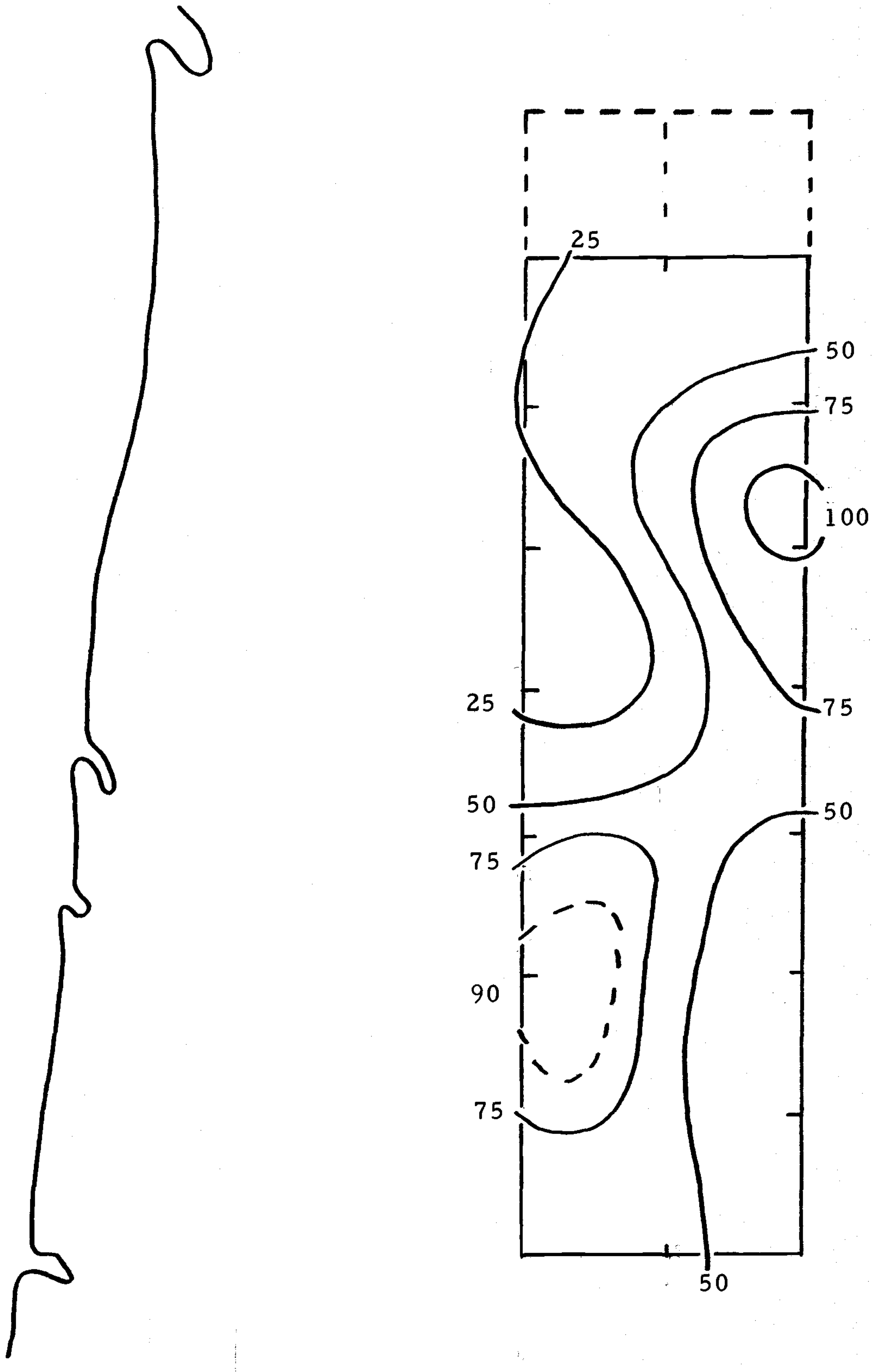
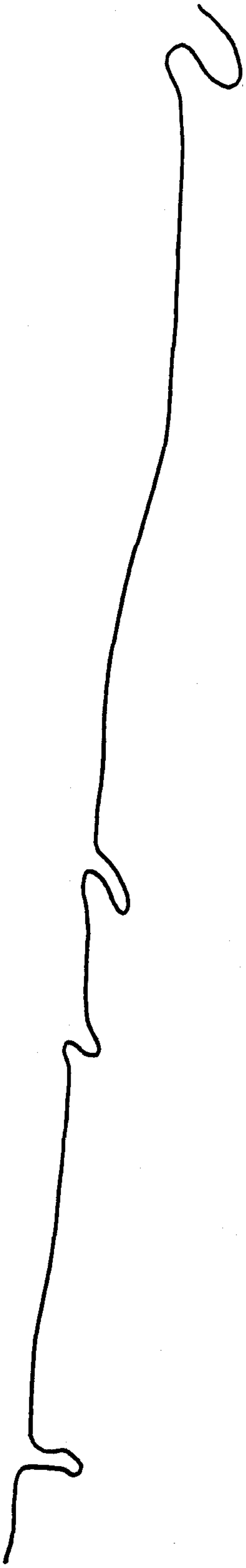


Figure A-2. Concentration pattern, CC-2, calculated with model. ($\mu g\ m^{-3}$)



10, 000	3, 000
20, 000	22, 000
3, 000	25, 000
3, 000	12, 000
16, 000	16, 000
25, 000	8, 000
25, 000	8, 000
8, 000	3, 000

Figure A-3a. Distribution of emissions, CC-3.
(kg day^{-1}/20-km square)

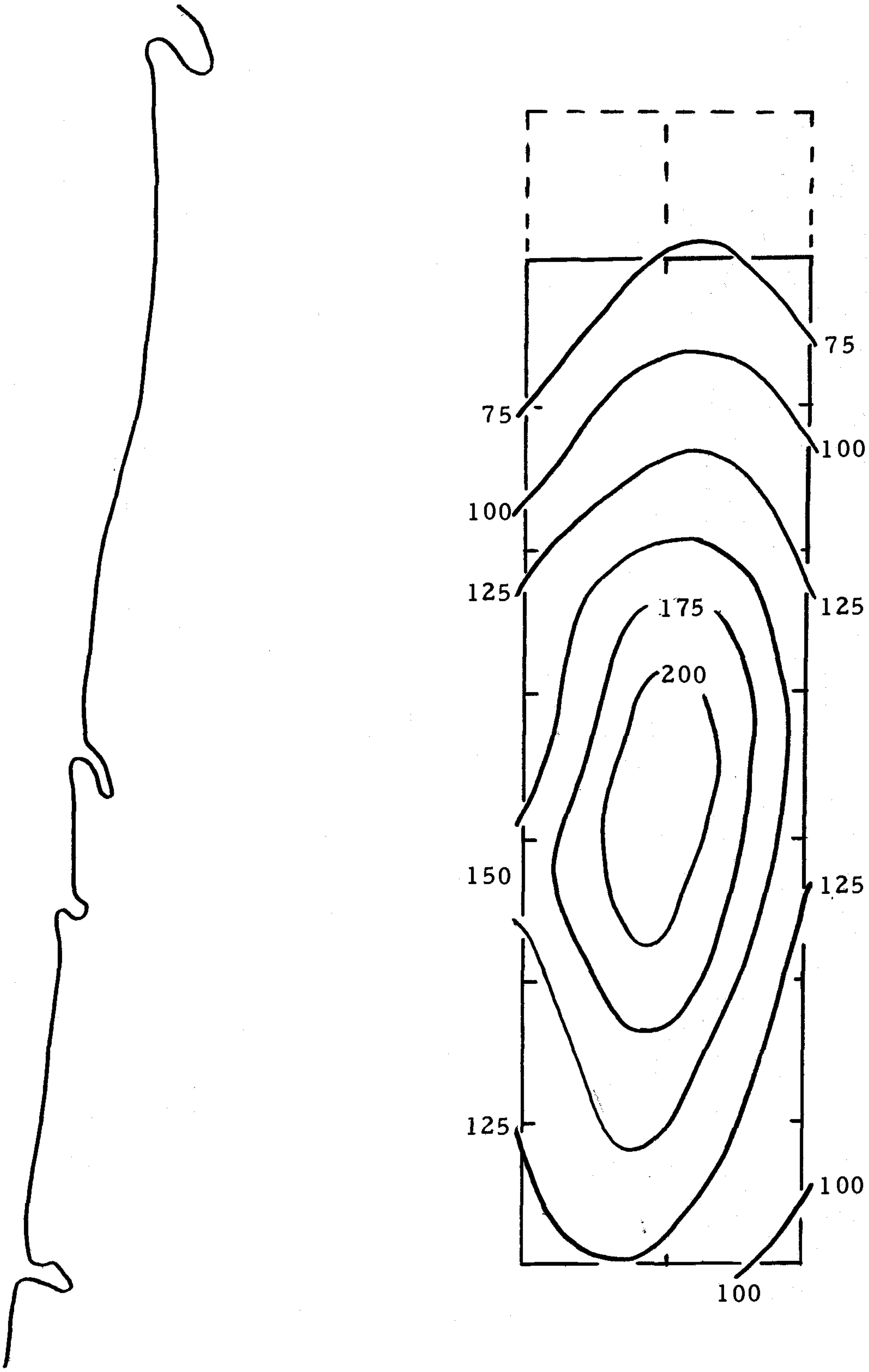


Figure A-3b. Net travel during episode, CC-3. (km)

