AD-A956 502

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

2. REPORT DATE [illegible]

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
DIGITAL MODEL STUDY OF DIISOPROPYLMETHYLPHOSPHONATE (DIMP) GROUNDWATER CONTAMINATION ROCKY MOUNTAIN ARSENAL NEAR DENVER, COLORADO, FINAL REPORT

5. FUNDING NUMBERS

6. AUTHOR(S)
ROBSON

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
GEOLOGICAL SURVEY (U.S.)

8. PERFORMING ORGANIZATION REPORT NUMBER
812P.R02

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ROCKY MOUNTAIN ARSENAL (CO.)
COMMERCE CITY, CO

DTIC
ELECTE
NOV 30 1993
S A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

THE ROCKY MOUNTAIN ARSENAL REQUESTED THAT THE USGS CONDUCT A DIGITAL-MODEL STUDY OF THE DIMP CONTAMINATION OF GROUND WATER ON THE ARSENAL AND SURROUNDING PROPERTY IN ORDER TO PROVIDE DATA USEFUL IN MEETING THE REQUIREMENTS OF THE CEASE AND DESIST ORDER. SPECIFIC INFORMATION WAS NEEDED CONCERNING THE AREA AFFECTED, CONCENTRATIONS, AND RATE AND DIRECTION OF MOVEMENT OF THE PLUME OF CONTAMINATED GROUND WATER. IN ADDITION, AN EVALUATION WAS MADE TO DETERMINE WHETHER OR NOT BRIGHTON'S MUNICIPAL WELL FIELDS WILL BE AFFECTED AND, IF SO TO DETERMINE FUTURE ARRIVAL TIMES AND CONCENTRATIONS. THE STUDY WAS UNDERTAKEN IN THREE PHASES. PHASE I INVOLVED THE CONVERSION OF THE EXISTING CHLORIDE TRANSPORT MODEL OF THE ARSENAL TO A DIMP TRANSPORT MODEL IN ORDER TO EVALUATE THE MAGNITUDE OF THE GROUND WATER CONTAMINATION IN THE IMMEDIATE AREA OF THE ARSENAL. PHASE II INVOLVED BUILDING A SECOND DIMP TRANSPORT MODEL OF A LARGER AREA IN ORDER TO INVESTIGATE THE POTENTIAL FOR DIMP MOVING INTO THE CITY OF BRIGHTON'S FIELD WELL AND OTHER ADJACENT AREAS. IN PHASE III OF THE STUDY, THE

14. SUBJECT TERMS
MODEL CALIBRATION, CHEMICALS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED			

E. BERRY
8/20/R02

AD-A956 502

UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

DIGITAL-MODEL STUDY OF GROUND-WATER CONTAMINATION BY DIISOPROPYLMETHYLPHOSPHONATE (DIMP), ROCKY MOUNTAIN ARSENAL NEAR DENVER, COLORADO-FINAL REPORT

By S. G. Robson
U.S. Geological Survey

Prepared for the

U.S. DEPARTMENT OF THE ARMY,

ROCKY MOUNTAIN ARSENAL

ADMINISTRATIVE REPORT

FOR OFFICIAL USE ONLY

June 1977

8128.R02

UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

DIGITAL-MODEL STUDY OF GROUND-WATER CONTAMINATION BY DIISOPROPYLMETHYLPHOSPHONATE (DIMP), ROCKY MOUNTAIN ARSENAL NEAR DENVER, COLORADO-- FINAL REPORT

By S. G. Robson
U.S. Geological Survey

Prepared for the

U.S. DEPARTMENT OF THE ARMY,

ROCKY MOUNTAIN ARSENAL

ADMINISTRATIVE REPORT

FOR OFFICIAL USE ONLY

June 1977

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

METRIC CONVERSION FACTORS

To convert English units	*Multiply by*	*To obtain metric units*
feet (ft)	0.3048	meters (m)
feet per day (ft/d)	.3048	meters per day (m/d)
feet squared per day (ft^2/d)	.0929	meters squared per day (m^2/d)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
acres	4.047×10^{-3}	square kilometers (km^2)
cubic feet per second (ft^3/s)	28.32	liters per second (L/s)
	.0283	cubic meters per second (m^3/s)
gallons per minute (gal/min)	6.309×10^{-3}	cubic meters per second (m^3/s)
tons (short)	.9072	metric tons (t)
tons per year (tons/yr)	.9072	metric tons per year (t/yr)

One microgram per liter (µg/L) is approximately equal to one part per billion. One milligram per liter (mg/L) is equal to 1,000 micrograms per liter and is approximately equal to one part per million.

DIGITAL-MODEL STUDY OF GROUND-WATER CONTAMINATION BY DIISOPROPYLMETHYLPHOSPHONATE (DIMP), ROCKY MOUNTAIN ARSENAL NEAR DENVER, COLORADO--FINAL REPORT

By S. G. Robson

ABSTRACT

Diisopropylmethylphosphonate (DIMP) is an organic compound produced as a byproduct of the manufacture and detoxification of GB nerve gas agent at the Rocky Mountain Arsenal, Colo. Ground-water contamination by DIMP occurred from unlined industrial waste-disposal ponds during 1952-56. DIMP appears to function as a nonreactive tracer in an aqueous environment, for a combination of ground-water and surface-water transport has spread the contaminant to an area in excess of 28 square miles (73 square kilometers) between 1952 and 1975. This study was undertaken for the Rocky Mountain Arsenal with the purpose of building ground-water solute-transport models for use in evaluating the mechanism of DIMP transport and the effectiveness of various water-quality management alternatives.

Saturated alluvium, as much as 60 feet (18 meters) thick, is the geologic unit primarily involved in the ground-water transport of DIMP. Ground water moves to the northwest across the arsenal and ultimately discharges to either the South Platte River or First Creek. Long-term estimates of mean annual flow indicate that: (1) 0.24 cubic foot per second (6.8 liters per second) of ground water enters the arsenal from the southeast, (2) an additional 0.83 cubic foot per second (24 liters per second) of water is recharged to the aquifer from five unlined ponds on the arsenal, (3) 0.77 cubic foot per second (22 liters per second) of water crosses the northwest boundary of the arsenal, and (4) 0.30 cubic foot per second (8.5 liters per second) crosses the north arsenal boundary of which 0.14 cubic foot per second (4.0 liters per second) discharges to First Creek.

Two mathematical models based on idealized aquifer conditions were used to simulate the water-table elevation and DIMP concentrations in the alluvial aquifer near the arsenal. The models are based on an iterative alternating-direction-implicit mathematical solution of the ground-water flow equation coupled with a method-of-characteristics solution to the solute transport equation. The steady-flow, transient transport model calculations were calibrated

by comparison with long-term mean water levels and DIMP concentrations for May-July 1975. Model simulations indicate that the contaminated ground water moves with velocities as much as 15 feet per day (4.6 meters per day) to the northwest of the disposal ponds and with velocities of about 1 foot per day (0.3 meter per day) to the north of the disposal ponds. Some of the contaminated ground water that moves to the north enters First Creek from springs and seeps and, ultimately, either enters Barr Lake or returns to the aquifer between First Creek and Barr Lake, thus affecting the ground-water quality between the arsenal and the city of Brighton, Colo. Model simulations indicate that DIMP-contaminated ground water would not reach the Brighton municipal well field by 1995 even if additional discharge of contaminants continues near a lined industrial waste-disposal reservoir on the arsenal and no attempts are made to retard contaminant movement.

A comparison of model simulations of selected water-management alternatives suggests that a physical barrier to the movement of ground water, located near the downgradient edge of a contaminated zone and manages so as to prevent water-level changes both above and below the barrier, would be the most effective means considered for preventing further migration of contaminated ground water. None of the simulations with the barrier produced a rapid decrease in DIMP concentration in First Creek, thus supplemental measures may be required if the DIMP concentrations in ground water near Barr Lake and Brighton are to be reduced in the near future.

INTRODUCTION

Historical Background of the Contamination Problem

The Rocky Mountain Arsenal was established in 1942 and presently encompasses about 27 mi^2 (70 km^2) immediately northeast of the city of Denver, Colo. (pl. 1). The northern boundary of the arsenal is about 7 mi (11 km) south of the city of Brighton, Colo. The arsenal was constructed to produce toxic chemical and incendiary munitions--about 242,000 tons (220,000 t) of which were manufactured during World War II (Reynolds, 1975). After a postwar reduction in activities, the arsenal began a second manufacturing phase in 1953, upon completion of a new toxic-chemical-agent facility. This manufacturing and filling facility manufactured GB nerve gas agent from 1953 to 1957. One byproduct of this manufacturing process was the organic compound diisopropylmethylphosphonate (DIMP). The arsenal has subsequently been involved in manufacturing anticrop agents and removing toxic chemicals from munitions. From 1973 to the present (1976) the GB-manufacturing facility has been used to detoxify the GB agent held in bulk storage and in bombs and warheads.

The manufacturing and detoxification activities at the arsenal have produced industrial effluents, some of which have high dissolved-solids concentration and (or) high concentrations of organic compounds. Prior to 1956, these effluents were disposed of in unlined surface ponds. Effluent percolating through the bottom of these ponds has degraded the chemical quality of the ground water in a shallow alluvial aquifer. Subsequent to 1956, industrial effluents have been discharged to a lined reservoir (Reservoir F, pl. 2) and the unlined ponds have been either unused or used temporarily to hold surface runoff or freshwater.

