UNITED STATES · ENVIRONMENTAL PROTECTION AGENCY

Office of Air and Water Programs
Air Pollution Training Institute

Cost Effectiveness of Air Pollution Control Strategies

Training Course Manual

COST EFFECTIVENESS OF AIR POLLUTION CONTROL STRATEGIES

Conducted by
CONTROL PROGRAMS DEVELOPMENT DIVISION
Air Pollution Training Institute
Research Triangle Park, North Carolina 27711
April, 1973

This course is designed for professional persons in the field of air pollution control. The course manual has been prepared specifically for the trainees attending the course, and should not be included in the reading lists of periodicals as generally available.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

US | EPA

AIR POLLUTION TRAINING INSTITUTE

CONTROL PROGRAMS DEVELOPMENT DIVISION

OFFICE OF AIR AND WATER PROGRAMS

The Air Pollution Training Institute (1) conducts training for the development and improvement of state, regional, and local governmental air pollution control programs, (2) provides consultation and other training assistance to governmental agencies, educational institutions, industrial organizations, and others engaged in air pollution training activities, and (3) promotes the development and improvement of air pollution training programs in educational institutions and state, regional, and local governmental air pollution control agencies.

One of the principal mechanisms utilized to meet the Institute's goals is the intensive short term technical training course. A full time professional staff is responsible for the design, development and presentation of these courses. In addition the services of scientists, engineers and specialists from other EPA programs, governmental agencies, industry, and universities are used to augment and reinforce the Institute staff in the development and presentation of technical material.

Individual course objectives and desired learning outcomes are delineated to meet specific training needs. Subject matter areas covered include process evaluation and control, atmospheric sampling and analysis, field studies and air quality management. These courses are presented in the Institute's resident classrooms and laboratories at various field locations.

Francis J. King, Chief
Air Pollution Training Institute
Control Programs Development Division

TABLE OF CONTENTS

3. USER'S GUIDE

AS A MATTER OF INTRODUCTION

SCENARIO

USER'S MANUAL FOR OPERATING THE TERMINAL FOR THE TRAINING EXERCISE

1. Computer Programs
2. Entering, Amending and Deleting Data
3. Exercising the Conversational Mode
4. Preparing Input for the Batch Mode
5. Running the Batch Mode

SECTION 1

SECTION 1. INTRODUCTION

PROJECT DESCRIPTION

The training exercise is an active learning experience through which participants are introduced to computerized techniques for estimating the effects of alternative strategies planned for air pollution control. The exercise utilizes a computer program which has come to be referred to as the Training Model. It is performed at a terminal, such as a teletype, that is linked to a time-share computer system. This facility provides for real-time computations of fairly intricate mathematical expressions, and for "conversational" interaction between participant and computer program.

The exercise is keyed to an atmospheric transport and diffusion model for determining average annual (or seasonal) ground level pollutant concentrations. Input consists of emission data and meteorological data, which are derived from a scenario of regional dimensions. Emissions may be reduced by the imposition of control measures that are determined by the user's strategy. Output of ground level sulfur oxide and suspended particulate concentrations is compared with preset air quality goals. The object is to meet these goals and at the same time achieve the maximum reduction for the least costly control strategy. A benefit-cost ratio is determined from the soiling cost reduction (benefit) and the associated cost of controls.

OBJECTIVE AND SCOPE

For the Training Exercise, the key word is "Training". In several respects the Training Model echoes large scale operational models for regional analysis, as in its logical, realistically fashioned scenario and its use of NAPCA sanctioned control data, emission factors, dispersion model, and soiling cost expressions. But through simplification, it primarily serves Training, not operational objectives. It is intended to demonstrate the powerful support that computerized techniques can offer to air quality management by providing real-time solutions for the impact of control strategies before decisions on implementation are made.

BACKGROUND

The Institute for Air Pollution Training

Under the Air Quality Act of 1967, the principal responsibilities of the Federal government are to provide coordination, guidance, leadership, research, financial support, and manpower development. It is for the State and local control agencies to bear the brunt of abatement, control, and air resources management. To meet their increased responsibilities under the Act, these agencies have been upgrading inhouse capabilities through expansion of staff and facilities. Most are encountering a scarcity of personnel who are well-qualified and up-to-date in outlook and training. Yet, these agencies reside in the midst of vehemently conflicting interests that will be vitally affected by their judgment and decisions. Their control action must be supported by the great weight of scientific, technological, social, and economic experience. To measure up to this stature, control agencies must interrelate more closely with authorities beyond their parochial arenas: the academic and institutional realms, professional societies, private independent consultants and researchers, and their Federal correlatives.

It is in this context that the NAPCA Office of Manpower Development (OMD) plays a vital role. Through program and career development activities, fellowship and traineeship awards, and sponsorship of training sessions, OMD works to provide the quality of manpower necessary to carry out the provisions of the Act. The Institute for Air Pollution Training (IAPT) conducts a variety of courses at Research Triangle Park and in cities across the nation, and helps other government agencies, educational institutions, and industrial organizations to establish or improve their own training facilities. The Institute for Air Pollution Training courses provide an excellent forum for the interchange of ideas. From the Federal side, they also serve as a propagation and testing medium for the newest findings and techniques developed under Federal auspices. This, then, is the framework for design and implementation of the training exercise to be described in the pages that follow.

SECTION 2

DESCRIPTION OF THE TRAINING EXERCISE

- Exercise Elements
- Scenario
    - Demographic Data
    - Power
    - Space Heating
    - Solid Waste
- Emission Inventory
    - Identification of Sources
    - Source Characteristics and Emission Factors
- Control Alternatives
    - Fuel Switching Costs
    - Tall Stacks
    - Air Cleaners
- Transport and Diffusion Model
    - Description
    - Features and Limitations
    - Meteorological Data
- Effects
    - Ground Level Concentrations
    - Damage Costs
    - Benefit and Benefit-Cost Ratio
    - Population Factors
    - Selection of Receptor Sites

SECTION 2. DESCRIPTION OF THE TRAINING EXERCISE

EXERCISE ELEMENTS

The Training Exercise is comprised of the following three elements:

- Scenario
- Class Problem
- Training Model

The first two set the ground rules for the exercise; the third is the mechanism for solution. Details follow.

SCENARIO

The hypothetical region designed for this exercise is shown in Figure 1. It measures 50 km by 50 km, and is designated as the PDQ Region because it covers portions of three counties, Prince, Duchess, and Queen. Most other place names are derived from the International Phonetic Alphabet.

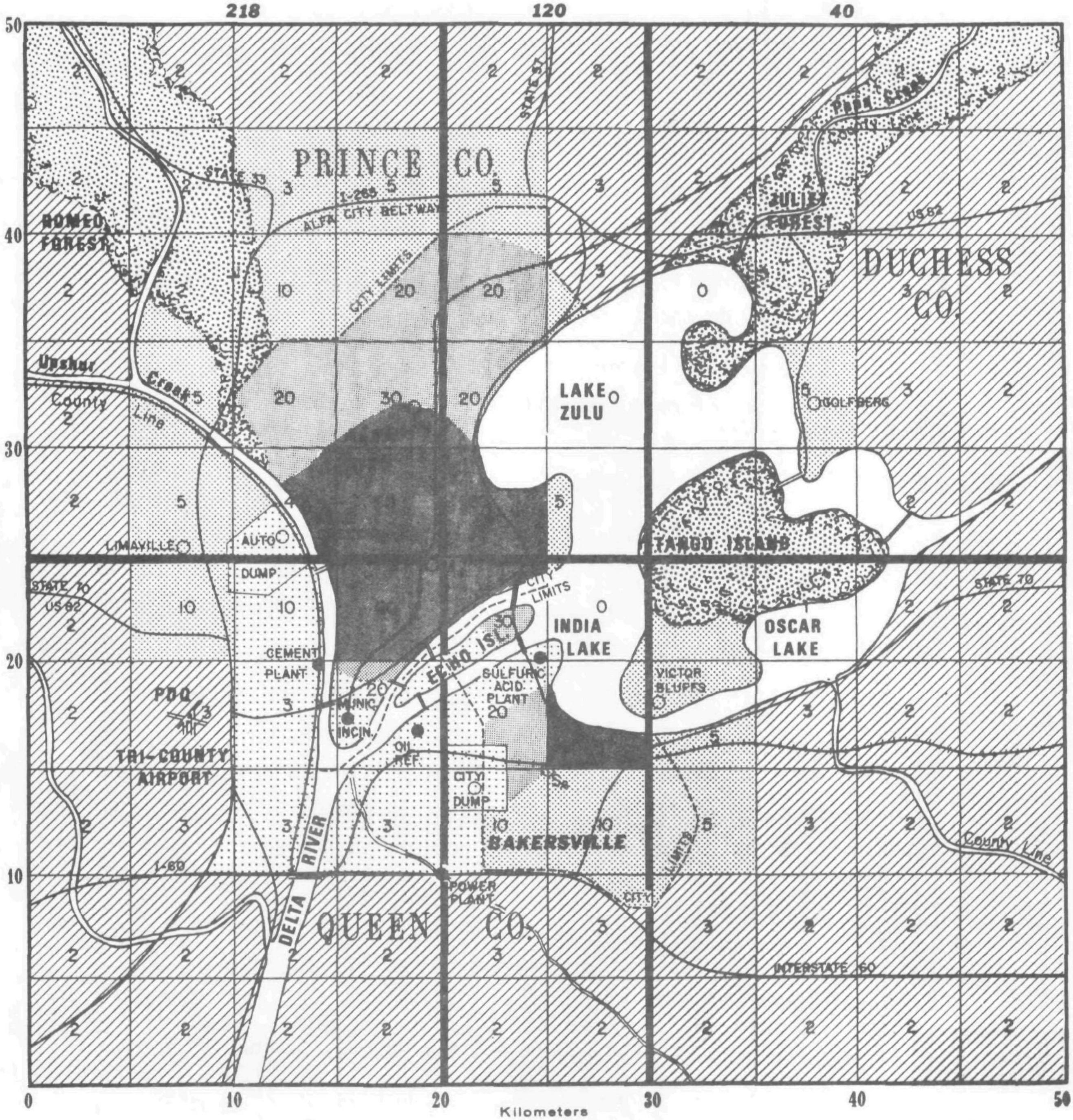
Airline distance between the two cities within the region, Alfa City and Bakersville, is about 10 km, downtown to downtown. Alfa City, the larger of the two, is a progressive community in which civic pride and affluence is much in evidence. Bakersville is gradually emerging from its drab beginnings as living quarters for workers in the nearby heavy industries. This contrast is reflected in the following statistical details for the tri-county region.

Demographic Data

Total population of the PDQ region is 706,000, divided as follows:

County	Prince	Duchess	Queen
City:	Alfa City	(none)	Bakersville
total	356,000		102,000
(Central City)	(240,000)		(60,000)
Suburban	35,000	10,000	66,000
Exurban	38.500	37,000	62,000
Totals	429,000	47,000	230,000

FIGURE 1
HYPOTHETICAL AIR QUALITY REGION



LEGEND

	Area source centroids	
Exurban	Incineration, Alfa City	M_a
Urban, Low Density	Space Heating, Alfa City	S_a
Urban, Medium Density	Incineration, Bakersville	M_β
Urban, High Density	Space Heating, Bakersville	S_β
Wooded area		
Water		
Industrial Area		

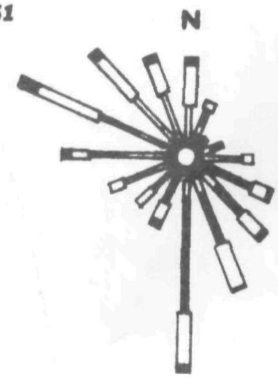


Figure 1 shows the population distribution by 5 km grid spaces.

In Alfa City, of the 240,000 people living in the heart of the city, 80% live in multiple family dwellings, 20% in single-family dwellings. The remaining 116,000 within city limits live in single-family dwellings. The average family unit has 4 persons, and the average multiple-family dwelling has 40 units. The 80 - 20 ratio and 4 persons per family also applies to Bakersville, but in the heart of town where 60,000 people reside the average multiple has 20 units.

Power

Power generation for the entire region has been consolidated in one central power plant built in 1952. The plant has a capacity of 1,500 mw, provided by three 500 mw boilers, each burning 3150 tons per day of 3% sulfur, 12% ash content coal. Each boiler emits 1,000,000 acfm of flue gas, which passes through multicyclones, then up a 300 ft stack into the atmosphere. Recent checks show the multicyclones to be 74.6% efficient for removal of particulates.

Space Heating

In Prince County, coal burning has been discontinued by county ordinance. Commercial buildings and apartment houses (multiples) burn either #5 or #6 oil, the mix averaging 1.7% in sulfur content. Home space heating is done by burning #2 oil, which contains 0.3% sulfur. Facilities for natural gas are becoming more available, and it is hoped that there will be enough to handle 40% of all fuel demands by next year.

In Queen County, coal furnaces are still used in 60% of the private houses, mainly in Bakersville. The remaining single-family houses use #2 oil, and all multiple-family dwellings use the same mix of #5 and #6 oil as does Alfa City, with average sulfur content of 1.7%.

In Duchess County, only #2 fuel oil is in use.

COUNTY	UNITS PER MFD	NUMBER OF MFD's	NUMBER OF SFD's	SPACE HEATING FUEL MFD	SPACE HEATING FUEL SFD	SOLID WASTE DISPOSAL MFD	SOLID WASTE DISPOSAL SFD
PRINCE	40	1,000	67,250	Heavy Oil 1.7%	#2 Oil 0.3%S	50% Municipal Incinerator 50% In-House Incinerator	100% Municipal Incinerator plus Landfill
DUCHESS	--	0	11,750	--	#2 Oil	--	100% Backyard Burning
QUEEN	20	600	45,500	Heavy Oil 1.7%S	27,300 Coal: 3%S 18,200 #2 Oil: 0.3%S	100% In-House Incinerator	100% Dump Open Burning

MFD: Multiple-Family Dwelling SFD: Single-Family Dwelling

TABLE 1. AREA SOURCE CHARACTERISTICS OF PDQ REGION

After the sources were checked for consistency with problem objectives, emission factors listed in NAPCA publications[2] were applied to process rates to produce an emission inventory. The procedure is shown in Appendix A, and the inventory results are in Table 2.