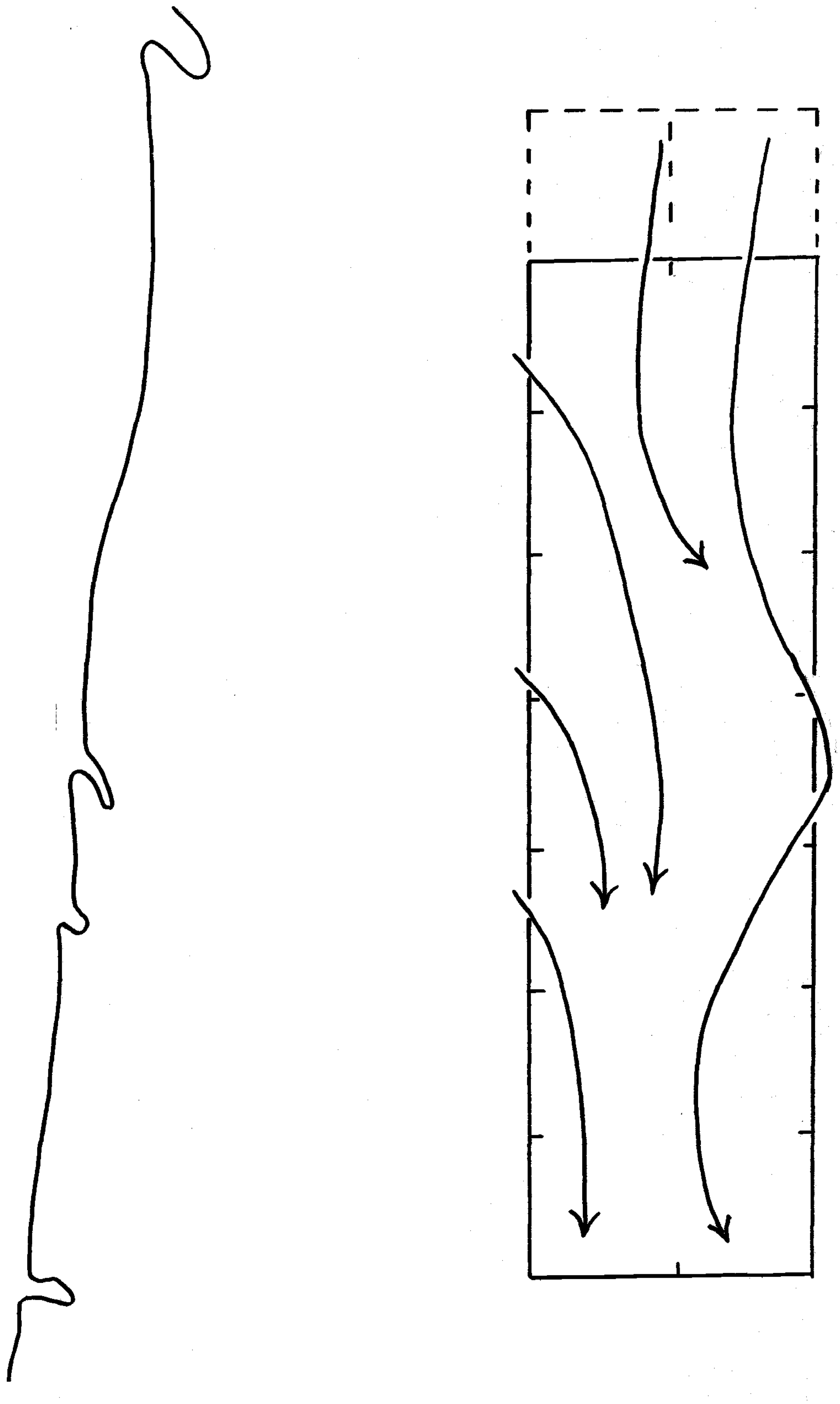


Figure A-3c. Episode-resultant streamlines, CC-3.

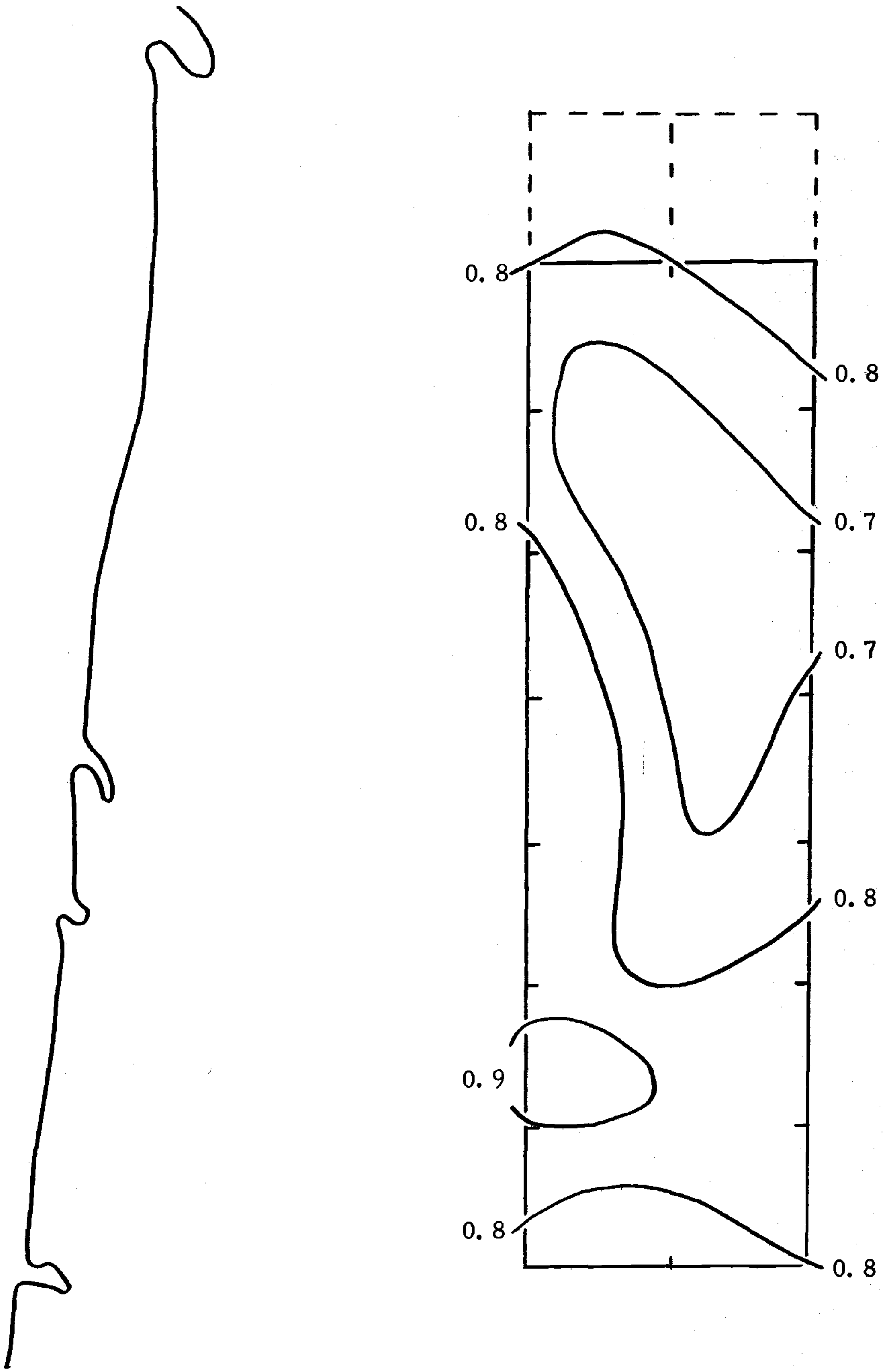


Figure A-3d. Depth of mixed layer, CC-3. (km)

