Land Use and Land Cover Information and Air-Quality Planning

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1099-B

Land Use and Land Cover Information and Air-Quality Planning

By WALLACE E. REED *and* JOHN E. LEWIS

THE INFLUENCES OF LAND USE AND LAND COVER IN CLIMATE ANALYSIS

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An example of environmental analysis using land use and land cover information

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LAND USE AND LAND COVER INFORMATION AND AIR-QUALITY PLANNING

By WALLACE E. REED [1] and JOHN E. LEWIS [2]

ABSTRACT

The land use and land cover information developed by the U.S. Geological Survey in the Central Atlantic Regional Ecological Test Site project has been proven useful when used in an improved technique for estimating emissions, diffusion, and impact patterns of sulfur dioxide (SO_2) and particulate matter.

Implementation of plans to control air quality requires land use and land cover information, which, until this time, has been inadequate. The land use and land cover data were used in updating information on the sources of point and area emissions of SO_2 and particulate matter affecting the Norfolk-Portsmouth area of Virginia for the 1971–72 winter (Dec.-Jan.-Feb.) and the annual 1972 period, and for a future annual period—1985. This emission information is used as input to the Air Quality Display Model of the Environmental Protection Agency to obtain diffusion and impact patterns for the three periods previously mentioned. The results are: (1) During the 1971–72 winter, estimated SO_2 amounts over an area with southwest-northeast axis in the central section of Norfolk exceeded both primary and secondary levels, (2) future annual levels of SO_2, estimated by anticipated residential development and point-source changes, are not expected to cause serious deterioration of the region's present air quality, and (3) for the 1971–72 winter, and annual 1972, period the diffusion results showed that both primary and secondary standards for particulate matter are regularly exceeded in central Norfolk and Portsmouth. In addition, on the basis of current control programs, the 1985 levels of particulate matter are expected to exceed the presently established secondary air-quality standards through central Norfolk and Portsmouth and in certain areas of Virginia Beach.

Land use and land cover information can be used to estimate emissions for inputs to diffusion models and to interpret the implications of diffusion patterns for: (1) Implementing various control strategies, (2) selecting sites of air sampling stations, and (3) predicting the effects that proposed changes in land use and land cover might have on emission patterns and air quality.

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INTRODUCTION

As an initial step toward satisfying the nationwide need for current, comparable land use and land cover information, the U.S. Geological Survey (USGS) compiled land use and land cover information in its Central Atlantic Regional Ecological Test Site (CARETS) project.[3] Among the many uses of that information are its applications in evaluating air-quality control strategies and implementation programs.

A majority of the States' air-quality control implementation plans proposed during 1972 are highly dependent upon emission-control strategies. Basic guidelines for preparing State air-quality implementation programs were established in the Clean Air Act of 1970 (PL 90–604) as well as in the Federal Registers, April 7 and August 14, 1971 (U.S. Environmental Protection Agency, 1971b and 1971c). Effective consideration of alternative quality-control strategies and implementation plans was seldom feasible due to lack of time and inadequate land use and land cover information. Necessary land use and land cover information for those purposes was compiled during the CARETS study.

This paper examines the relationship between air quality and land use and land cover, and identifies the types of land use and land cover information needed to evaluate air quality control strategies. It also presenst a description of the land use and land cover information available, and suggests applications of this information to Norfolk area air-quality planning.

[3] The CARETS Project was sponsored in part by the National Aeronautics and Space Administration under Interagency Memorandum of Understanding No. S–70243–AG. (See Reed and Lewis, 1975 NTIS No. E–77–10018.)

The data were collected during a study of the air quality in the Norfolk-Portsmouth, Virginia, Standard Metropolitan Statistical Area (SMSA) and focuses on strategies to control the effects of sulfur dioxide and suspended particulates. The Norfolk area was selected for two primary reasons. First, the physical characteristics of its location and its air-quality planning problem are similar to those of many other metropolitan regions. Second, the greatest range of land use and land cover data and specific information produced in the CARETS project had been for the Norfolk area (Alexander, 1972).

ACKNOWLEDGMENTS

The extensive advice and assistance received from the staff of the Commonwealth of Virginia, State Air Pollution Control Board and personnel of the board's Air Quality Control Region VI in Virginia Beach; the Southeastern Virginia Planning District Commission; Virginia Department of Highways; the Environmental Protection Agency, Region III, Philadelphia, Pa.; and the Office of Air Programs, Office of Land Use Planning in North Carolina are gratefully acknowledged, as are the research efforts of Gregory A. Shoemaker and Nelson M. Nones.

LAND USE AND LAND COVER AND AIR-QUALITY PLANNING

Developing and evaluating air-quality control strategies depend on identifying current and anticipated relationships between patterns of land use and land cover and: (1) amounts of air pollutants over specific land use and land cover categories; (2) amounts of air pollutants over adjacent or downwind areas; and (3) the impacts of various concentrations of air pollutants on land uses and land cover.

Land use and land cover activities affect air quality by emitting manmade and natural pollutants. These pollutants are dispersed by local, regional, and global airflow and affect the health, safety, operating costs, and other characteristics of all land use and land cover activities. The intensity of effect depends on the types of chemical and physical impacts that pollutants may produce, on the degree to which pollutants are concentrated in the air, and on the length of time a given activity or process is exposed to pollutants. The concentration of pollutants depends on the quantity emitted and on the location of emitting sources relative to the direction and stability of airflows. Land surface characteristics such as roughness, albedo, thermal diffusivity, amount of water, and amount of transpiring surfaces in a given area influence the meteorological conditions affecting the stability of airflows. Each of these surface characteristics can be extensively modified by the activities or processes conducted on and structures that occupy urban and rural land.

AIR-QUALITY CONTROL STRATEGIES

Given the relationships between land use and land cover and airflows, one can employ a number of strategies to achieve given levels of air quality. The various perspectives from which strategies may be developed include:

I. Focus on emission sources—emission-source control

1. Change in type of activity.
2. Change in fuel and other process inputs.
3. Installation of emission-control devices.
4. Change in timing of emission.
5. Change in the spatial distribution of stationary sources with respect to airflow and receptor locations.

II. Focus on airflow—airflow modification

1. Changes in surface roughness.
2. Changes in surface albedo.
3. Changes in transpiring surface area.
4. Changes in local precipitation.

III. Focus on receptor

1. Change in the activities affected by pollutants.
2. Change in contact between air and receptor through structural and air-conditioning modifications.
3. Change in the timing of stationary and mobile receptor activities to avoid periods of high concentration.
4. Change in the spatial distribution of stationary and mobile receptors.

Each of these strategies involves varying degrees of land use and land cover management and the need for land use and land cover information.

For further discussions of control strategies focused on urban areas see Allan M. Voorhees and Associates and Ryckman, Edgerley, Tomlinson and Associates (1971); and Kennedy and others (1971).

STRATEGY EVALUATION BY FEDERAL AND STATE AGENCIES

The Clean Air Act of 1970 and Environmental Protection Agency (EPA) action required State and local air-quality planning agencies to identify air-quality control regions, to select pollutant control strategies, and to develop implementation plans by early 1972 (PL 90–604 and U.S. Environmental Protection Agency, 1971b and 1971c). Because of time and cost constraints, most planning agencies could not assemble the types of land use and land cover information needed to evaluate fully the range of strategies that might have been applied in each region. Therefore, EPA most frequently encouraged the collection of land use and land cover information suitable for identifying regions with similar air-quality control problems and suitable for analyzing strategies focused on emission source controls.

The strategy of controlling emissions at their source required land use and land cover information to identify sources and was in line with the goal of reducing total nationwide emissions regardless of the spatial distribution of sources. Furthermore, given the types of sources and the political realities facing planners in most air-quality control regions, emission-source control strategies appeared to be the easiest to implement. Because the Federal Government is attempting to control mobile emission sources, local and State action could be directed toward controlling point and area emission sources, the cost of which appeared to be less than the cost of reorganizing land use and land cover patterns or changing the timing of activities or processes emitting or receiving pollution.

In the absence of more detailed land use and land cover information, emission-source control strategies appeared to be most effective in achieving primary and secondary air-quality standards without inhibiting growth in each control region. Based on this strategy, regional implementation plans were developed that called for rollback procedures or proportional reductions in regional emissions (U.S. Environmental Protection Agency, 1970 and 1971c).

Although the emission-source strategy is reasonable, strategies focusing on land use management, as yet unevaluated, might be more effective, either individually or in combination with adopted emission-source strategies, in specific air-quality control regions. EPA's current program of planning for Air Quality Maintenance Areas calls for the refinement of existing strategies and plans and the evaluation of alternative strategies.

Information adequate for this planning and testing of alternatives is becoming available. Specifically, the U.S. Geological Survey is supplying current, comparable land use and land cover information that can easily be related to the emission, receptor, and airflow characteristics of local, regional, or nationwide areas. Detailed meteorological data for air-quality control regions are available from the National Oceanic and Atmospheric Administration. Air-quality sampling networks are operating or being established in each control region. Where these sampling programs are not yet adequate and where adequate meteorological and land use and land cover data exist, models for estimating pollutant diffusion and concentration can be used to evaluate planning strategies related to land use and land cover.

LAND USE AND LAND COVER INFORMATION NEEDED FOR COMPREHENSIVE AIR-QUALITY PLANNING

Comprehensive air-quality plans should evaluate the short- and long-term physical and social impacts of a range of strategies along with their potential for implementation. The types of land use and land cover information needed for comprehensive plans include:

1. *Activity location.*—For each type of process or fuel consumed, the current and anticipated location of stationary and mobile activities emitting and receiving pollutants.
2. *Activity behavior.*—For each type of pollutant, the timing and intensity of emissions or reception.
3. *Activity physical characteristics.*—The geometry, albedo, and surface material of the area and the region's activities and processes affecting local airflows.

These types of land use and land cover information are essential for developing detailed emission inventories, for analyzing airflow patterns, for evaluating probable impact on receptor activities, for identifying locations for air-quality sampling stations, and for improving the calibration of models used to estimate pollutant diffusion. Much of this land use and land cover information is being provided directly or can easily be estimated from the USGS land use and land cover information.

LAND USE AND LAND COVER INFORMATION DEVELOPED IN THE CARETS PROJECT

The CARETS project was one of a series of experimental studies by the USGS to establish a coordinated Federal program for the standardization and production of land use and land cover data. These activities consisted of interpreting land use and land cover data from remotely sensed imagery provided by NASA's Aircraft and Earth Resources Satellite Programs, organizing these data into specific types of information, and providing this infor-

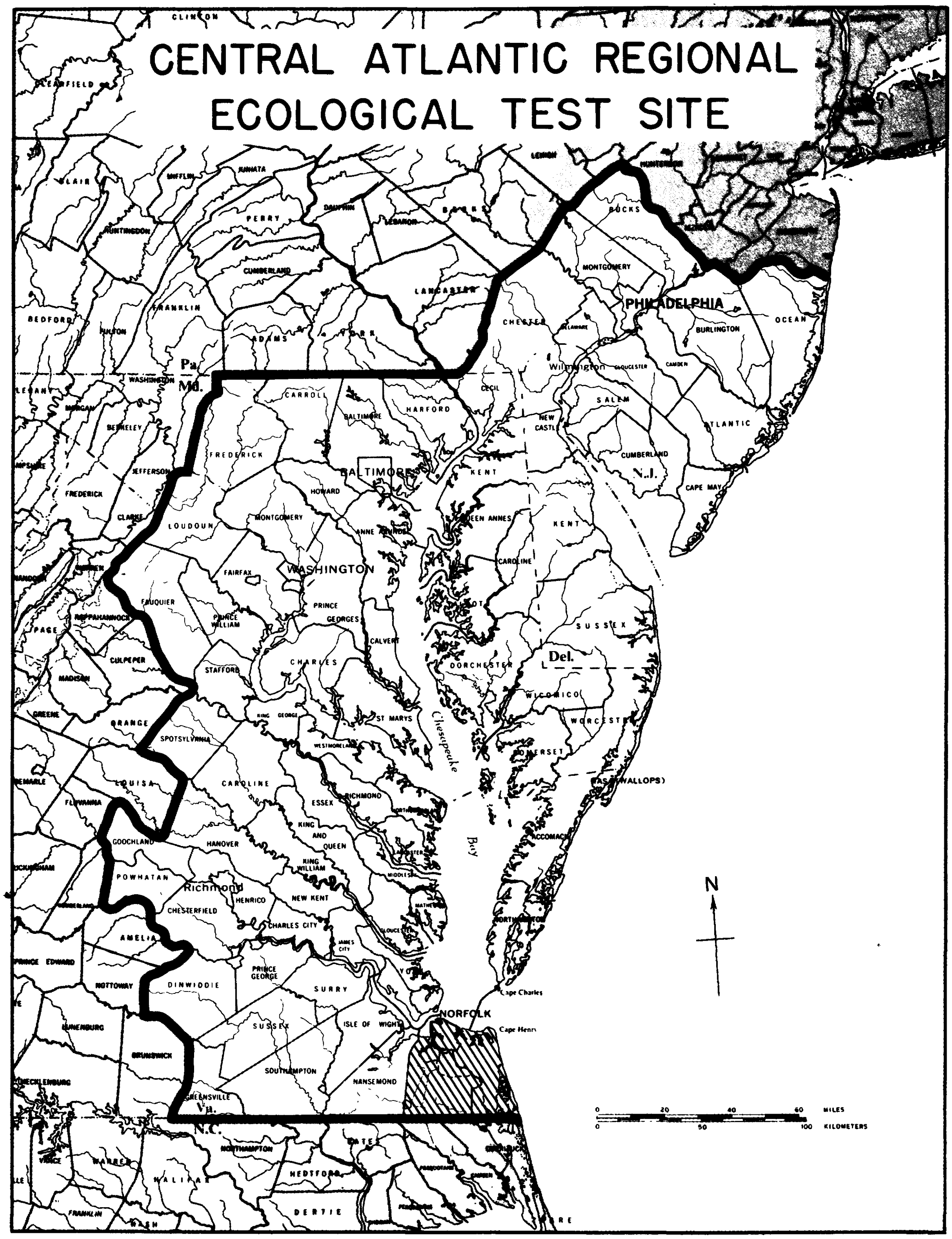


FIGURE 1.—Map of CARETS showing 1970 Norfolk-Portsmouth Standard Metropolitan Statistical Area (SMSA).

mation in statistical and graphical formats to cooperating State, regional, and private users with responsibilities for land use and land cover planning and management. The CARETS project includes the Norfolk-Portsmouth SMSA (Standard Metropolitan Statistical Area) area of Virginia (fig. 1).

LAND USE AND LAND COVER CLASSIFICATION SCHEME FORMULATED BY THE U.S. GEOLOGICAL SURVEY

To be of maximum effectiveness to users, land use and land cover data must be organized in categories related directly to a range of land management decisions or in categories from which estimates of such data can easily be made. The first version of the USGS land use and land cover classification scheme (Anderson and others, 1972) is represented by Levels I and II in table 1. In table 1, Levels III and IV provide examples of how the basic system can be expanded to meet the needs of various users, in this case, those of air-quality planners.

In the CARETS project the land use and land cover classification system was organized to derive Level I information primarily from satellite data. This level is intended for use in the most general forms of land use and land cover analysis and decisionmaking. Level II is intended to be derived primarily from high-altitude aerial photographs and can be used for decisions requiring increasingly detailed information. Successively more detailed levels of classification of land use and land cover (Levels III and IV of table 1) can be provided by State and local user agencies for local air quality evaluation and planning. Such planning usually requires more information on urban and agricultural activities than can be provided directly by Level II data. Many other Level I and II categories such as information

TABLE 1.—*Land use and land cover classification scheme for use with remotely sensed data*

Level I		*Level II*		*Level III*		*Level IV*	
1	Urban and built-up	11	Residential	111	High-density residential.	1111	High-density residential structures.
		12	Commercial and services.	112	Medium-density residential.	1112	Yards and open space.
		13	Industrial	113	Low-density residential.	1113	Parking.
		14	Extractive	114	Residential construction.	1114	Streets and highways.
		15	Transportation communications and utilities.			1115	Height of structures.
		16	Institutional			1116	Height of vegetation.
		17	Strip and clustered settlement.				
		18	Mixed				
		19	Open and other				
2	Agricultural land	21	Cropland and pasture				
		22	Orchards, groves, bush fruits, vineyards, and horticultural areas.				
		23	Feeding operations				
		24	Other				
3	Rangeland	31	Grass				
		32	Savannas (palmetto prairies).				
		33	Chaparral				
		34	Desert shrub				
4	Forest land	41	Deciduous				
		42	Evergreen (coniferous and other).				
		43	Mixed				
5	Water	51	Streams and waterways				
		52	Lakes				
		53	Reservoirs				
		54	Bays and estuaries				
		55	Other				
6	Nonforested wetlands	61	Vegetated				
		62	Bare				
7	Barren land	71	Salt flats				
		72	Beaches				
		73	Sand other than beaches.				
		74	Bare exposed rock				
		75	Other				
8	Tundra	81	Tundra				
9	Permanent snow and icefields.	91	Permanent snow and icefields.				

Source: Anderson and others, 1972.

on water and bare land activities can be used effectively as provided by the systems. The example Level III and IV categories are suggested classifications related to specific activities or processes (industry by Standard Industrial Code, agriculture by crop type, construction affecting each type of Level III activity) from which emissions or receptor impact can be estimated. These categories can also be used to identify three-dimensional profiles of structures and materials for various land uses and land cover that may affect airflow. Each of these categories could be measured uniformly nationwide or modified for the specific urban and rural characteristics of various EPA administrative or control regions.

MEASUREMENT DETAIL AND ACCURACY

The data used in this report are from high-altitude aerial photographs and were mapped onto a controlled photomosaic base at a scale of 1:100,000. Land uses covering an area of not less than 4 ha (hectare) can be interpreted effectively at this scale at Level I and II. This degree of detail insures the rapid assembly of data useful to a wide range of Federal and State users.

Figure 2 shows a part of a controlled photomosaic covering the Norfolk, Va., area, and figure 3 shows the same area as mapped at Level I and Level II.

Experiments are proceeding to determine the levels of accuracy needed by various users. With EPA and State-sponsored registration systems in use to identify the principal emission sources, air-quality evaluators might be able to accept levels of error in land use and land cover areal measurement of 5 percent or greater, in favor of rapid complete regional coverage and frequent updating of area measurements indicating land use and land cover change.

POLYGON RECORDING SYSTEM

Land use and land cover data are prepared for computer manipulation by converting the boundaries of the individual land use units (known as polygons) into digital form. In this form a wide variety of computations can be made upon the data. For example, computations for percentage of total area for particular land use categories can be calculated easily for specific census tracts, jurisdictions, or other enumeration areas such as grid patterns established for air pollutant emission estimating.

USER PRODUCTS

After the data have been digitized and stored in computer-readable form, various types of information can be derived. Tables of area, perimeter, rate of change and other characteristics of land use and land cover type can be prepared for any jurisdiction requested. In addition to tabular output, graphic information can be provided or, if needed, the original remotely sensed data.

By the end of 1973, land use and land cover information having a minimum mapping unit size of 4 ha was available for the entire CARETS area.

EPA anticipates the early completion of a nationwide information system to monitor the location and change in major point and area emission sources. This National Emission Data System (NEDS) will identify, by Universal Transverse Mercator (UTM) coordinates, all point sources emitting more than 100 megagrams (Mg) annually of any of the five major pollutants along with any other high-emission sources (U.S. Environmental Protection Agency, 1971b and 1971c). Area and mobile source emission contributions will be monitored by county on the basis of fuel purchases.

The currently operational USGS nationwide land use and land cover mapping and data compilation program provides a useful source of land information for air-quality control analysis. The evaluation of air-quality control strategies for the Norfolk-Portsmouth SMSA presented in this report provides an example of the type of use which can be made of the information products prepared by this program.