CONTROL ALTERNATIVES

Control measures specified for the Training Exercise are limited to the following:

- Fuel switching
- Tall stacks
- Air cleaners
- Other (upgrading or eliminating a source)

A number of control alternatives for a given source may be available

A number of control alternatives for a given source may be available within each of the three categories. Fuel switching may be done from coal to oil or to gas, or from oil to gas, or from high sulfur to lower sulfur content coal or oil. In the case of low stack replacement by a taller stack, the alternatives from which a selection is to be made are the height increments for the tall stack. As for air cleaning devices, control alternatives are limited to specific types and sizes appropriate to each industry and process. The common characteristic of all three categories is incremental cost.

Fuel switching and air cleaner use are directed to the reduction of pollutant emissions. Fuel switching is at present the most effective way of reducing sulfur oxide emission from combustion processes, but it may also result in lower emission of particulates. Air cleaners are designed primarily for the control of particulate emissions, but certain scrubbers remove a small amount of sulfur oxides as well.

---

2. In particular:

   R. L. Duprey, "Compilation of Air Pollutant Emission Factors." Public Health Service Publication No. 999-AP-42, (1968)

   G. Ozolins and R. Smith, "A Rapid Survey Technique for Estimating Community Air Pollution Emissions." Public Health Service Publication No. 999-AP-29 (1966).

TABLE 2. SOURCE AND EMISSION DATA

	SOURCE	COORDINATES (km) X	Y	AREA (sq.km)	STACK HT. (m)	EMISSION (T/DAY) SO_x	PARTIC.
1.	Power Plant	20.0	10.0	0.0	100.0	538.65	300.00*
2.	Municipal Incinerator	15.4	17.2	0.0	25.0	0.42	3.58
3.	Oil Refinery	19.0	16.8	0.0	25.0	0.00	3.72
4.	Cement Plant	14.0	19.8	0.0	25.0	0.00	18.24
5.	Lead Smelter	14.2	19.8	0.0	25.0	44.70	46.20
6.	Sulfuric Acid Pl.	24.8	20.1	0.0	25.0	32.40	4.04
7.	Alfa City: Incinerator	19.6	24.5	78.5	25.0	0.08	3.14
8.	Alfa City: Space Heating, Multpl	18.5	32.0	254.0	0.0	23.88	1.84
9.	Auto Dump	12.2	25.4	10.1	0.0	0.00	1.20
10.	Bakersvl: Incin.	25.9	16.9	10.1	25.0	0.02	0.79
11.	Bakersvl: Space Heating, Multpl	25.1	14.9	78.5	0.0	6.07	4.69
12.	Bakersvl. Dump	21.5	14.0	9.1	0.0	0.01	1.74
13.	Alfa City: Space Heating, Single	18.5	32.0	254.0	0.0	2.80	0.59
14.	Bakersvl: Space Heating, Single	25.1	14.9	78.5	0.0	8.21	18.00
15.	Bakersvl: Space Heating, Single Oil	25.1	14.9	78.5	0.0	0.36	0.77

*After control by mechanical cleaner, 74.6% efficient.

NOTE: Coordinates of Area sources are for centroid of area.

TABLE 3. FUEL SWITCHING ALTERNATIVES AND COST DATA

Applied to Power Plant and Space Heating Only

Source	Process Rate Units/Year	Present Fuel Type	Present Fuel Cost	Coal: Range: S=Sulfur % Cost Formula	Oil: #6 Range: Cost Formula	Oil: #5 Range: Cost Formula	Oil: #2 (S=0.3%) Cost	Gas: Firm Cost
Power Plant	Coal: 3.45(10^6)T Alt: Oil 5.49(10^8) gal Alt: Gas 5.43(10^{10})ft^3	Coal 3%S	\$7.05/T \$24.3(10^6) Ann.	S: 3.0 → 0.5 $Y=10.961-2.817S + 0.505 S^2$ (dollars/ton)	S: 2.0 → 0.5 Y=.058-.003S (dollars/gal)	S: 1.75 → 0.5 Y=.0585-.0025S (dollars/gal)	\$ 0.076/gal \$ 41.8(10^6) Ann.	\$ .001/ft^3 \$54.3(10^6) Ann.
Space Heating								
1. Alfa City a. Single Family	#2 Oil 43.3(10^6)gal Alt: Gas 42.7(10^8)ft^3	#2 Oil 0.3%S	\$0.153/gal 66.20(10^5) Ann.					\$.0016/ft3 \$68.30(10^5) Ann.
b. Multiple	#5 1/2 Oil 67.6(10^6)gal Alt: gas 66.2(10^8)ft^3	#5 1/2 oil 1.65%S	\$ 0.082/gal 55.20(10^5) Ann.		#5 1/2 oil 0.8%S \$ .089/gal \$ 59.80(10^5)Ann.		\$ 0.131/gal \$88.50(10^5) Ann.	\$.0015/ft^3 \$99.35(10^5) Ann.
2. Bakersvl a. Single Family	Coal 52.5(10^3)T Alt: #2 oil 8.38(10^6) gal Alt: gas 8.28(10^8)ft^3	Coal 3%S	\$20.30/T \$10.67(10^5) Ann .	S: 3.0 → 0.5 $Y=38.015-14.380S +2.825S^2$ (dollars/ton)			\$ 0.153/gal \$12.82(10^5) Ann.	\$.00169/ft^3 \$1167(10^5) Ann.
b. Single Family	#2 oil 5.6(10^6)gal Alt: gas 5.42(10^8) ft^3	#2 oil 0.3%S	\$0.153/gal \$8.39 (10^5) Ann.					\$.0016/ft^3 \$8.66(10^5) Ann.
c. Multiple	#5 1/2 oil 17.1(10^6)gal. Alt: gas 1.69(10^9)ft^3	#5 1/2 oil 1.65%S	\$0.082/gal \$14.03(10^5) Ann.		#5 1/2 oil: 0.8%S \$ 0.089/gal \$15.22(10^5)		\$ 0.131/gal \$22.38(10^5) Ann.	\$.0015/ft^3 \$25.30(10^5) Ann.

Tall stacks effect no reduction in the quantity of pollutant that is emitted. Elevated emission sources merely take advantage of a larger volume of air through which pollutants are diluted before reaching ground level, and winds at higher levels of the atmosphere carry the material to greater distance than with lower sources. The net result is that ground level concentrations close to the source may be considerably reduced by implementation of the tall stack option.

Fuel Switching Costs

Several factors including boiler conversion determine the incremental cost of a fuel change, but the most significant factor is the cost of the fuel itself. Cost figures selected for use in this exercise are derived from the report entitled "The Fuel of Fifty Cities".[3] A number of simplifications were made to adapt the reported figure to the purposes of the exercise. In the cases of coal and heavy oil, cost and sulfur percentage data were fitted to a polynomial in order to derive generalized expressions of costs for all intermediate values of sulfur content. Table 3 lists the fuel switching applications and costs adopted for the exercise.

In the second column headed Process Rate, alternative fuel amounts were calculated on the basis of requirements to produce the same annual number of BTU's as provided by the fuel in present use. Calculations, shown in Appendix A, assume combustion efficiencies published in Ozolins and Smith, (1966).[4]

A change from high sulfur to low sulfur coal or from high sulfur to low sulfur oil will reduce emissions of sulfur oxide but not particulates. However, calculations using emission factors show that a

3. Ernst and Ernst, "The Fuel of Fifty Cities", report prepared for Department of Health, Education and Welfare, National Air Pollution Control Administration, November 1968.

4. Ibid, p. 43.

TABLE 4. AIR CLEANER ALTERNATIVES AND COST DATA

Source	Type of Cleaner: Feasible	Existing	Eff	ALTERNATIVES: Code	Eff.%: SO_x	Eff.%: P	Annual Costs: Inst(1/15)	Annual Costs: O & M	Annual Costs: Total	Code	Eff.%: SO_x	Eff.%: P	Annual Costs: Inst(1/15)	Annual Costs: O & M	Annual Costs: Total	Code	Eff.%: SO_x	Eff.%: P	Annual Costs: Inst(1/15)	Annual Costs: O & M	Annual Costs: Total
Power Plant	EP	MC	74.6	5	0	80	$120K	$345K	$465K	6	0	90	$160K	$450K	$610K	7	0	95.7	$220 K	$570K	$790K
Other Alt. Tall Stack Fuel Switch	MC			11						12	0	80	$ 48K	$300K	$348K	13	0	90.0	$ 60 K	$360K	$420K
Municipal Incinerators	MC (plus wetted baffles)	0	0	11	0	70	$1.1K	$ 9K	$10.1K	12	0	80	$1.7K	$ 10K	$11.7K	13	0	90.0	$2.5 K	$ 12K	$14.5K
	WS			8	80	85	$1.9K	$ 22K	$23.9 K	9	80	92	$3.3K	$ 42K	$45.3K	10	80	95.6	$6.0K	$160K	$166.0K
	FF(Baghouse															16	0	99.3	$ 50 K	$ 23K	$ 73K
Oil Refinery (Boiler and process heater only)	EP plus elevated flare (direct flame afterburner)	0	0	5+17	0	90	$ 34K	$133K	$167K	6+17	0	93	$ 43K	$153K	$196K	7+17	0	95	$ 55 K	$175K	$230K
Cement, Plant	EP	0	0	5	0	90	$4.7K	$ 14K	$18.7K	6	0	93	[illegible]	[illegible]	$25.5K	7	0	95.7	$11.3K	$ 24K	$35.3K
	MC			11	0	60	$0.9K	$8.0K	$8.9K	12	0	80	$1.3K	$ 9.0K	$10.3K	13	0	90	$ 2.0K	$10.5K	$12.5K
	FF			14	0	98.5	$33.3K	$ 17K	$50.3K	15	0	99.3	$40.0K	$18 K	$58.0K	16	0	99.7	$51.3K	$20 K	$71.3K
Lead Smelter	MC	0	0							12	20	[illegible]	$8.4K	$105K	$113.4K						
Other Alt: Tall Stack (Corrosivity Factor=3x)	FF															16	0	99.3	$300K	$ 30K	$330K
Sulfuric Acid Plant	WS	0	0	8	40	80	$40 K	$ 6K	$10.0K	9	55	88	$7.4K	$ 16K	$23.4K	10	68	[illegible]	$10.7K	$ 45K	$55.7K
(Corrosivity Factor=5x)	EP + mist eliminators															7	0	99.3	$ 75 K	$10.74K	$182.41

Code: EP: 5, 6, 7 (for Low, Med, Hi eff.)
WS: 8, 9.10 (for Low, Med, Hi eff.)
MC: 17,18,19 (for Low, Med, Hi eff.)
FF: 20,21,22 (grade)
Afterb.: 24,25,26
Other: 27

change from coal to oil reduces particulates by one or two orders of magnitude, and also lowers sulfur oxide emission even if the percentage of sulfur is the same for oil as for coal. A change from either coal or oil to gas virtually eliminates both pollutants.

Tall Stacks

A widely accepted cost figure for erection of tall stacks is $1000 per foot. For this exercise, the cost has been rounded to $3200 per meter, and the total cost is amortized over fifteen years.

Air Cleaners

Table 4 shows air cleaner options that conform with NAPCA control recommendations[5] for the sources listed. The following abbreviations are used in the Table:

EP: electrostatic precipitator
WS: wet scrubber
MC: mechanical cleaner (dry centrifugal)
FF: fabric filter (baghouse)
Afterb: afterburner

The number code in the lower left hand corner of the table refers to a list developed for the computer subroutine on control alternatives. Costs are given, where applicable, for low, medium, and high efficiency control devices. Costs and efficiencies are derived from data and charts in the NAPCA Control Techniques document. The single cost figure that is used for each device includes purchase and installation cost amortized over fifteen years, plus annual cost of operation and maintenance. This cost is most

5. "Control Techniques for Particulate Air Pollutants", National Air Pollution Control Administration Publication No. AP-51, January 1969.

Other Controls

Emissions from the two dumps and apartment house incineration in both cities are best controlled by measures other than those specified for the exercise. The dumps could, of course, be closed down; however, reasonable alternatives and associated costs must be provided. To simplify matters, it was decided to eliminate open burning by specifying an incinerator with precipitator for the auto dump, and conversion of the municipal dump to a landfill operation. The alternative decided upon for the two cases of apartment house incineration was upgrading of incinerators to multiple-chamber types which result in 87% reduction in particulate emissions. The controls listed below are coded in the exercise as "No. 27, Other", under Air Cleaner Alternatives.

Source	Control	Eff.(S)	Eff. (P)	$/Year
7. A-City Incineration	New Incinerators	0	87%	962,000
9. Auto-Dump	Incinerator w/ precipitator	0	98.5%	650,000
10. B-City Incineration	New Incinerators	0	87%	481,000
12. B-City Dump	Landfill	100%	100%	185,000

7B. Jerome Z. Holland, "A Meteorological Survey of the Oak Ridge Area", USAEC Report ORO-99, 554-559, Oak Ridge Laboratory, 1953.

directly dependent upon the size of the equipment, which in turn depends upon the volume of air to be cleaned (acfm). In this regard, the volumes determined for air cleaners in this exercise have been checked for consistency with the process or production rates.

TRANSPORT AND DIFFUSION MODEL

Description

The atmospheric transport and diffusion used for the training exercise is a simplified version of the model developed in 1968 by D.O. Martin and J. A. Tikvart.[6] The model is designed for calculating average ground level concentrations of any air pollutant at one or more downwind receptor locations resulting from multiple sources of emissions. For each receptor location the model sums the effect of each source over a complete set of climatological conditions prorated according to frequency of occurrence. In this simplified version of the model, the only parameter prorated by frequency of occurrence is wind direction, reported to sixteen points of the compass.