Petri and Smith (1956) studied the ground-water quality near the arsenal in 1955 and 1956. They found that high concentrations of sodium and chloride in the aquifer extended from near the arsenal disposal ponds northwest to the South Platte River. Data from this and subsequent work were used by Konikow (1975) to prepare detailed maps of the bedrock-surface elevation, water-table elevation, and aquifer saturated thickness and transmissivity near the arsenal. Konikow later expanded this work to include a digital ground-water-quality model capable of simulating the movement and dispersion of chloride in the aquifer (Konikow, 1976).

In 1974 the first analyses for DIMP revealed the presence of the compound in ground water on the arsenal and surrounding property to the north and west. Trace concentrations were detected in an area in excess of 28 mi^2 (73 km^2) and in wells as much as 7 mi (11 km) downgradient from the arsenal disposal ponds and within 1.0 mi (1.6 km) of two wells in the city of Brighton's municipal well field (pl. 1). Concern has been expressed about DIMP in potable ground water because little is known about toxicity levels or the effect of long-term consumption of trace amounts of the compound. This and an associated problem of ground-water contamination by a pesticide byproduct, dicyclopentadiene (DCPD), led the Colorado Department of Health to issue a Cease and Desist Order against the Rocky Mountain Arsenal and the Shell Chemical Co. The Shell Chemical Co. plant on the arsenal property is thought to be the source of the DCPD. The Cease and Desist Order states, in general, that the Rocky Mountain Arsenal and the Shell Chemical Co. are to:

1. Immediately stop the off-arsenal discharge of DIMP and DCPD from both surface- and ground-water flow.

2. Submit a proposed plan of action to preclude such future off- arsenal discharge and take action on the approved plan.

3. Develop and institute a surveillance plan to verify compliance with items 1 and 2.

Purpose and Scope

The Rocky Mountain Arsenal requested that the U.S. Geological Survey conduct a digital-model study of the DIMP contamination of ground water on the arsenal and surrounding property in order to provide insight into the mechanism of DIMP transport and to provide data useful in meeting the requirements of the Cease and Desist Order. Specific information was needed concerning the area affected, concentrations, and rate and direction of movement of the plume of contaminated ground water. In addition, an evaluation was made to determine whether or not Brighton's municipal well fields (pl. 1) will be affected and, if so, to determine future arrival times and concentrations.

The study was undertaken in three phases. Phase I involved the conversion of the existing chloride transport model (Konikow, 1976) of the arsenal to a DIMP transport model in order to evaluate the magnitude of the ground-water contamination in the immediate area of the arsenal. Phase II involved building a second DIMP transport model of a larger area in order to investigate the potential for DIMP moving into the city of Brighton's well field and other adjacent areas. Both models assume conservative (nonreactive) transport of DIMP and were calibrated using 1975 data on DIMP concentrations in the aquifer. In Phase III of the study, the models developed in Phases I and II were used to evaluate the effectiveness of various proposed methods of combating the spread of contaminated ground water near the arsenal.

Acknowledgments

Existing data on the DIMP concentrations in ground and surface waters were provided by the Rocky Mountain Arsenal. These data included chemical analyses made by the Colorado Department of Health, Shell Chemical Co., and the Rocky Mountain Arsenal. The arsenal also made DIMP analyses on supplemental samples collected by the U.S. Geological Survey. James W. Warner of the U.S. Geological Survey contributed materially to this investigation through his work on the numerous computer runs leading to the final model simulations.

MODEL DEVELOPMENT

The model used for both the chloride and DIMP transport studies at the arsenal is based on an iterative alternating-direction-implicit mathematical solution of the ground-water flow equation coupled with a method of characteristics solution of the solute transport equation as described by Bredehoeft and Pinder (1973). These mathematical procedures require that the area to be modeled (pl. 2) be divided into numerous small rectangular segments or nodes of equal dimensions. At each node in the area to be modeled the average geohydrologic and chemical characteristics of the aquifer within the area of the node are described.

In the Phase I model (pl. 3), a 1,000-ft (300-m) grid interval was used, as was used in the previous chloride model of Konikow (1976). This grid interval enabled a detailed simulation of the aquifer in the immediate area of the arsenal but was not practical for simulating conditions over larger areas due to the excessive number of nodes required. To simulate the larger area from the arsenal to north of Brighton, the Phase II model was built with a grid interval of 2,000 ft (600 m) (pl. 2). The advantage of being able to simulate aquifer conditions over a large area is partly offset by the loss of resolution in the model. In either model, the smallest feature that can be considered must have an effect over an area comparable to the size of the model node. Because of the resolution limitation, the Phase I model was primarily used to simulate conditions in the immediate area of the arsenal while the Phase II model was used to simulate more general conditions at a greater distance from the arsenal.

The geohydrologic characteristics of the alluvial aquifer in the study area have been described by Konikow (1975); Hurr, Schneider, and others (1972); and Smith, Schneider, and Petri (1964). They found that the direction of ground-water movement on the east side of the South Platte River is generally from the southeast to the northwest (pl. 3). On the west side of the river, movement generally is toward the northeast, resulting in ground-water discharge to the river. The aquifer is discontinuous near the Rocky Mountain Arsenal because numerous bedrock highs separate areas in which the alluvium is saturated. In this area the direction of ground-water movement is controlled by the configuration of the aquifer. The saturated thickness of the alluvial aquifer ranges from 0 to 60 ft (0 to 18 m) (fig. 1) with the thicker areas located near the present or abandoned courses of the South Platte River and its tributaries. The transmissivity (fig. 2) of the aquifer is as much as 20,000 ft^2/d (1,900 m^2/d) with the areas of highest transmissivity near the areas of greatest saturated thickness. Porosity and storage coefficient of the aquifer are estimated to be 0.30 and 0.25, respectively, and are reasonably constant throughout the aquifer.

Water-level hydrographs for wells north and west of the arsenal show that there have been minimal long-term water-level changes in the area between 1937 and 1975 (Brookman, 1969). The most significant short-term water-level change occurred during the 1954-57 drought when water levels temporarily declined 3 to 5 ft (0.9 to 1.5 m). The varying rates of recharge from the disposal ponds on the arsenal undoubtedly produced ground-water-level changes near the ponds. However, adequate historical data are not available to document pond recharge rates or fluctuations in ground-water levels near the ponds. It is thought that short-term pond recharge variations would affect only a small area near the ponds and that the long-term effects of the ponds are of primary concern. As a result, it was assumed, for modeling purposes, that the ground-water-flow system was in a steady-flow condition from the time of DIMP discharge (1952-56) to 1975. To simulate these conditions, a steady-state flow model was coupled with a transient-state transport model. This modeling procedure enabled the simulation of the steady ground-water-flow system in conjunction with aquifer DIMP concentrations that change during the 1952-75 simulation period.

The boundary conditions for the two DIMP models were handled in the same manner as were those for the chloride model. Model boundaries extending through parts of the aquifer were treated as constant-head boundaries; that is, boundaries at which the rate of flow across the boundary may vary but the head at the boundary is held constant. No-flow boundaries were assumed between the aquifer and the bedrock outcrops. Although the bedrock is known to contain permeable zones (McConaghy and others, 1964), the hydraulic conductivity of these zones is generally much less than that of the alluvium. As a result, the assumption of impermeable model boundaries is thought to be valid. This assumption is further strengthened by the success of the model in simulating historical concentrations of DIMP in the aquifer.

The quantity and distribution of recharge and discharge (pl. 3 and table 1) to the Phase I DIMP model were similar to those used in the chloride model, with one exception. Industrial effluent high in chloride was disposed into ponds A through E from about 1943 to 1956. Effluent containing DIMP was thought to be disposed into ponds A through E from only 1952 to 1956. Unfortunately, no data are available on the concentration of DIMP in the effluent or the volume of effluent recharged to the aquifer. As a result, the DIMP source concentrations used in the Phase I model were determined by trial and error as those which produced the best agreement between the 1975 field data