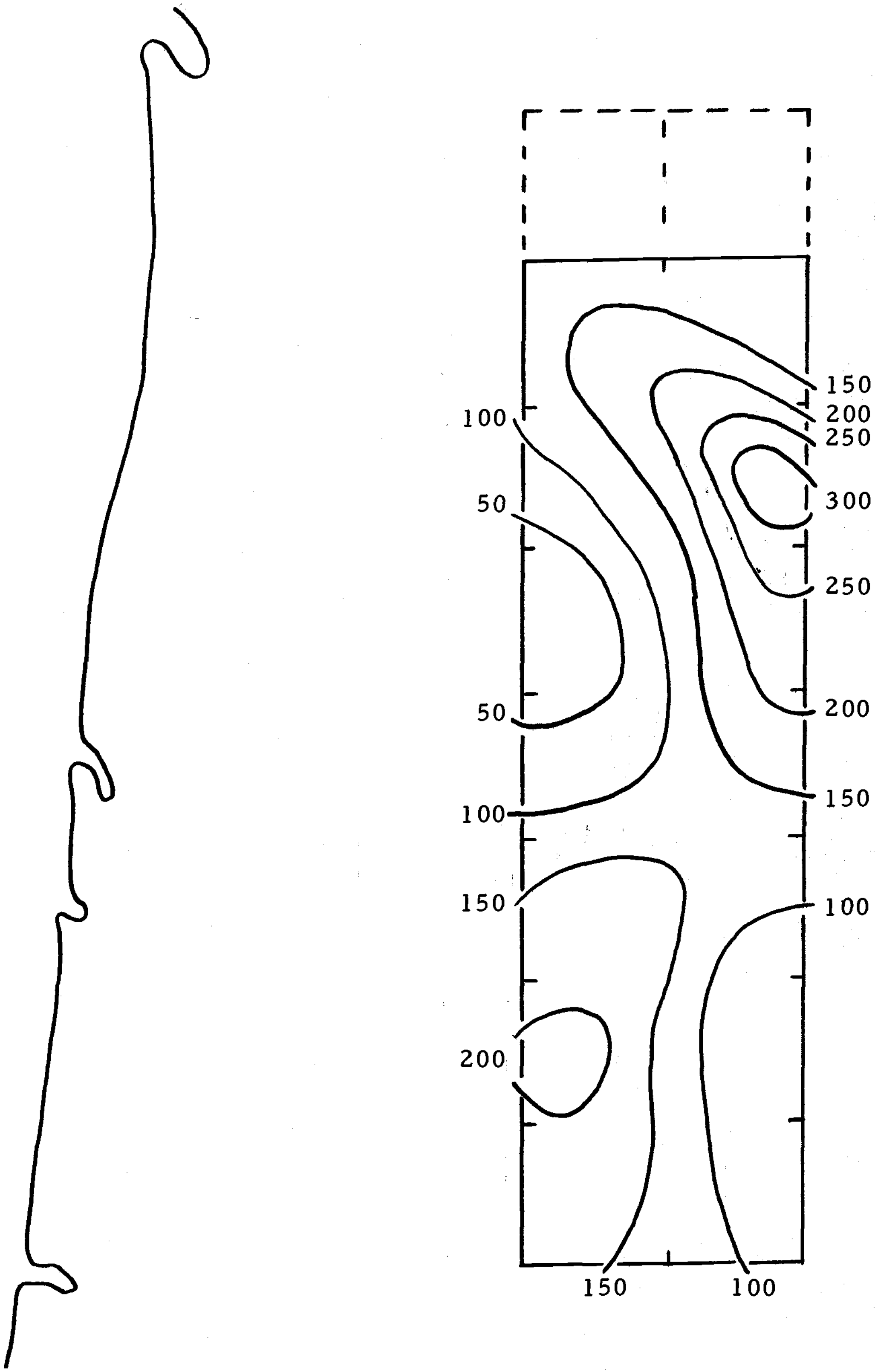
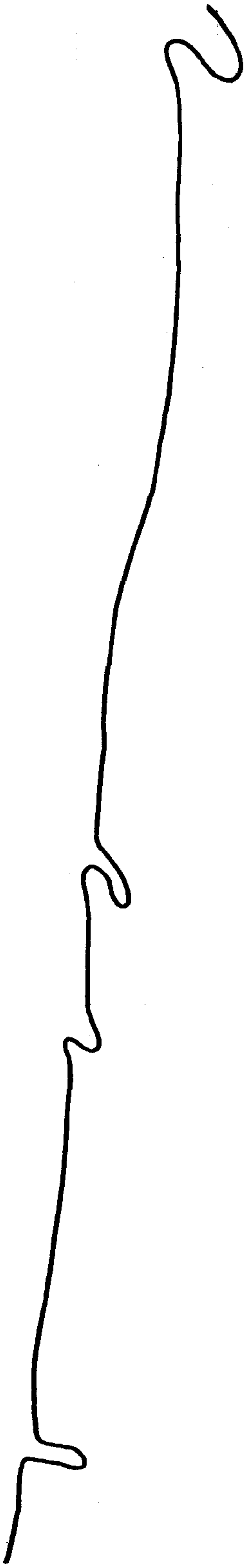


Figure A-4. Concentration pattern, CC-3, calculated with model. ($\mu g\ m^{-3}$)



10, 000	3, 000
20, 000	22, 000
3, 000	25, 000
3, 000	12, 000
16, 000	16, 000
25, 000	8, 000
25, 000	8, 000
8, 000	3, 000

Figure A-5a. Distribution of emissions, CC-4.
(kg day^{-1}/20-km square)

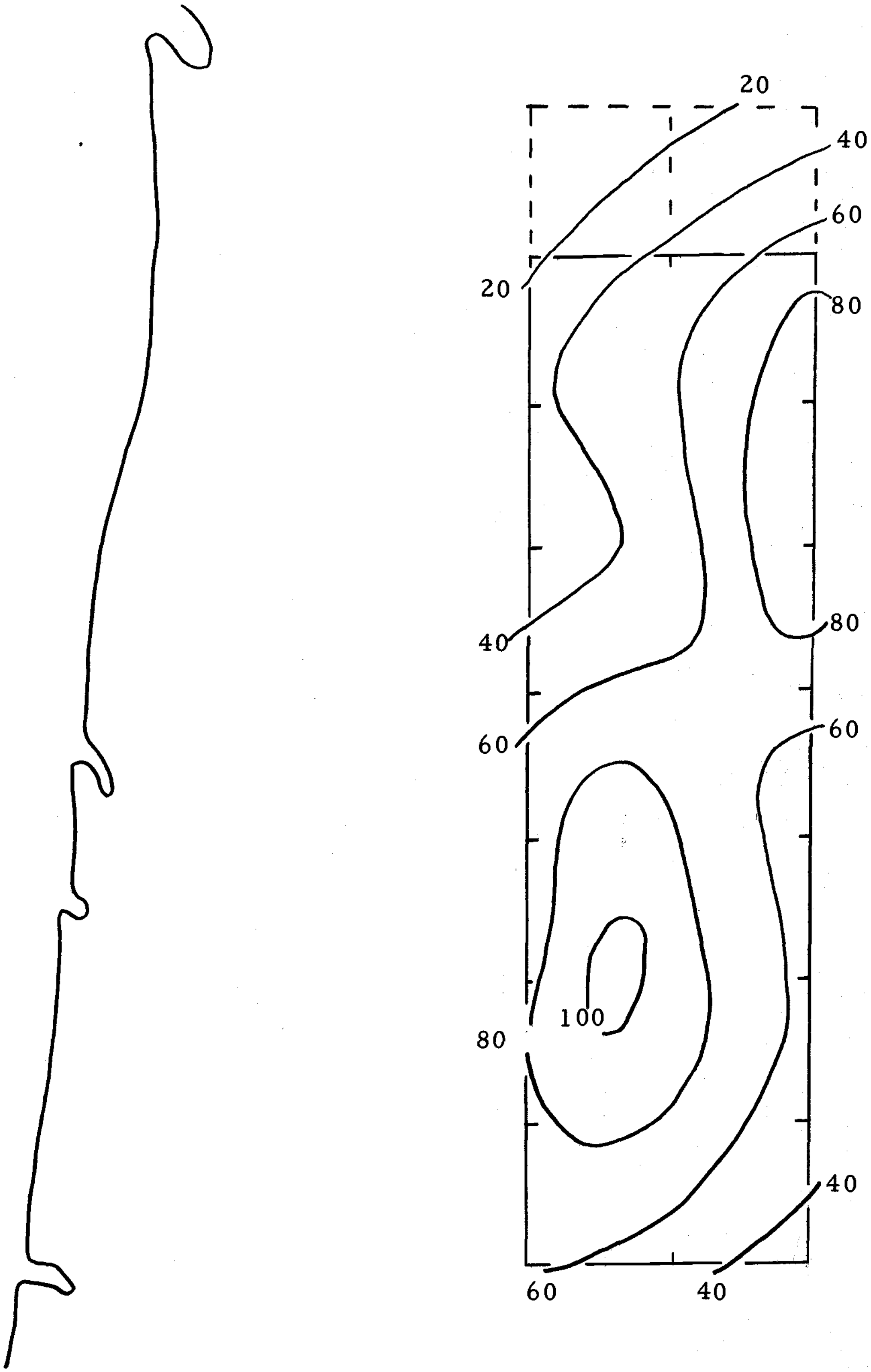


Figure A-5b. Net travel during episode, CC-4. (km)