Wind speed is represented by a single average value for each wind direction instead of a frequency distribution for five wind speed classes used in the complete model. Similarly, atmospheric stability is represented by one category designated as "D" or "neutral" by Turner[7], instead of being prorated by frequency of six stability categories. For each of the sixteen wind directions, at each receptor point, an atmospheric diffusion calculation is made and the ground level concentrations contributed by emission sources individually are summed at each receptor point. Because of the number of calculations required, a computer is used.

6. Ibid, Paragraph 1.3.2

7. D. Bruce Turner, "Workbook of Atmospheric Dispersion Estimates." U. S. Department of Health, Education and Welfare, National Center for Air Pollution Control, Cincinnati, Ohio, Rev. 1969, Public Health Service, Publication No. 999-AP-26, 6.

Features and Limitations

Although the exercise makes no presumption regarding operational usefulness of the model in either its complete or variously modified forms, the scope and limitations of the model should be recognized. Underlying assumptions include:

- Steady-state, equilibrium conditions
- Wind invariant in time and space within each directional sector
- Smooth, flat terrain
- No mechanism for removal of airborne contaminants (e.g. no scavenging by clouds or precipitation, no capture by surface bodies of water or impact on structures, chemical changes in transport except for a 3-hour half life exponential decay rate assumed for sulfur dioxide).

The model is geared to climatological time periods and averages, and should not be used for analyses of short term cause-effect relations between sources and pollutant concentrations. It is a stochastic, not a dynamic model, although its basic transport and diffusion equations are developed on physical principles including the effects of elevated sources (effective stack height calculated by the Holland equation[7B])

Meteorological Data

Data for computing wind transport of airborne contaminants were adapted from the annual wind rose for St. Louis, which was used in the previous training exercise. As may be noted from Table 5, southerly and northwesterly winds occur most frequently. The scenario takes this situation into account. Note that in Figure 1, which shows a map of the hypothetical region, the major point sources are located generally west and south of the "target" population centers.

WIND DIRECTION	FREQUENCY OF OCCURRENCE (%)	AVERAGE SPEED (m/sec)
N	4.4	2.4
NNE	3.7	2.3
NE	3.8	2.2
ENE	3.7	2.2
E	3.9	2.4
ESE	5.9	2.2
SE	6.9	2.3
SSE	8.3	2.9
S	10.5	3.0
SSW	6.9	2.7
SW	6.2	2.6
WSW	5.7	2.6
W	6.1	2.6
WNW	9.2	3.0
NW	9.1	3.1
NNW	5.9	2.6

TABLE 5. Wind Rose Data for Training Exercise

EFFECTS

The discussion now considers two effects of pollutant dispersion at the receptor locations:

- ° Ground level concentrations of sulfur oxides and particulates
- ° Damage costs resulting from exposure to higher concentrations of particulates

Ground level concentrations

The direct output of a transport and diffusion model computation is the list of ground level concentrations of sulfur oxides in parts per million (ppm) and particulate concentrations in micrograms per cubic meter ($\mu g/m^3$), at each receptor point. Charts of ground level concentrations under initial conditions are shown in Section 4, within the User's Manual that is included in this report. Separate charts are presented for sulfur oxides and particulates, for each major source individually and for all sources combined.

In performing the training exercise, the user compares the initial output with specified air quality goals, and develops a control strategy for reduction of ground level concentrations to the specified standard at minimal cost. When the classroom exercise is performed in "Conversational Mode," described in Section 4, concentrations before and after controls are printed out side by side. A printout is illustrated in the User's Guide, Section 3 of this manual.

Damage Costs

Estimates of air pollution damage costs can be widely disparate. When biological effects are considered, it is clearly impossible to put a price tag on population mortality and morbidity (the insurance community notwithstanding!), and almost as difficult to establish a cause-effect relation between pollutant concentration levels and rises in mortality and morbidity. Damage cost estimates are a little better substantiated when they apply to effects upon inanimate receptors.

Nonetheless, economic effects of air pollution are all-pervasive to the problem; for it is in the context of economics that much of the air pollution problem has arisen and must be solved. Hence, the proper evaluation of control strategies must invoke economic judgments.

For the training exercise, the one economic effects parameter that is considered appropriate is soiling cost. Soiling cost is defined as expenses of maintenance and cleaning made necessary by excessive deposits of dirt, dust, soot, and other airborne particulates. Costs are calculated for cleaning automobiles, clothing, furnishing, and household appurtenances including houses themselves. Soiling cost can be little more than an indicator of total damage costs of air pollution. However, the good correlations established by authors such as Michelson[8], in studies that cover several cities across the country, lend justification to the adoption of a particulate concentration-soiling cost relation for this exercise. The following expression is used:

$$Y = 2.56X - 90.44$$

where Y = annual soiling cost, in dollars per capita
X = annual average concentration of particulates, in micrograms per cubic meter

For total soiling costs, Y is multiplied by the population that is exposed to the X level of concentration.

Benefit and Benefit-Cost Ratio

The reduction in total soiling costs resulting from the use of a control strategy is called the benefit for that strategy. For determining control benefit, damage costs for the initial condition must first be determined, then the damage costs for the post-control situation. The difference is the benefit.

The benefit-cost ratio, also referred to in this exercise as the strategy-effectiveness ratio, is defined as the benefit divided by the corresponding control strategy cost. In performing the exercise, one of the objectives is to achieve a high benefit-cost ratio. However, this achievement must be consistent with the other objective, which is

8. Irving Michelson, unpublished findings developed on contract with NAPCA. Some of Michelson's work is described by Richard D. Wilson and David W. Minnotte in their paper, "A Cost-Benefit Approach to Air Pollution Control." Journal of the Air Pollution Control Association, vol. 19, no. 5, 303-314, May 1969.

to meet air quality goals.

Concentrations of sulfur oxides are not considered in the determination of damage costs and benefits because no firm relation has been established between concentrations and damage costs for this pollutant. The reduction levels of sulfur oxides requires a control cost but achieves no dollar benefit in the exercise. Inclusion of a control cost for sulfur oxides results in lower overall benefit-cost ratios than would be calculated for particulates alone. As an expression of this "diluted" benefit-cost ratio, the term "strategy-effectiveness ratio" is used in the computer programs for the training exercise.

Population Factors

The number of people exposed to a given ground level concentration of particulates is multiplied by the corresponding soiling cost per capita to give damage costs for that segment of the population. Since concentrations are not uniform across the region, a better approximation of total damage costs is obtained by subdividing the region into areas in which concentrations are more uniform, then summing the individual soiling costs of the subdivisions.

In the training exercise, two subdivision scales are used. By the coarser scale, the region is divided into six subregions, identified in Figure 1 (which see) by the heavily drawn boundary lines. Reading from left to right, the subregions on the lower half of the map should be numbered 1, 2, and 3; those on the upper half, 4, 5, and 6. The heavy numbers shown outside the lower and upper boundaries of the region are the populations in thousands for the subdivisions nearest to the numbers. The population breakdown is as follows:

Subdivision:	Population (thousands)	Subdivision:	Population (thousands)	Subdivision:	Population (thousands)
4:	218	5:	120	6:	40
1:	137	2:	140	3:	51

By the finer scale, the region is divided into 100 grid sectors each measuring 5 km square, as shown in Figure 1. The number at the center of each sector represents the population (in thousands) within that sector. The numbers vary from 60 (thousand) in sectors within the centers of Alfa City and Bakersville, to 2 (thousand) in exurban areas and zero in Lake Zulu. Note that an 11 by 11 grid, a total of 121 grid intersections, is required to enclose the 100 grid sectors.

The coarser scale is used during the classroom session, when expeditious performance of the exercise is desired at the expense of precision. It is a feature of the "Conversational Mode," the computer program designed for close on-line interaction between computer and user during class. The finer scale is used for high resolution output of initial and post-control concentrations, the latter serving to check the total costs computed for subdivisions against total costs for the sectors. Since it takes about 20 minutes for the terminal to print out results at 121 grid points, this part of the program is run in "Batch Mode" off-line, outside of classroom hours.

Selection of Receptor Sites

In the Conversational Mode, the user must select a receptor site for each of the six subdivisions. The analogous problem is the selection of sampling sites of an air pollution monitoring system. Remote site selection for a monitoring system is governed by a variety of factors including representativeness. In the training exercise, site representativeness is virtually the sole criterion. The major test of user skill shall be the selection of subdivision receptor sites at which ground level concentration and soiling cost and benefit data come closest to corresponding values averaged over all grid sectors within the subdivision. If this were not a condition of the exercise, the user could achieve high strategy effectiveness ratios by locating receptors near the edges of the map, where initial concentrations are minimal. Hence, the comparison of Conversational Mode and Batch Mode results tests not only strategy effectiveness but also representativeness of receptor locations. This comparison could be quantified and expressed as a Skill Score.

SECTION 3

TRAINING EXERCISE FOR COST-EFFECTIVENESS EVALUATION OF AIR POLLUTION CONTROL STRATEGIES

USER'S GUIDE

TRAINING EXERCISE FOR BENEFIT-COST EVALUATION OF AIR POLLUTION CONTROL STRATEGIES

User's Guide

AS A MATTER OF INTRODUCTION.........

What is the Training Exercise?

The Training Exercise is an active learning experience designed to give the user an appreciation of computerized techniques, currently being developed under NAPCA auspices, for determining effects of alternative control action. Its objective is to demonstrate the powerful support these techniques can offer to air quality management personnel by providing real-time solutions regarding the probable impact of control strategies before decisions on implementation are made.

Who are the intended users of the exercise?

The exercise is geared to the level of education and experience that is normally to be found among technical personnel of a moderately active municipal, county, or state air pollution control agency. However, others in related academic or administrative pursuits could benefit by this exercise.

Where is the Training Exercise conducted?

Home base for this training session is at Research Triangle Park, N. C., at the facility of NAPCA Office of Manpower Development, Institute for Air Pollution Training. However, the session may be conducted at any site served by commercial telephone provided prearrangements are made for the required library storage, and a teletype terminal and acoustic coupler can be accommodated. A number of commercial time-share services are available at most locations; however, for minimum telephone charges, one should determine which of the competing services has the closest multiplexer.

Is familiarity with computer programming a prerequisite for the user?

No. All the programming is already installed in the system. The user need only know the standard typewriter keyboard. A "hunt and peck" typing ability is entirely satisfactory.

Besides the computer terminal, what training material and preparation are required?

Training material includes the scenario, specific problems requiring observance of air quality goals, and the user's instruction manual. Prior study of this material is desirable, since it will insure greater facility in exercise performance at the terminal, and allow more widespread use of the equipment. The user should come to the training session with firm plans on the combination of control measures to be tested.

How is the class arranged for conducting a training exercise?

Several classroom arrangements are possible. For example, the instructor leading the responses may request a class consensus for each of the more critical decisions to be entered at designated points in the exercise. Another arrangement is for the class to be divided into groups, each developing its own control strategy and operating the terminal in its turn. After all groups have completed their runs, results are compared and discussed. Still another arrangement is for groups to work alongside each other on several terminals short of a maximum number permissible on the particular time-share service.

What operational procedure is followed at the terminal? Specifically, how does the user know when and how he enters his data?

After the desired computer program is commanded and completes its listing of scenario data, it prints out instructions to be used at each point designated by a question mark where a user response is required. The user's input is usually a number or set of numbers.

See the following User's Manual for details.

SCENARIO

The following figures show a map of the hypothetical air quality region upon which are superimposed total ground level concentration patterns for all emission sources and individual patterns for the most significant point sources.

Figure U-0. Annual Wind Rose for St. Louis, Mo.

Figures U-1 to U-4 show annual arithmetic average ground level concentrations of sulfur oxides.

Figures U-5 to U-8 show annual arithmetic average ground level concentrations of particulates.