LAND USE AND LAND COVER INFORMATION FOR AIR-QUALITY PLANNING IN THE NORFOLK-PORTSMOUTH STANDARD METROPOLITAN STATISTICAL AREA

The land use and land cover, geographic setting, and air-pollution characteristics of the Norfolk-Portsmouth SMSA, which includes the cities of Norfolk, Portsmouth, Chesapeake, and Virginia Beach, present a site and air-quality planning problem similar to many East Coast and Midwestern metropolitan areas. Air-quality planning for this major segment of Virginia's Air Quality Control Region VI indicates how land use and land cover information can be used at regional, State and national scales. Virginia Air Quality Control Region VI includes both the 1970 Norfolk-Portsmouth SMSA, and the industrial area of Newport News and Hampton, separated from Norfolk by Hampton Roads, the broad estuary at the mouth of the James River (Commonwealth of Virginia, 1972a).

The Norfolk area is located on the coastal plain of Virginia at the mouth of the Chesapeake Bay and contains the only stretch of ocean frontage

FIGURE 2.—Controlled photomosaic showing part of the Norfolk-Portsmouth SMSA.

which is easily accessible to much of central Virginia and northern North Carolina (fig. 1). The area's economy and land use reflect strong and rapidly growing industrial, commercial, transportational, institutional, recreational, and residential components.

Geographic characteristics that influence the area's airflows and pollutant dispersion are a nearly flat topographic surface, extensive water surface in wetlands, rivers, and estuaries, proximity to the open Atlantic Ocean, and an extensive mixture of agriculture and forest lands.

Primary activities in the Norfolk area include the base of naval operations for the Atlantic Fleet, shipbuilding and repair, coal and grain exporting, general shipping, chemical and fertilizer manufacturing, wholesaling to surrounding eastern Virginia and North Carolina, truck farming and fishing, and tourism focused on the area's ocean beaches, estuarine waterfront, and wetlands. The processing, power generation, heating, and transportation associated with each of these activities are the primary contributors to Norfolk area air pollution. The area's strong economy and attractive setting for

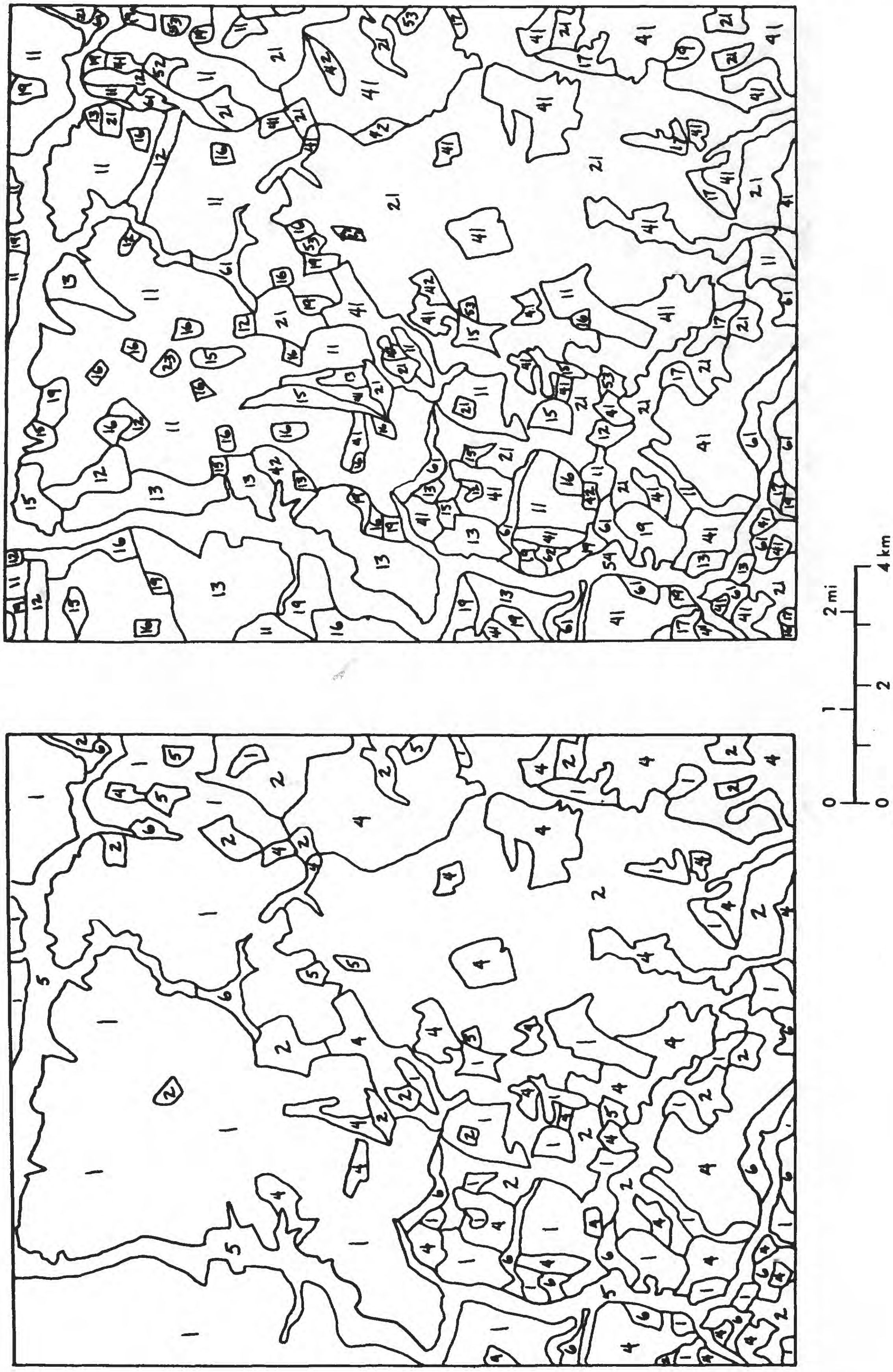


FIGURE 3.—Maps showing Level I and Level II land use and land cover of a part of the 1970 Norfolk-Portsmouth SMSA.

retirement have resulted in extensive residential development and a concomitant increase in area source contributions to pollution from space heating and automobiles. Sulfur dioxide and suspended particulates are the primary Norfolk area pollutants because of the types of fuel oil used for heating and power generation in the area, the large amounts of sulfur used in producing fertilizer and other area manufacturing processes, the patterns of traffic flow, the large construction projects underway throughout the area, the age of many of the area manufacturing facilities, and the processing technologies of those facilities. These two pollutants are the focus of this study of air quality planning.

LAND USE AND LAND COVER INFORMATION USED FOR THE INITIAL NORFOLK AREA CONTROL STRATEGY AND IMPLEMENTATION PLAN

While developing its sulfur dioxide and suspended-particulate control strategy and implementation plan for the Norfolk-Portsmouth SMSA, the Virginia Air Pollution Control Board had little time or money for collecting a wide range of land use and land cover and geographic information on the area (Commonwealth of Virginia, 1972a). In selecting its strategy, the board followed procedures recommended by EPA (Ozolins and others, 1966; Duprey, 1968; U.S. Environmental Protection Agency, 1970). These procedures rely on the availability of land use and land cover information adequate for identifying the location of general areas and specific points having different activities and pollutant emission characteristics. Having identified the configuration of area and point sources, they estimated annual and seasonal emissions to identify regions for air-quality control planning. From estimated total levels of regional emissions, the Air Pollution Control Board designed a specific emission reduction strategy focused on controlling point and area sources to bring the region within primary and secondary air-quality standards without inhibiting the region's growth.

AVAILABLE LAND USE AND LAND COVER INFORMATION

To develop its Norfolk area control strategy, the Virginia Air Pollution Control Board had access to the following land use and land cover information: The 1965 Southeastern Virginia Planning District Commission regional land use and land cover map; U.S. Geological Survey 1:24,000-scale topographic maps; various highway and city maps; low-altitude black and white aerial photographs; and directories of commercial, industrial, and other activities (Southeastern Virginia Planning District Commission, 1969). This land use and land cover information was of differing accuracy, scale, and date, and considerable time and cost were required to recompile the information at a uniform scale and in categories suitable for air quality planning.

ESTIMATING THE INITIAL EMISSION INVENTORY

In preparing its initial inventory of sulfur dioxide and particulate emissions in the Norfolk area, the Air Pollution Control Board used the land use and land cover information to determine the location of large point emission sources and to construct the grid system in figure 4 identifying areas having relatively homogeneous types and densities of activities.

The cells of the grid pattern constructed by the board seldom coincided in size and shape with the areas of usage designated on available land use and land cover maps. Thus, land use and land cover densities for each grid often had to be interpolated. To estimate area emissions for residential land use and land cover, the percent of each 1970 U.S. census enumeration district contained in each cell was estimated, and that percentage of the district's population was assigned to the cell. Traffic counts supplied by State and Federal agencies indicated the highway, airline, rail and shipping traffic densities for each cell. Using the previously mentioned information and data on total local fuel purchases and materials used in different types of manufacturing, the board estimated the total area emissions of sulfur dioxide and particulates for the 1971 annual, winter, and summer periods. Quantities of point source emissions for annual and seasonal periods were reported by various firms and institutions, or emission amounts were estimated from the timing of operations, magnitude, and type of activity at the source.

EVALUATING AND REFINING STRATEGIES FOR THE NORFOLK AREA

SELECTION OF INITIAL CONTROL STRATEGY

When preparing its plan, the board had little time for detailed evaluation of the spatial distribution of housing and other land uses that emit or receive air pollutants. Nor could it sample or estimate pollutant diffusion patterns in the area. Rather, it compared the initially estimated annual total Norfolk area emission inventory to national and State primary and secondary standards for levels of sulfur dioxide and particulates. The board then designed an areawide emissions reduction strategy

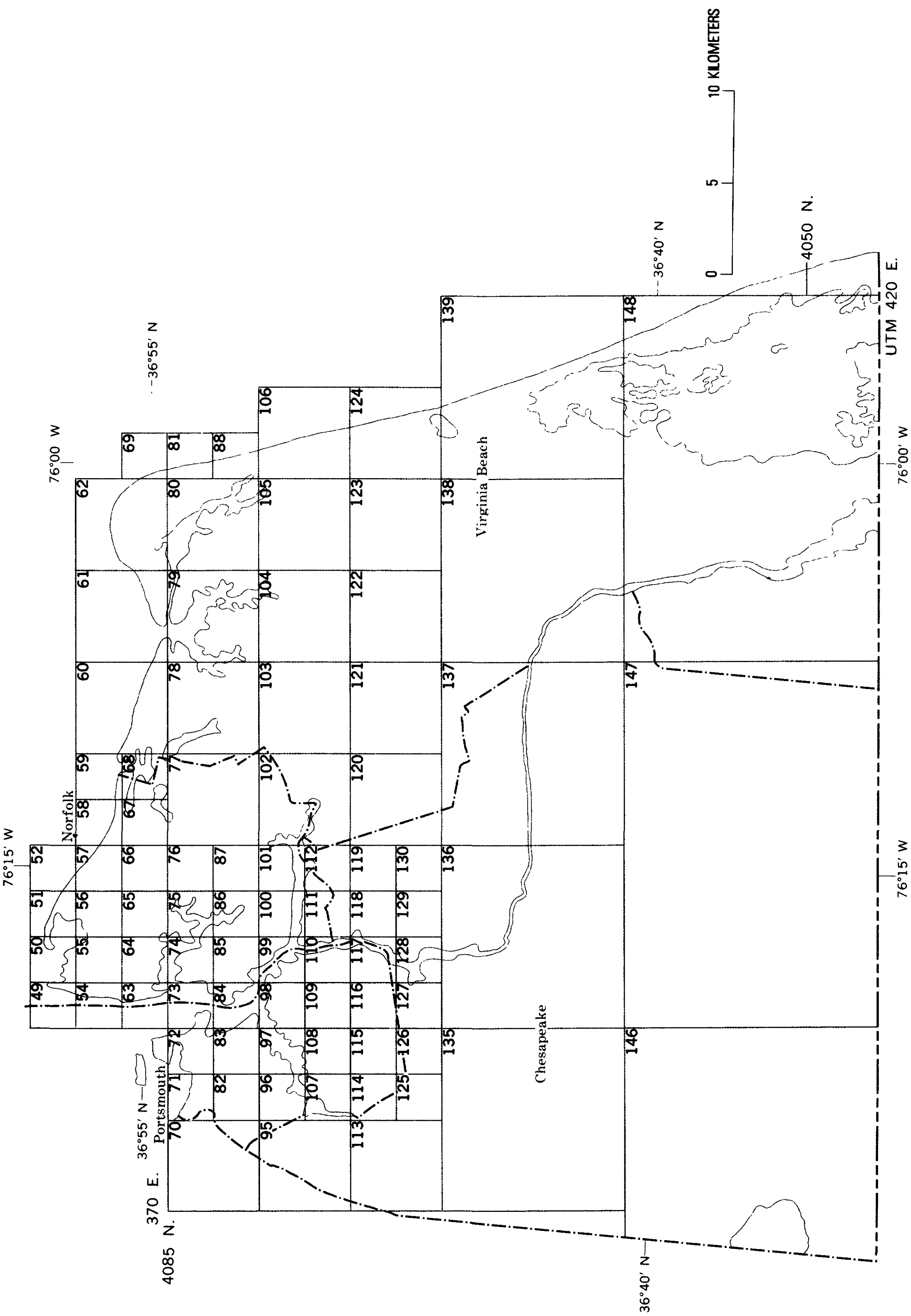


FIGURE 4.—1970 Norfolk-Portsmouth SMSA, area source emission estimating grid cell system.

and an air-quality sampling program. The strategy and program focused mainly on controlling local point sources and on anticipating the local impact of the nationwide auto-emission control (Commonwealth of Virginia, 1972a).

EVALUATING THE INITIAL CONTROL STRATEGY

The Air Pollution Control Board recognized that it could make considerable improvement in the initial inventory. Since July 1972, collection of point source information has been improved by the institution of a mandatory registration and permit program (Commonwealth of Virginia, 1972b). This program requires that all large sources emitting pollutants provide detailed information on types of pollutants, levels of pollution, hours of operation, and physical conditions that affect emission levels and diffusion, such as stack height, pollutant exit velocities, and temperatures. Data-collection programs related to residential space heating and other area source emissions are not as detailed. To evaluate currently adopted and alternative strategies for controlling sulfur dioxide and suspended particulates in the Norfolk area, specific types of land use and land cover and airflow information are needed to supplement these improved emissions data. This information includes the location of activities emitting these pollutants; the level and timing of their emission; the pattern of their diffusion and concentration over receptor land uses; and the impact of such concentration on these land uses and land cover. This information should be available for both current and future periods.

Much of the land use and land cover information needed to update and improve the area source emission inventory and to evaluate alternative air-quality control strategies for the Norfolk area was available from the U.S. Geological Survey. The CARETS project produced Norfolk area land use and land cover information interpreted at Levels I and II at a 4-ha minimum mapping unit size. The CARETS project supplied to the Air Pollution Control Board maps of these data at a scale of 1:100,000 for 1959 and 1970, and a similarly scaled UTM-gridded photomosaic of the area.

The 1970 Level II land use map was overlaid with the area source emission estimating grid cell system previously established by the board (fig. 4). For each grid cell the area and percentage of different Level II land uses and land cover were calculated. Experience gained in developing the earlier area source emissions inventory indicated that differentiation of Norfolk area residential land use and land cover (Level II) into a more detailed Level III classification of low-, medium-, and high-density residential areas would provide a more useful base for area source estimates. Areas of differing density were identified from Southeastern Virginia Planning District Commission records, plans, and standards. Their locations were plotted on the Level II map. Level III residential areas were calculated and included in the land use and land cover area statistics for each grid cell. The percentage of land use and land cover for various cells (table 2) provides an example of the type that can be generated from such maps.

The initial emission source inventory indicated that a map of a selected set of Level I, II, and III land uses and land cover would effectively emphasize the spatial relationship between emitter and receptor land uses and land cover and could highlight the problems of selecting particular control strategies. Figure 5 displays the Norfolk-Portsmouth SMSA pattern of residential, commercial/business, water, and other land uses and land cover. This figure was prepared from the Level I, II, and III maps and was overlaid with local jurisdictional boundaries along

TABLE 2.—*Example of land use and land cover statistics*

[Percentage of 1970 Level II and III land use in the Norfolk-Portsmouth SMSA by selected area emission source grid cells (fig. 4). All category codes keyed to classification in table 1]

Cell No.								
49	Category Code	15	12	54				
	Percentage of Area	15	05	80				
50	Category Code	15	19	54	112			
	Percentage of Area	05	05	54	112			
51	Category Code	111	19	54				
	Percentage of Area	25	10	65				
52	Category Code	12	16	111	54			
	Percentage of Area	05	03	15	77			
54	Category Code	42	12	15	54			
	Percentage of Area	03	20	17	60			
55	Category Code	54	16	111	19	15		
	Percentage of Area	05	30	05	35	25		
56	Category Code	54	16	15	53	112		
	Percentage of Area	10	35	25	05	25		
57	Category Code	54	12	16	19			
	Percentage of Area	05	05	05	15	70		
58	Category Code	54	112					
	Percentage of Area	60	40					
59	Category Code	12	111	54				
	Percentage of Area	05	15	80				
60	Category Code	54	52	112	15	19		
	Percentage of Area	60	10	05	20	05		
61	Category Code	54	74	112	12	42	19	15
	Percentage of Area	82	05	05	03	02	02	01
62	Category Code	54	41	112	74	16	19	15
	Percentage of Area	60	22	07	03	05	02	01
63	Category Code	54	19	12	16	15	13	
	Percentage of Area	66	08	18	02	03	03	
64	Category Code	112	54	12	19	16		
	Percentage of Area	55	15	16	06	08		
65	Category Code	54	15	12	16	112	19	
	Percentage of Area	04	08	18	22	36	12	
66	Category Code	112	52	15	12			
	Percentage of Area	70	04	04	22			

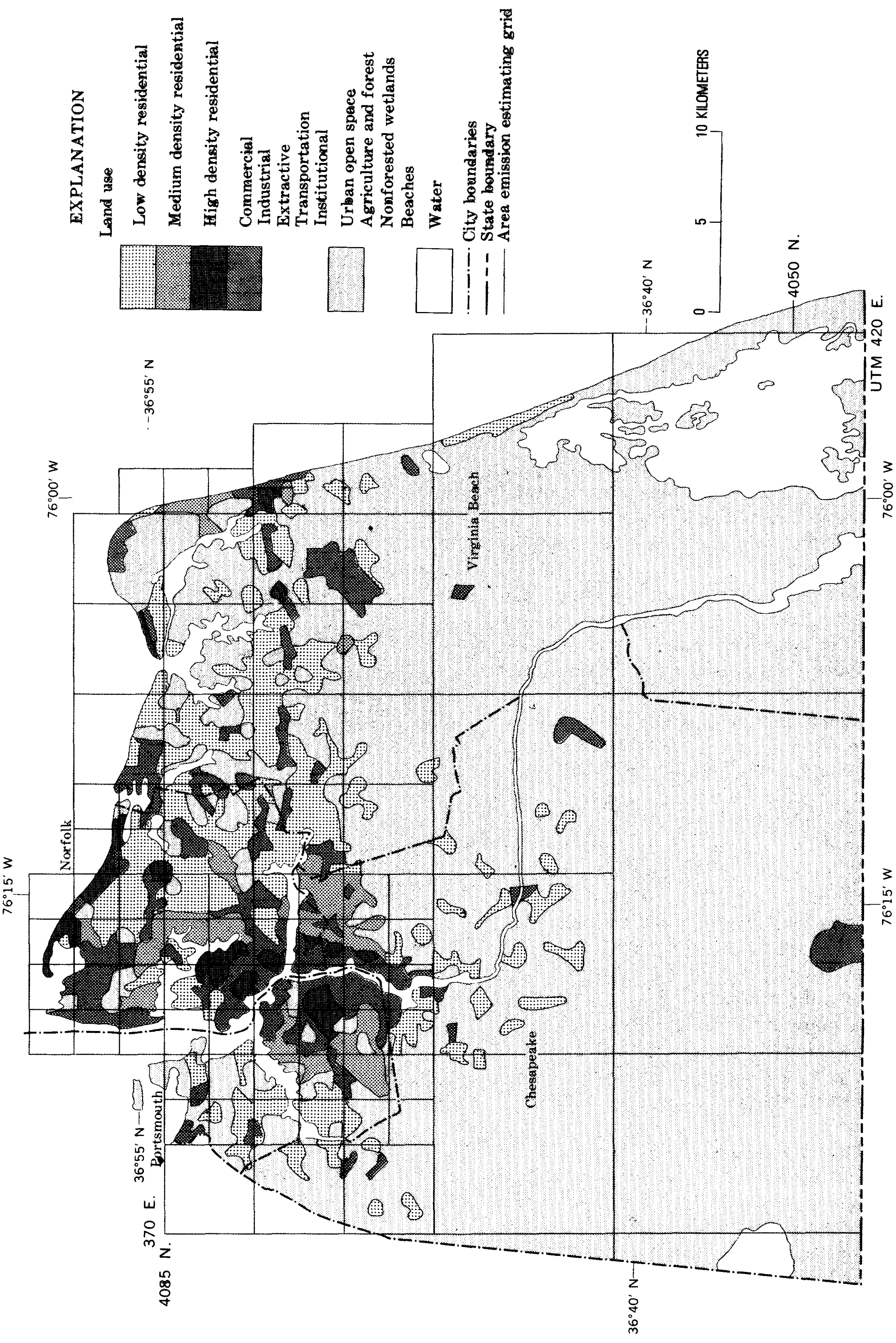


FIGURE 5.—1970 Norfolk-Portsmouth SMSA, 1970 land use and land cover selected for air quality planning.

with the board's original area source emission estimating grid cell system (fig. 4).