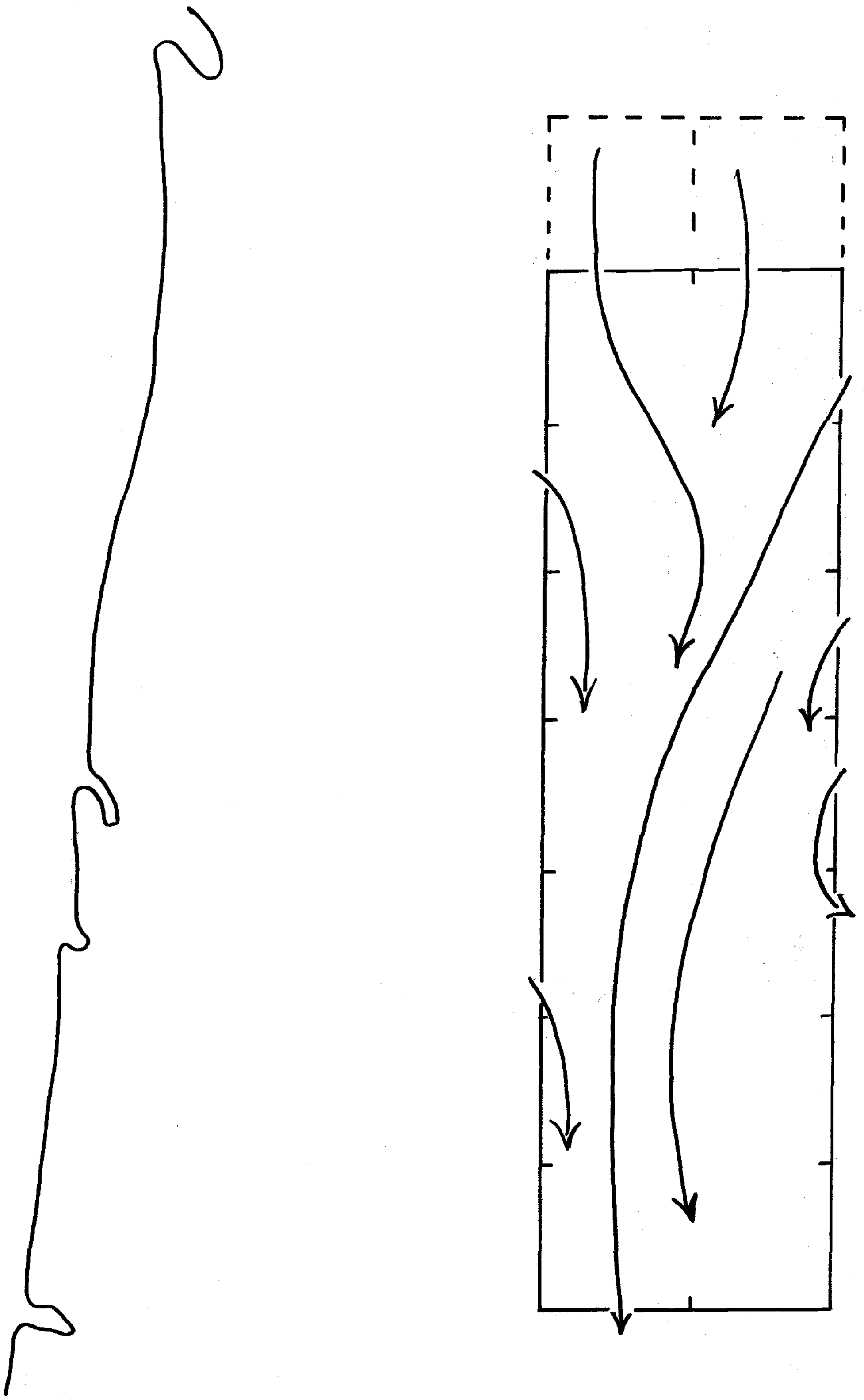


Figure A-5c. Episode-resultant streamlines, CC-4.

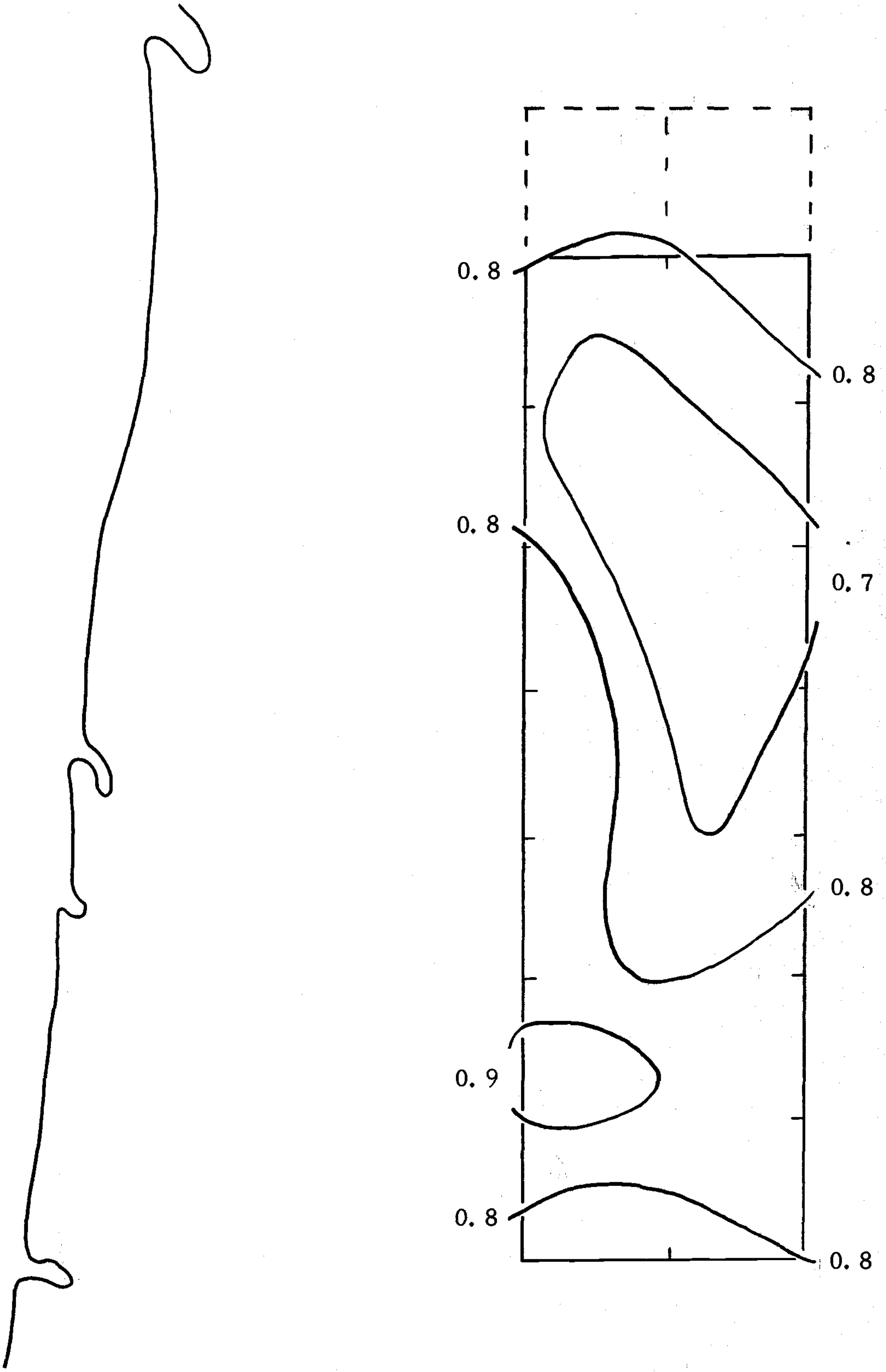


Figure A-5d. Depth of mixed layer, CC-4. (km)

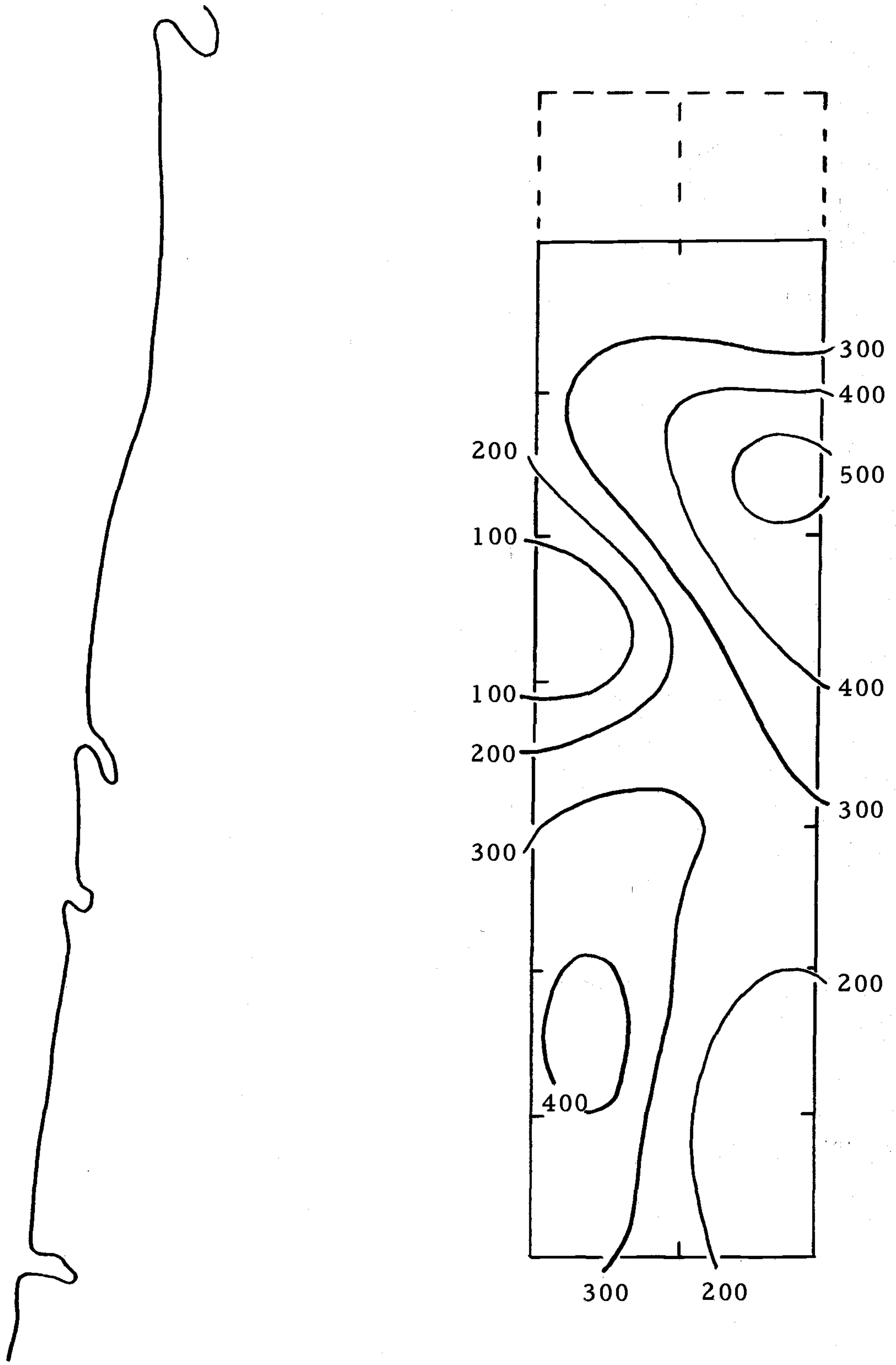


Figure A-6. Concentration pattern, CC-4, calculated with model. ($\mu g\ m^{-3}$)

Appendix II.