LIST OF FIGURES

Figure 1

HYPOTHETICAL AIR QUALITY REGION

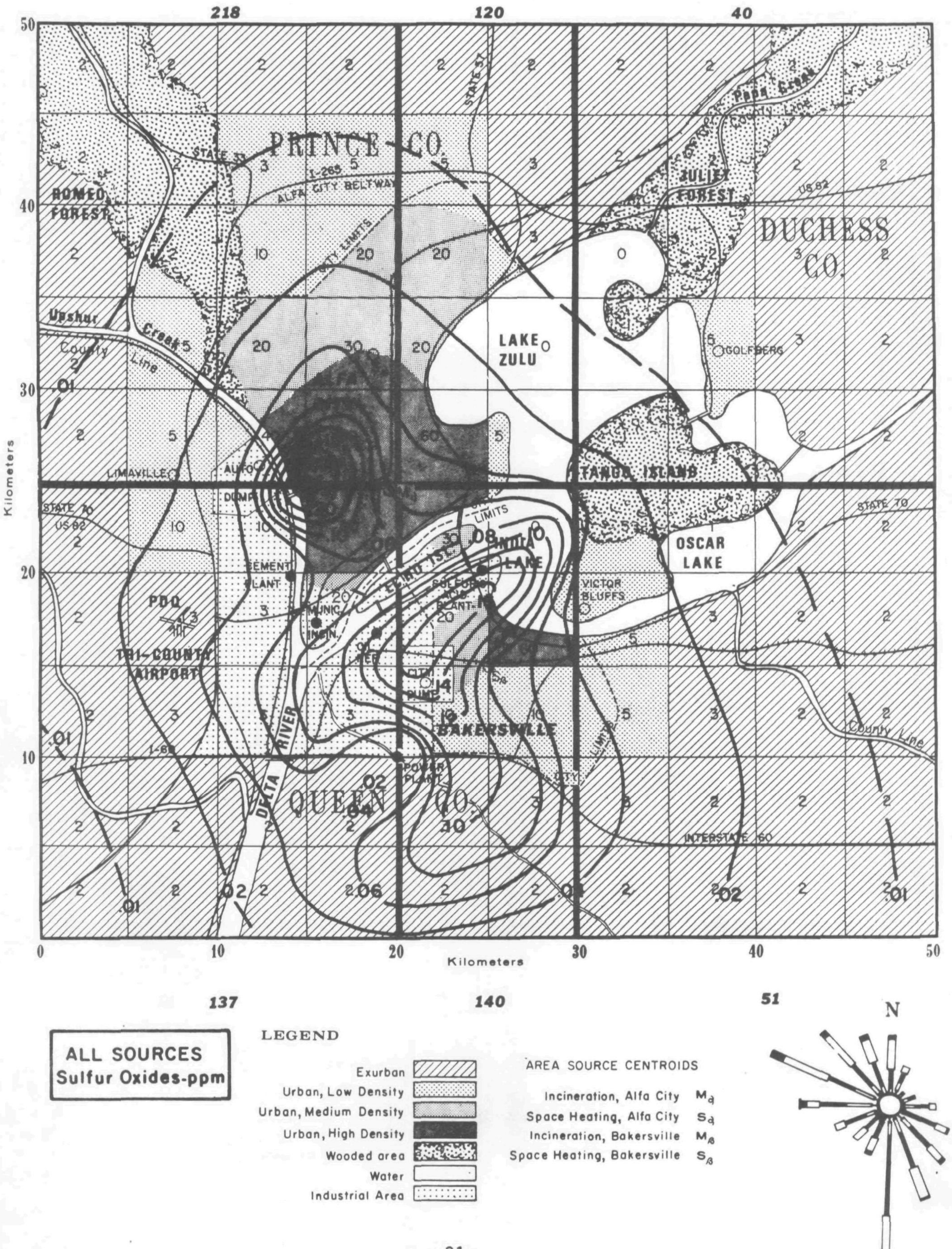
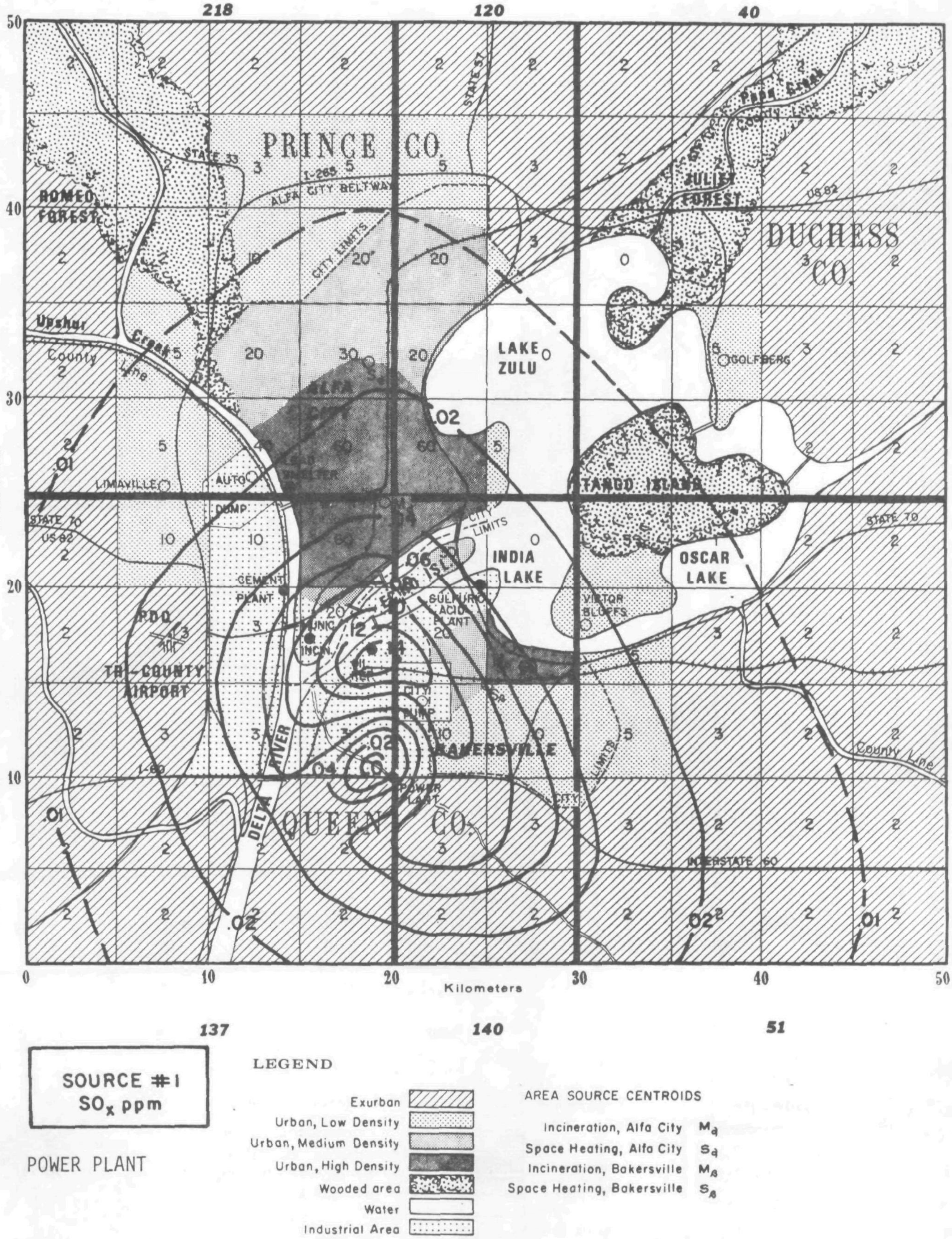


Figure 2

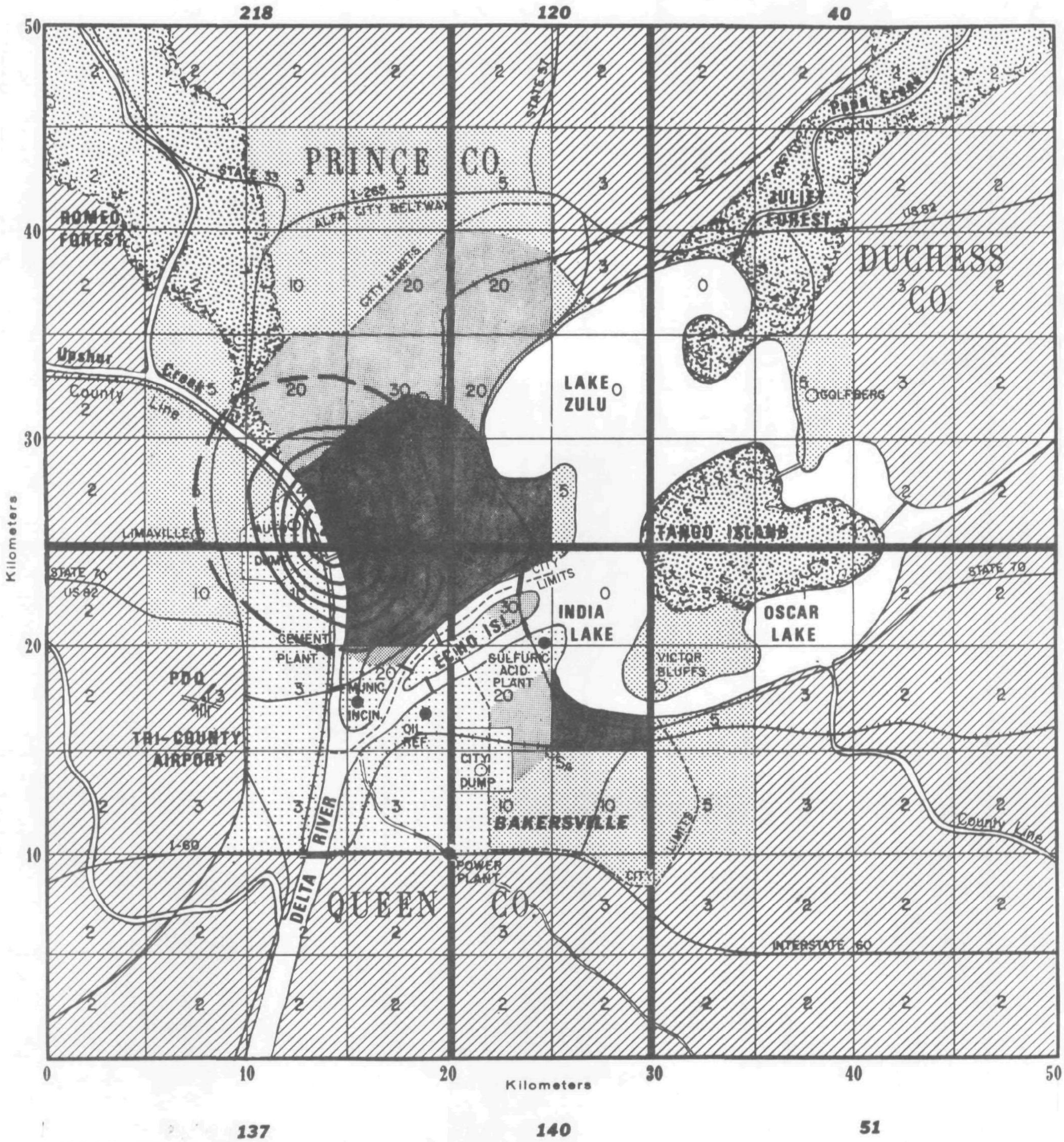
HYPOTHETICAL AIR QUALITY REGION



POWER PLANT

Figure 3

HYPOTHETICAL AIR QUALITY REGION



SOURCE #5
SO_x ppm

LEAD SMELTER

LEGEND

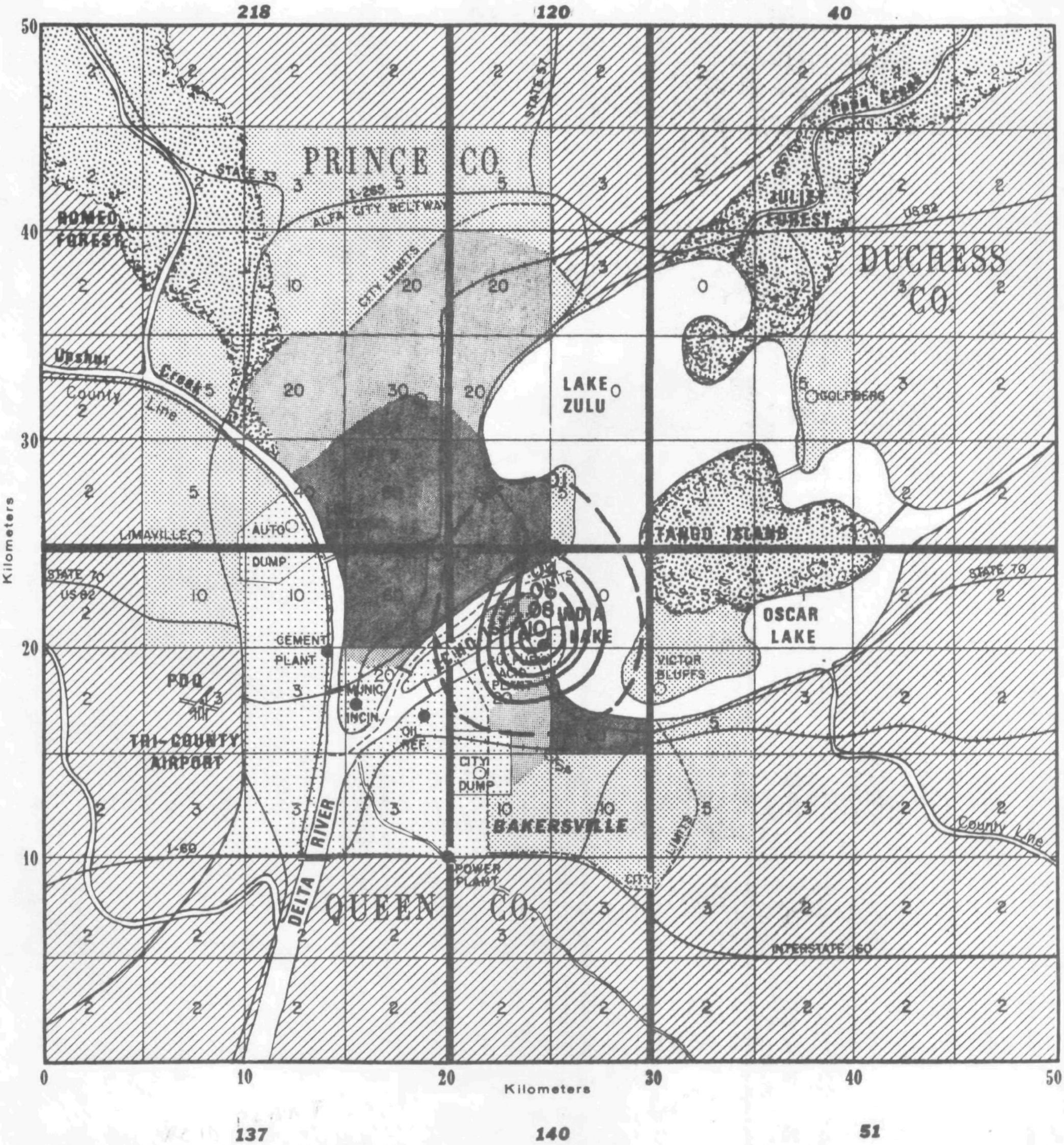
- Exurban
- Urban, Low Density
- Urban, Medium Density
- Urban, High Density
- Wooded area
- Water
- Industrial Area

AREA SOURCE CENTROIDS

- Incineration, Alfa City M_a
- Space Heating, Alfa City S_a
- Incineration, Bakersville M_B
- Space Heating, Bakersville S_B

Figure 4

HYPOTHETICAL AIR QUALITY REGION



SOURCE #6
SO_x ppm

SULFURIC ACID PLANT

LEGEND

- Exurban
- Urban, Low Density
- Urban, Medium Density
- Urban, High Density
- Wooded area
- Water
- Industrial Area

AREA SOURCE CENTROIDS

- Incineration, Alfa City M_a
- Space Heating, Alfa City S_a
- Incineration, Bakersville M_B
- Space Heating, Bakersville S_B