LAND USE AND LAND COVER AND EMISSION ESTIMATES

AREA SOURCES

The pattern of variously sized area source emission estimating grid cells established by the board encompasses similar densities and types of land use and land cover (fig. 5). The 25-km^2 and 100-km^2 cells to the east and south of Norfolk and Portsmouth, however, are less diversified than the smaller cells covering the central cities.

The detailed Level II and III land use and land cover map was used to verify the concentration of housing and other activities on which the board based its initial estimate of area emissions. Where densities of land use and land cover appeared to be underestimated or overestimated, adjustments for the area emission values in these cells were made and later confirmed by officials of the Virginia Air Pollution Control Board, Region VI. In the course of this checking, it was found that some values that the initial inventory attributed to area emission sources should have been assigned to point sources.

From updated land use and land cover analysis and changes in traffic patterns, an annual 1972 and winter 1971–72 emissions inventory was estimated. Several stations selected from this inventory are presented in table 3.

Figure 6 indicates the centroid of each cell's area source emission. In developing air-quality sampling programs and estimating pollutant diffusion, working with this centroid of activities is much more useful than dealing with the geographic center of each cell, especially for the larger cells in the Norfolk area where urban activities contributing most to area emissions are seldom located in the geographic center of a cell.

POINT SOURCES

Of the major point emission sources identified in the board's initial emissions source inventory, many had closed down or substantially reduced their emissions by 1972. The initial inventory of point sources was located on the Level II land use and land cover map and their current annual levels of emission were verified from August 1972 board registration records. Other industrial, extractive, transportational, and institutional uses identified in the board's registration program were located on the Level II land use and land cover map, and the board's staff identified those with the greatest levels of emissions. In this way, 44 point sources having high levels of emission or emissions that had persisted over long periods were identified as the most significant to

TABLE 3.—*Sample pages of table of estimated Norfolk-Portsmouth SMSA, 1972 annual, winter 1971–72, and estimated annual 1985 emission inventories*[1]

Source No.	SIC code	Site code	Source location (kilometers) Horizontal	Vertical	Source area (sq km)	Emission rate (megagrams/day) SO_2	Part	Stack height (meters)	Stack diameter (meters)	Exit velocity (m/sec)	Exit temperature (degrees K)
Annual 1972 Source data, October 5, 1972											
1 ------	50	99	384.0	4,090.0	0.0	0.08	0.42	35.0	4.0	30.0	450.0
2 ------	55	100	382.7	4,089.0	0.0	13.49	1.52	35.0	4.0	30.0	450.0
20 ------	111	121	386.4	4,076.9	0.0	0.00	0.50	10.0	0.0	0.0	0.0
46 ------	9,999	50	383.1	4,090.1	6.3	0.02	0.06	3.0	0.0	0.0	0.0
55 ------	9,999	60	397.0	4,086.0	25.0	0.08	0.05	8.0	0.0	0.0	0.0
Winter 1971–72 Source data, October 5, 1972											
1 ------	50	99	384.0	4,090.0	0.0	0.12	0.46	35.0	4.0	30.0	450.0
2 ------	55	100	382.7	4,089.0	0.0	438.09	2.85	35.0	4.0	30.0	450.0
20 ------	111	121	386.4	4,076.9	0.0	0.00	0.50	10.0	0.0	0.0	0.0
46 ------	9,999	50	383.1	4,090.1	6.3	0.04	0.06	3.0	0.0	0.0	0.0
55 ------	9,999	60	397.0	4,086.0	25.0	0.24	0.09	8.0	0.0	0.0	0.0
Estimated annual 1985 October 6, 1972											
1 ------	50	99	384.0	4,090.0	0.0	0.08	0.42	35.0	4.0	30.0	450.0
2 ------	55	100	382.7	4,089.0	0.0	13.49	1.52	35.0	4.0	30.0	450.0
20 ------	111	121	386.4	4,076.9	0.0	0.00	0.34	10.0	0.0	0.0	0.0
46 ------	9,999	50	383.1	4,090.1	6.3	0.02	0.06	3.0	0.0	0.0	0.0
55 ------	9,999	60	397.0	4,086.0	25.0	0.08	0.05	8.0	0.0	0.0	0.0

[1] Data from Virginia State Air Pollution Control Board Implementation Plan, 1972.

the area's air quality and were included in the updated point source emissions inventory (fig. 6 and table 3).

SEASONALITY

The Air Pollution Control Board's original inventory divided the emissions of area and point sources into seasonal increments. The current registration program does not provide seasonal or other periodic emission rates. When the staff of the board could determine that point sources had modified their winter operating patterns, the original winter season estimates were reduced or increased to reflect these changes. For the remaining point and area sources, however, winter emissions levels were taken as estimated in the original inventory.

FUTURE EMISSION PATTERNS

Air-quality planning for the Norfolk area must consider the impact of growth and future emission levels. Along with its utility for estimating current patterns of emissions, the land use and land cover information can be used to estimate emission levels from projected future land use and land cover patterns.

For each grid cell the rate of change between 1959 and 1970 in Level I and II land use categories was determined from the graphic information provided by the CARETS project maps. The Southeastern Virginia Planning District Commission provided 1985 population and employment projections for each of the SMSA jurisdictions along with estimated amounts of land use and land cover that would be required to accommodate a recommended pattern of future land use and land cover (fig. 7). Residential and commercial land use and land cover changes to 1985 were postulated for the area by extrapolating past trends in land use and land cover change given by the pilot system and the commission's projections of utility and transportation installations (Henningson, Durham, and Richardson, 1972, and Wilbur Smith and Associates, 1969). The likelihood of a given area emissions estimating cell being developed to a given level by 1985 was estimated from this information as were standards for population density, zoning regulations, and anticipated building practices suggested by the commission.

It was assumed that emission levels from existing area sources would continue unchanged to 1985 because much of the SMSA's residential development is of recent origin; decreases in emissions per vehicle would be offset by an increased number of vehicles; and small new area sources would compensate for the existing area emissions that have recently upgraded their controls or ceased emissions. Emission levels per square kilometer from residential and associated land uses and land cover to be developed by 1985 were estimated on the basis of anticipated space heating procedures, 1985 traffic volumes, and land uses to be permitted in various areas. These estimates, 0.01 megagrams of sulfur dioxide and 0.25 megagrams of particulates per day/km^2 were multiplied by the number of kilometers of residential and other land uses projected for each cell. These values were added to the existing amount of area emissions to estimate the 1985 total area source emissions for each cell.

Future emission levels for the 44 point sources included in this study were estimated on the basis of control programs proposed to the Air Pollution Control Board by various firms. These control programs incorporate standards for levels of emissions currently required by Virginia legislation and the Air Pollution Control Board rules (Commonwealth of Virginia, 1972b and 1972c). For purposes of this study it was estimated that no new major point source would locate outside areas of existing industrial development. Table 4 gives the inventory of point emissions sources used in 1985 estimates.

LAND USE AND LAND COVER AND NORFOLK AREA EMISSION PATTERNS

Plotting the spatial distribution of area and point source emissions provides basic information for evaluating the design of air quality sampling programs and estimating the likely impact of different air quality control strategies. Figures 8 through 13 show the estimated average quantity and distribution of sulfur dioxide and particulate emission in the Norfolk area for 1972 annual and winter 1971–72 periods and for an annual 1985 period. Total emissions by area cell, like those given in table 3, were converted to values per square kilometer and are indicated by isolines. The average of major point source emissions for each cell are also plotted. The similarity between sulfur dioxide and particulate emission patterns in these figures reflects the emission of both pollutants by most sources throughout the Norfolk area. Because of the area's space heating traffic, and industrial characteristics, particulate matter is emitted at higher levels than sulfur dioxide from all but a few point sources.

In these figures the pattern of high annual emission from point and area sources clearly reflects the concentrations of industrial, commercial, and old,

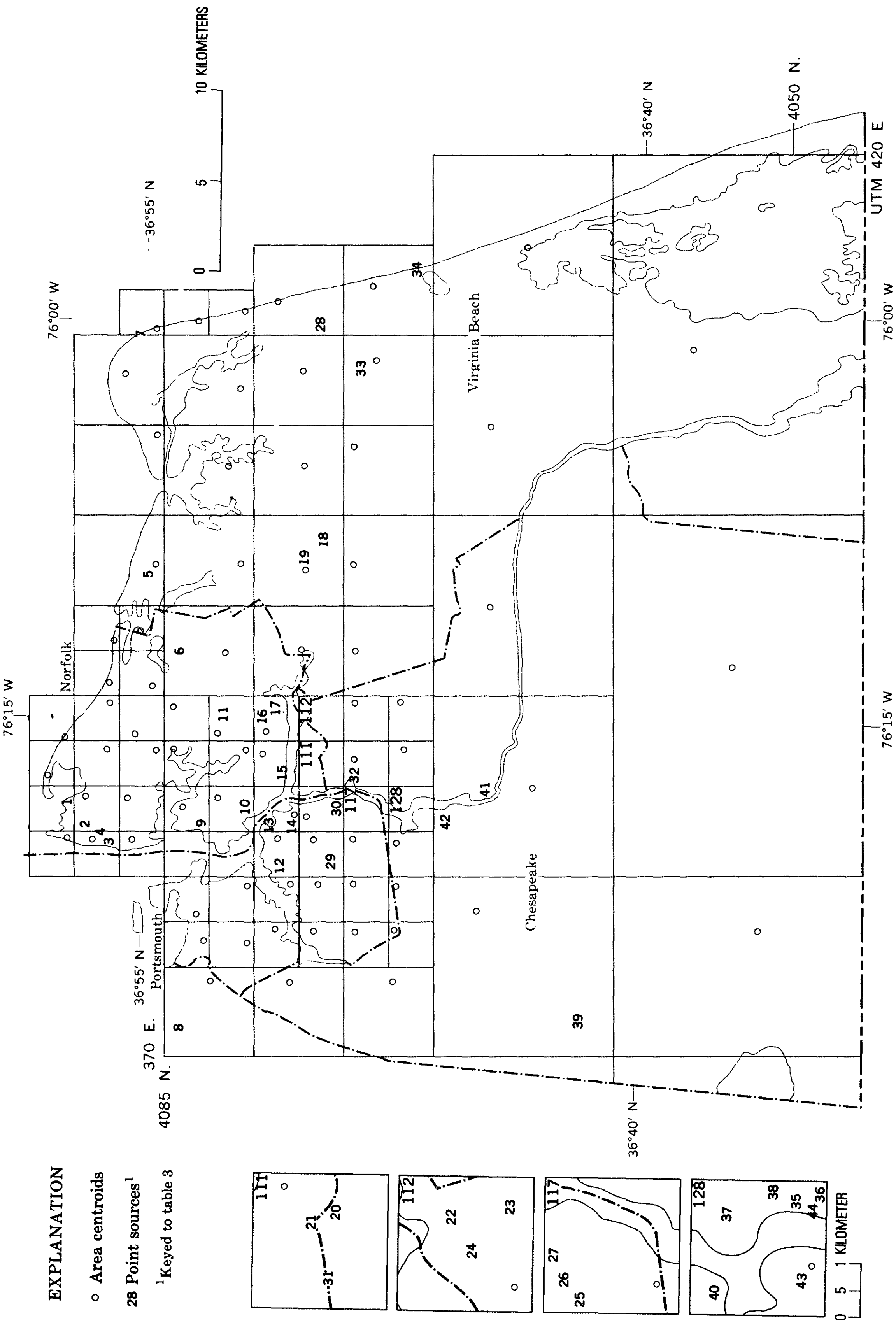


FIGURE 6.—1970 Norfolk-Portsmouth SMSA, selected point sources and centroids of area emission cells.

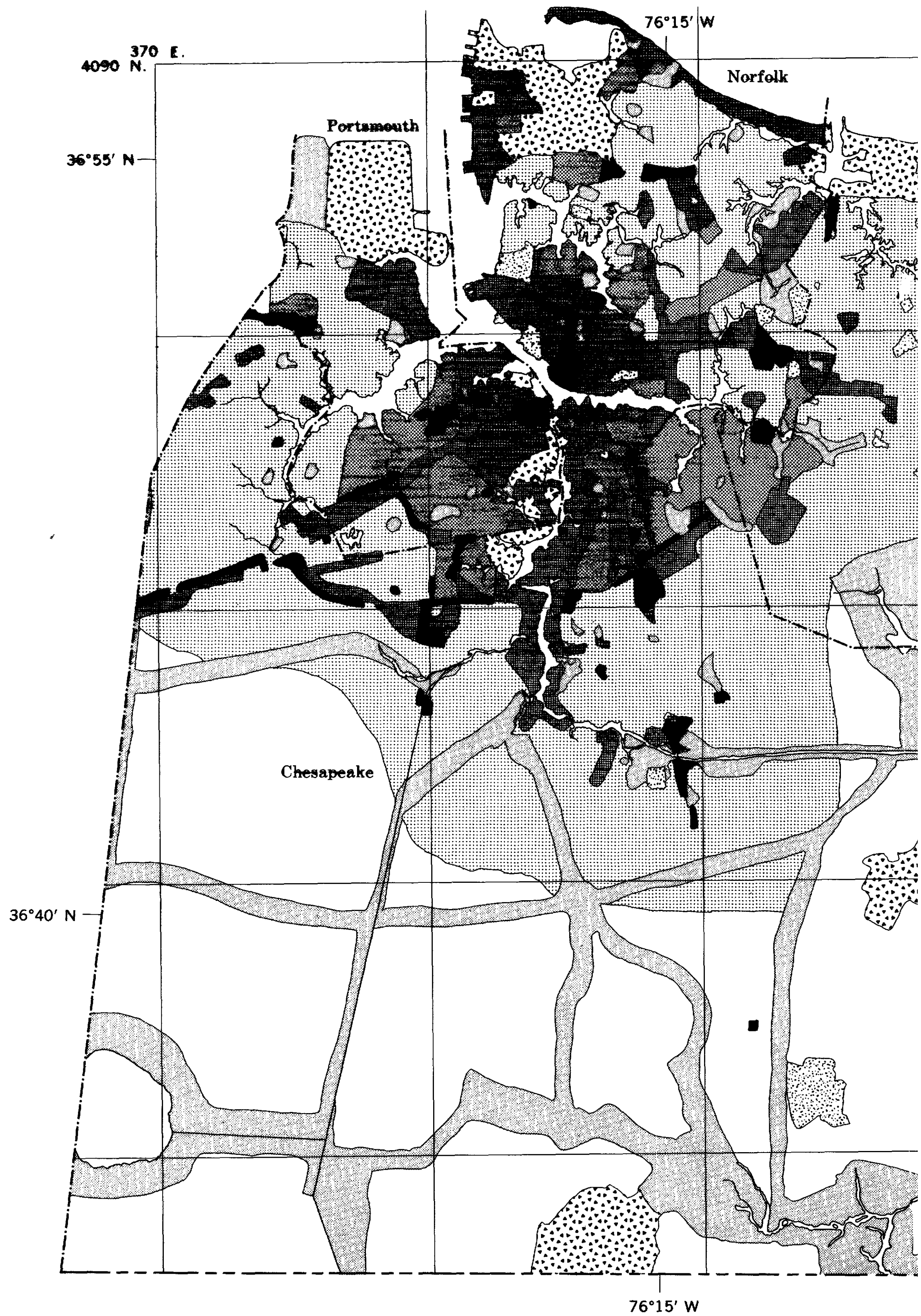
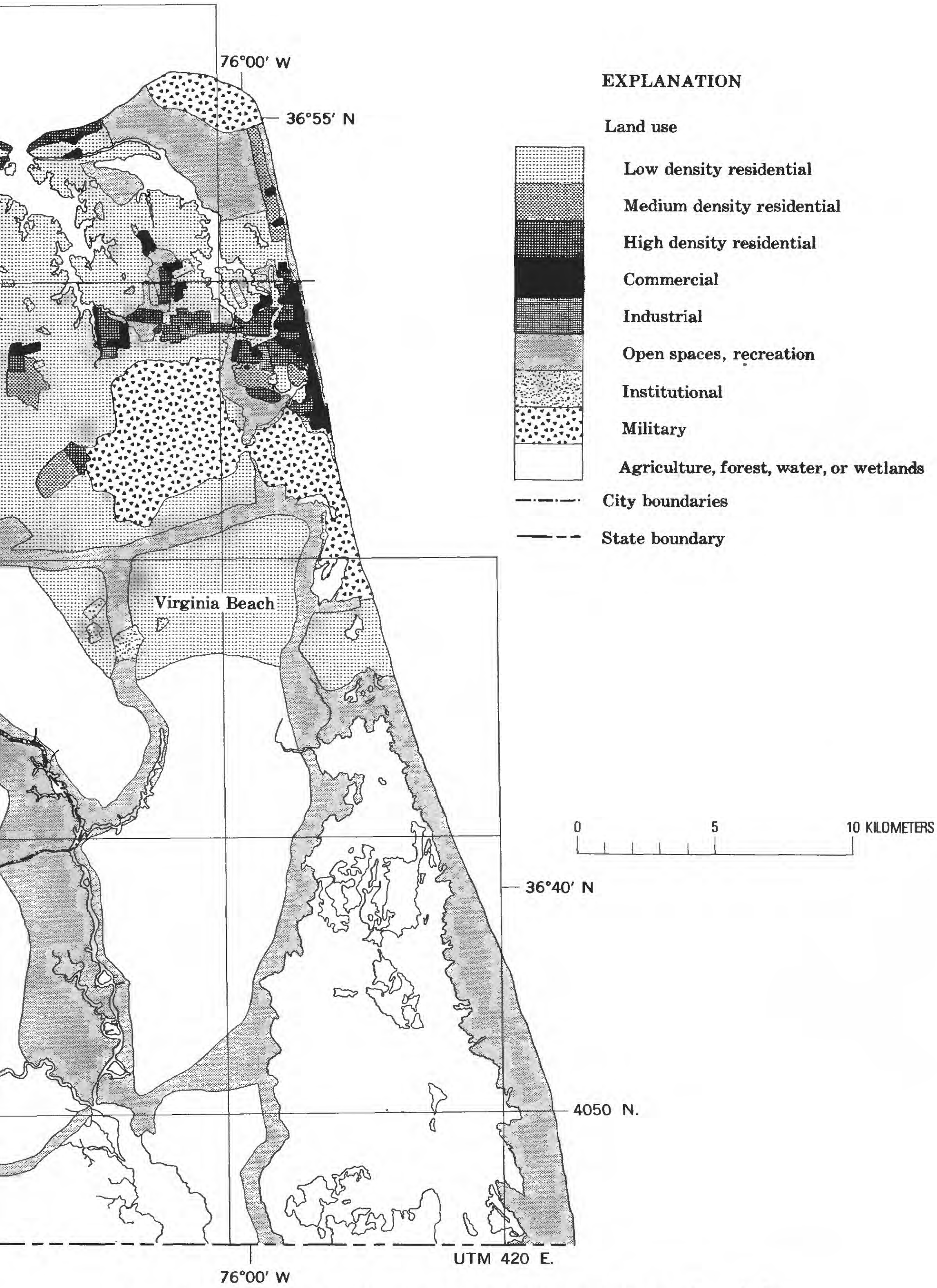


FIGURE 7.—1970 Norfolk-Portsmouth SMSA, proposed land use and land cover, 1985.