In this appendix, two additional analyses using the inverse configuration of the airshed-episode model are shown. As was input IC-1, for the analysis shown in Chapter IV. B., each of the net travel inputs has been applied as a North resultant wind.

Input IC-2, Figures A-7a and A-7b, includes an imaginary net travel pattern chosen to show a double maximum with a range approximately the same as input IC-1. As in that case, episode length is nine days, but here the mixed depth tends to dome over the mid-Valley as seems reasonable when the minimum net travel occurs there. Figure A-8 shows the pattern of emission rates calculated from input IC-2 with Equation (7).

The third net travel and mixed depth input, Figures A-9a and A-9b, is the same as input CC-4 for the conventional configuration shown in Appendix I. The top of the mixed layer is relatively flat and the layer is shallow. Episode length is ten days in order to simulate a relatively serious episode with not only a shallow mixed layer, but also very limited travel. The output map is Figure A-10.

As with input IC-1 in Chapter IV. B., these two sets of data were also applied to the special case in which an "industrial area" was inserted in the airshed. Figure 14 is repeated here as Figure A-11 to illustrate the limiting concentration allowed in the various

10-kilometer square boxes. The optimal allocations, Figures A-12 and A-13, illustrate the more widespread effect of the industrial area on emission rates when the atmosphere is more stagnant.

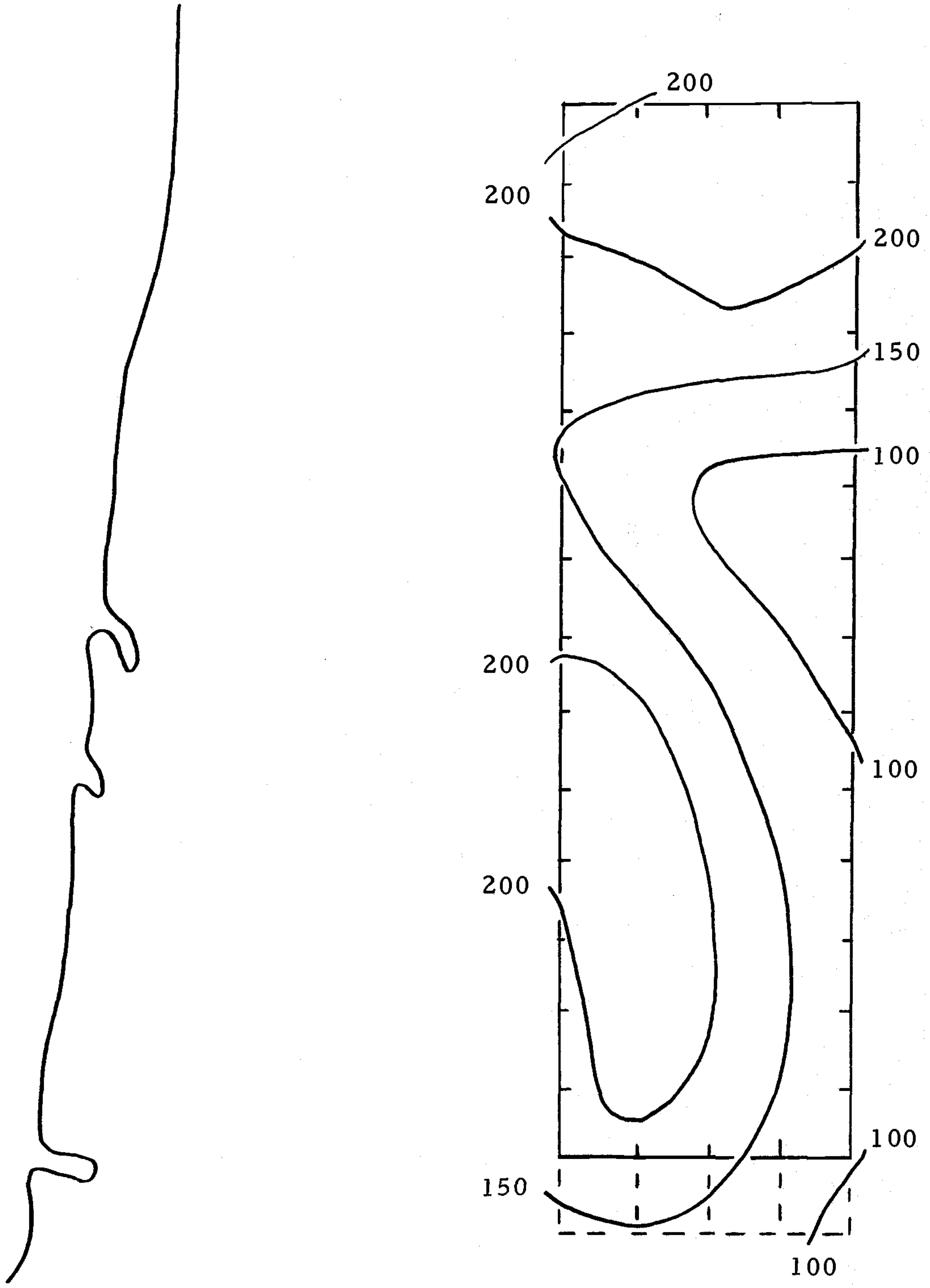


Figure A-7a. Net travel during episode, IC-2. (km)

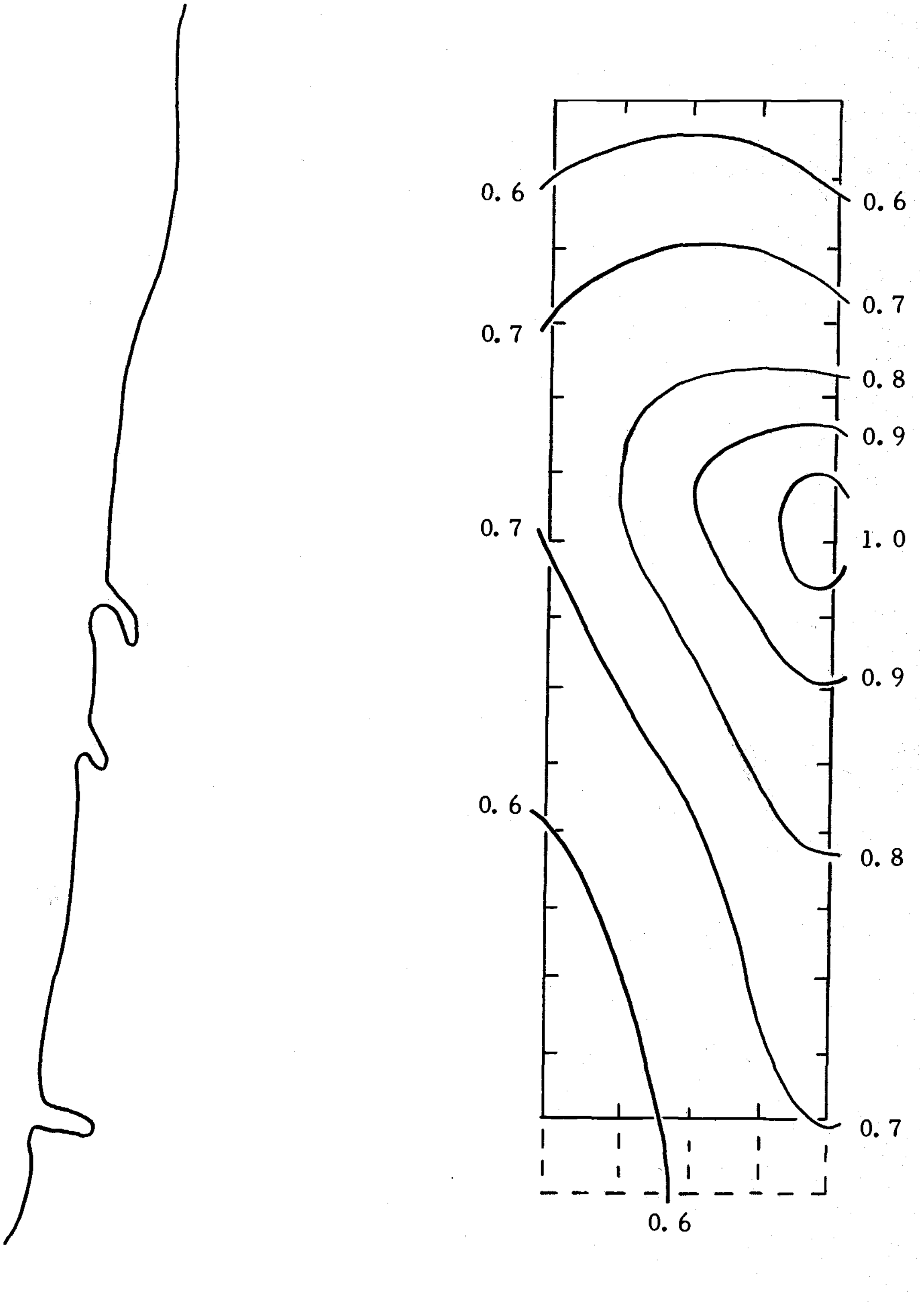


Figure A-7b. Depth of mixed layer, IC-2. (km)