Figure 5

HYPOTHETICAL AIR QUALITY REGION

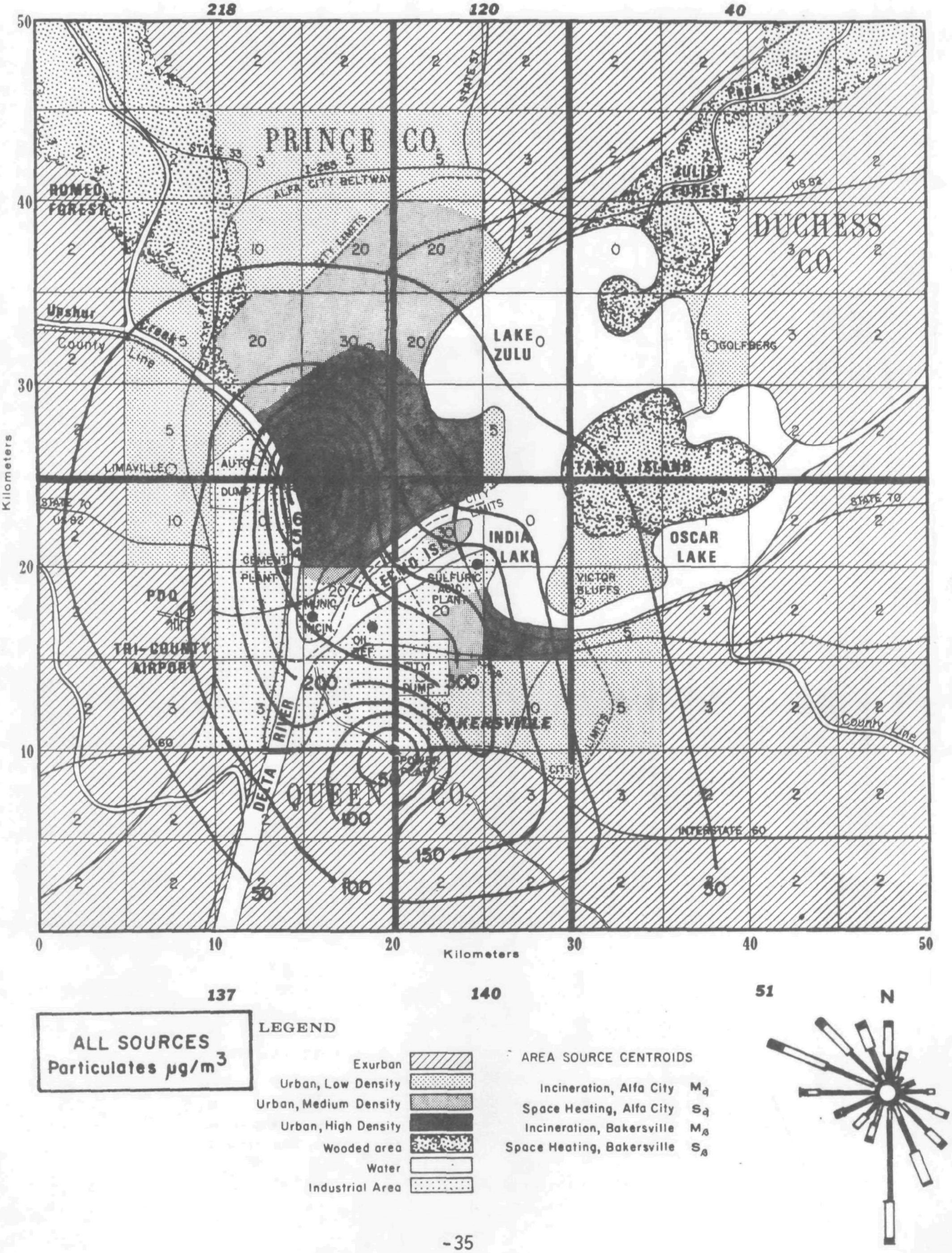
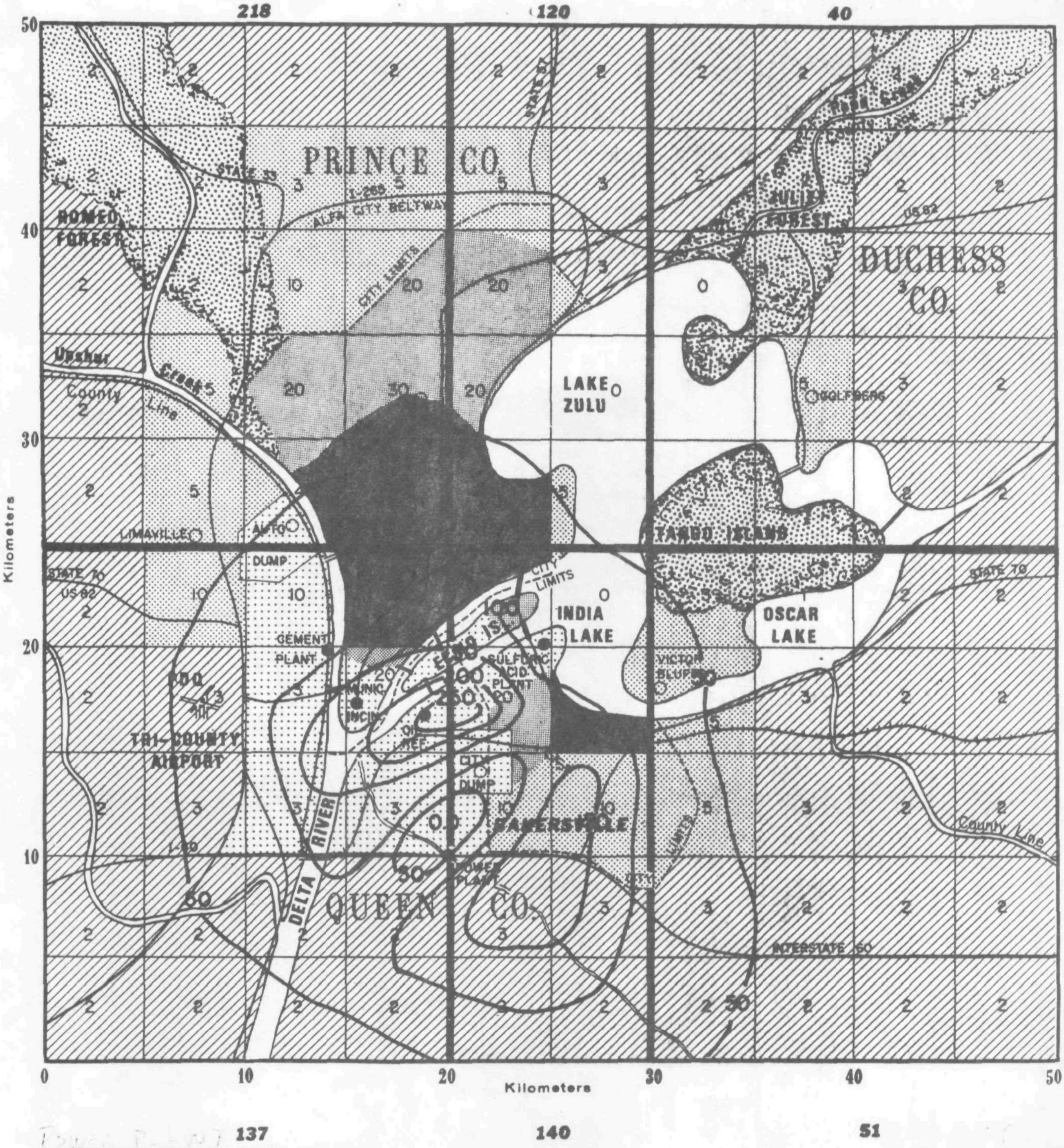


Figure 6

HYPOTHETICAL AIR QUALITY REGION



SOURCE #1
Particulates $\mu g/m^3$

POWER PLANT

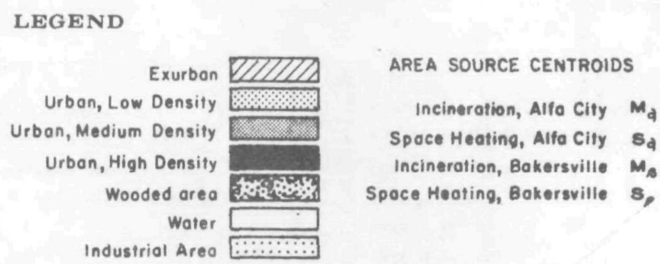


Figure 7

HYPOTHETICAL AIR QUALITY REGION

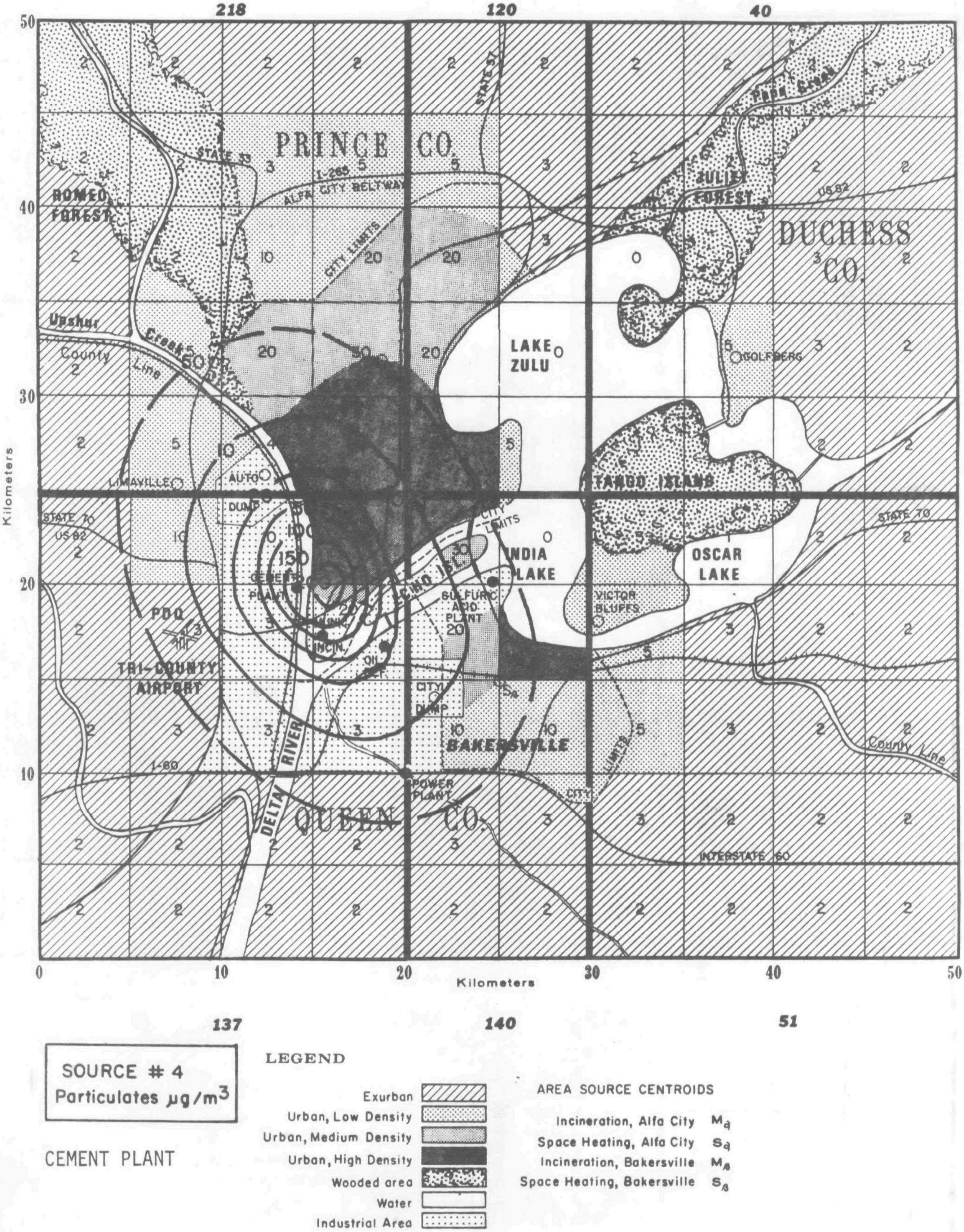
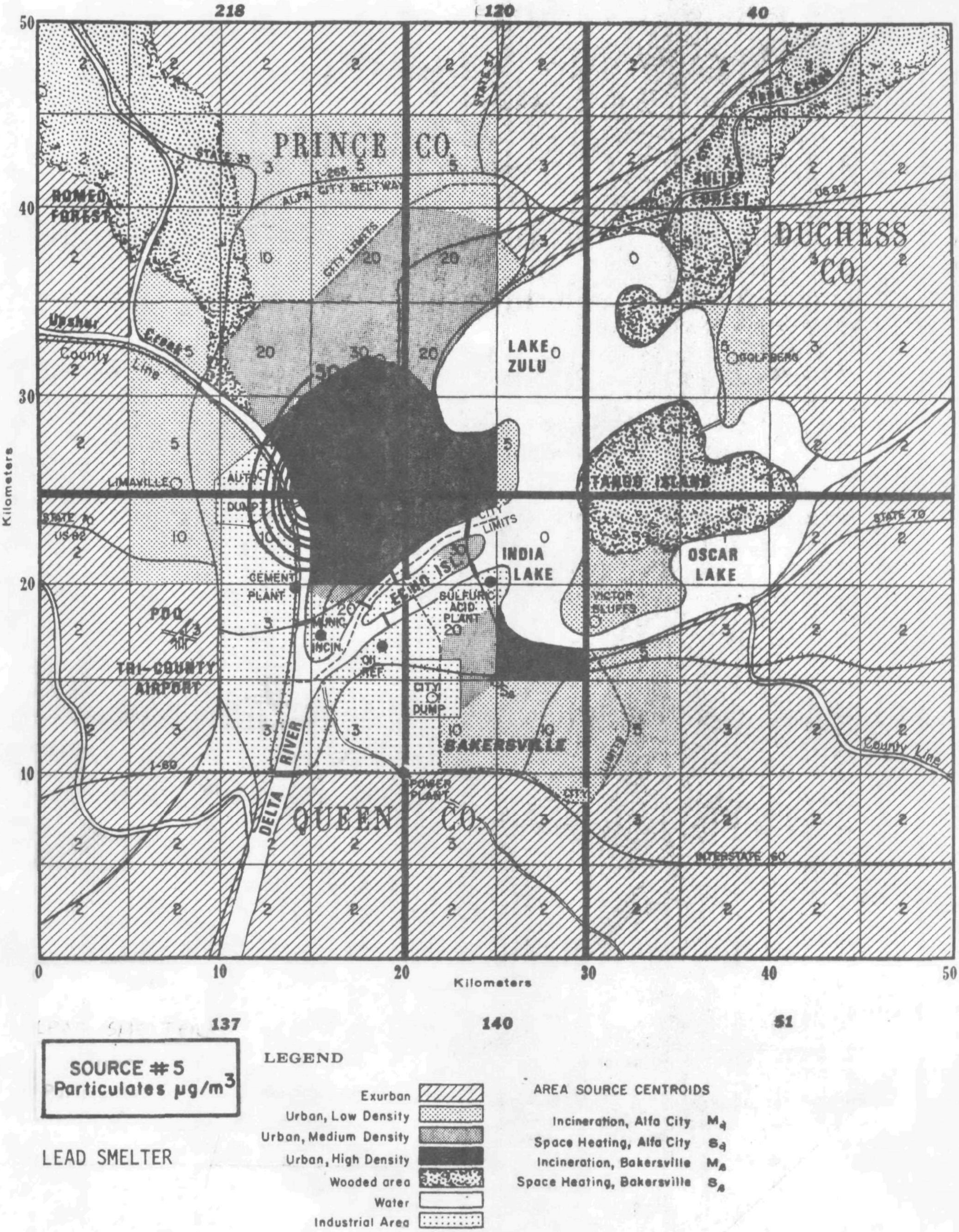