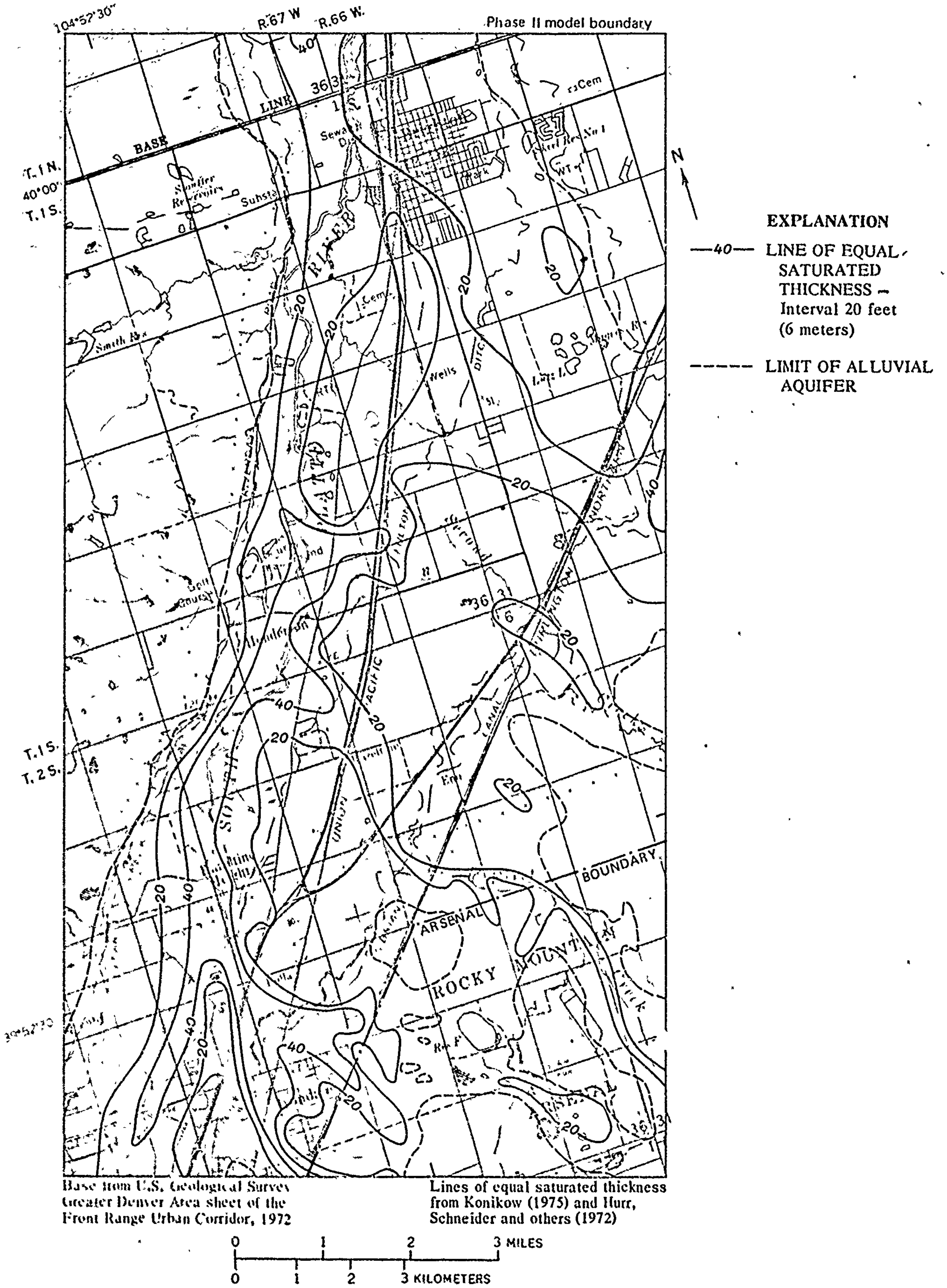
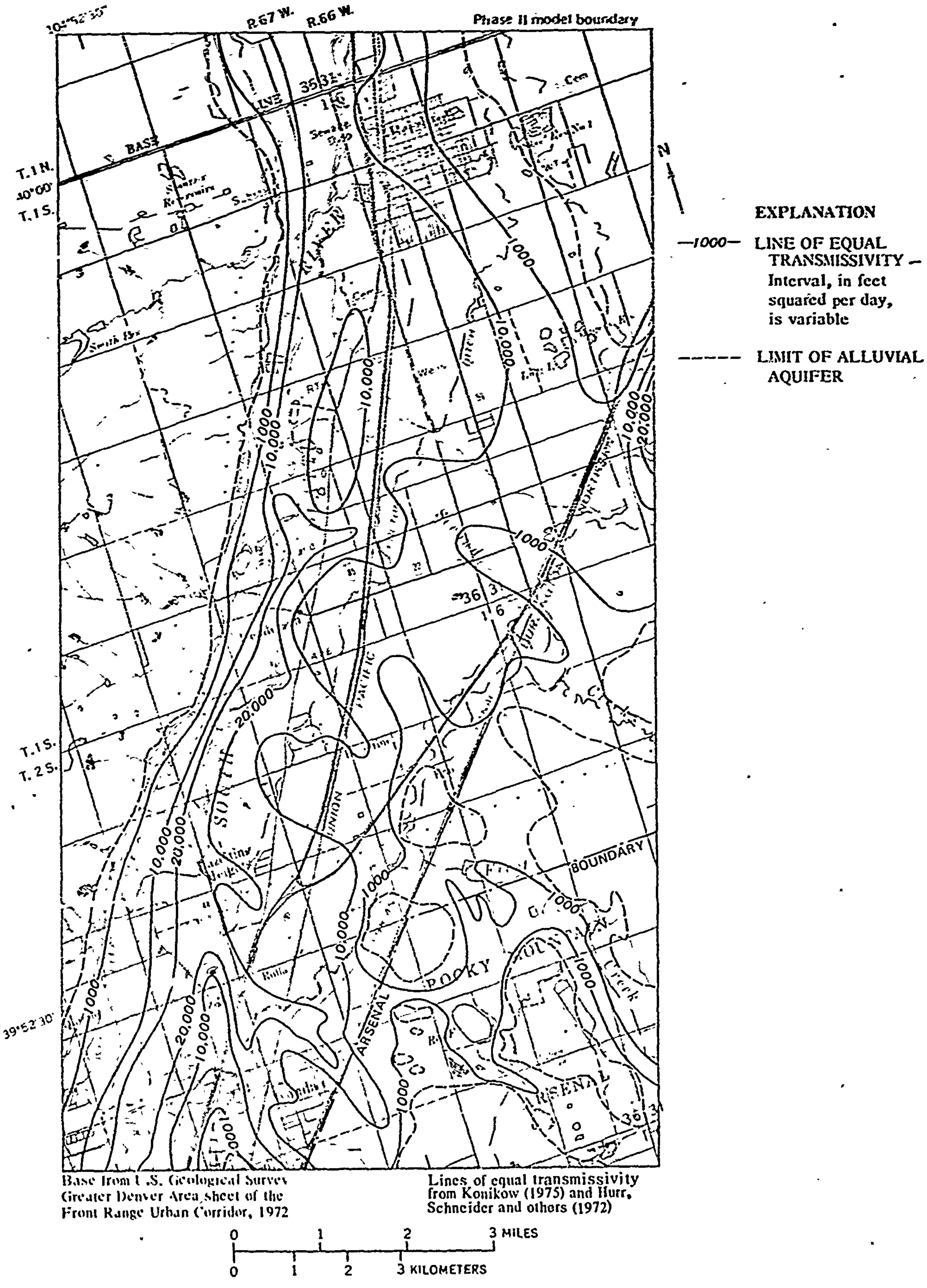


Figure 1.--Saturated thickness of alluvial aquifer.



Base from U.S. Geological Survey Greater Denver Area sheet of the Front Range Urban Corridor, 1972

Lines of equal transmissivity from Konikow (1975) and Hurr, Schneider and others (1972)

Figure 2.--Transmissivity of alluvial aquifer.

and the corresponding model calculations. The volume of effluent recharged to the Phase I model was similar to that used in the chloride model.

Table 1.--*Recharge, discharge, and concentration of DIMP data for Phase I model*

Source[1]	1952-75 average recharge or discharge, in cubic feet per second		Average DIMP concentration, in micrograms per liter		
	Recharge	Discharge	1952-56	1956-74	1974-75
A---------------	0.072	------	17,000	0	0
B---------------	.012	------	17,000	0	0
C---------------	.662	------	17,000	0	3,000
D---------------	.059	------	1,000	0	0
E---------------	.027	------	1,000	0	0
F---------------	.816	------	(2)	(2)	(2)
I---------------	6.540	------	(2)	(2)	(2)
L---------------	.048	------	0	0	0
O---------------	1.351	------	0	0	0
R---------------	------	12.959	------	---	-----
S---------------	------	.142	------	---	-----
U---------------	4.755	------	0	0	0
W---------------	------	1.242	------	---	-----
Reservoir F (lined pond)--	0	0	------	---	-----
Total------	14.342	14.343			

[1]See plate 3 for location of sources.
[2]DIMP concentration in recharge varies during 1952-75 period.

The DIMP source concentrations determined in the Phase I model were also used in the Phase II model. The quantity and distribution of recharge and discharge used in the Phase II model (table 2) were similar to those used in the Phase I model in the areas where the two models coincide. The larger simulation area of the Phase II model incorporates more sources of recharge and discharge as indicated by the 14.3 ft^3/s (0.41 m^3/s) of total recharge in the Phase I model as opposed to the 47.9 ft^3/s (1.36 m^3/s) of total recharge in the Phase II model.

Both Phase I and Phase II models were constructed so that the discharge of DIMP-contaminated ground water at springs and seeps along First Creek could affect the quality of water in the O'Brian Canal below the confluence of the creek and canal. As a result, the Phase II model is capable of simulating the

DIMP concentration in ground water near Brighton and Barr Lake resulting from the recharge of contaminated surface water from the O'Brian Canal and Barr Lake.

Table 2.--*Recharge, discharge, and concentration of DIMP data for Phase II model*

Source[1]	1952-75 average recharge or discharge, in cubic feet per second		Average DIMP concentration, in micrograms per liter		
	Recharge	Discharge	1952-56	1956-74	1974-75
A----------------	0.072	------	17,000	0	0
B----------------	.012	------	17,000	0	0
C----------------	.662	------	17,000	0	3,000
D and E----------	.086	------	1,000	0	0
F----------------	2.690	------	(2)	(2)	(2)
G----------------	1.000	------	0	0	0
H----------------	.160	------	0	0	0
I----------------	19.760	------	(2)	(2)	(2)
L----------------	3.420	------	(2)	(2)	(2)
O----------------	1.930	------	0	0	0
R----------------	------	35.751	------	---	-----
S----------------	------	.225	------	---	-----
T----------------	9.017	------	0	0	0
U----------------	9.151	------	0	0	0
W----------------	------	11.948	------	---	-----
Reservoir F (lined pond)--	0	0	------	---	-----
Total------	47.924	47.924			

[1]See plate 2 for location of sources.
[2]DIMP concentration in recharge varies during 1952-75 period.