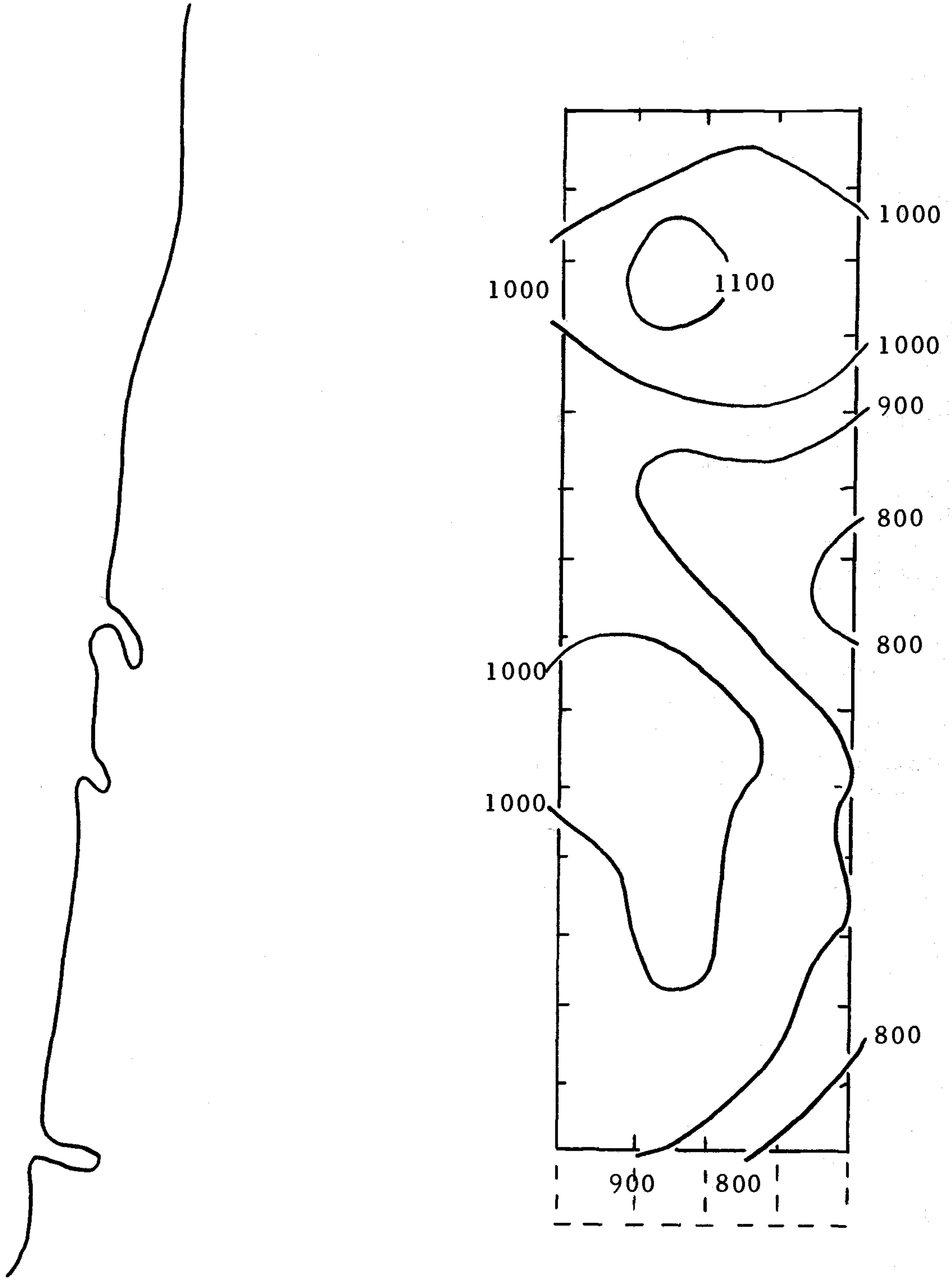


Figure A-8. Optimal allocation of emission rates, IC-2. (kg day^{-1}/10-km square)

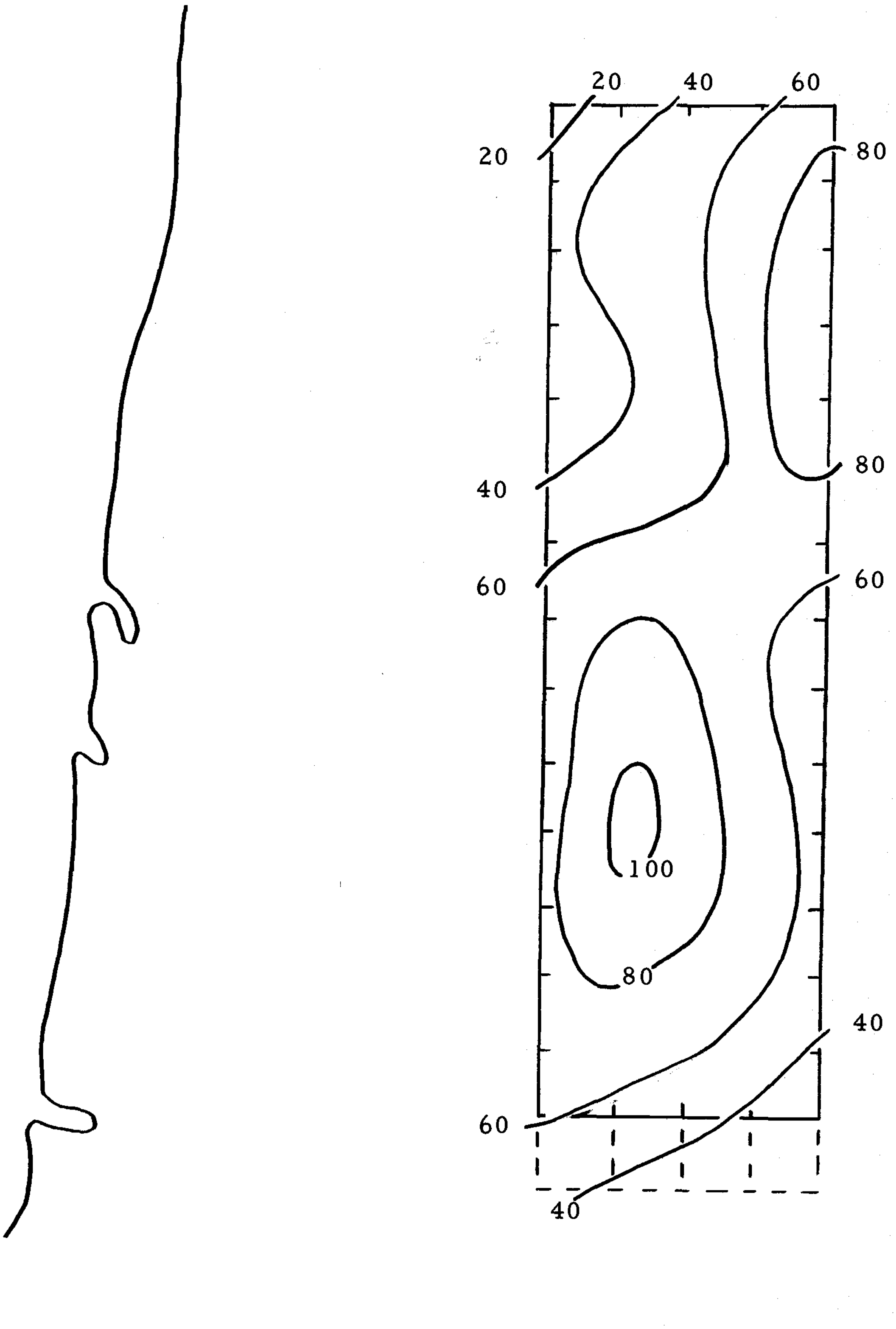


Figure A-9a. Net travel during episode, IC-3. (km)