Figure 8

HYPOTHETICAL AIR QUALITY REGION



USER'S MANUAL FOR OPERATING THE TERMINAL FOR THE TRAINING EXERCISE

1. Computer Programs

The following two programs are available for the training exercise:

- The Conversational Mode
- The Batch Mode

Instructions for initiating a program are given in the Instructor's Manual.

Before class convenes, the Batch Mode will be run to present initial conditions on a fine scale. During class, you will engage in close interaction with the computer in the Conversational Mode. At the end of the exercise, the Batch Mode may be rerun, using the final combination of controls you specified for your Conversational Mode solution.

2. Entering, Amending, and Deleting Data

Enter data only after a question mark (?) is printed out. The required data format is specified in the text that precedes the question mark.

For the Conversational Mode, all input data must be numeric (with or without an optional decimal point). Enter only one number at a time, except that when the power station and receptor coordinates are requested, enter two numbers separated by a space.

After entering a number, press the "RETURN" key.

For the Batch Mode, enter numbers the same way as for the Conversational Mode. In addition, entry of an alphabetic description of thirty or less characters is required for the control device in use. When this information is requested, type a single quote ('), then the appropriate description, and end with a single quote.

If you have made an error in your entry, or wish to change data before it is processed, you can do so if you have not yet pressed the RETURN key.

First, back space over the error by using the "left arrow" (←), which is at the upper case position on the letter O key (NOT THE NUMBER ZERO). Keep the SHIFT key down when you strike for the arrow. Each strike deletes the printed character in the preceding position.

For example, if you notice you have entered "21 10" when you intended "20 10", press four "left arrows" to cover the "1" of "21". Then enter "0 10". Now press the RETURN key after the correct entry, and the computer will confirm it by printing out "20 10".

Five or more successive back space arrows will delete the entire line, and are sometimes used for this purpose. Hence, in the example described, if you plan to delete all of "21 10" and retype "20 10", you use five "left arrows" and would find that all data on the line have been deleted.

If you do not spot your error until it has been processed, you must wait until you are asked to enter your control option. At this point, enter "-99" and you must restart the exercise from the beginning.

3. Exercising the Conversational Mode

Please refer to the printout that has been reproduced in the Appendix with added narrative. Some teletypes will print out your entry; others will not, as in the sample shown. In either case, your entry will be confirmed by the computer before it proceeds to the next step.

Once the Conversational Mode has been initiated, it immediately requests an entry for the power station coordinates. This information request and each one that follows is designated here as a "STEP".

Step 1. Enter "20 10", unless the instructor specifies a different location. Note that a space must separate the X and Y coordinates.

After confirming your entry, the computer will print out three tables of scenario data that it will use to compute initial ground level concentrations and soiling costs. The first table is the Source and Emission Inventory. The second table lists the fuels in current use. The third table is an abstract of the scenario map showing the population (in thousands) within each of the hundred 5-km square grid sectors, and the boundaries of six subregions.

Step 2. Enter six receptor coordinates in the manner requested. Be sure that the coordinates of each receptor are within the specified limits.

Note: You are not restricted to whole numbers for coordinate points. You may use numbers like "15.3 25.7" but little is gained by going beyond one decimal place. For best results, each receptor should be located at a point that is "representative" of both the population distribution, and the average ground level concentrations of pollutants within its respective subregion <u>before and after controls</u>. The preliminary Batch Mode printout and the scenario charts will help you decide where to locate the receptors, but your skill and best judgment are essential.

As soon as you enter a receptor location, the computer operates the transport and diffusion model source by source to determine the total ground level concentrations (GLC) of sulfur oxides and particulates that will be received at this receptor. After you have completed the sixth receptor location, the computer tabulates results for all six.

Your strategy begins when the printout reads "CONTROL OPTION: ENTER..." You have four options:

1. Select a source to be controlled, and when requested, add a control from among those listed as available.
2. Select a source from which controls are to be removed, and when requested, specify the control to be removed.
3. Having either added or removed controls, compute new ground level concentrations (GLC).
4. Restart or terminate the exercise.

Options may be repeated as often as desired until a final strategy is determined.

<u>Before you enter your first option</u>, it is recommended that you tear off all previous data printouts and keep the sheet alongside you for handy reference.

Step 3. Enter your desired control option in the manner indicated by the information request. This request will be made at several

decision points throughout the exercise. The first time it is made, you will want to add a control. Hence, enter a number, from 1 to 15, that identifies the source you wish to control.

The computer now produces a listing of NAPCA-sanctioned control measures that are applicable to the selected source. Also listed for each control are:

a. Control effectiveness for sulfur oxides (S) and particulates (P), that is, percentage of emission reduction by utilization of the control device. This is omitted for fuel substitutions and stack height changes.

b. Annualized cost: sum of annual operating and maintenance cost and installation cost amortized over 15 years. For stack height changes, the printout shows only $3200 per meter, which is the cost of erecting a new stack. However, the annualized cost developed internally by the computer is 1/15 the total cost. For lower sulfur content coal and heavy oil, the annualized costs are not listed but are computed on a sliding scale based upon the percentage of sulfur selected between the lower and upper limits shown.

Step 4. Enter a number which corresponds to the control measure you have selected. You may use as many authorized controls for a source as you desire, and you may add controls to as many of the 15 sources as you desire, consistent with your overall strategy. However, the program allows you to add them only one at a time.

After the control selection is confirmed, and if necessary particularized by additional steps described below, the program repeats a request for Step 3. Enter then the next source number you plan to control, and in the following Step 4, the control measure desired.

If your control option is a fuel switch to lower sulfur coal or heavy oil, the computer requests the sulfur content selected.

Step 5. Enter the sulfur content as a whole number or as a number and decimal to no more than two places.

If your control option is a stack height change, the computer will request the new stack height, in meters.

Step 6. Enter the new stack height, rounded off to the nearest 25 meters. Higher precision can be handled but will not significantly affect the results.

You may wish to know the new GLC's after your first control option or any cumulative control options up to the final combination of options in your strategy. You may do so when the next request for Step 3 is repeated. Hence, for GLC's:

Step 3: Enter "0".

In response, the following four items are printed out:

a. A listing of all controls in effect

b. A tabulation of GLC's for sulfur oxides and particulates under original and controlled conditions for each of the six receptors.

c. A statement of soiling costs before and after control, and the total of all control costs.

d. The ratio between soiling cost reductions (benefits) and total control cost, here termed the "Strategy-Effectiveness Ratio".

The results are followed by another request for Step 3 information. Refer to the listing of controls in effect. If you now decide to remove a control, you do so in two steps.

Step 3. Enter a minus sign (-) followed by the number of the source you wish to act upon.

(Example: "-5" means remove a control from Source 5).

The program omits the usual confirmation and immediately requests the number of the control device to be removed from the source.

Step 7. Enter the number of the control measure to be removed from the designated source. If you wish to remove all controls from this source, enter "0".

The program now confirms the entries for Steps 3 and 7 in a combined statement, and follows with a repeat request for Step 3. You may then proceed to enter new controls at the last source treated, delete, change, or augment controls at other sources, request new GLC's at any Step 3 request point along the way, repeat these steps as often as desired, or adopt your last strategy as final. To exercise last option, respond as follows to the Step 3 request.

Step 3: Enter "-99".

With this entry, all foregoing material is removed from storage. You may use this control option if you wish to start over and select new receptor locations, or eliminate a large number of control devices that had accumulated in the previous exercise. Otherwise, the next user may begin the exercise.

Instruction for terminating the call are given in the Instructor's Manual.

4. Preparing Input for the Batch Mode

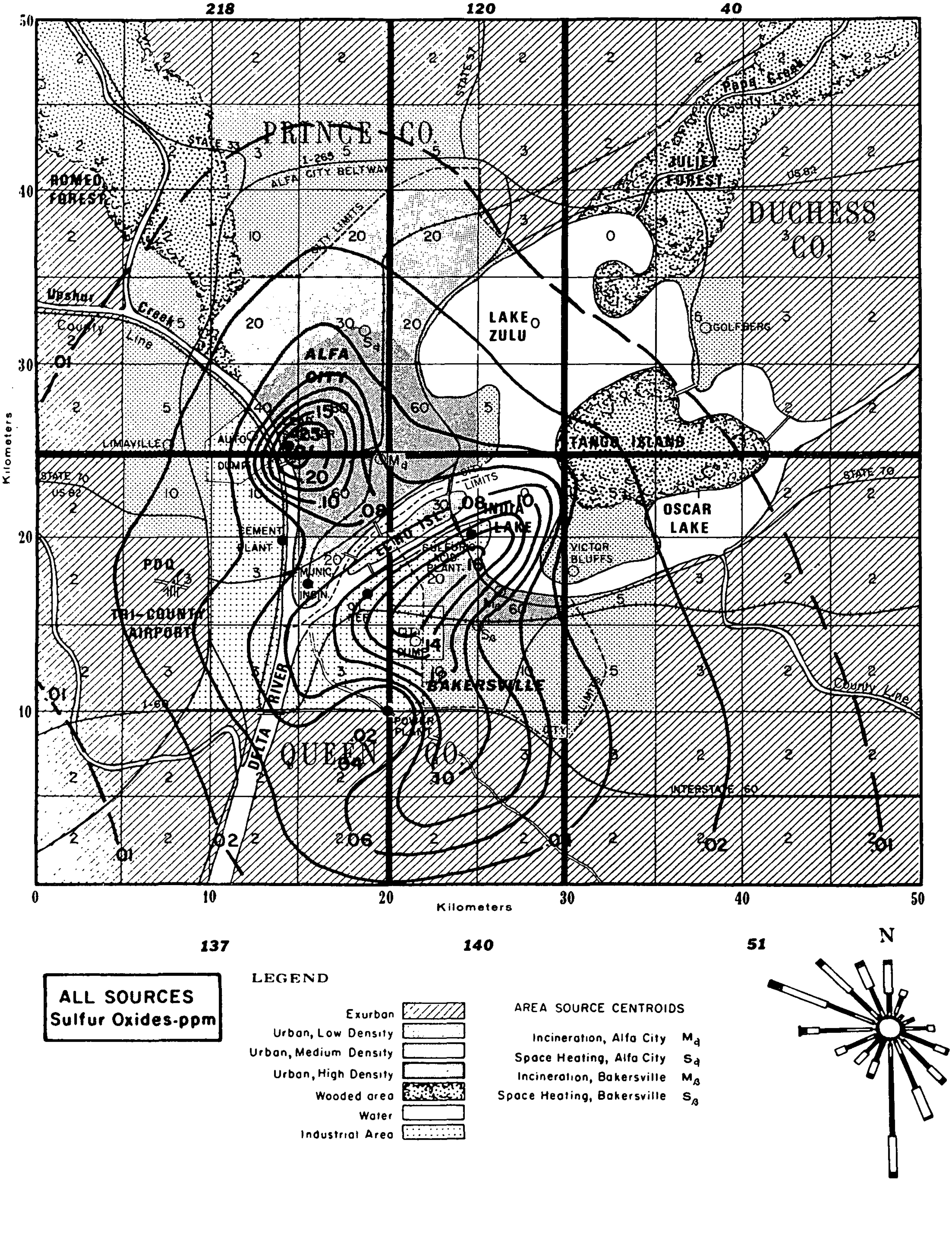
The post-control Batch Mode requires certain input that is produced by the final Conversational Mode run. For each source controlled, the following information should be provided:

a. The source identification number
b. The percentage of sulfur oxide and particulate emissions removed by each control
c. The new stack height, if a change has been made
d. The annualized cost for each control.