From plan proposed by Southeastern Virginia Planning District Commission.

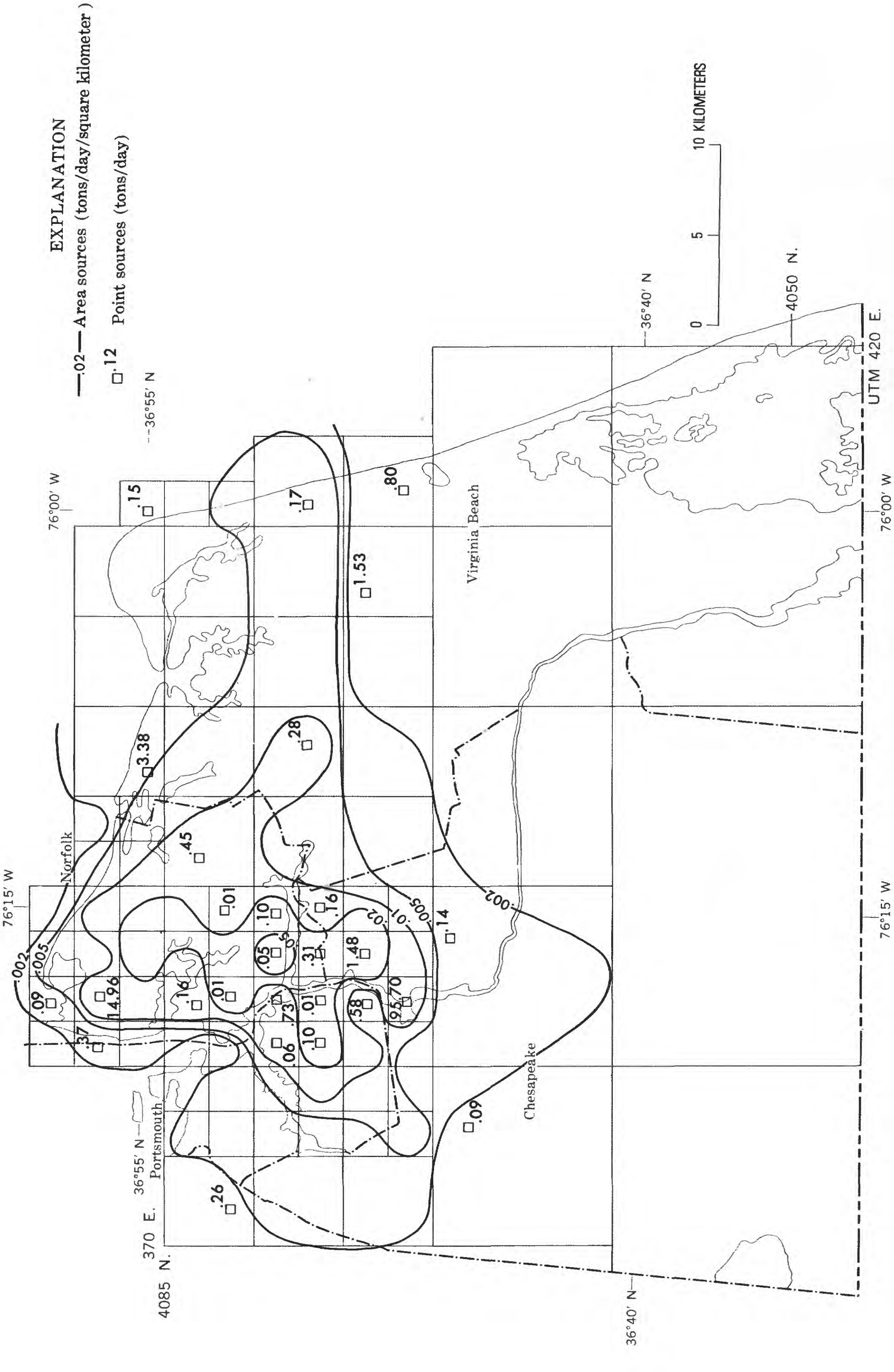


FIGURE 8.—1900 Norfolk-Portsmouth SMSA, estimated emissions of sulfur dioxide, 1972.

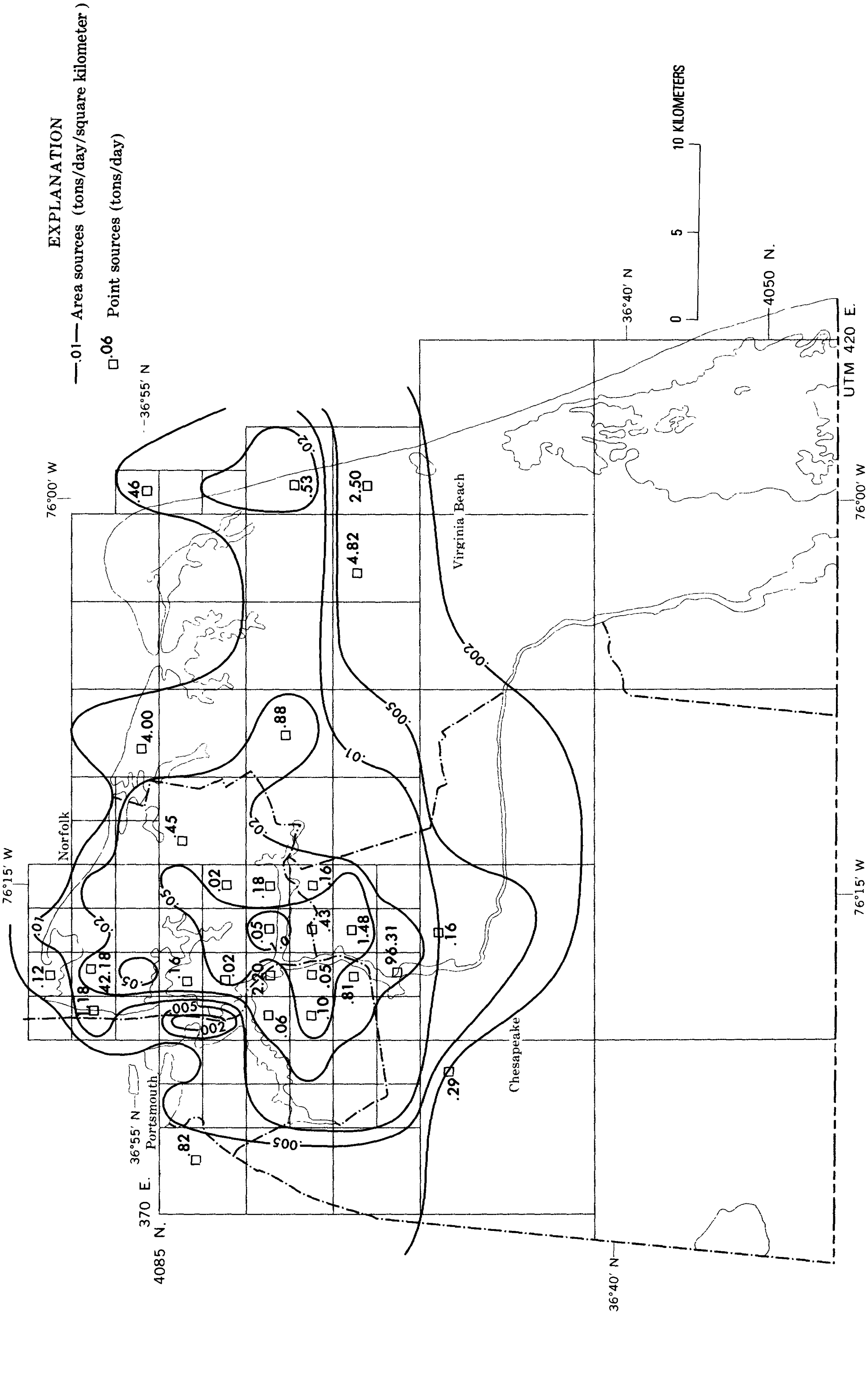


FIGURE 9.—1970 Norfolk-Portsmouth SMSA, estimated emissions of sulfur dioxide, winter 1971–72.

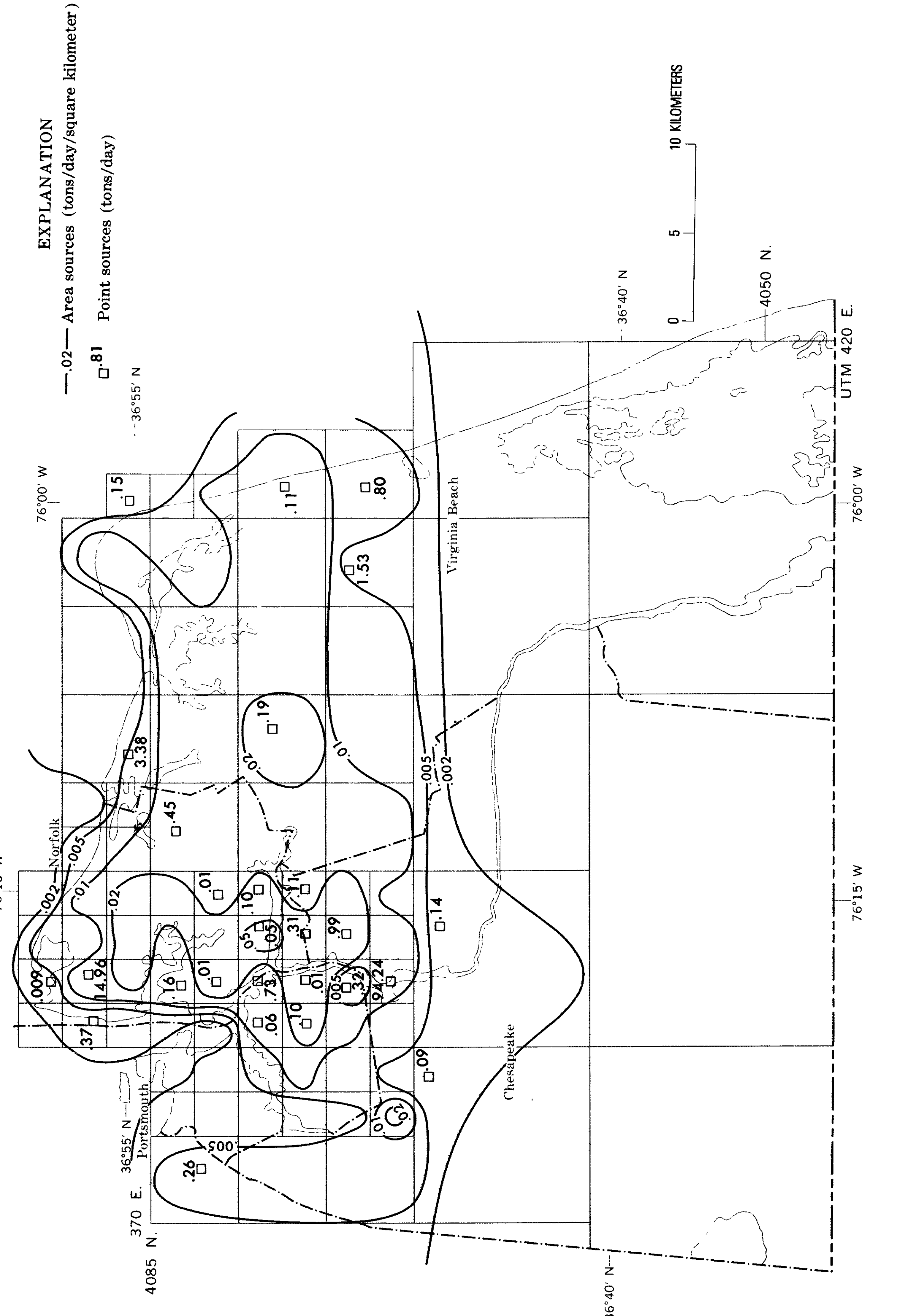


FIGURE 10.—1970 Norfolk-Portsmouth SMSA, estimated emissions of sulfur dioxide, 1985.

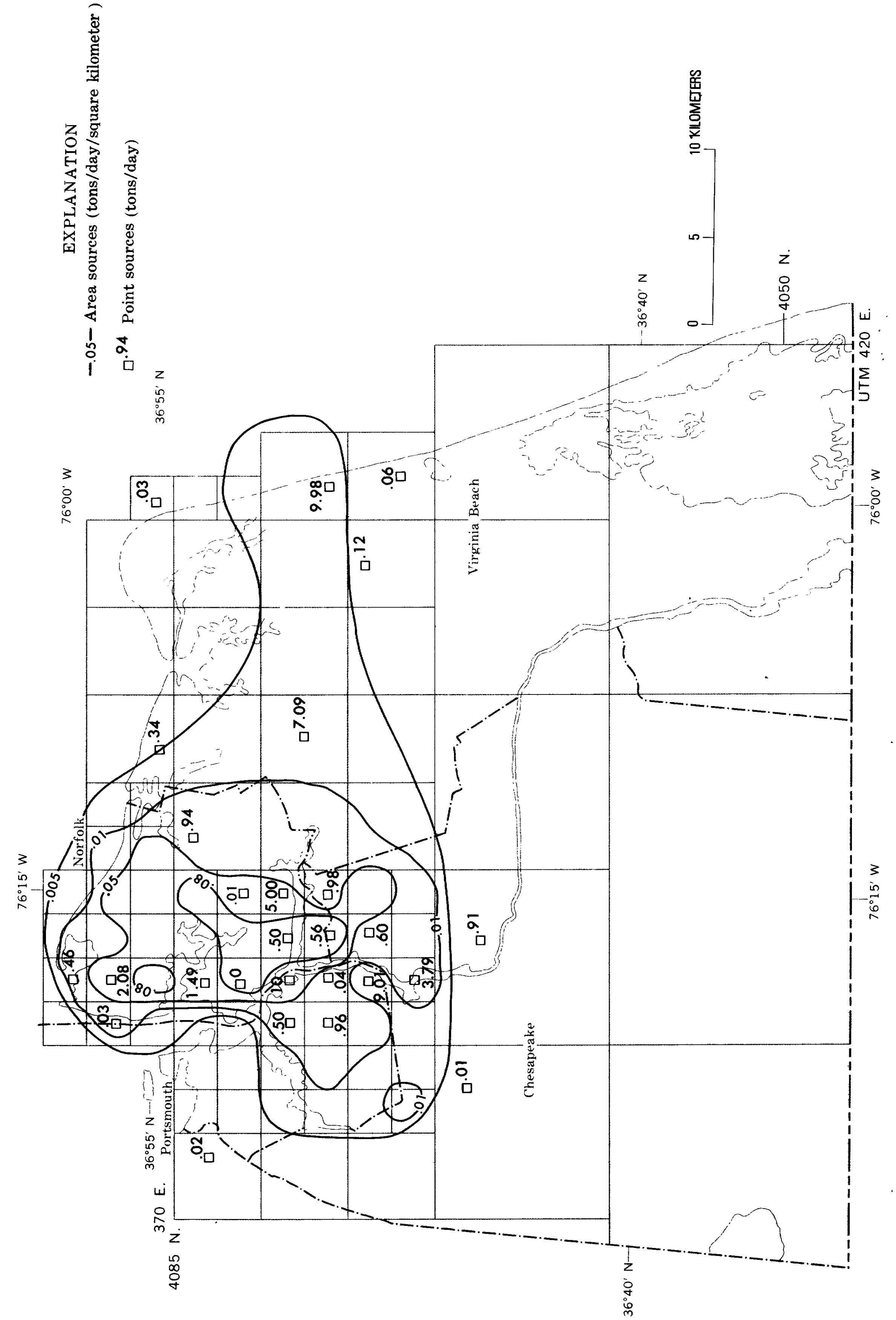


FIGURE 11.—1970 Norfolk-Portsmouth SMSA, estimated emissions of particulates, 1972.

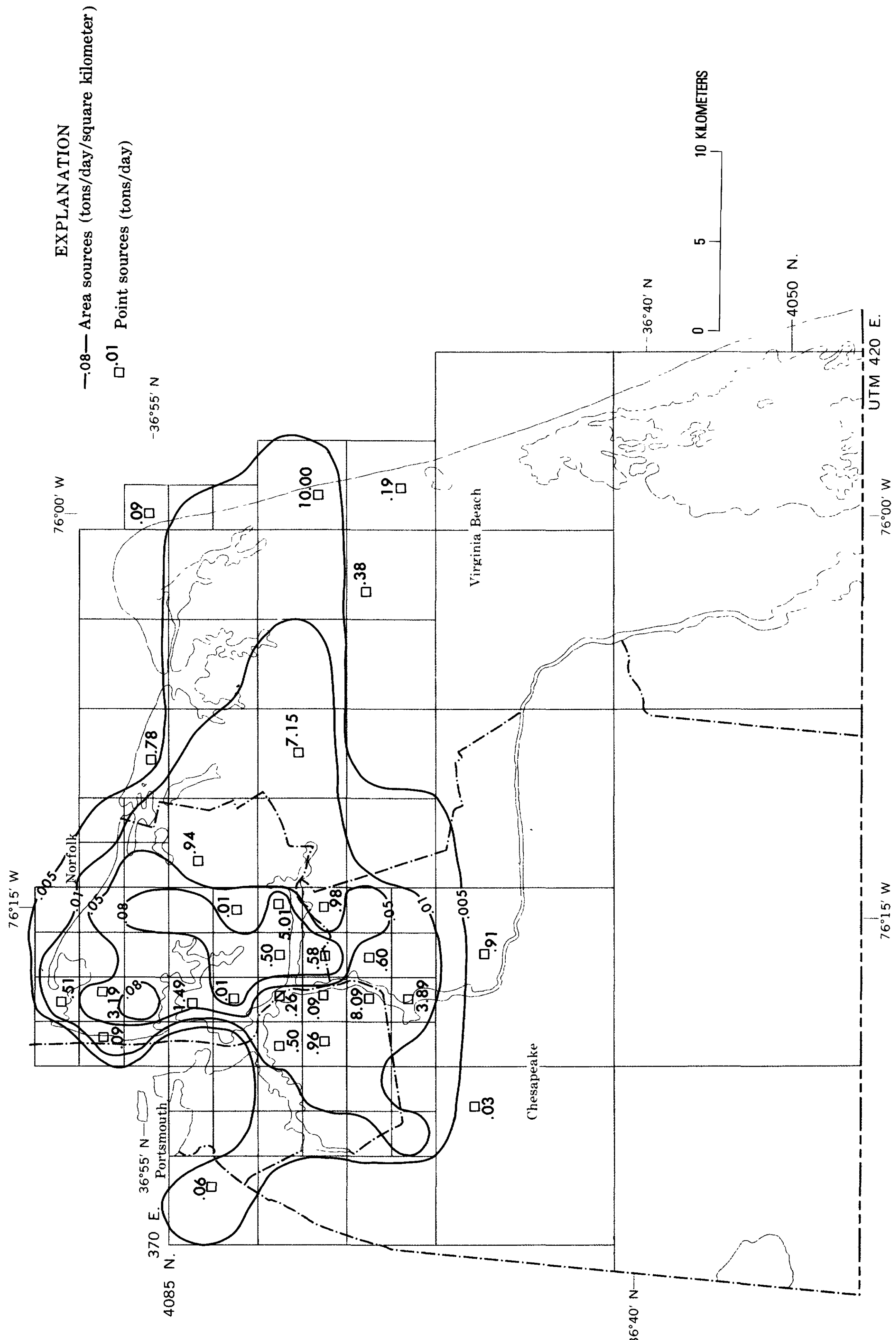


FIGURE 12.—1970 Norfolk-Portsmouth SMSA, estimated emissions of particulates, winter 1971–72.