The Phase I and Phase II models assume that DIMP is conservative; that is, does not sorb on the soil matrix, precipitate, evaporate, or undergo chemical alteration as it moves through the aquifer. This assumption is thought to be reasonable although based only on indirect evidence. DIMP was discharged to Reservoir F (a lined reservoir) in 1956 and is still present in concentrations of about 4×10^5 µg/L 20 years later. In addition, DIMP is widespread in the alluvial aquifer and can be detected much further from the arsenal than can the chloride contamination that occurred at about the same time. Model results indicate that high concentrations of chloride and DIMP have moved through parts of the aquifer which in 1975 had low concentrations of these constituents. If DIMP were significantly sorbed on the aquifer sediments and subsequently redissolved, these areas of low DIMP concentration likely would not exist. The same transverse and longitudinal dispersivity (100 ft or 30 m) proved adequate in both the chloride and DIMP models, further suggesting that DIMP may be correctly treated as a conservative tracer.

If DIMP is not a conservative tracer, then the model results based on the assumption that it is conservative will tend to show too much contaminant movement and thus present a prediction of a worst-case concentration distribution. A determination of the ground-water transport characteristics of DIMP is beyond the scope of this investigation, but should be undertaken if more detailed and accurate modeling is needed or if a better understanding of the transport characteristics is required.

MODEL CALIBRATION

A calibration procedure was used to check the validity of the DIMP transport models. Calibration involved a comparison of (1) the observed water-table elevations with model-calculated water-table elevations, and (2) observed May-July 1975 DIMP concentrations with the model-calculated 1975 DIMP concentrations. The agreement between the observed and calculated quantities is indicative of the capability of the model to simulate water-table elevations and DIMP concentrations in the aquifer. The lack of data on the quantities of water discharged to each pond, the concentration of DIMP in this water, and the concentrations of DIMP in the ground water between 1952 and 1975, together with the assumptions regarding the conservative nature of DIMP, contribute uncertainties to the models which are evidenced as discrepancies between the calculated and the observed data. Keeping these limitations in mind, the agreement attained between the model calculations and the observed data is sufficient to consider the model calibration as satisfactory. Because of the number of poorly defined parameters in the models, it is possible that a different combination of estimates for these parameters might result in an equally satisfactory calibration. Although the models are considered to be valid within the limits of the data, care needs to be used in interpreting model results so that more accuracy is not read into the results than the data would justify.

The Phase I model-calculated water-table elevations are generally within 3 ft (0.6 m) of those shown on plate 3, and all of the model-generated water-level contours are located horizontally within 700 ft (210 m) of the corresponding contour shown on plate 3. The similarity between the observed DIMP concentrations and the calculated concentrations may be seen by comparing plate 1 and figure 3. In these and all subsequent DIMP concentration maps, concentrations less than the 0.5-μg/l analytical-detection limit for DIMP are considered to be zero.

In the process of calibrating the Phase II model, minor revisions were made in the previously calibrated Phase I model in order to assure the compatibility of the two models. The resulting final calibration of the Phase I

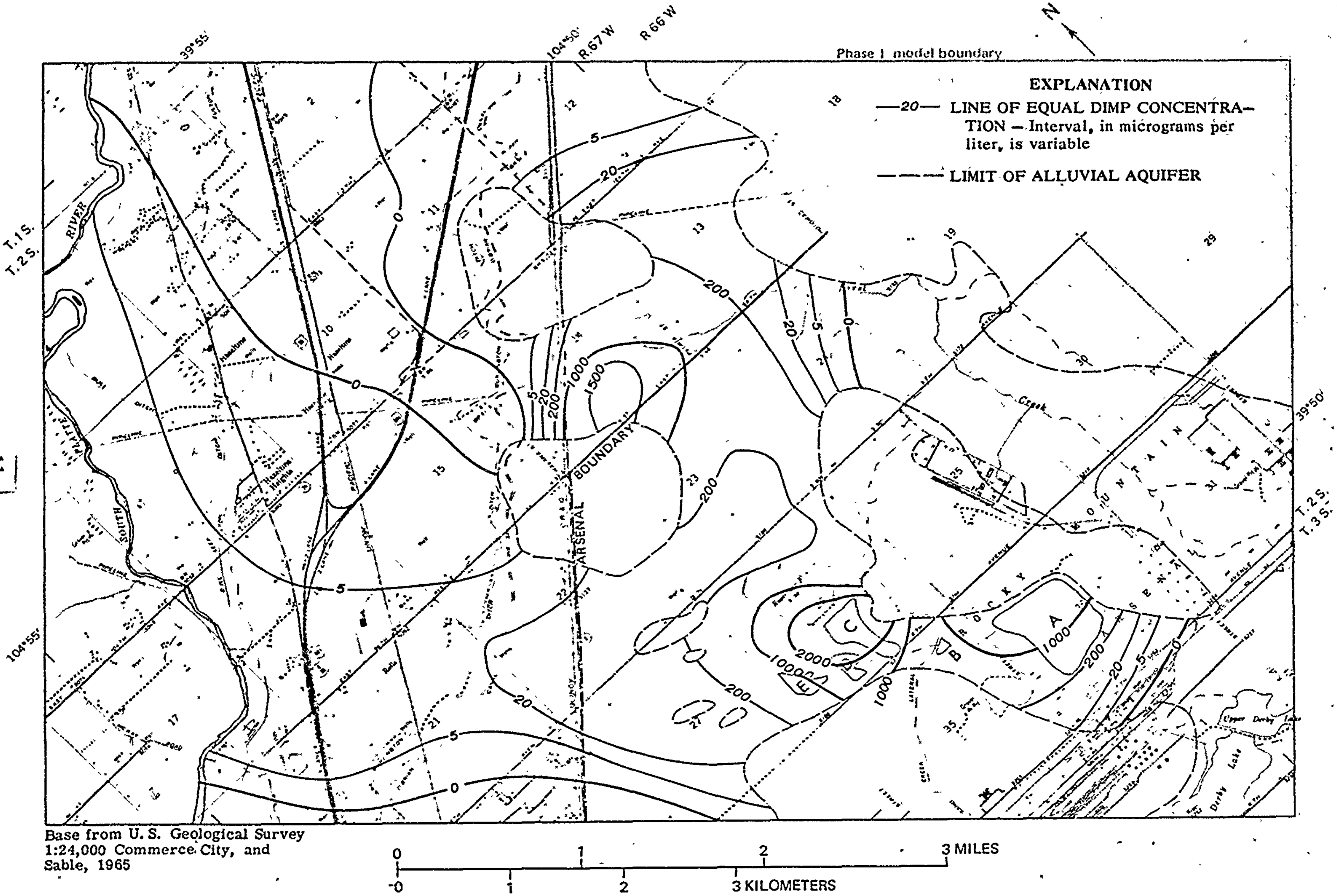


Figure 3.--Phase I model-calculated 1975 concentrations of DIMP in ground water.

model (fig. 3) was not materially improved over the previous calibration but differed slightly from that shown on plate 3 of the progress report for Phase I dated February 1976.

The correlation between the Phase II model-calculated water-table elevations and the observed elevations was similar to that achieved in the Phase I model. The area of greatest water-table discrepancy occurred near the small bedrock areas west of Reservoir F and was thought to be due to the inability of the Phase II model to adequately simulate these small features. Good agreement was achieved between the Phase II model-calculated 1975 DIMP concentrations and the observed data (pl. 1 and fig. 4).