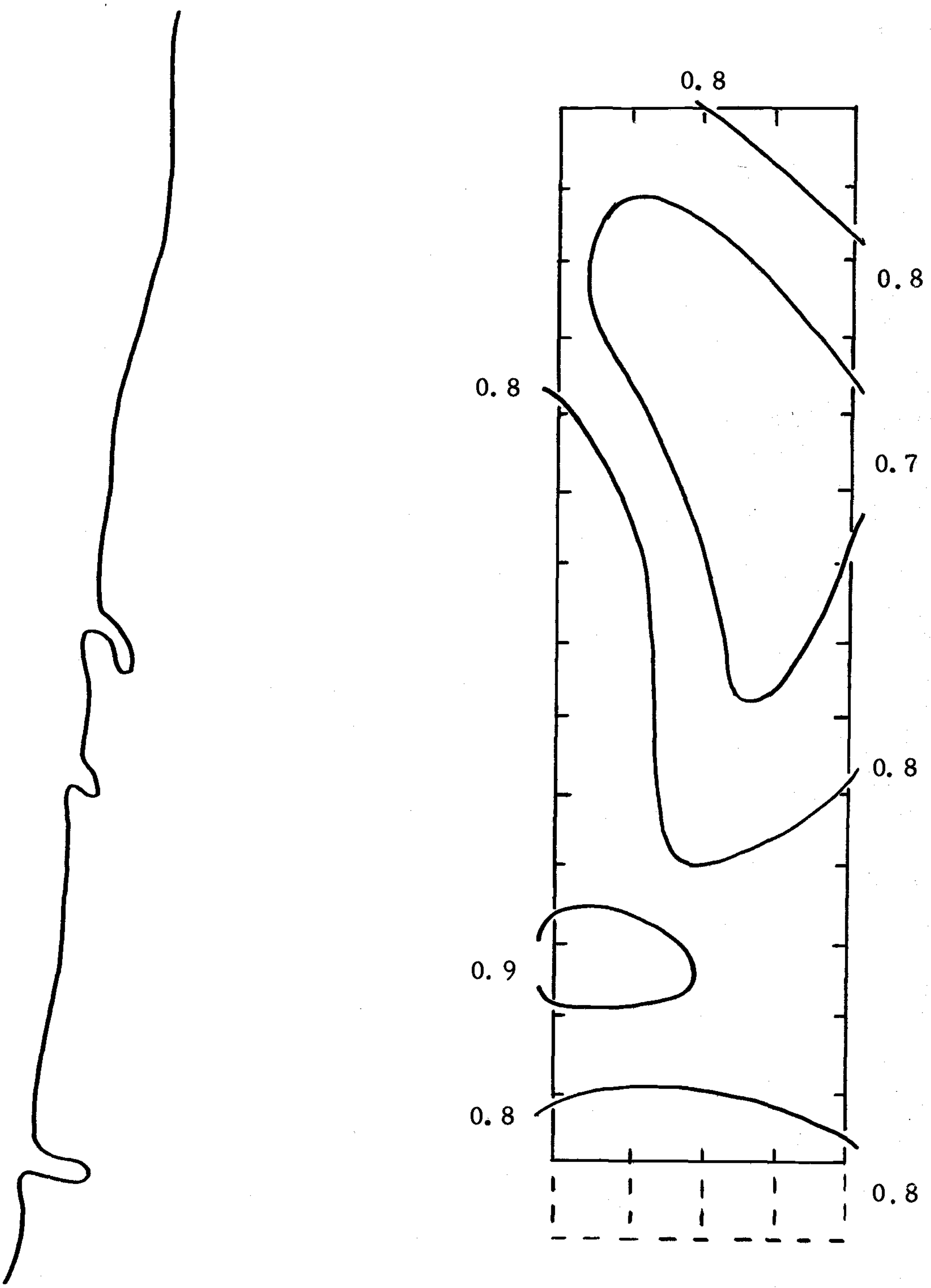


Figure A-9b. Depth of mixed layer, IC-3. (km)

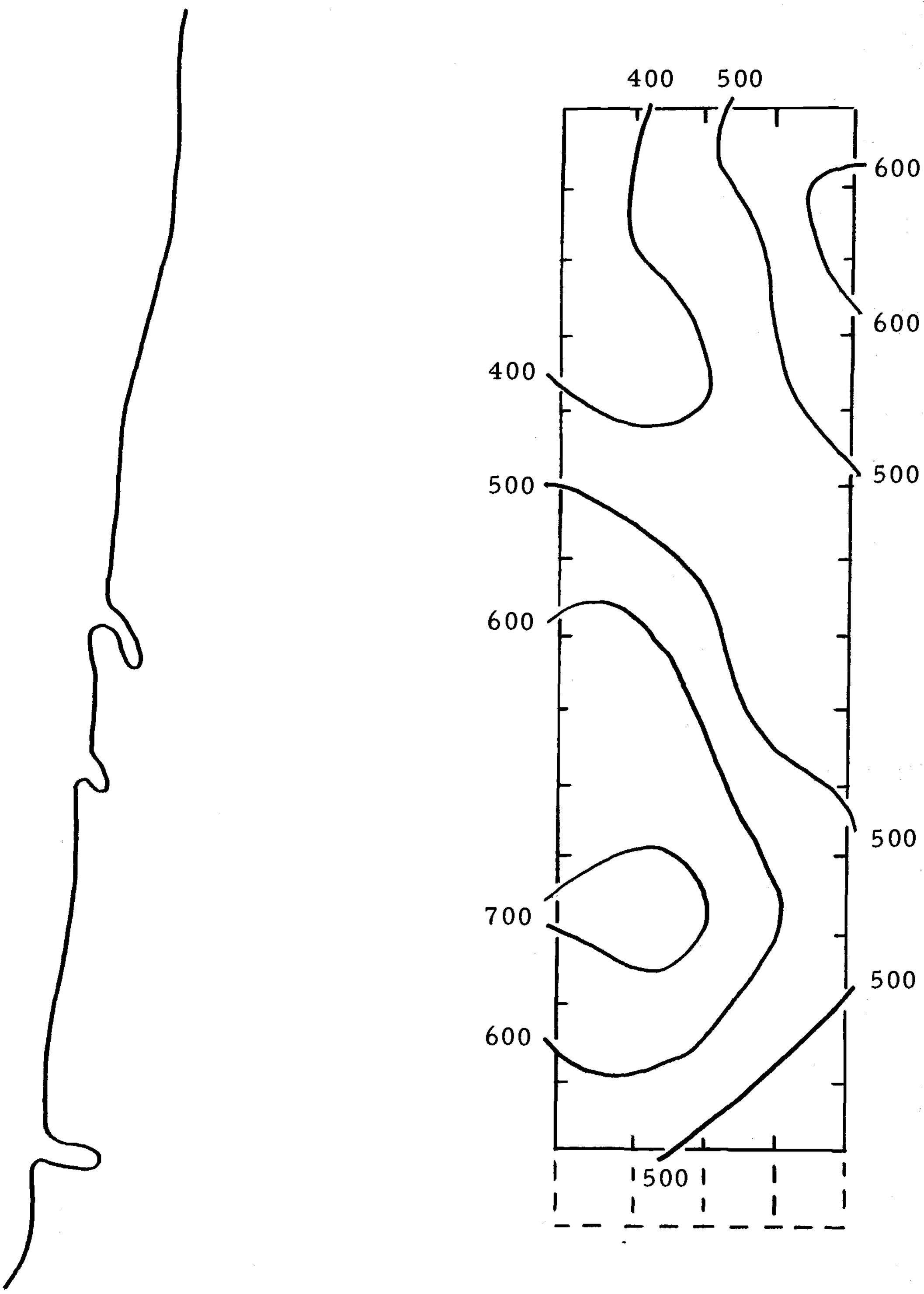


Figure A-10. Optimal allocation of emission rates, IC-3. (kg day^{-1}/10-km square)