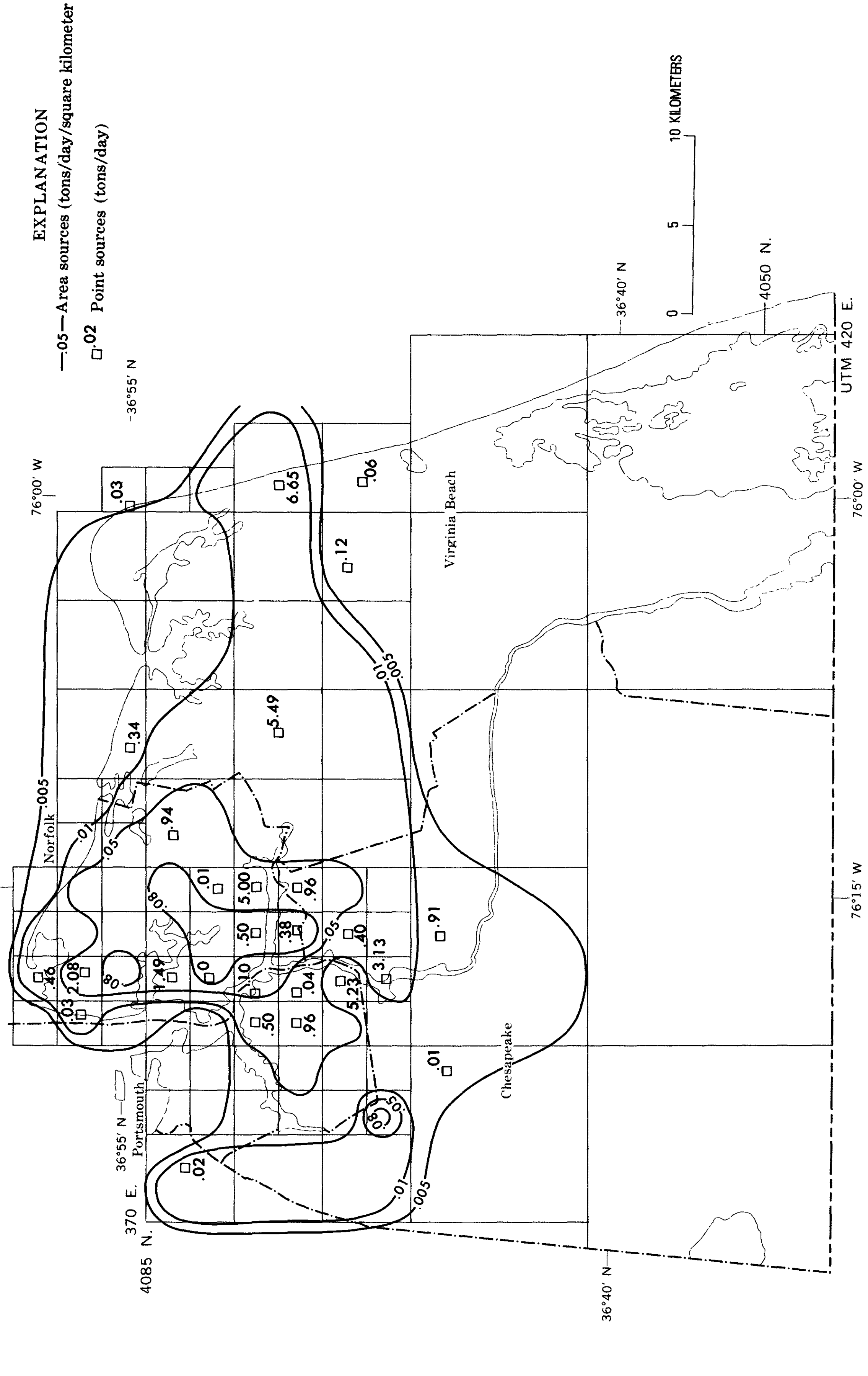


FIGURE 13.—1970 Norfolk-Portsmouth SMSA, estimated emissions of particulates, 1985.

TABLE 4.—*Point sources included in air diffusion modeling of Norfolk-Portsmouth SMSA*

Identification No.[1]	Name of source[2]
1	Naval Air Rework Facility, Norfolk Naval Air Station.
2	Naval Public Works Center, Norfolk Naval Air Station.
3	Naval Supply Center, Norfolk Naval Air Station.
4	Sheller Globe Corp.
5	Naval Amphibious Base.
6	Norfolk Regional Airport.
7	Fort Story.
8	Tidewater Community College, Frederick Campus.
9	City of Norfolk Incinerator.
10	Owen Pattern Foundry and Manufacturing Co.
11	Colonial Block Corp.
12	Georgia Pacific Corp.
13	Dixie Manufacturing Co.
14	U.S. Naval Hospital.
15	City of Norfolk Incinerator.
16	Ames and Webb, Inc.
17	Southern Block and Pipe.
18	Contractors Paving Co.
19	Asphalt Roads and Materials.
20	Richard Foundry Corp.
21	Colonna's Shipyard, Inc.
22	Ford Motor Co.
23	Norfolk Redevelopment and Housing Authority.
24	Southland Cork Co.
25	Atlantic Creosoting Co.
26	Portsmouth Paving Corp.
27	Norfolk Veneer Mills, Inc.
28	Finley Paving Corp.
29	City of Portsmouth Incinerator.
30	Norfolk Naval Shipyard.
31	Norfolk Shipbuilding and Drydock Corp.
32	Royster Co.
33	Oceana Naval Air Station.
34	Fleet Anti-Air Warfare Training Center.
35	Swift Agricultural Chemicals Corp.
36	Weaver Fertilizer Co.
37	Lone Star Industries.
38	Southern States Coop., Inc., Fertilizer Division.
39	Lone Star Industries.
40	Naval Ammunition Depot, St. Julien Creek.
41	Solite Masonry Units Co.
42	Intercoastal Steel Corp.
43	Virginia Electric and Power Co.
44	Smith-Douglass.

[1] Identification numbers keyed to table 3 and figure 6.

[2] Selection of sources based on high levels of emission identified in Commonwealth of Virginia, State Air Pollution Control Board Implementation Plan, "Inventory Section," Richmond, Va., January 1972, and in point-source emission registration forms received by the Virginia State Air Pollution Control Board, July and August 1972.

dense residential activities in central Norfolk and Portsmouth (figs. 8 and 11). To the east, lower emissions reflect the combination of low-density residential, commercial, transportation, and industrial land use and water and agricultural land use and land cover. The extent of high area source emissions surrounding central Norfolk and Portsmouth is larger in winter due to increased space heating in medium- and low-density residential areas (figs. 9 and 12), but otherwise the patterns of winter emissions reflect annual patterns.

The estimated 1985 annual emission patterns (figs. 10 and 13) show the projected urban expansion into nonurbanized area. Because of the attraction of waterfront property, the Southeastern Virginia Planning District Commission anticipates that Atlantic Ocean and Chesapeake Bay waterfronts will be filled by 1985.

DETERMINING SPATIAL DISTRIBUTION PATTERNS OF AIR QUALITY

To evaluate Norfolk area control strategies, patterns of emission need to be related to actual levels of pollutant (sulfur dioxide and particulates) concentration determined by air quality sampling throughout the region.

The air-quality sampling stations shown in figure 14 were established by October 1972; the majority of them had been in operation less than 1 year (Commonwealth of Virginia, 1972b). Figure 14 suggests that their spatial distribution does not reflect the diversity and density of land uses and land cover impacted by sulfur dioxide and particulates. Because reliable sampling information was not available, estimates of the areawide dispersion and concentration of sulfur dioxide and suspended particulates were made.

ESTIMATING POLLUTANT DIFFUSION PATTERNS

The problem of estimating pollutant dispersion and the characteristics of a pollution plume is couched in the exercise of describing the turbulent motion of air. As turbulence is best described at this time by probabilistic means, the most widely used and successful model for characterizing pollution dispersal is the Gaussian plume model. Wanta (1968, p. 217) outlined this model in simple terms,

> the mass of pollutant emitted from a continuous point source moves downwind at a constant speed, at the same time spreading horizontally and vertically in such fashion that while the mass in any cross section remains constant, the distribution of concentration of pollutant in the cross section along either the horizontal or vertical direction is bell-shaped, i.e., normal or Gaussian. The standard deviations of these two normal distributions are adjustable and increase with distance and time; they are diffusion coefficients or simple functions of them. The standard deviation of the horizontal profile of pollutant concentration is generally much greater than that of the vertical. Allowance can be made for the presence of nearby reflecting planes such as the ground or an elevated ideal temperature inversion. Modifications for instantaneous source and other geometrics are also available.

Wanta (1968) presents an excellent outline of urban air pollution diffusion models, especially sum-

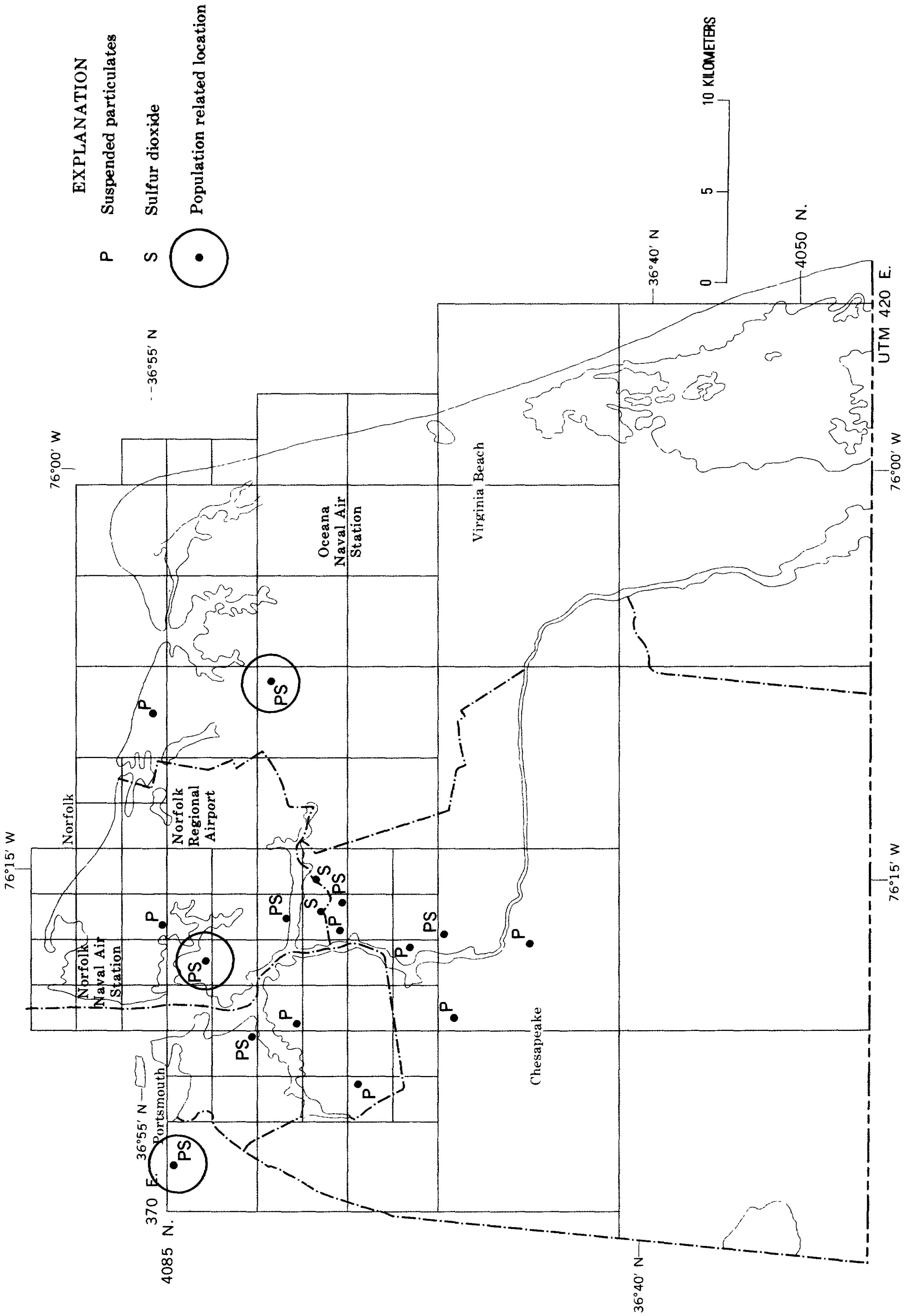


Figure 14.—1970 Norfolk-Portsmouth SMSA, location of air-quality sampling stations, October 1972.

marizing Smith (1961), Pooler (1961), Turner (1964), Clarke (1964), Koogler and others (1967), and Miller and Holzworth (1967); all of these models are variations of the basic Gaussian model.

Turner (1970) has published a workbook for calculating a numerical solution for pollutant concentration and diffusion, and Forsdyke (1970) has briefly summarized meteorological factors concerned with the Gaussian model.

Hanna (1971) has described a simple but physically realistic model for estimating pollutant concentrations resulting from area source emissions in a city. Pollutant concentrations for the surface are directly proportional to local area source strength and inversely proportional to wind speed. The model is simple, yet results appear to compare favorably with more complex diffusion models.

Investigators have also worked with other types of models. Getis and Jackson (1971) have constructed a model to determine the probability of a specified area being polluted by a specified number of sources. This model is based on a Poisson distribution function that is used to generate areal pollution zones. Lamb (1971) and Egan and Mahoney (1971) have used a deterministic approach in estimating pollution dispersal; the general method is to solve the system of partial differential continuity equations with suitable initial and boundary conditions. This approach is much less tractable than the Gaussian model and, accordingly, less popular. Egan and Mahoney (1972) have also discussed the use of specified source models and box models for estimating pollution dispersal.

All of the models mentioned above can be calculated for either point or area source emissions or both. With a Gaussian model, the nature of the emission source and its strength are primary factors.

Work has begun on the development of receptor models based on either Bayesian statistics or on some other probability function that can characterize pollution concentration only in terms of receptor information. In the future this type of model may find wider applications than the source models now in use (U.S. Environmental Protection Agency, 1974).

MODEL USED TO ESTIMATE NORFOLK AREA AIR QUALITY

The Martin-Tikvart model, entitled the Air Quality Display Model (AQDM), is the diffusion model used in this analysis. It has been used by EPA to assess air quality standards for the designated air control regions in the United States (U.S. Environmental Protection Agency, 1970). The basic equation in the model is a slightly modified Gaussian diffusion equation for an elevated, continuously emitting point source. The calculations have been adjusted to estimate long-term average concentrations for multiple polluting sources, both point and area, under a variety of meteorological conditions.

Wind direction in the AQDM is assumed to be specified on a 16-point compass, corresponding to 22.5° sectors. For an averaging period, all wind directions within a given sector are assumed to occur with equal chance.

Hourly data are used to calculate the joint frequency distribution of meteorological conditions. Wind speed is grouped into six classes and the nature of the atmospheric stability into five classes. These factors are discussed in a following section and relate directly to characteristics of the Norfolk area. For a particular combination of meteorological conditions at any receptor point at distance (p) within a given distance, the ground-level concentration (X; g/m^3) due to a point source with emission rate (Q; g/s) is: $X(p,1,S) = \{2Q[(2\pi)^{1/2} q_z(p,1) \mu(S)(2\pi p/16)] \exp[-1/2(H/q_z(p,1))^2]\}$ where μ (S) is wind speed in meters per second representative of a wind speed class (S), H is effective stack height in meters, and $q_z(p,1)$ is the standard deviation of the vertical concentration distribution (Gaussian) for a ground-level emission in meter. This expression is a function of the distance (p) from the source and the atmospheric stability class (1). The model also includes a time-delay function for SO_2, for which the half life used in this exercise was 4 hours.

For each receptor location, the model sums the effect of all sources over a wide range of meteorologic conditions. Modifications are made for q_z under certain conditions, and effective stack height (H) is determined in the usual manner. For more detailed information on these two aspects see Martin (1971). Area sources in the model are treated as a virtual point source at some distance upwind from the center of the area source (fig. 15).

In summarizing, the input data consist of pollutant emission source, source configuration and location, receptor location, and the meteorological information. Output data are listed for each grid and nongrid receptor specified. The output results are the arithmetic mean of ground level concentration of either SO_2, or geometric means of particulates, or both; additional information is supplied for five user-selected receptor sites of the five maximum receptor sites. The contribution of a given point or

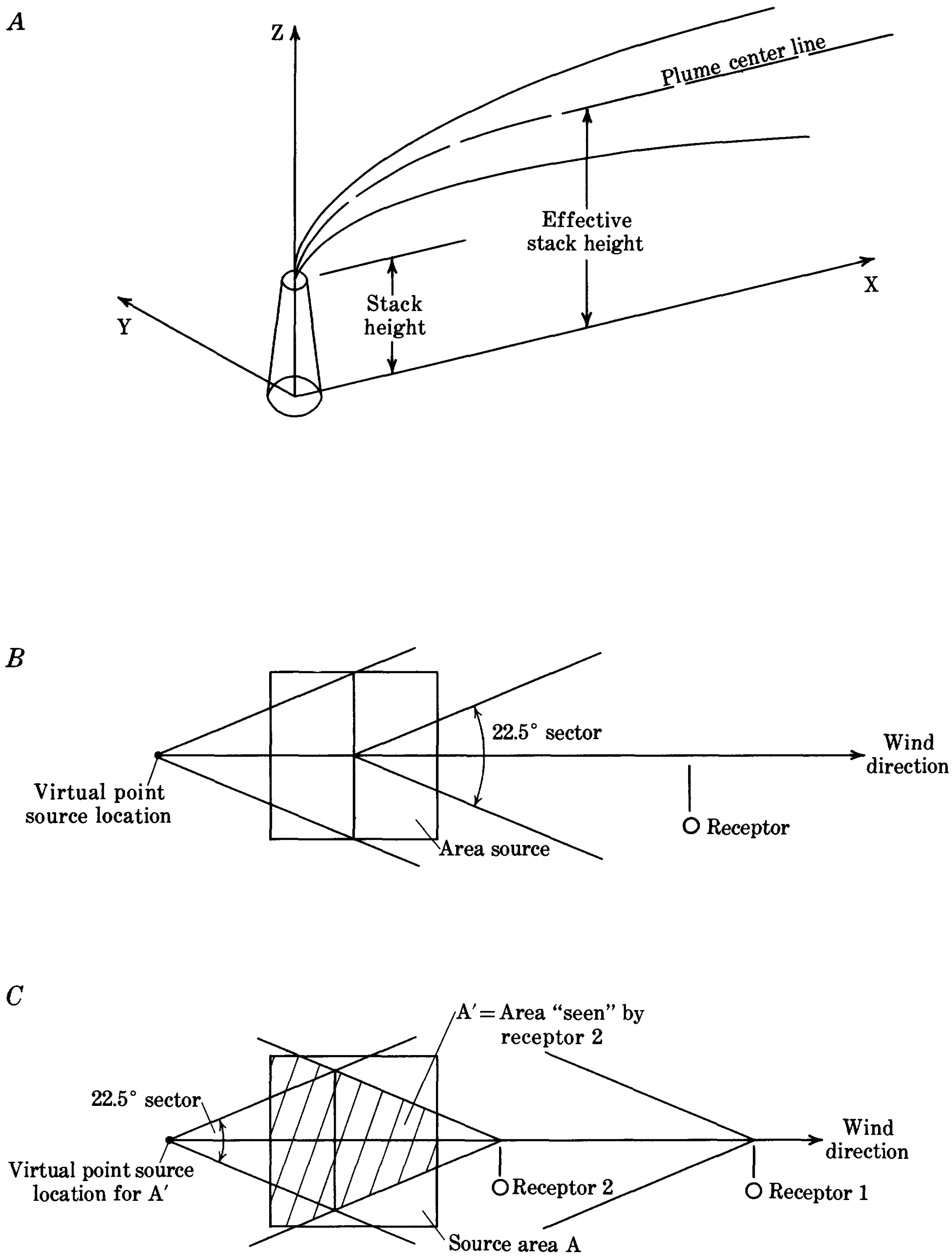


FIGURE 15.—Treatment of point (*A*) and virtual point for area source (*B* and *C*) diffusion patterns in air-quality display model (AQDM).

area source to each receptor is indicated as a percentage of the total concentration on the receptor grid, and this information is displayed by the construction of an isopleth map of the pollution distribution. The receptor grid used in the Norfolk area consisted of 2.5-km^2 cells; the nature and rationale for this grid size will be discussed in a later section.