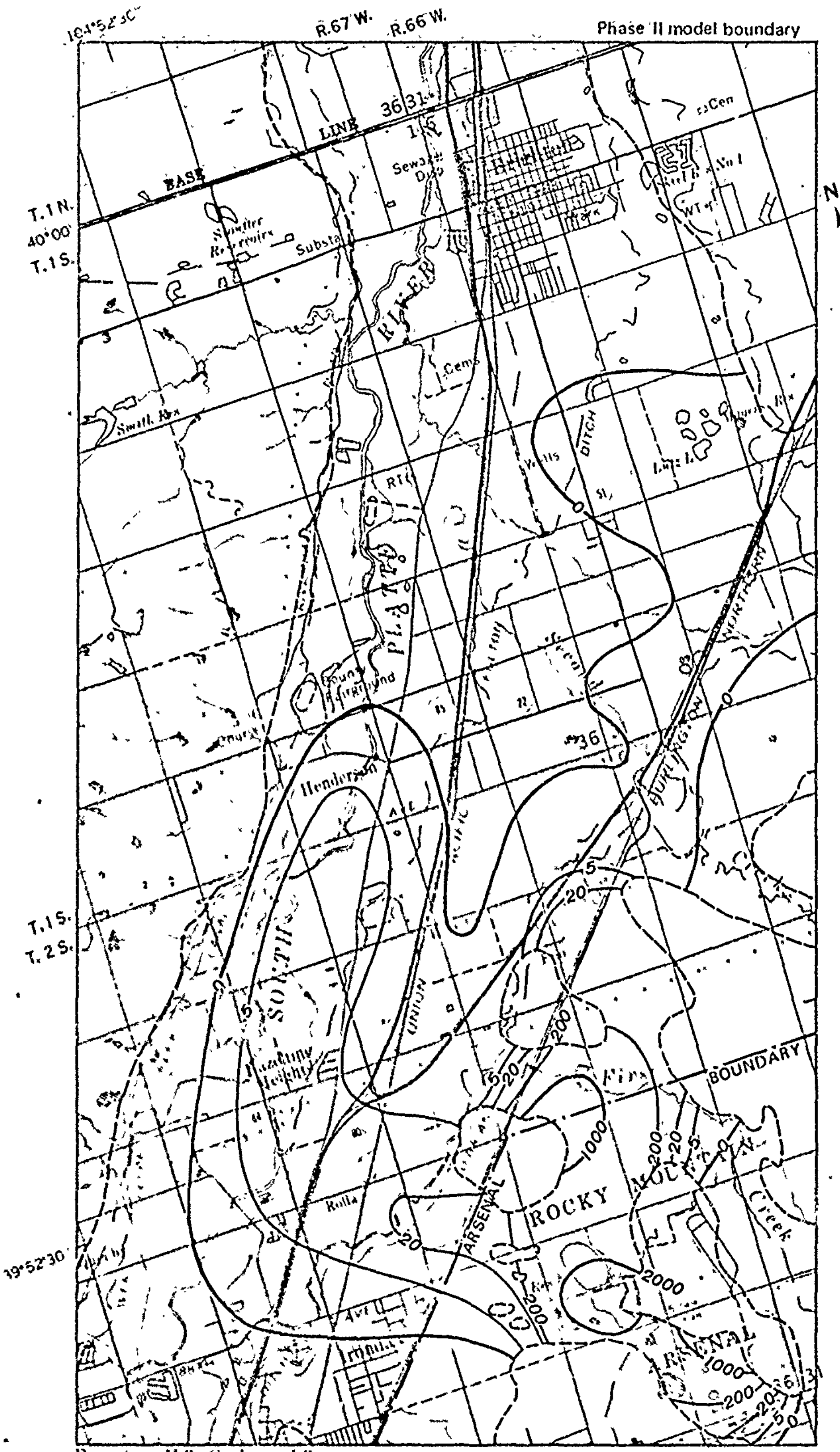
Because ground-water DIMP-concentration data are not available for years prior to 1974, the model calibration is based on known concentrations at the beginning (zero initial DIMP concentration) and end of the simulation period. The lack of data for intermediate checks on calibration probably is not a severe limitation because of the congruence between the DIMP-transport models and the chloride-transport model. Chloride data were available for intermediate calibration checks on the chloride model. As the hydrologic factors that affect chloride transport also affect DIMP transport, the calibration of the chloride model adds support to the less extensive calibration of the DIMP models.

Ground-water discharge occurs at springs and seeps along a reach of First Creek from near 96th Avenue to the O'Brian Canal. The models indicated that a maximum DIMP concentration of about 2 µg/L would occur in the canal as a result of water from First Creek discharging into the canal. This is consistent with the 2.5 µg/L of DIMP found in two samples of water from Barr Lake (the terminus of the O'Brian Canal).

The calibrated DIMP models were used to calculate the ground-water flow velocities in the alluvial aquifer (fig. 5). Velocities ranged from less than 1.0 ft/d (0.3 m/d) in the southeast part of the model area to more than 15 ft/d (0.46 m/d) near the South Platte River. When figure 5 is used in conjunction with the direction of ground-water movement shown on plate 3, the ground-water travel time between adjacent points in the aquifer may be calculated.

The model calculates annual DIMP concentrations in the ground water resulting from the estimated average rate and concentration of recharge from each pond from 1952 to 1975. By examining the calculated spatial distribution of DIMP in the aquifer at different times, it is possible to better understand the mechanism by which the DIMP contamination reached its present locations. This is important not only in retrospect but also as a means of understanding what future changes would likely occur if a DIMP source was again allowed to contaminate the aquifer near pond C.

The DIMP concentrations in the aquifer were assumed to be zero in 1952, prior to the disposal of DIMP to the environment. During the following 4 years, DIMP was disposed in the unlined ponds A, B, C, D, and E. After 4 years (1956) of this disposal, the model calculations show DIMP concentrations in excess of 200 µg/L in the area shown on figure 6. After the completion of



EXPLANATION

—5— LINE OF EQUAL DIMP CONCENTRATION – Interval, in micrograms per liter, is variable

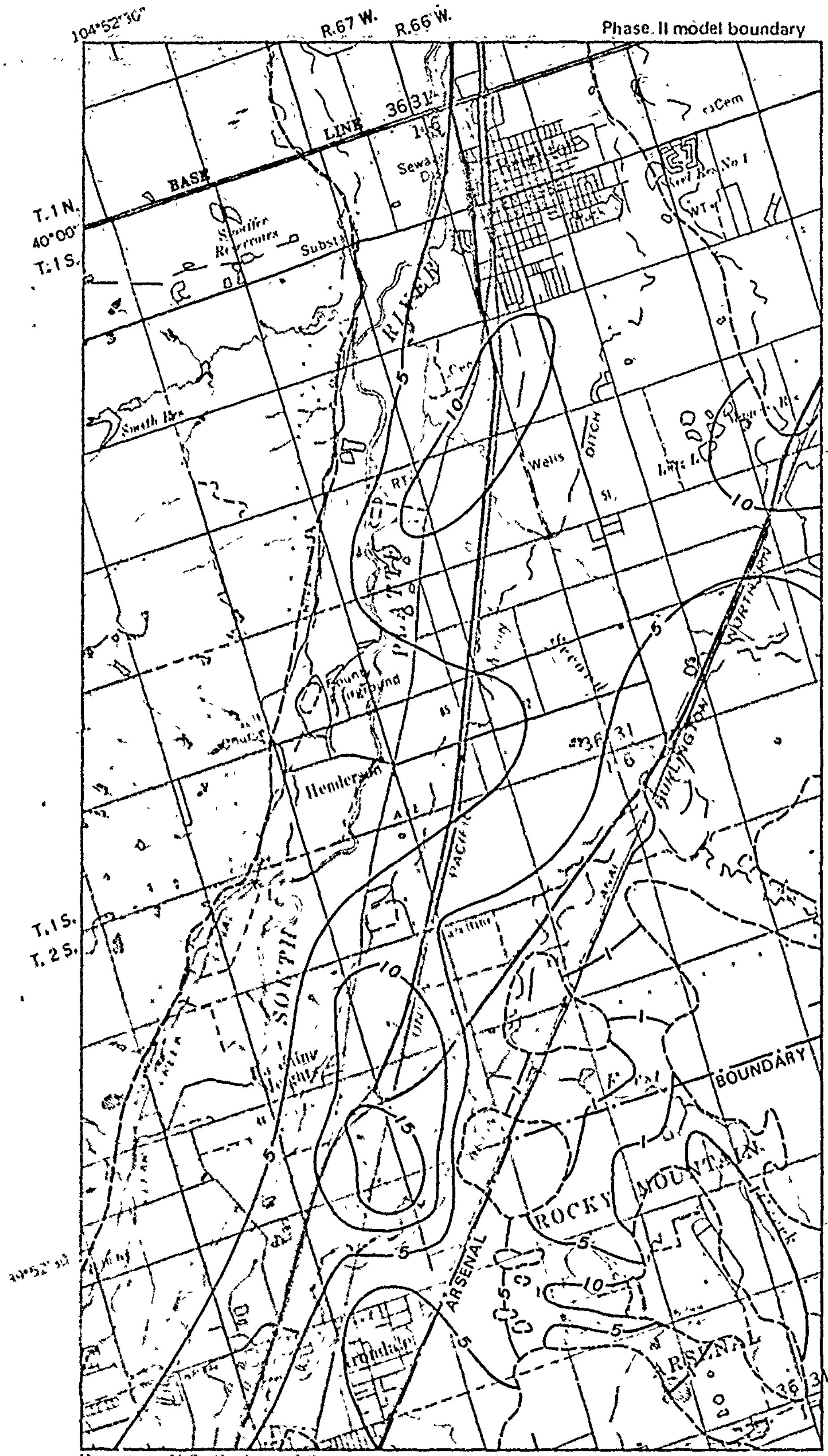
----- LIMIT OF ALLUVIAL AQUIFER

Base from U.S. Geological Survey Greater Denver Area sheet of the Front Range Urban Corridor, 1972

0 1 2 3 MILES

0 1 2 3 KILOMETERS

Figure 4.--Phase II model-calculated 1975 concentrations of DIMP in ground water.



Base from U.S. Geological Survey Greater Denver Area sheet of the Front Range Urban Corridor, 1972

0 1 2 3 MILES
0 1 2 3 KILOMETERS

EXPLANATION

—10— LINE OF EQUAL GROUND-WATER VELOCITY — Interval, in feet per day, is variable

------ LIMIT OF ALLUVIAL AQUIFER

See plate 3 for direction of ground-water movement

Figure 5.--Model-calculated ground-water velocities.