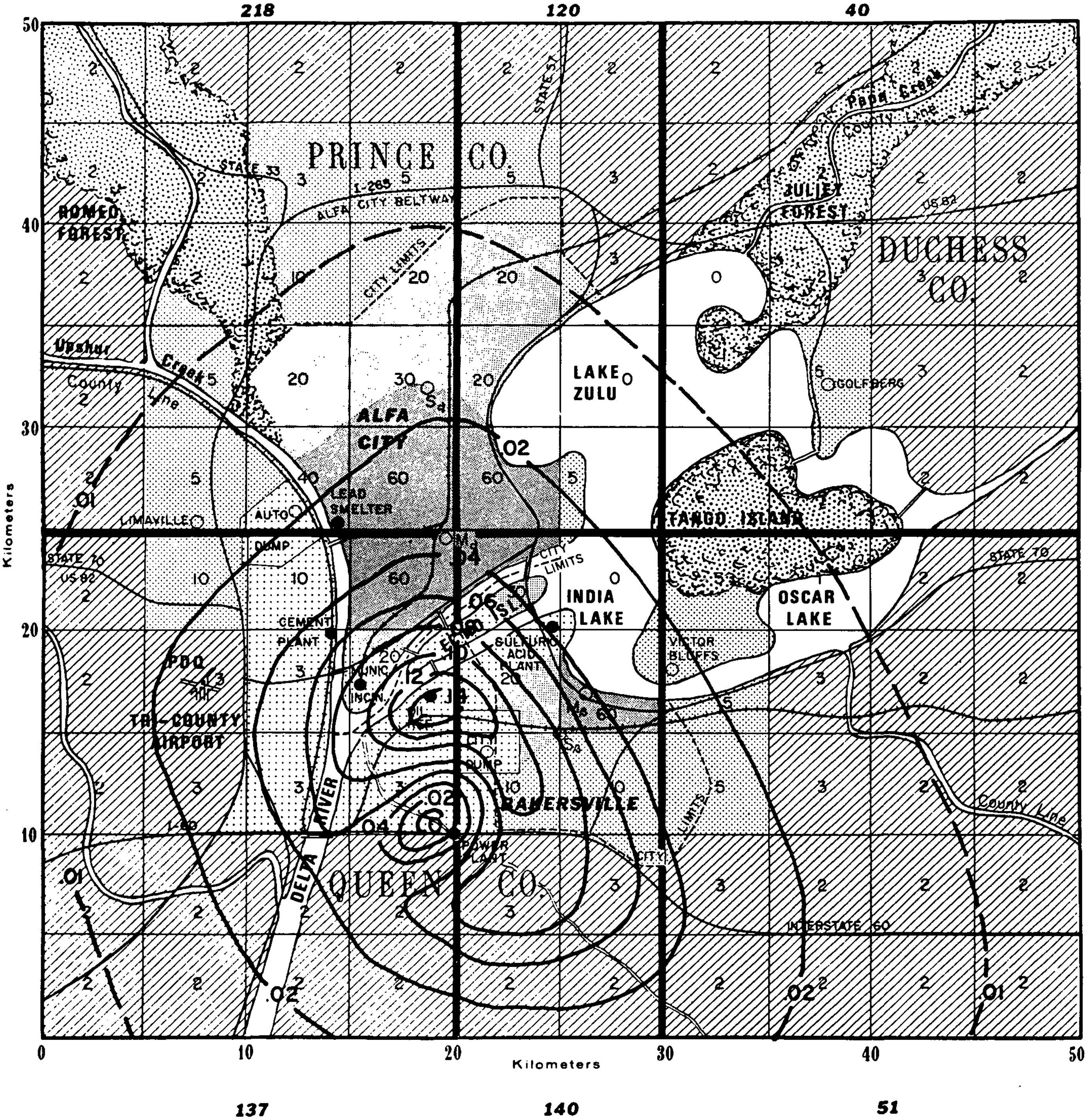
5. Running the Batch Mode

Since the Batch Mode is normally run outside of classroom hours, instructions for running the Batch Mode are found in the Instructor's Manual.

HYPOTHETICAL AIR QUALITY REGION



HYPOTHETICAL AIR QUALITY REGION



SOURCE #1
SO_x ppm

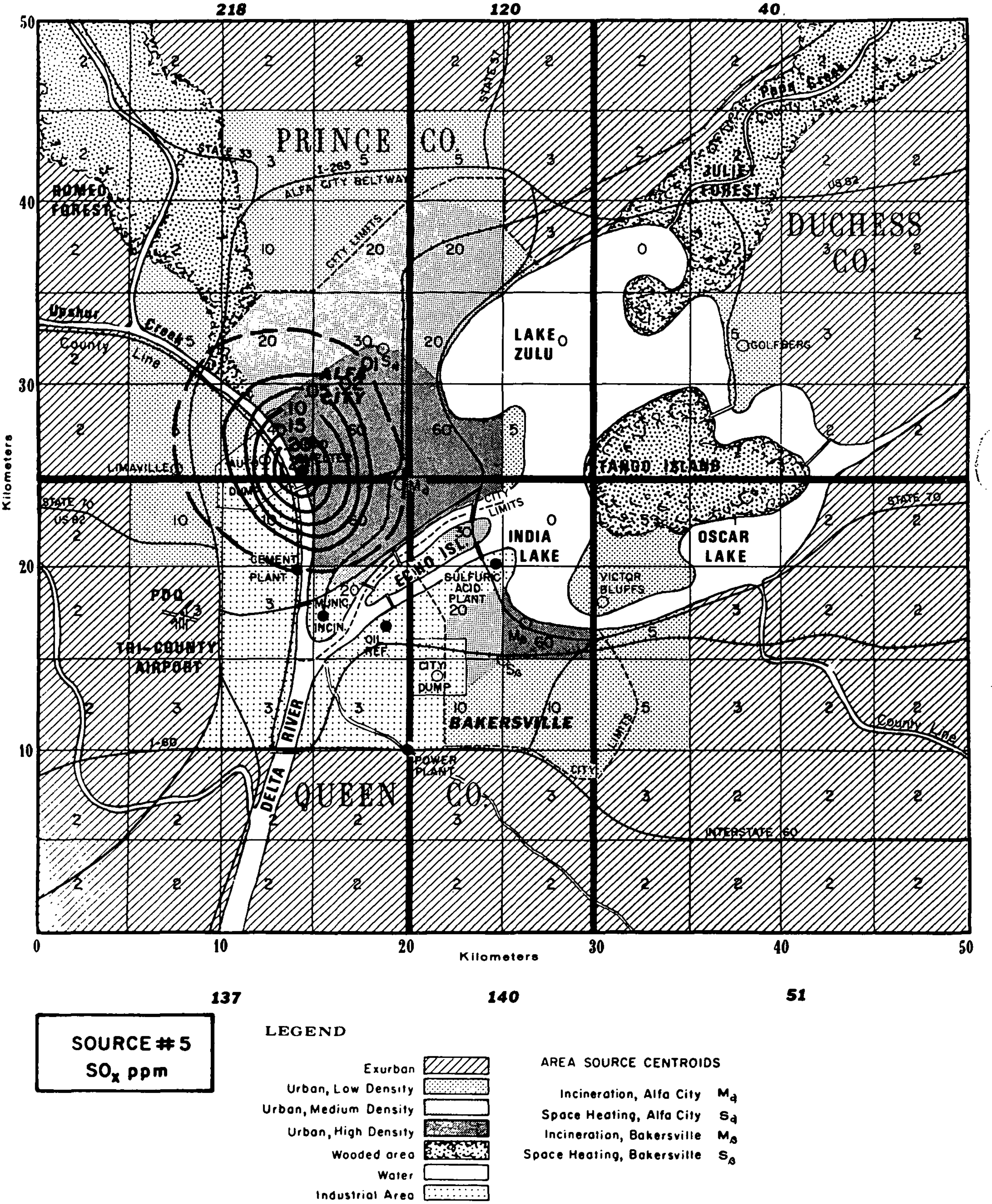
LEGEND

- Exurban
- Urban, Low Density
- Urban, Medium Density
- Urban, High Density
- Wooded area
- Water
- Industrial Area

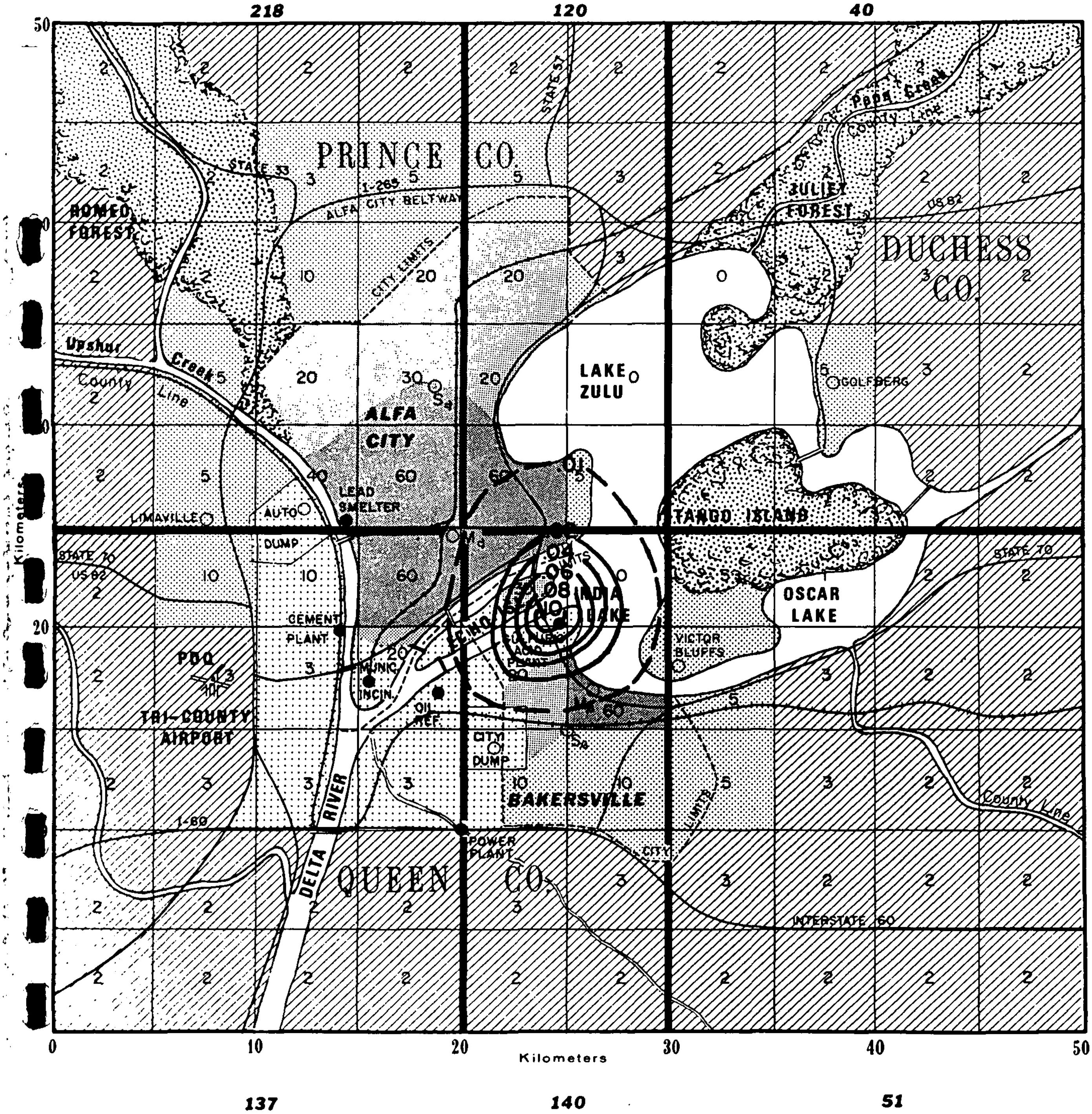
AREA SOURCE CENTROIDS

- Incineration, Alfa City M_a
- Space Heating, Alfa City S_a
- Incineration, Bakersville M_β
- Space Heating, Bakersville S_β

HYPOTHETICAL AIR QUALITY REGION



HYPOTHETICAL AIR QUALITY REGION



SOURCE # 6
SO_x ppm

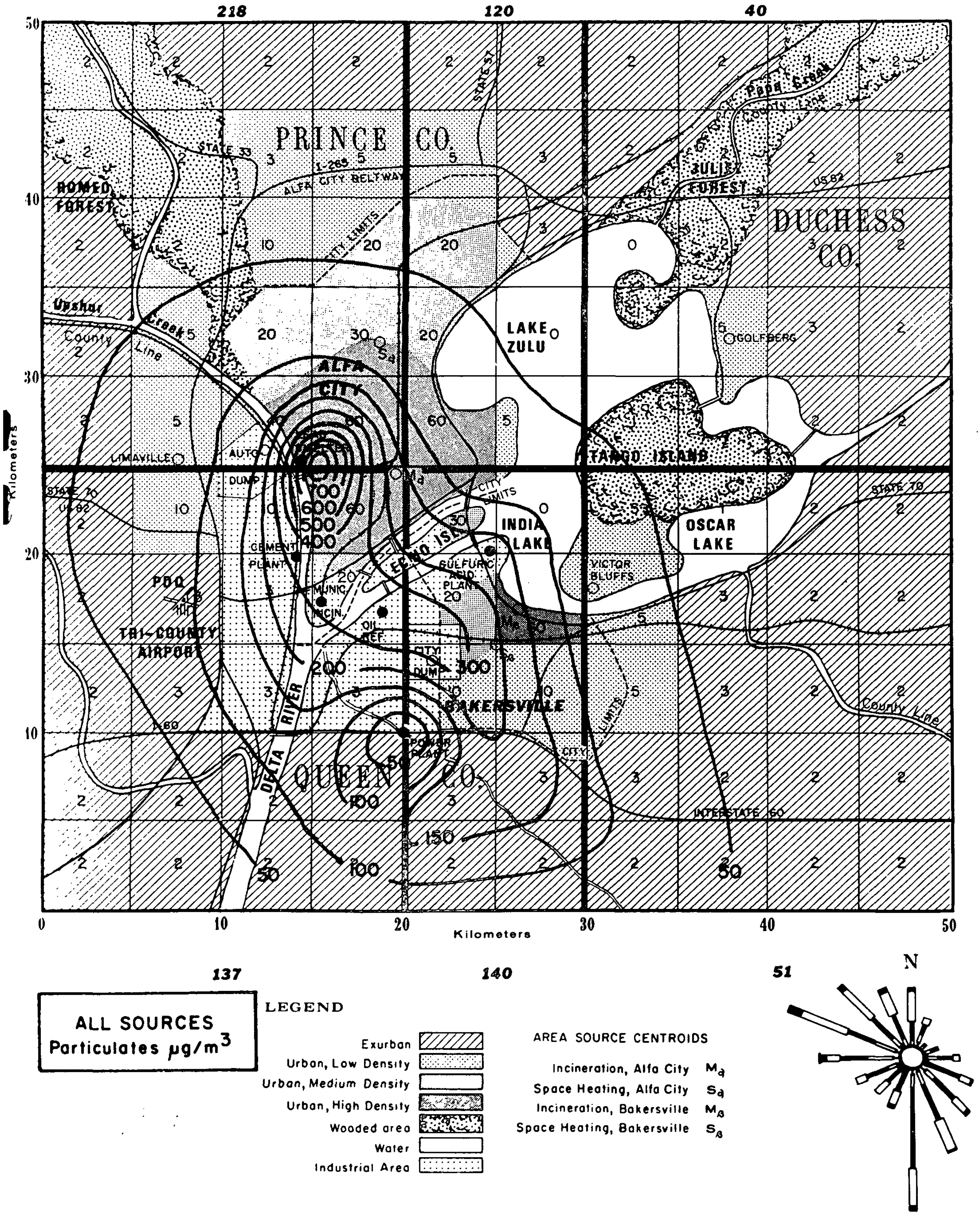
LEGEND

Exurban
Urban, Low Density
Urban, Medium Density
Urban, High Density
Wooded area
Water
Industrial Area