Calibration of the AQDM for a particular area begins with the measurement of concentration values—3 to 100 values for each pollutant studied—at specified measuring stations. A least-square regression analysis is conducted between the measured (independent variable) values of pollutant concentration.

If the regression line adequately describes a "good" association between measured and observed values, the model output results are adjusted at each receptor point according to the parameters calculated from the regression equation. The "goodness" of the association is determined by the calculation of a correlation coefficient that is compared to a maximum theoretical value that could have resulted due to chance. When the correlation is termed nonsignificant, the calculated concentration will be output without adjustment. Because of the lack of sample data, this correlation procedure was not utilized in this work.

Some caution must be expressed concerning the use of this type of model and the assumption upon which it is based: (1) The model was originally developed to represent plume behavior from actual point sources over open, flat terrain for distances of less than a few kilometers; the Norfolk area approximates this situation fairly closely, as it is located on a peninsula with little relief and the buildings are predominantly one-story residential complexes. (2) The surface meteorological data often provide poor characterization of the vertical nature of the lower atmosphere. (3) Emission inventories input to the AQDM are subject to compoundable errors in that the model uses annual average emission figures that may be influenced by significant diurnal and seasonal variation (TRW Systems Group, 1969, p. 2–6, 2–7 and A–3.

NORFOLK AREA AIRFLOW CHARACTERISTICS

The meteorological factors that influence the dispersion of pollutants are wind speed and atmospheric stability, that is, the observed lapse rate. The effects of turbulence are included in both of these factors. Concentration at any point downwind is inversely proportional to wind speed, since increasing the wind speed increases the volume into which the pollutant is dispersed for a given time period. The observed lapse rate determines whether vertical motion in the atmosphere will be enhanced or suppressed, and thus determines the rate of dispersion of pollutants. Both of these parameters are used as inputs to the AQDM.

Stability of the atmosphere is classified into five categories based on the works of Pasquill as found in Turner (1964), who states:

> * * * Stability near the ground is dependent primarily upon net radiation and wind speed. Without the influence of clouds, insolation (incoming radiation) during the day is dependent upon solar altitude, which is a function of time of day and time of year. When clouds exist, their cover and thickness decreases incoming and outgoing radiation. In this system insolation is estimated by solar altitude and modified for existing conditions of total cloud cover and cloud ceiling height. At night, estimates of outgoing radiation are made by considering cloud cover * * *. The stability classes are (A) extremely unstable, (B) moderately unstable, (C) slightly unstable, (D) neutral, and (E) slightly stable.

The seasonal and annual wind distribution (direction and speed percentages) and frequency of Pasquill stability classes have been calculated by the National Climatic Center, Asheville, N.C., (Job 13599) for Station No. 13750, Norfolk, Va., Naval Air Station. On the basis of 24 observations a day from December 1966 to November 1971, it was determined from Slade and others (1961), that the Naval Air Station (NAS) site gave good representation of the annual and and winter wind rose for the greater Norfolk area. This representativeness and the hourly measurements were the overriding considerations in the choice of Norfolk NAS rather than one of the other three meteorological stations in the area. A slight discrepancy exists between Norfolk NAS and Oceana NAS during the winter afternoons—a small increase in the wind direction from the east and southeast for Oceana NAS, which is located east of the Norfolk NAS and close to the Atlantic Ocean.

On an annual basis the stability frequency is as follows: 6 percent-B, 12 percent-C, 47 percent-D, and 32 percent-E, which accounts for 97 percent of all stability occurrences (fig. 16). The greater frequency of D and E stability classes is an apparent anomalous condition for an urban setting. Stability class C usually predominates in urban areas becauses the cityspace provides greater surface roughness, which increases mechanical turbulence, and because the higher temperature of cities versus rural areas (the urban heat-island effect) produces more thermal turbulence. The Norfolk area has more instances of stable conditions because of its geographic setting. The Norfolk region is situated on a peninsula where the abjacent water areas decrease both the thermal turbulence caused by the urban heat-island effect and mechanical turbulence. The latter occurs because the water has a lower surface roughness (Van der Hoven, 1967).

The wind direction for the annual period is as follows, in decreasing percentages based on 16 points of the compass: (1) 10.5 percent-SSW; (2) 9.1 percent-S, and 9.1 percent-N; (3) 7.5 percent-W;

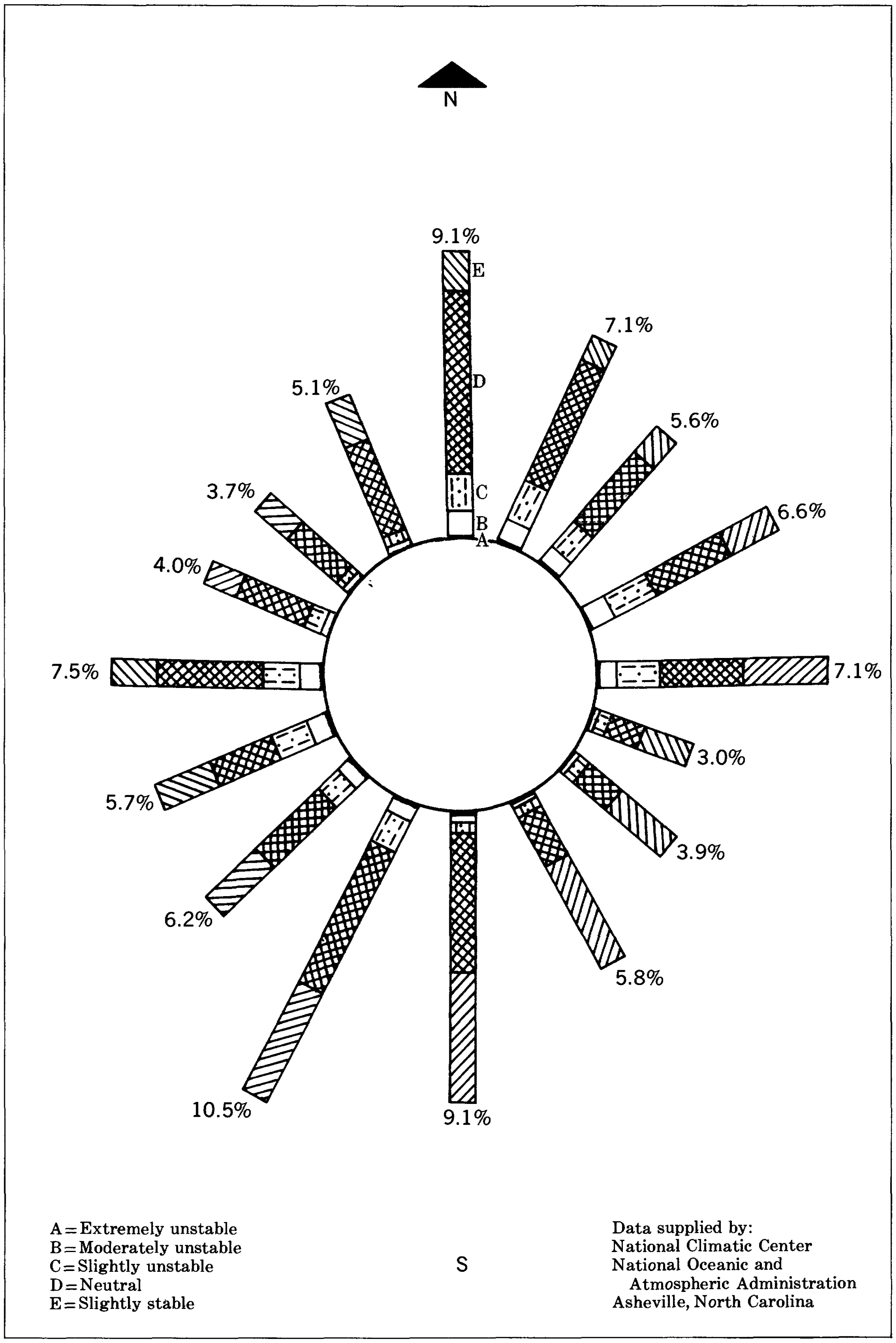


FIGURE 16.—Annual stability wind rose, December 1966–November 1971, Norfolk Naval Air Station.

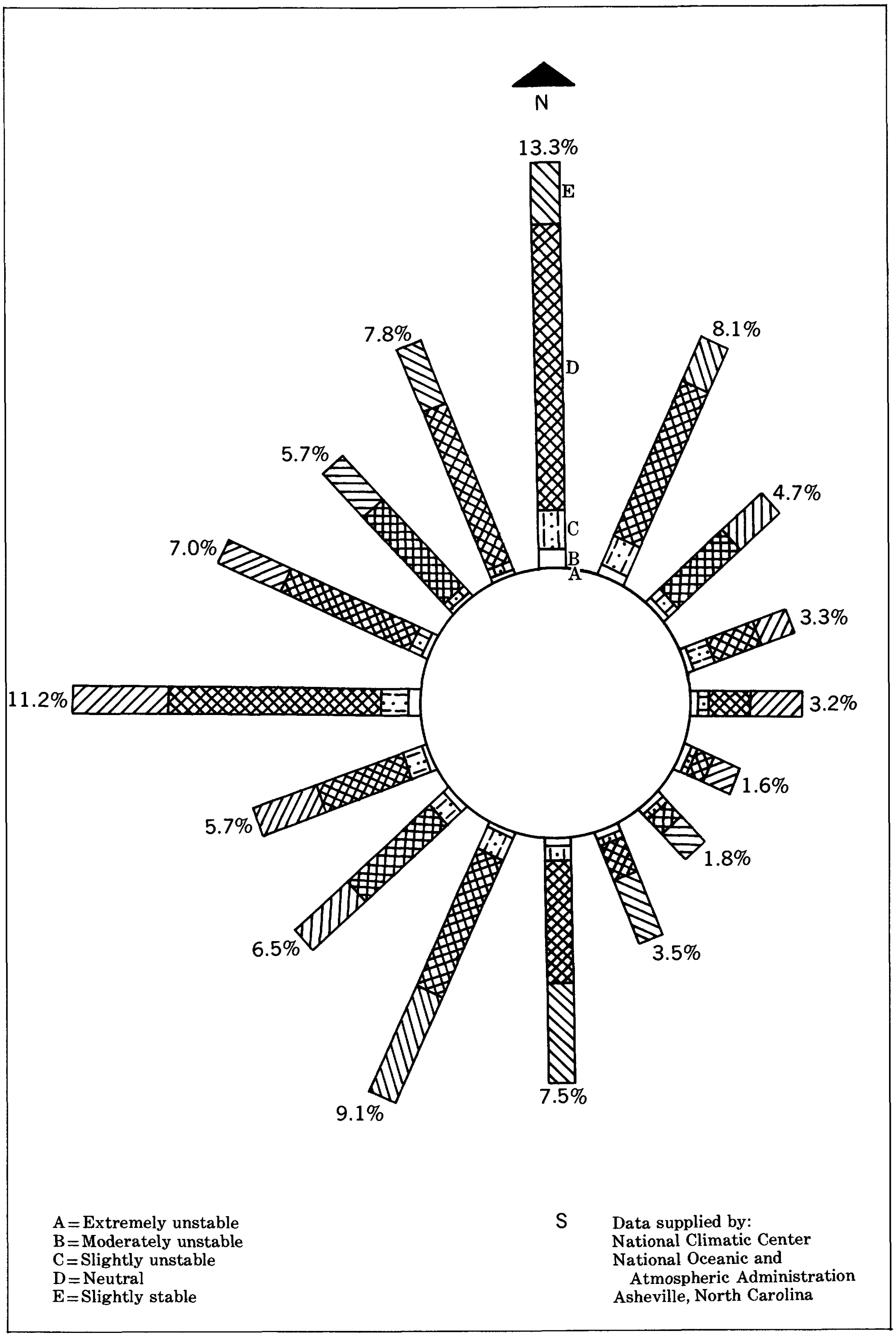


FIGURE 17.—Winter stability wind rose, December 1966–November 1971, Norfolk Naval Air Station.

and (4) 7.1 percent from both E and NNE (fig. 16). The remaining directions each account for less than 7 percent. The lowest value is 3 percent from the east southeast. The highest average wind speed was from the north and north northeast at 10.2 knots. A 6 percent incidence of calm was reported.

The winter season (Dec.–Jan.–Feb.) displays slight variations from the annual situation. The stability class percentages are: (1) 7 percent–C, (2) 58 percent–D, and (3) 31 percent–E (fig. 17). A greater percentage of more stable conditions exists during the winter, as seen in the increase of the class D and the decrease of the class C. As compared to the annual period, the wind directions in winter turn more to the north and west: (1) 13.3 percent–N; (2) 11.2 percent–W; (3) 9.1 percent–SSW; (4) 8.1 percent–NNE; (5) 7.8 percent–NNW; (6) 7.5 percent–S; and (7) 7 percent–WNW. The remaining directions each are less than 7 percent; the lowest is 1.6 percentf rom the east southeast. The highest wind speeds during the winter, 10 to 11 knots, all come from the northwest quadrant. The lowest average speed was 5 knots from the southeast. Six percent calms were reported for the winter period: (1) the greatest frequency of calms for a given hour occurred at 2200 h; (2) the greatest frequency of low-level inversion occurred at 0300-G.m.t. when the wind direction was from the south southwest, with fairly comparable percentages through to the northwest; (3) the seasonal frequency of precipitation by wind direction was primarily from the north northeast and north and secondarily from the south southwest and north northwest, but only 11.5 percent of total yearly rainfall occurred during the winter season. Holzworth (1964) gives an afternoon mixing depth of 600 m for Norfolk. This mixing depth appears to be a very conservative estimate, as Holzworth has recently updated his analysis to an annual afternoon mixing depth of 1200 m for the Norfolk area (Holzworth, 1972). This revised value was not available at the time this experimental study was undertaken.

SELECTION OF GRID PATTERNS FOR ESTIMATING POLLUTANT CONCENTRATIONS

Given this diffusion-estimating procedure, atmospheric data, and the emission inventories described earlier, current and future levels of sulfur dioxide and particulate concentrations could be calculated for locations throughout the Norfolk area. To relate this estimated pollution pattern to patterns of land use and land cover and selected points for air quality sampling, a grid for estimating pollution concentration for receptors was established. Although the land use and land cover information had a 4 ha minimum mapping unit, the spatial resolution of this grid was constrained by the estimating of area source emission inventories at a resolution of 6.25 km^2 or larger. To remain within the precision of the emission inventories and the capabilities of the estimating model itself, researchers determined that attempts to estimate pollution concentration at resolutions larger than 6.25 km^2 were not warranted.

From the location of point and area source emissions shown in figure 6 and the location and density of land uses and land cover to be impacted, a regular receptor grid of 2.50 km^2 cells was selected and superimposed on the area source emissions estimating grid at approximately the center of the 6.25 km^2 cells (fig. 18). Because of the distance decay function in the model, locating the receptor points coincident with emission centroids for point or area sources would have resulted in estimated levels of pollution much higher than would be expected to occur as pollutants diffuse over the entire area of a cell. Alternatively, to have randomly offset the grid from area or point emission sources would have resulted in many clusterings of receptor points, leaving large areas unevaluated. The 2.50-km density of receptor points was extended into the 10-, 25,- and 100-km^2 grid cells to estimate how these rapidly developing lower density cells are currently being impacted. In addition, a set of receptor points was specifically placed coincident with the location of existing air quality sampling stations indicated in figure 14. The same grid was used for future estimation.

NORFOLK LAND USE AND LAND COVER AND ESTIMATED AIR POLLUTANT CONCENTRATION PATTERNS

On the basis of the estimated emissions inventories and receptor grid, the air pollutant concentration estimating program, ADQM, of the Air Quality Implementation Planning Program was used to estimate 1972 annual, 1971–72 winter, and 1985 annual concentrations of sulfur dioxide and suspended particulates throughout the Norfolk area (U.S. Environmental Protection Agency, 1970). Figures 19–24 present the estimated spatial patterns. Table 5 is an example of the data produced by the AQDM program used to produce these figures. Table 6, another example of the program's output, gives point and area source contributions to receptor points having high concentrations and suggests emission reductions necessary to achieve

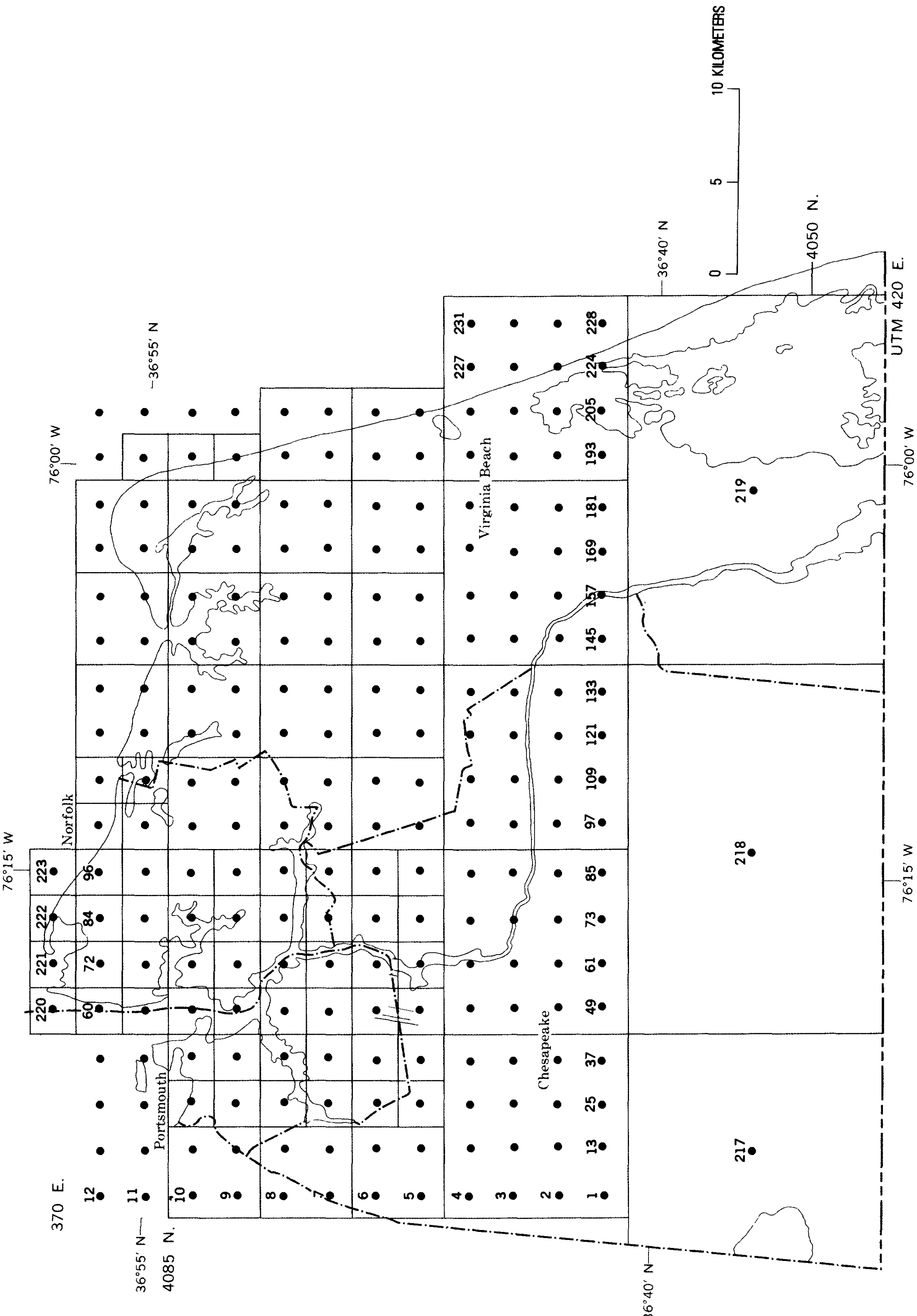


FIGURE 18.—1970 Norfolk-Portsmouth SMSA, pollution concentration estimating points.