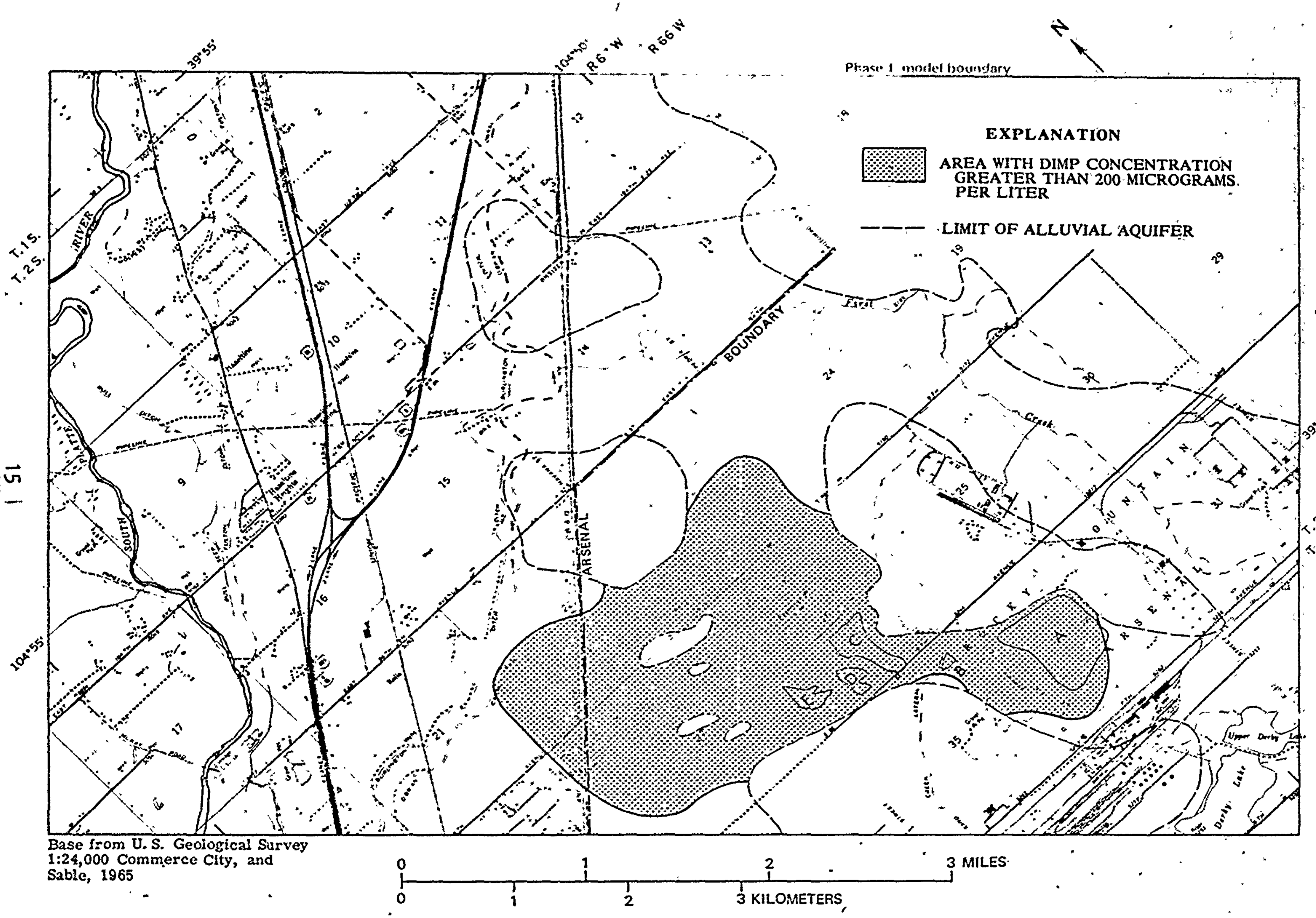


Figure 6.--Phase I model--calculated 1956 concentrations of DIMP in ground water.

the lined Reservoir F in 1956, ground water recharged from the ponds was assumed to no longer contain DIMP. After 4 years (1960), the model calculations show an improvement in ground-water quality near ponds C and D with the area of concentrations in excess of 200 µg/L extending off the arsenal through the alluvial aquifer to the west of Reservoir F (fig. 7). After an additional 4 years (1964) (fig. 8), the main body of the contaminated plume had moved off the arsenal and continued to spread through the aquifer toward the South Platte River where it left the aquifer by flowing into the river. This process continued over the next 4 years (1968) (fig. 9) until only a small remainder of the contaminated plume existed in the aquifer west of the arsenal. By 1972 (fig. 10), water with concentrations in excess of 200 µg/L no longer existed in the aquifer to the west of the arsenal. The area in excess of 200 µg/L near ponds A and B in 1956 remained near this location through subsequent years due to the low ground-water velocities in the area. A similar situation occured in the contaminated plume to the northeast of Reservoir F. This plume slowly moved into the area of First Creek (figs. 7, 8, and 9) where it affected the quality of water in the creek. Water with concentrations in excess of 200 µg/L remained near this area through 1975 (pl. 1).

When no additional DIMP input after 1956 was assumed in the Phase I model, the simulations for 1975 show an area larger than 1 mi^2 (3 km^2) near ponds C, D, and E, and Reservoir F with a DIMP concentration of less than 5 µg/L. However, the actual DIMP concentrations observed in ground-water samples obtained during May-July 1975 in this area range between about 300 and 3,000 µg/L (pl. 1). This discrepancy suggests that an additional input of DIMP occurred in the area subsequent to 1956. The change in DIMP concentration with time for well 41, shown in figure 11, demonstrates that a major change in DIMP concentration has occurred in the area during 1974-75. The rapid increase and decrease in DIMP concentration in well 41 is likely due to the close proximity of the well and a high-concentration source of DIMP. The period of record for wells 141 and 127 is short but seems to indicate that one or more longer duration sources of contamination also may exist in the area. Neither of these sources appears to be upgradient (southeast) of well 145 due to the relatively low concentrations of DIMP found in this well. The anomalously low DIMP concentrations found in well 117 are thought to be due to the periodic recharge of uncontaminated water in pond C and are not representative of the general ground-water quality in the area.

An examination of the concentration ratios for the assumed conservative constituents chloride, fluoride, and DIMP in ground water in the affected area indicates that it is possible for Reservoir F water to be a source of recent contamination to the aquifer. The ratios of chloride/DIMP, chloride/fluoride, and fluoride/DIMP shown in table 3 were calculated for selected wells and Reservoir F. In figure 12, the three ratios for each source have been plotted to show a pattern that is representative of the water type. For example, water from well 10 is thought to be chemically representative of the water that was diverted from Derby Lake into pond C and subsequently recharged the aquifer near pond C. This water type is shown in figure 12 by a pattern of ratios in which chloride/DIMP and fluoride/DIMP ratios are very large and plot well above the chloride/fluoride ratio. Of the wells considered, only wells 103 and 117 have water types similar to that of well 10 and the subsequent recharge from pond C. This suggests that wells 103 and 117 may have low DIMP