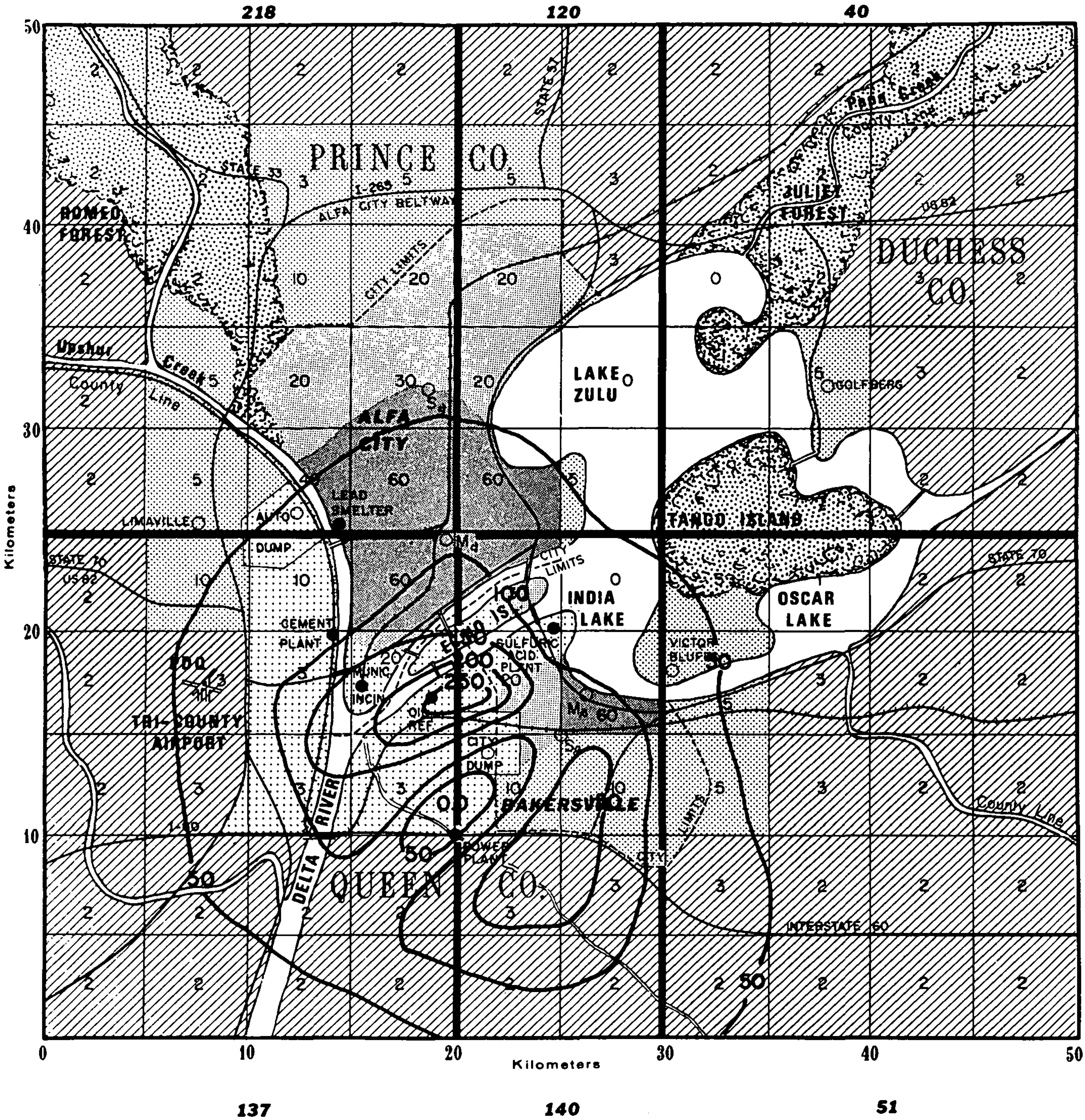
AREA SOURCE CENTROIDS

Incineration, Alfa City M_a
Space Heating, Alfa City S_a
Incineration, Bakersville M_β
Space Heating, Bakersville S_β

HYPOTHETICAL AIR QUALITY REGION



HYPOTHETICAL AIR QUALITY REGION



SOURCE #1
Particulates $\mu g/m^3$

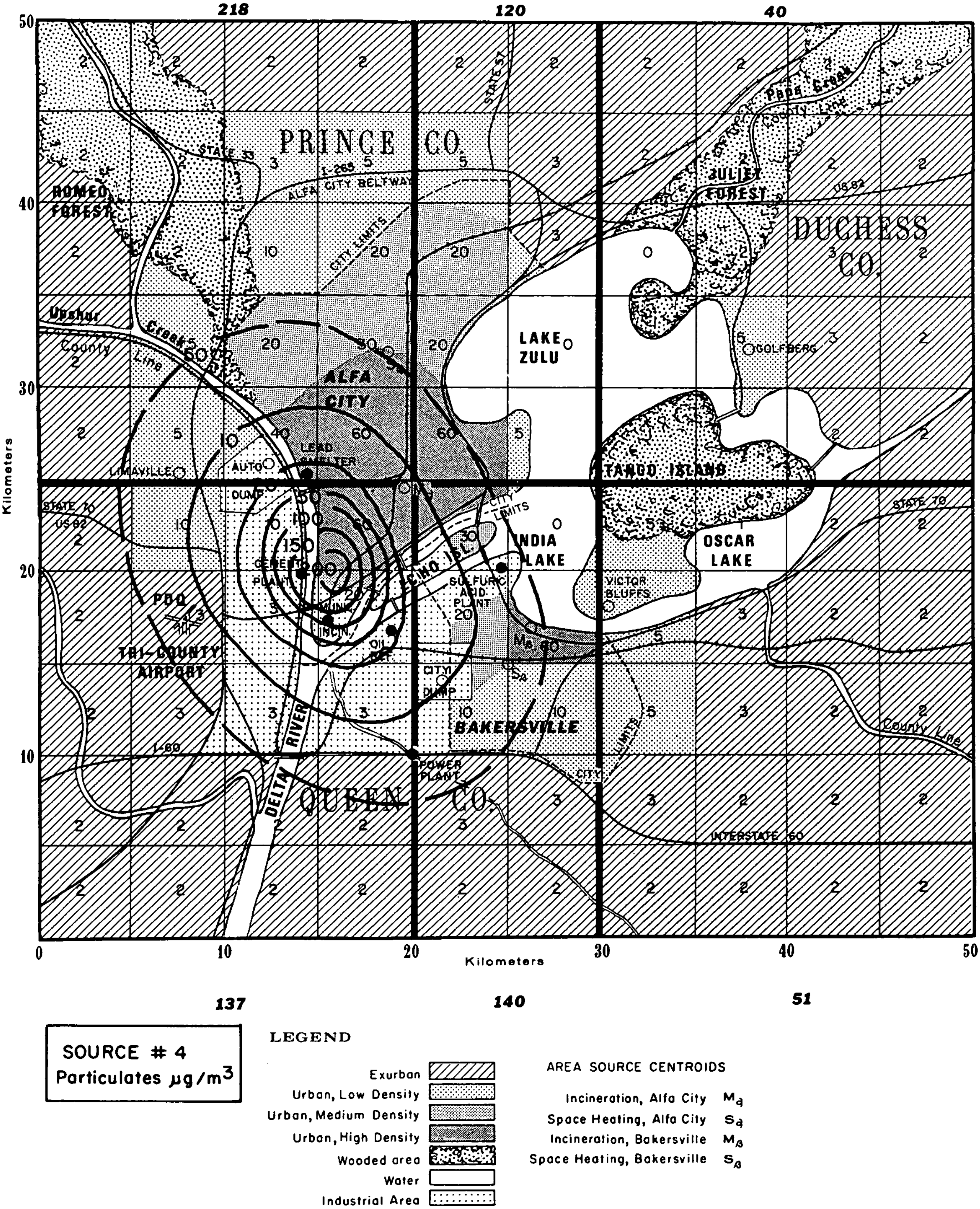
LEGEND

- Exurban
- Urban, Low Density
- Urban, Medium Density
- Urban, High Density
- Wooded area
- Water
- Industrial Area

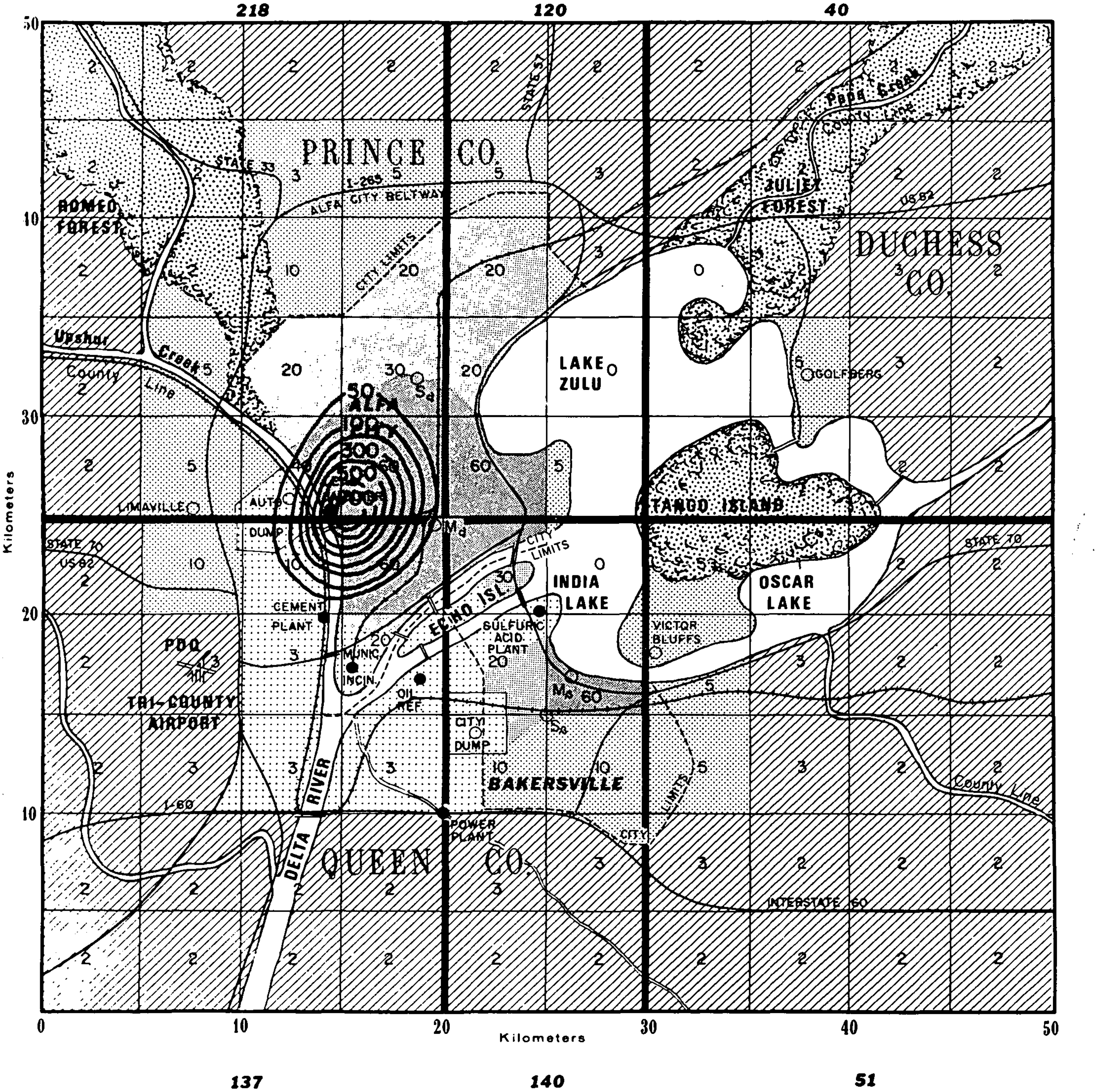
AREA SOURCE CENTROIDS

Incineration, Alfa City	M_A
Space Heating, Alfa City	S_A
Incineration, Bakersville	M_B
Space Heating, Bakersville	S_B

HYPOTHETICAL AIR QUALITY REGION



HYPOTHETICAL AIR QUALITY REGION



SOURCE # 5
Particulates μg/m³

LEGEND

Exurban	
Urban, Low Density	
Urban, Medium Density	
Urban, High Density	
Wooded area	
Water	
Industrial Area	

AREA SOURCE CENTROIDS

Incineration, Alfa City	M_α
Space Heating, Alfa City	S_α
Incineration, Bakersville	M_β
Space Heating, Bakersville	S_β