TABLE 5.—*Estimates of concentration of pollutants over receptors*

[Region: Norfolk area (annual). Date: October 5, 1972]
Receptor concentration data

Receptor No.	Receptor location (kilometers)		Expected arithmetic mean (micrograms/cubic meter)	
	Horizontal	Vertical	SO_2	Part
1	371.2	4,061.2	5.2	8.8
2	371.2	4,063.7	6.9	10.1
3	371.2	4,066.2	6.6	11.8
4	371.2	4,068.7	6.8	14.0
5	371.2	4,071.2	6.7	16.5
6	371.2	4,073.7	6.2	19.4
7	371.2	4,076.2	5.6	20.4
8	371.2	4,078.7	5.8	19.6
9	371.2	4,081.2	6.1	19.4
10	371.2	4,083.7	6.8	18.7
11	371.2	4,086.2	8.0	17.6
12	371.2	4,088.7	5.2	16.8
13	373.7	4,061.2	5.5	9.2
14	373.7	4,063.7	7.2	10.6
15	373.7	4,066.2	7.8	12.4
16	373.7	4,068.7	8.4	15.5
17	373.7	4,071.2	8.1	18.3
18	373.7	4,073.7	7.1	22.4
19	373.7	4,076.2	7.3	24.1
20	373.3	4,078.7	7.3	22.4
21	373.7	4,081.2	7.5	23.0
22	373.7	4,083.7	7.3	21.7
23	373.7	4,086.2	7.7	20.5
24	373.7	4,088.7	6.2	19.7
25	376.2	4,061.2	6.5	9.6
26	376.2	4,063.7	7.5	11.3
27	376.2	4,066.2	9.6	13.6
28	376.2	4,068.7	11.3	17.2
29	376.2	4,071.2	10.3	21.5
30	376.2	4,073.7	8.6	27.0
31	376.2	4,076.2	9.9	29.6
32	376.2	4,078.7	9.6	28.2
33	376.2	4,081.2	9.9	28.2
34	376.2	4,083.7	9.2	26.4
35	376.2	4,086.2	8.9	24.9
36	376.2	4,088.7	7.6	23.2
37	378.7	4,061.2	8.3	10.4
38	378.7	4,063.7	9.7	12.1
39	378.7	4,066.2	11.4	15.0
40	378.7	4,068.7	13.9	19.7

desired air quality. The program also produces estimate of the contribution of each point and a source at selected receptor points (table 7). luation of control strategies and implementation plans is based on these data and their relation to specific patterns of Norfolk area land use and land cover.

Although the area's air-quality sampling program was not yet fully operational, the range of annual and winter sulfur dioxide and suspended particulate samples drawn at selected stations are shown in figures 19, 20, 22, and 23 (Commonwealth of Virginia, 1972b). These initial values are based on a limited number of samples, many of which were subject to modification in sampling procedures during the startup period of the sampling system. These measured pollution values, however, generally reflect the estimated concentrations of sulfur dioxide and suspended particulates, suggesting that these model estimates are not unreasonable given the assumptions built into (1) the emissions inventories, and (2) the use of an airflow pattern for the Norfolk Naval Air Station. The large discrepancy between 1972 sampled and estimated levels for the sampling station in cell 103 appears to result from extensive construction occurring immediately adjacent to the sampling station during the previous year and by the station's proximity to an expressway and an asphalt plant, all of which tend to be averaged out in the cell's area emissions inventory.

The emissions inventory for particulates included both settleable and suspended material. Using Virginia State Air Pollution Control Board registration and initial inventory records, no method could be devised for estimating the percentage of suspended particulates in total emission and no definite information could be obtained on the rate at which settleable materials dropped out from different types and heights of sources. Most settleable materials, however, are assumed to drop out within a distance of 2 km from source locations. The initial operation of background sampling stations within the

LE 6.—*Example of estimates of point and area source contributions and recommended reduction programs for selected receptor points*

[Region: Norfolk area (annual). Date: October 5, 1972. Particulate pollutant concentrations above standard of 75.00 $\mu g/m^3$]

Receptor No.	Pollutant concentration (micrograms per cubic meter)			Pollutant reduction (percent)		
	Arithmetic mean concentration	Excess above air quality standard	Contribution from point sources	Contribution from area sources	Necessary for point sources	Necessary for all sources
--------------	315.7824	240.7824	306.8246	8.9579	78.4756	76.2495
--------------	164.3243	89.3243	148.9439	15.3804	59.9718	54.3586
--------------	155.5200	80.5200	150.3055	5.2144	53.5709	51.7747
--------------	125.3193	50.3193	114.4099	10.9095	43.9816	40.1529
--------------	104.8958	29.8958	94.9697	9.9262	31.4793	28.5005
--------------	92.5805	17.5805	88.0405	4.5400	19.9687	18.9894
--------------	89.6757	14.6757	53.5763	36.0994	27.3922	16.3653
--------------	83.1145	8.1145	80.0613	3.0531	10.1353	9.7630
--------------	77.5693	2.5693	69.7026	7.8668	3.6861	3.3123
--------------	75.7201	.7201	60.7036	15.0165	1.1862	.9510
--------------	75.2046	.2046	60.2716	14.9330	.3395	.2721

TABLE 7.—*Estimates of total contribution of specific sources to selected receptor estimating points, Norfolk-Portsmouth SMSA, 1972 annual*

[Region: Norfolk area (annual). Date: October 5, 1972. Source contributions to five selected SO_2 receptors in micrograms per cubic meter]

Source No.	Receptor=233		Receptor=234		Receptor=236		Receptor=239		Receptor=245	
	Q									
1	0.0107	0.04	0.0051	0.01	0.0014	0.01	0.0030	0.02	0.0034	0.01
2	1.7232	6.39	.6735	1.85	.2339	1.55	.4769	2.91	.5247	1.91
3	.2422	.90	.0755	.21	.0246	.16	.0357	.22	.0434	.16
4	.0605	.22	.0185	.05	.0060	.04	.0087	.05	.0107	.04
5	.8777	3.25	.6777	1.86	1.0398	6.89	.2863	1.75	.3767	1.37
6	.2271	.84	.1657	.46	.1149	.76	.0505	.31	.0716	.26
7	.0110	.04	.0103	.03	.0222	.15	.0064	.04	.0077	.03
8	.0516	.19	.0234	.06	.0110	.07	.0143	.09	.0160	.06
9	3.3192	12.31	.0758	.21	.0154	.10	.0252	.15	.0316	.12
10	.0725	.27	.0127	.04	.0013	.01	.0021	.01	.0031	.01
11	.0115	.04	.0089	.02	.0017	.01	.0018	.01	.0027	.01
12	.0224	.08	.0164	.05	.0037	.02	.0051	.03	.0061	.02
13	.1452	.54	.0634	.17	.0072	.05	.0116	.07	.0153	.06
14	1.1209	4.16	1.9298	5.30	.1090	.72	.1954	1.19	.2715	.99
15	.0905	.34	.5816	1.60	.0091	.06	.0153	.09	.0255	.09
16	.0332	.12	.1525	.42	.0141	.09	.0126	.08	.0204	.07
17	.0316	.12	.1655	.45	.0153	.10	.0128	.08	.0211	.08
18	.0022	.01	.0057	.02	.2631	1.74	.0033	.02	.0042	.02
19	.0351	.13	.0955	.26	5.5539	36.80	.0444	.27	.0616	.22
20	.0000	.00	.0000	.00	.0000	.00	.0000	.00	.0000	.00
21	.0107	.04	.1394	.38	.0023	.01	.0042	.03	.0086	.03
22	.0854	.32	.3089	.85	.0461	.31	.0484	.29	.0909	.33
23	.0117	.04	.0341	.09	.0069	.05	.0073	.04	.0155	.06
24	.0000	.00	.0000	.00	.0000	.00	.0000	.00	.0000	.00
25	.1492	.55	.2796	.77	.0334	.22	.0970	.59	.1600	.58
26	.0917	.34	.1114	.31	.0170	.11	.0418	.25	.0603	.22
27	.2050	.76	.4723	1.30	.0486	.32	.1551	.95	.2612	.95
28	.0099	.04	.0158	.04	.0588	.39	.0117	.07	.0149	.05
29	.0966	.36	.0772	.21	.0132	.09	.0249	.15	.0321	.12
30	.0086	.03	.0182	.05	.0018	.01	.0047	.03	.0075	.03
31	.2368	.88	.8188	2.25	.0677	.45	.2083	1.27	.5857	2.13
32	1.2355	4.58	3.4851	9.58	.2939	1.95	.9206	5.61	1.8194	6.63
33	.0704	.26	.1405	.39	.4238	2.81	.1553	.95	.1823	.66
34	.0194	.07	.0360	.10	.0793	.53	.0527	.32	.0537	.20
35	.4714	1.75	.9244	2.54	.1822	1.21	2.5800	15.73	4.1378	15.08
36	.0041	.02	.0077	.02	.0016	.01	.0212	.13	.0256	.09
37	.1352	.50	.2693	.74	.0434	.29	.3730	2.27	1.0359	3.78
38	.0000	0.00	.0000	.00	.0000	.00	.0000	.00	.0000	.00
39	.0126	.05	.0104	.03	.0044	.03	.0147	.09	.0135	.05
40	.0052	.02	.0089	.02	.0014	.01	.0059	.04	.0144	.05

Norfolk area suggested that a suspended particulate background level of approximately 40 $\mu g/m^3$ might exist because of salt spray from the ocean, erosion of exposed sand, and agricultural practices. This estimated background level of suspended particulates was not included in the model run. The near correspondence between levels of estimated and sampled suspended particulates may reflect a trade off between the loss of settleable particulates and the addition of suspended background matter in the sample values.

SULFUR DIOXIDE CONCENTRATIONS

Figures 19–21 show the estimated distribution of annual 1972, winter 1971–72, and annual 1985 sulfur dioxide concentrations and relate them to the distributions and levels of emissions from specific point sources and high employment areas in figures 8–10, and to the patterns of annual and winter airflow in figures 16 and 17. According to these estimates, the area most impacted by sulfur dioxide on an annual basis is the Naval Amphibious Base at Little Creek, in Virginia Beach east of Norfolk. This high estimate is partly a function of the location of a receptor estimating point nearly coincident with the point of emission. The powerplant's low stack suggest high levels may exist in the immediate vicinity. All other receptor locations are estimated to be below the national and State primary and secondary standards of 80 $\mu g/m^3$ and 60 $\mu g/m^3$ respectively. This area appears to be influenced by the incinerator and other area and point sources in cells 100 and 101 (fig. 18).

Winter patterns indicated in figure 20 reflect the greater frequency of winds from the northwest quadrant. The effect of increased space heating throughout central Norfolk and Portsmouth and in

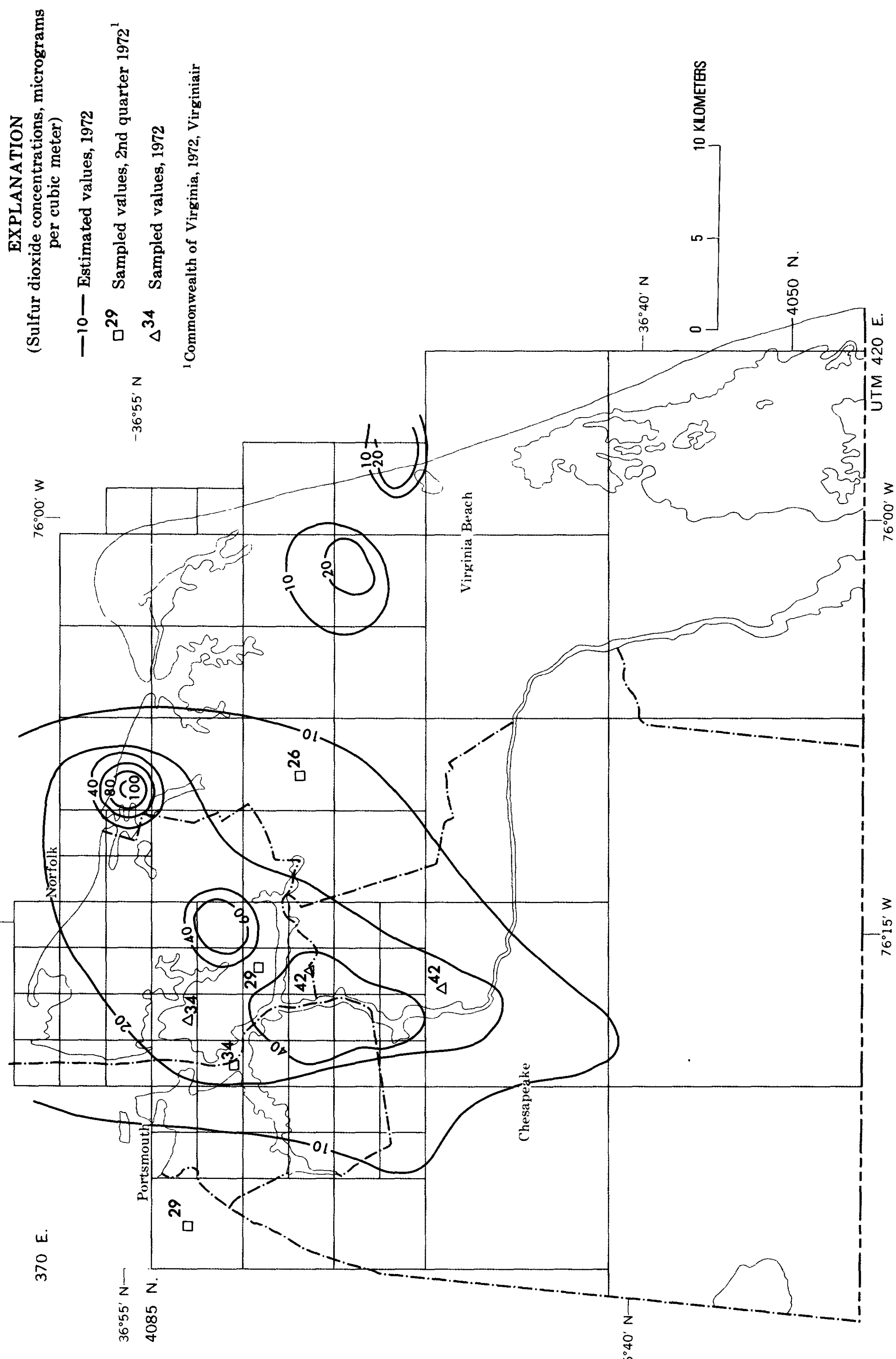


FIGURE 19.—1970 Norfolk-Portsmouth SMSA, estimated average concentration of sulfur dioxide, 1972.

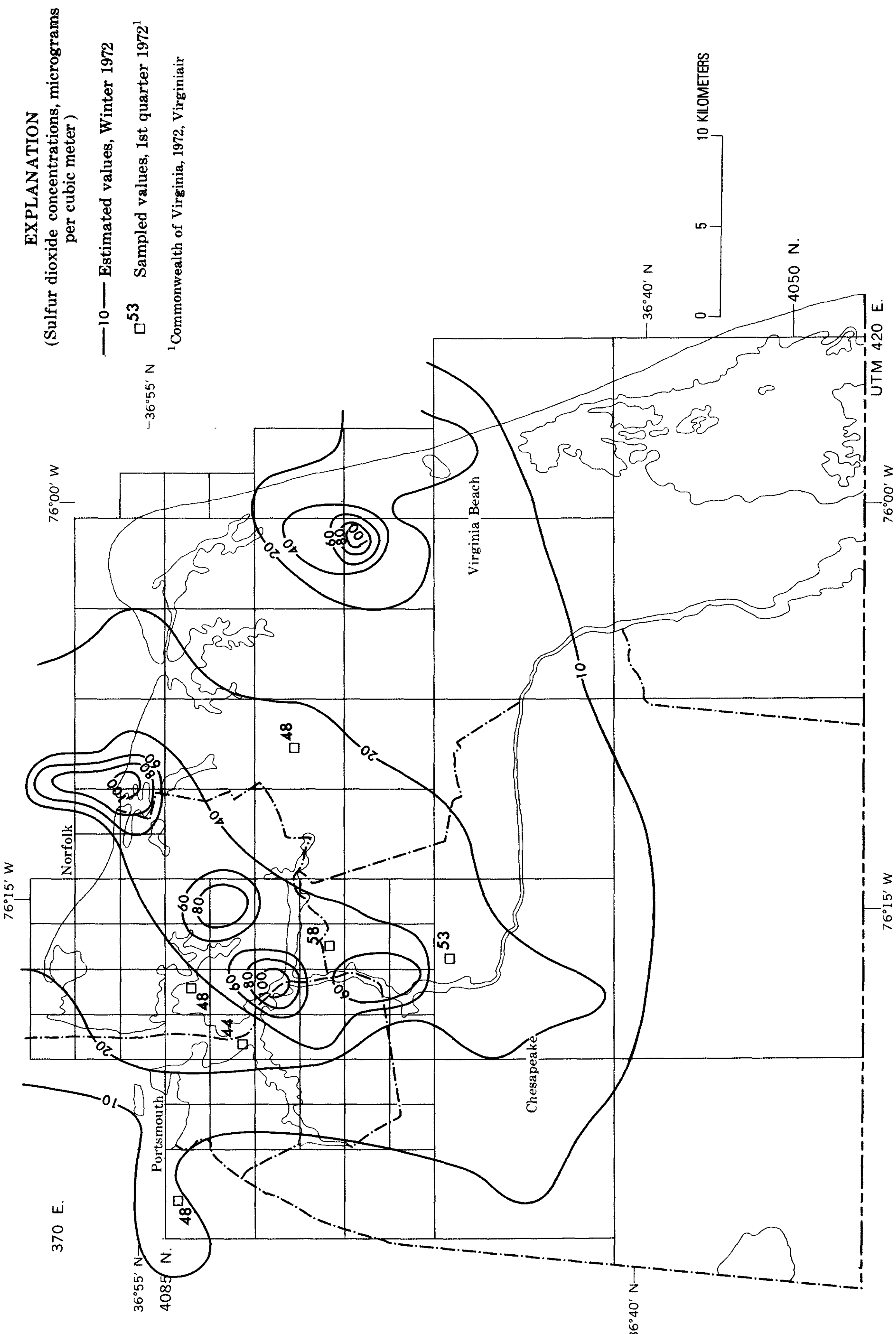


FIGURE 20.—1970 Norfolk-Portsmouth SMSA, estimated average concentrations of sulfur dioxide, winter 1971–72.