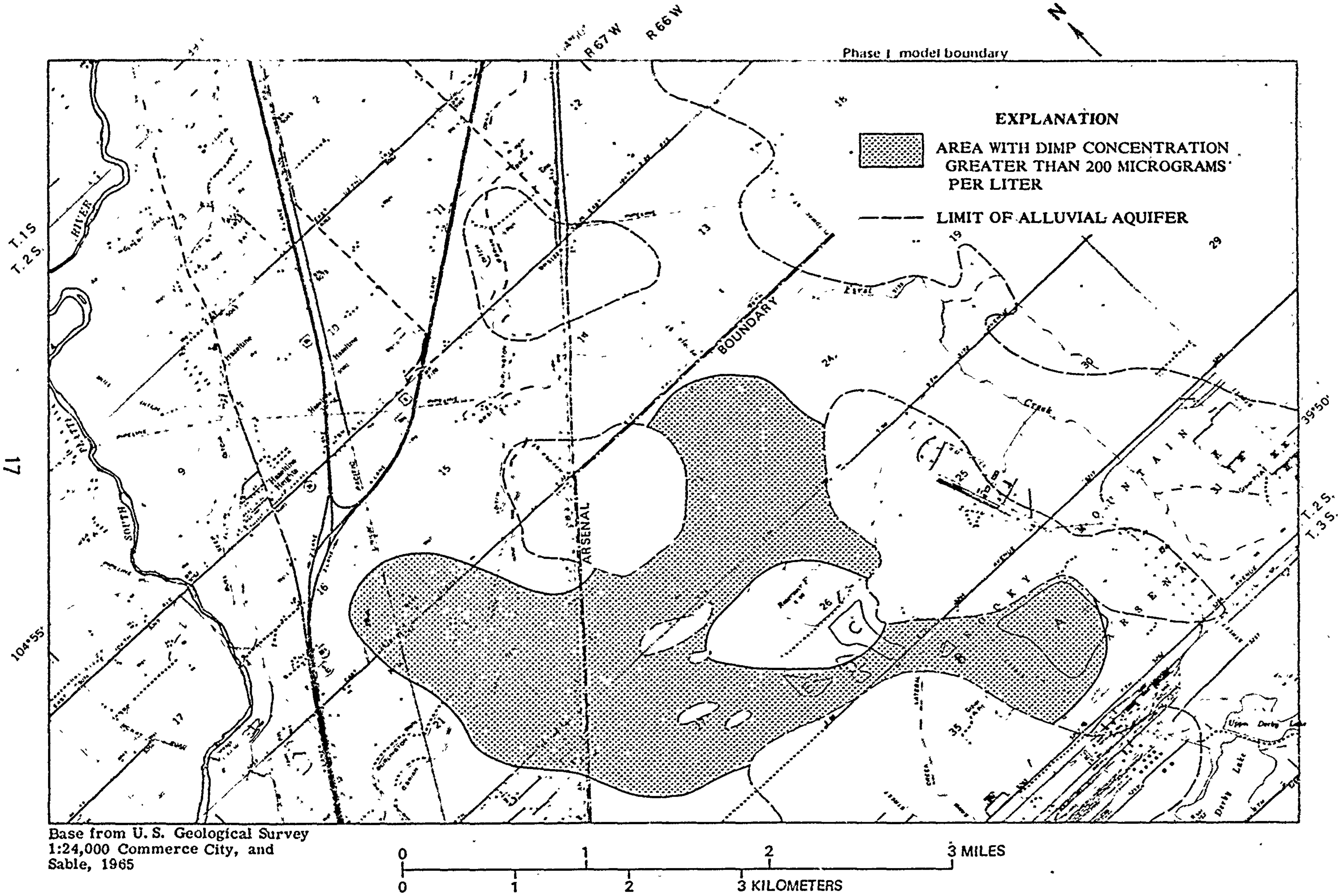


Figure 7.--Phase I model--calculated 1960 concentrations of DIMP in ground water.

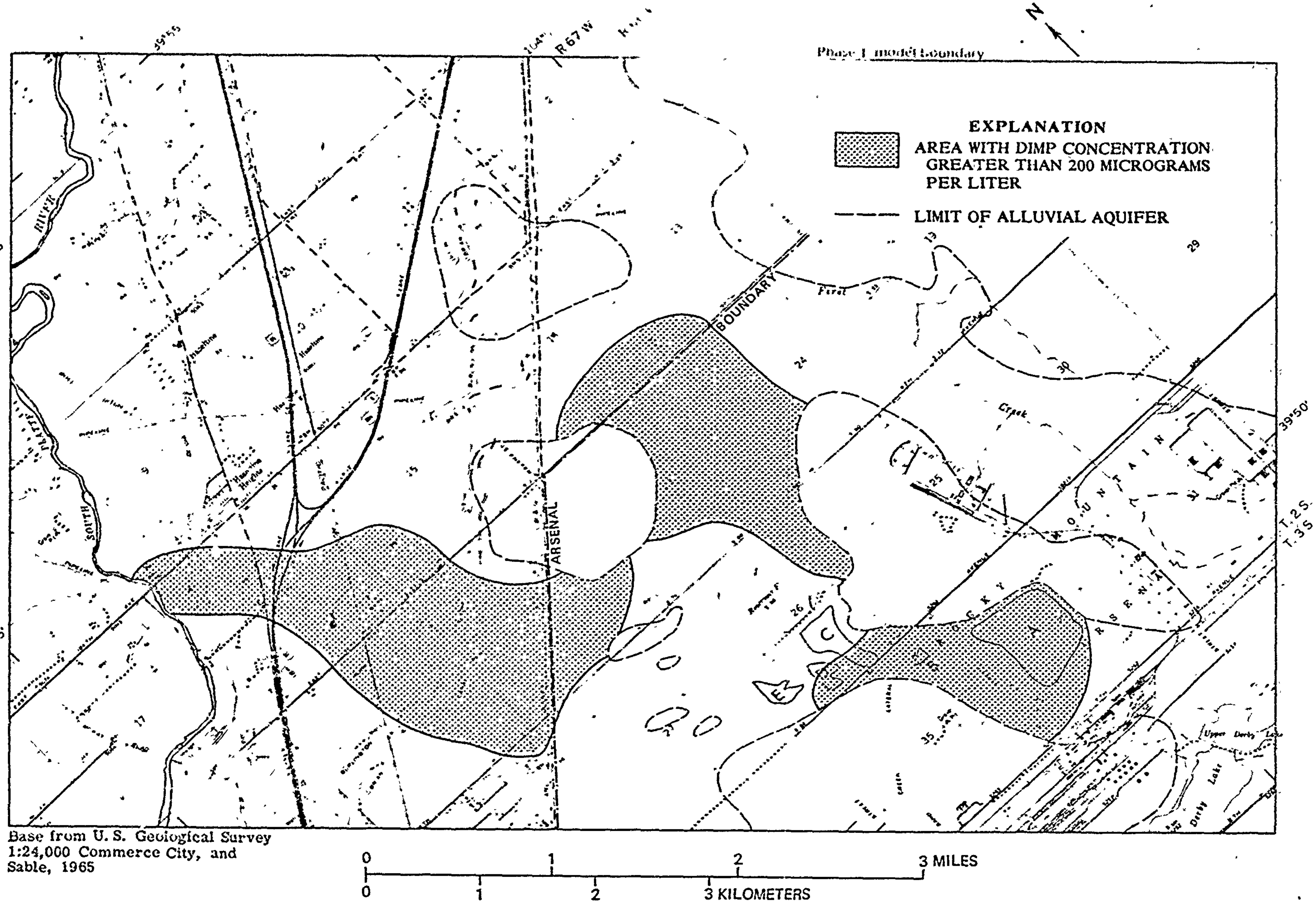


Figure 8.--Phase I model-calculated 1964 concentrations of DIMP in ground water.

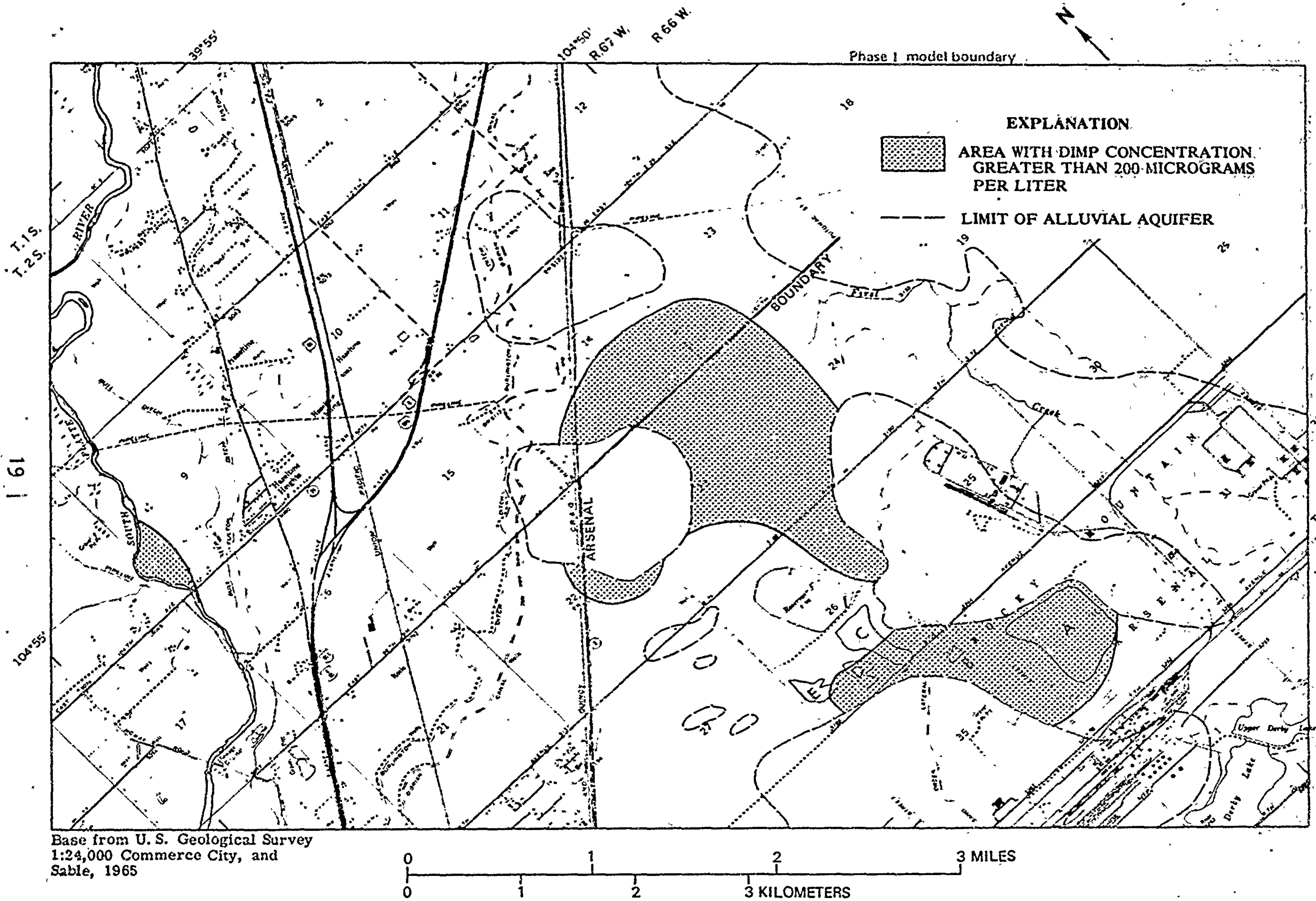
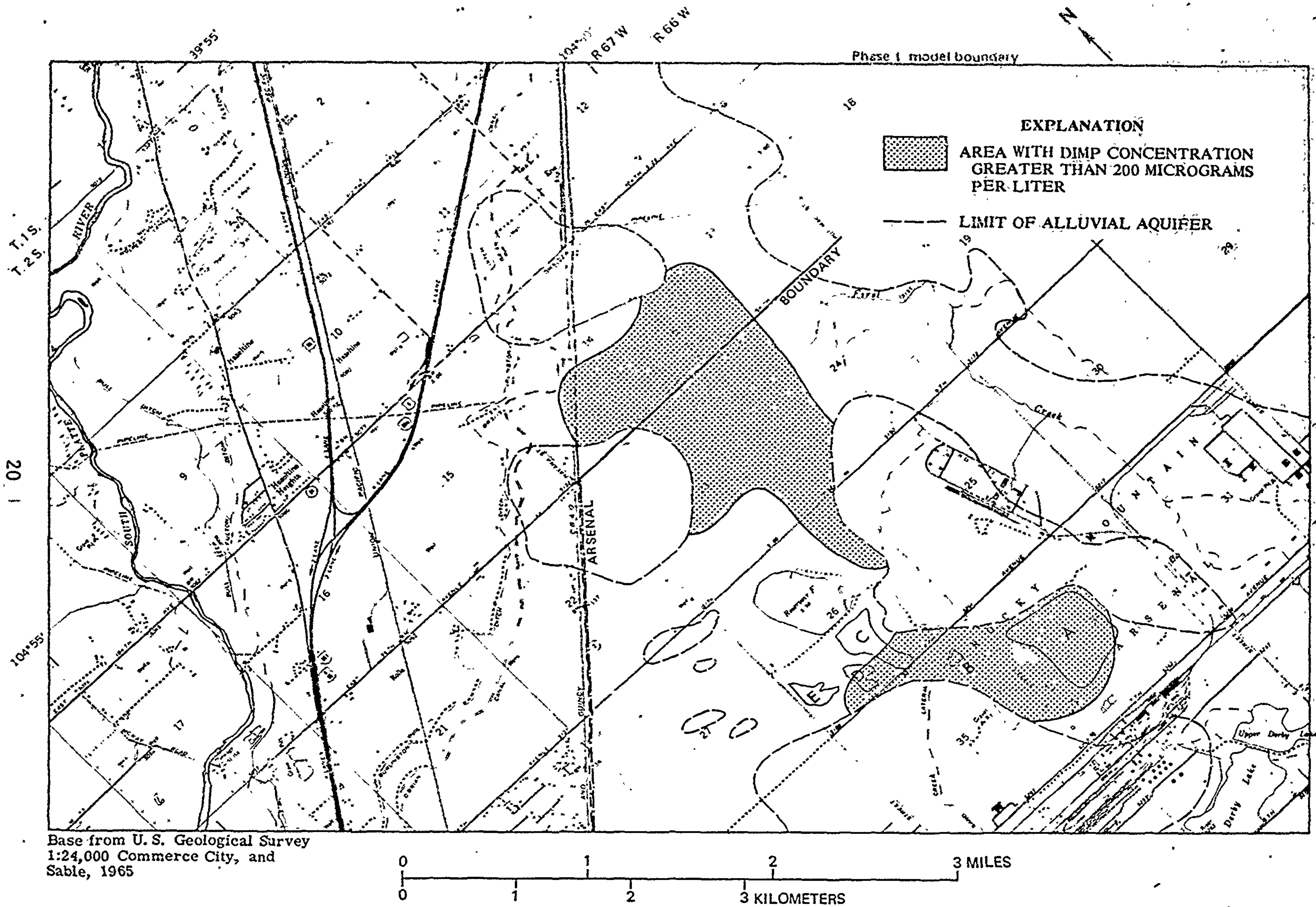