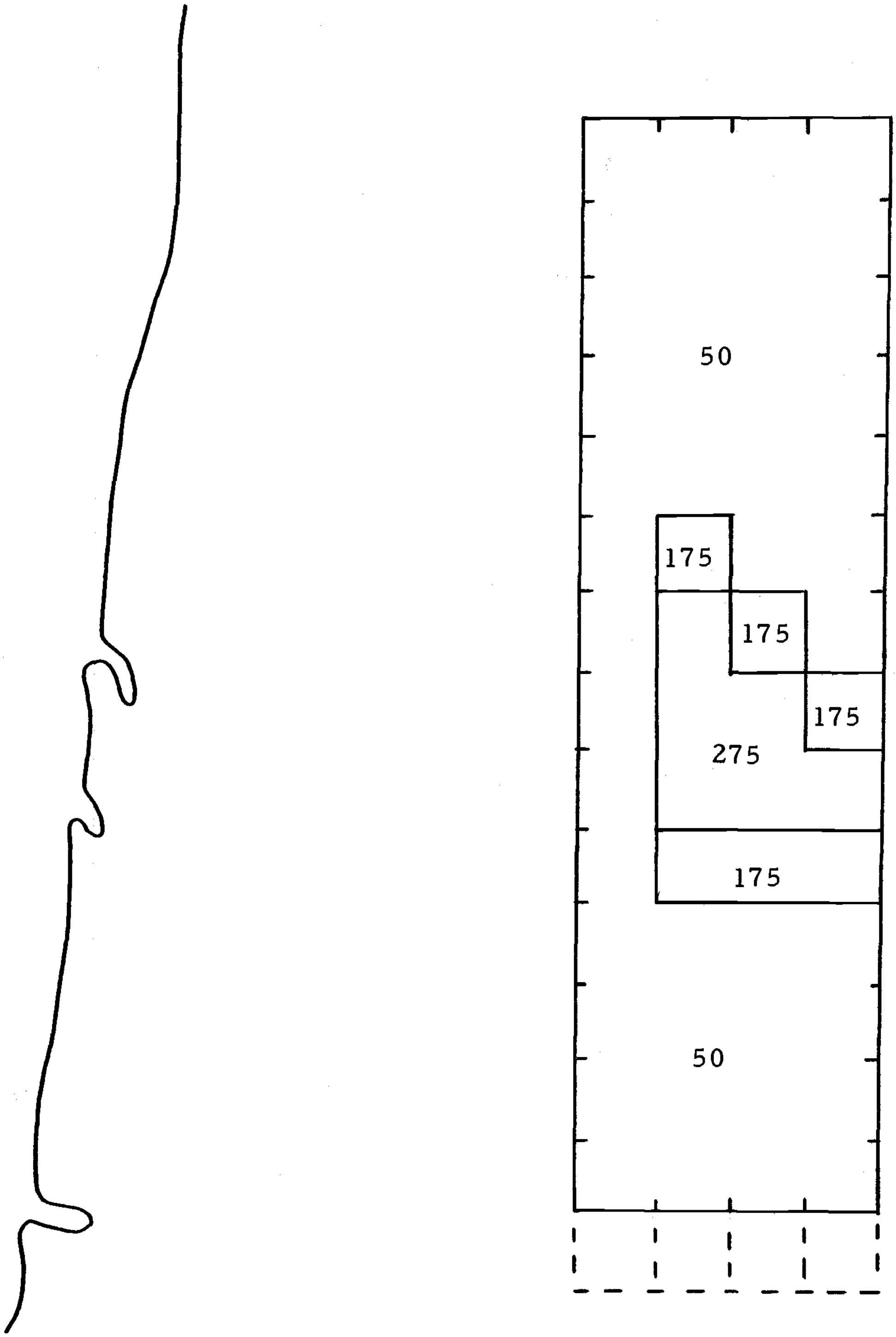


Figure A-11. Concentration limits; industrial area and buffer zone in mid-airshed. ($\mu g\ m^{-3}$)

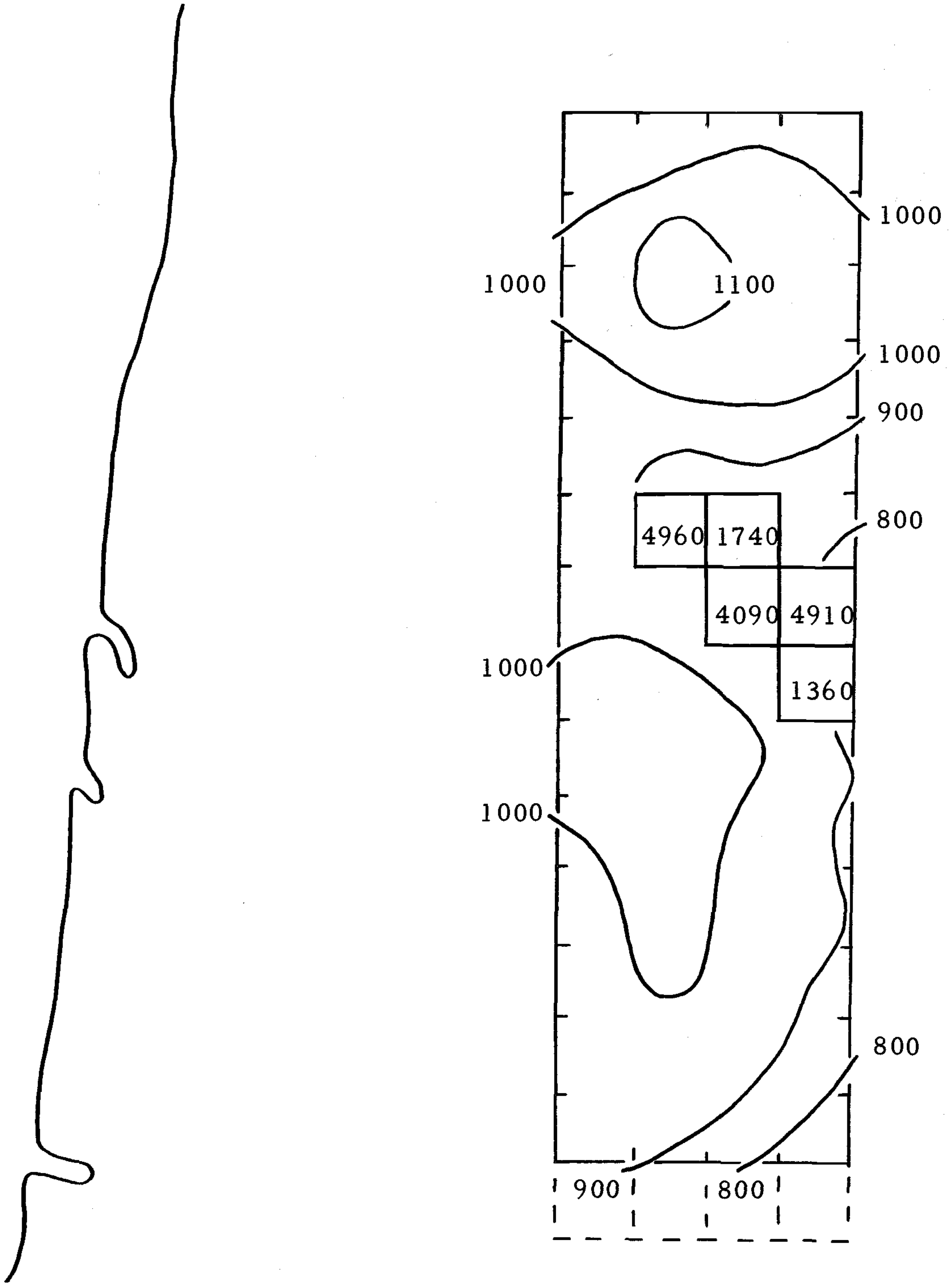


Figure A-12. Optimal allocation of emission rates, IC-2'. (kg day^{-1}/10-km square)

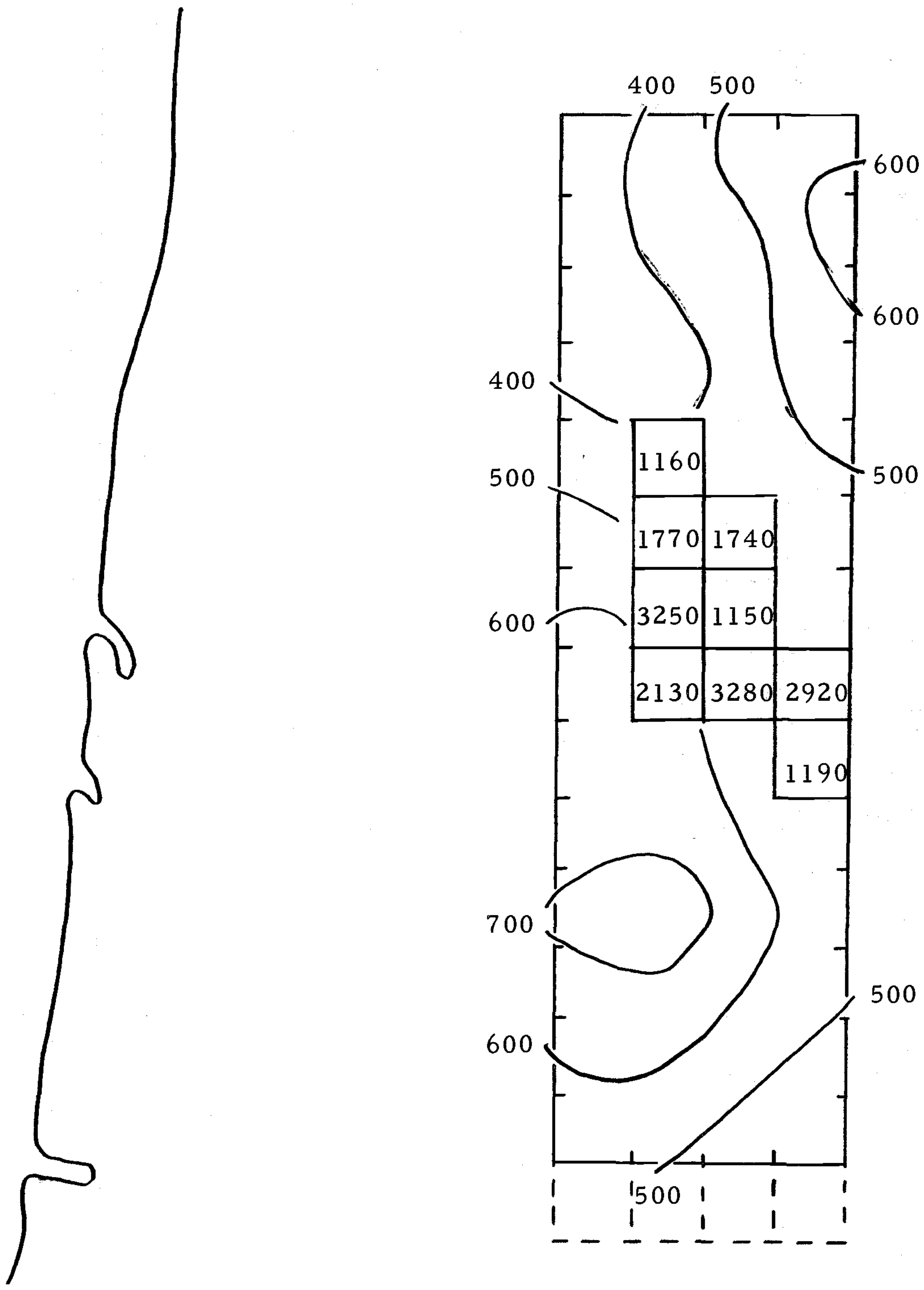


Figure A-13. Optimal allocation of emission rates, IC-3'. (kg day^{-1}/10-km square)