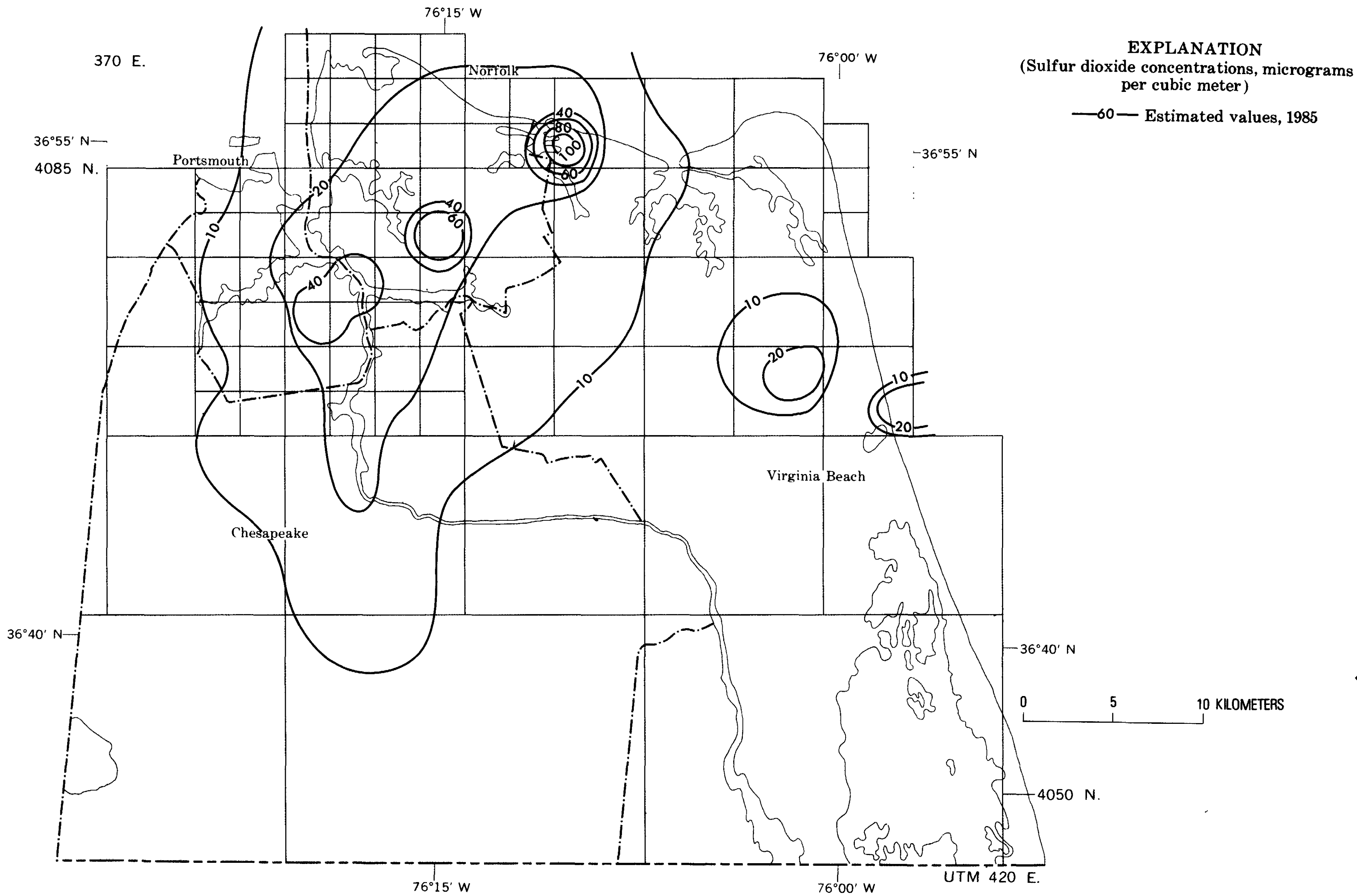


FIGURE 21.—1970 Norfolk-Portsmouth SMSA, estimated average concentrations of sulfur dioxide, 1985.

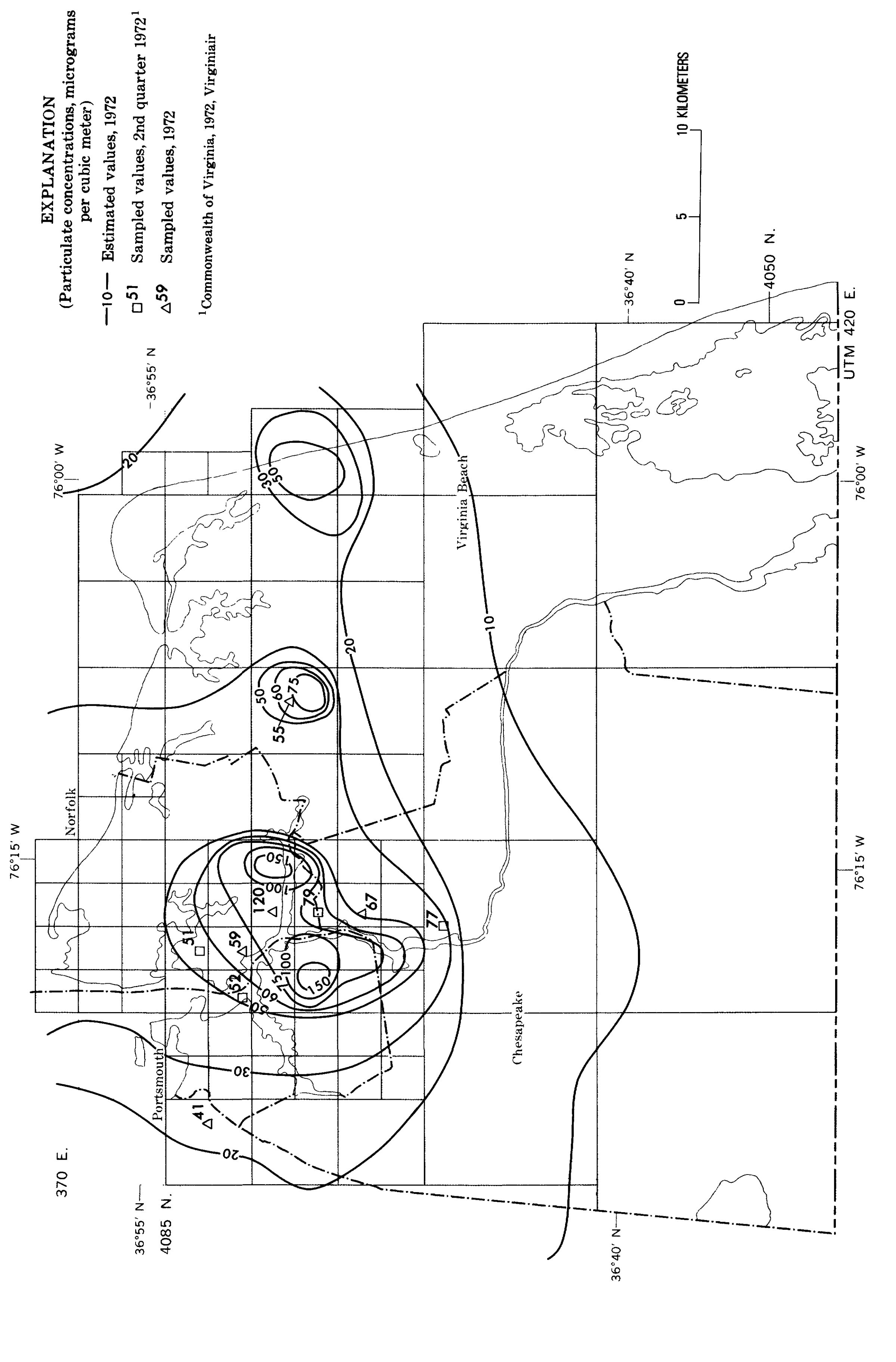


FIGURE 22.—1970 Norfolk-Portsmouth SMSA, estimated average concentrations of particulates, 1972.

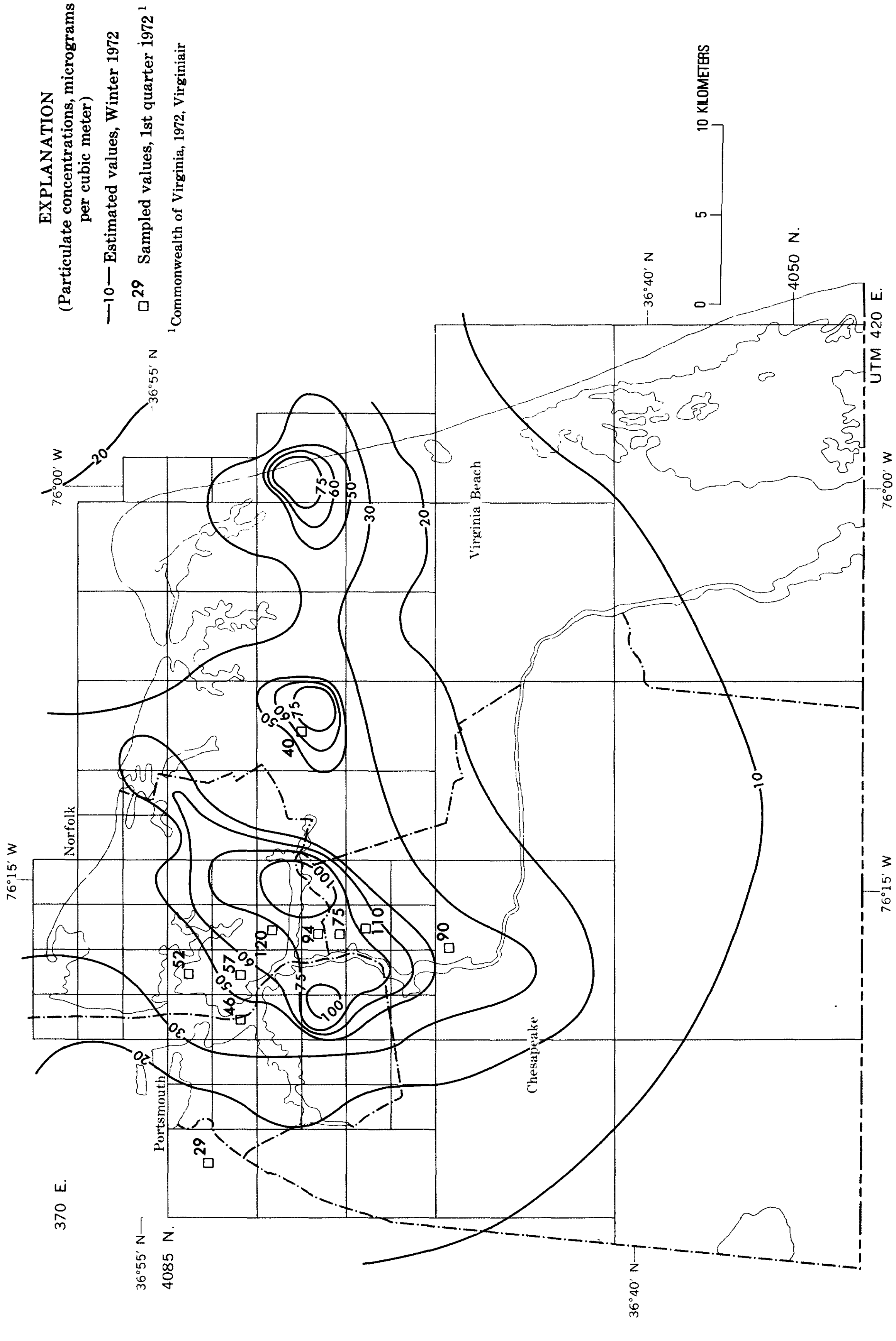


Figure 23.—1970 Norfolk-Portsmouth SMSA, estimated average concentrations of particulates, winter 1971–72.

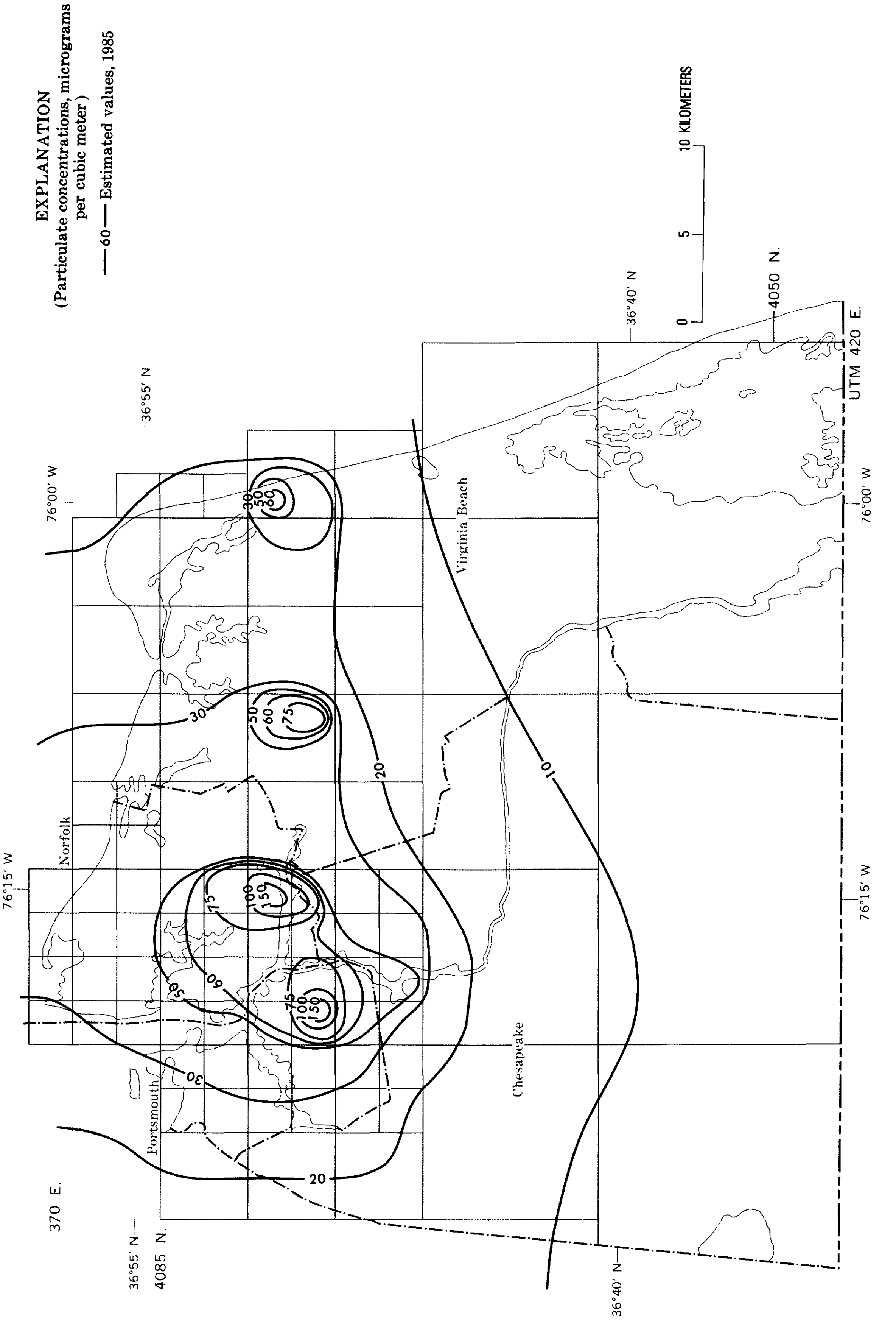


FIGURE 24.—1970 Norfolk-Portsmouth SMSA, estimated average concentrations of particulates, 1985.

Virginia Beach near Oceana Naval Air Station (fig. 14) is evident. The estimates suggest that primary and secondary standards for sulfur dioxide are exceeded throughout these high-density residential areas.

The estimated future pattern in figure 21 indicates that, given current control plans and rules for point sources, secondary and primary standards for sulfur dioxide may continue to be exceeded in central Norfolk and in the Little Creek area to the east. Elsewhere, anticipated future levels and patterns of sulfur dioxide emissions from the development of residential and other area sources are not expected to seriously deteriorate the region's air quality.

SUSPENDED PARTICULATE CONCENTRATIONS

Figures 22–24 show estimated distribution of annual 1972, winter 1971–72, and annual 1985 suspended particulate concentrations. Patterns of high concentrations for particulates are broader than for sulfur dioxide. This reflects the more ubiquitous contribution to particulate emissions from construction and general industrial and commercial activities throughout the Norfolk area (figs. 5, 6, and 11–13).

In view of the problem of mixing settleable and suspended particulates in the estimated emission inventory, these particulate patterns suggest that the national and State primary and secondary standards of 75 and 60 $\mu g/m^3$, respectively, are regularly exceeded in central Norfolk and Portsmouth. Current sampling values tend to confirm this, and it appears that point sources are the main contributors to these levels (table 4 and fig. 11).

The distribution and level of winter values reflect prevailing winds and increased space heating throughout the area. Large areas of residential land use and land cover in central Norfolk and Portsmouth and selected areas of Virginia Beach are estimated to be affected by concentrations above primary air quality standards.

On the basis of current control programs, 1985 levels of suspended particulates are estimated to exceed secondary standards throughout central Norfolk and Portsmouth and in certain areas of Virginia Beach. Existing point sources rather than anticipated 1985 area sources are the major contributors in this estimate (table 4 and fig. 13). These estimates suggest the need for improved procedures for estimating and sampling suspended particulate emissions and natural background levels to determine whether modifications in current rules and implementation plans may be needed.

CONCLUSIONS

The Virginia State Air Pollution Control Board adopted an emissions control strategy for sulfur dioxide and suspended particulates in the Norfolk area. The implementation plan focused on local action to control point sources. Adoption of this strategy and plan were certainly reasonable, given the time available for planning and the information available on the distribution of emission sources and receptor land uses and land cover, the level of emissions, the pattern of airflows, and the measured concentration of pollutants.

Using the U.S. Geological Survey's land use and land cover information, this more detailed analysis of the amount and distribution of pollutants in the area indicates that the board's initial air quality planning was sound. Distribution patterns of sulfur dioxide and suspended particulate concentrations, estimated using an adequate diffusion model and the best available airflow data, suggest that current and future concentrations are most affected by point source emissions. Given the levels of space heating and mobile source emissions expected for the type of low-density development anticipated for the area, this analysis suggests that current point source control programs may not achieve required standards. If additional reduction is required or desired, it is estimated that the greatest impact could be achieved through emission controls affecting institutional (military and municipal) land uses. Change in these land uses and land cover would most benefit land users in older areas of Norfolk and Portsmouth (fig. 5).

This use of the uncalibrated AQDM provides the means for rapidly estimating impacts of alternative locations for new point or area emissions sources. Pollutant concentration levels estimated in this study suggest that operators of new high emission sources should be encouraged to locate away from existing areas of high pollutant concentration. Further experimentation using the model should suggest sizes of compatible buffer land uses and land cover or alternate mixes of uses that could improve diffusion characteristics.

With an adequate sampling program the AQDM can be calibrated to predict more accurately the area's pollutant concentration levels. According to the Virginia's State Air Pollution Control Board Implementation Plan (Commonwealth of Virginia, 1972a), only the sampling stations in cells 70, 74, and 103 were planned to reflect the area's population concentrations. The land use and land cover and emission concentration distribution estimated in this study suggest the need for a wider dispersion of particulate sampling stations into cells 101, 106, and 109, and of sulfur dioxide sampling stations into cells 60, 87, 99, 110, 117, 123, and 128. Sampling programs in these and other cells have been undertaken by the board to confirm the validity of these estimated concentrations and to provide a basis for improved estimates. Past trends in land use and land cover change, and future change anticipated by local planners, suggest the need for greater detail in the board's area source emissions estimating grid to the east and south of the existing set of 6.25 km^2 cells (fig. 5). Improvement in future area source emission estimates could be achieved by recording the types of fuels to be used in large subdivisions as they are developed in each grid cell. In addition, computerizing traffic flow data and matching it with the location of specific land use densities in various grid cells could speed up and improve the detail of area source emission estimates.

Given the physical setting affecting Norfolk area airflow and the pattern of developed and anticipated land use and land cover, only minor modifications in the current emissions control strategy and implementation plan are suggested by this study utilizing detailed land use and land cover information.

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