Figure 9.--Phase I model—calculated 1968 concentrations of DIMP in ground water.



Base from U. S. Geological Survey 1:24,000 Commerce City, and Sable, 1965

Figure 10.--Phase I model-calculated 1972 concentrations of DIMP in ground water.

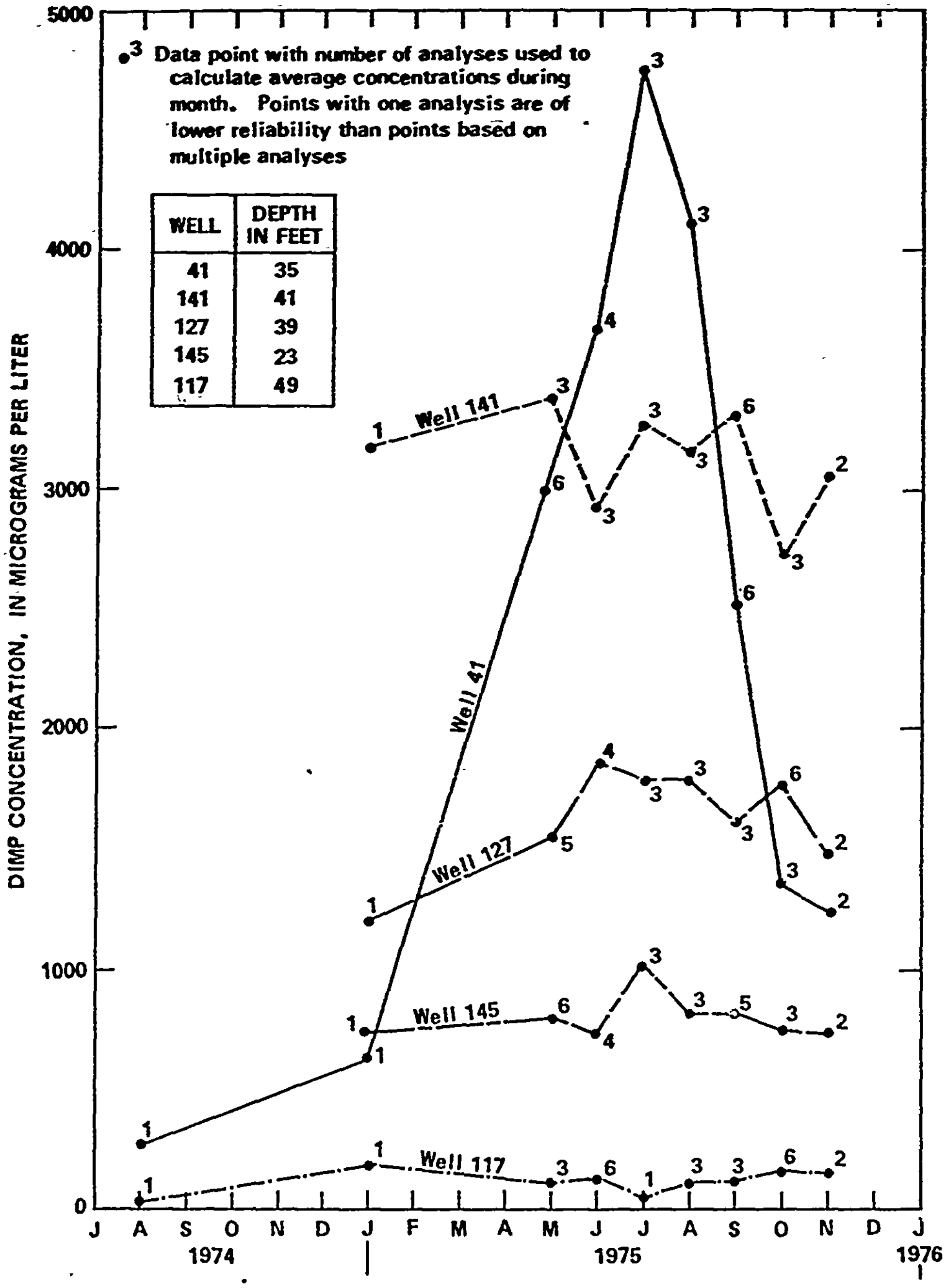


Figure 11.--Change in DIMP concentration with time in selected wells. (See figure 1 for location of wells)

Table 3.--*Concentrations and ratios of selected constituents*

Well number[1] or source	Date	Number of analyses	Concentration, in micrograms per liter			Ratio		
			Chloride	DIMP	Fluoride	Chloride/DIMP $\times 10^2$	Chloride/Fluoride $\times 10^2$	Fluoride/DIMP
	1975							
10----------	July 28	1	7.0×10^4	$>5.0\times10^{-1}$	9.4×10^2	>1,400	0.74	>1,900
11----------	June 9	3	3.9×10^6	4.7×10^4	2.7×10^2	.83	140	.0057
41----------	June 9	3	1.1×10^6	3.9×10^3	3.6×10^3	2.8	3.1	.92
103----------	June 4	3	1.8×10^5	1.1	7.5×10^2	1,600	2.4	680
117----------	June 11	3	7.6×10^5	1.2×10^2	1.8×10^3	63	4.2	15
127----------	June 11	3	7.0×10^5	1.8×10^3	2.4×10^3	3.9	2.9	1.3
141----------	June 9	3	9.8×10^5	2.9×10^3	1.6×10^3	3.4	6.1	.55
145----------	June 9	3	3.9×10^5	8.1×10^2	2.1×10^3	4.8	1.9	2.5
Reservoir F--	January	1	4.3×10^7	4.1×10^5	7.7×10^4	1.0	5.6	.19

[1]Well locations shown on plate 1.

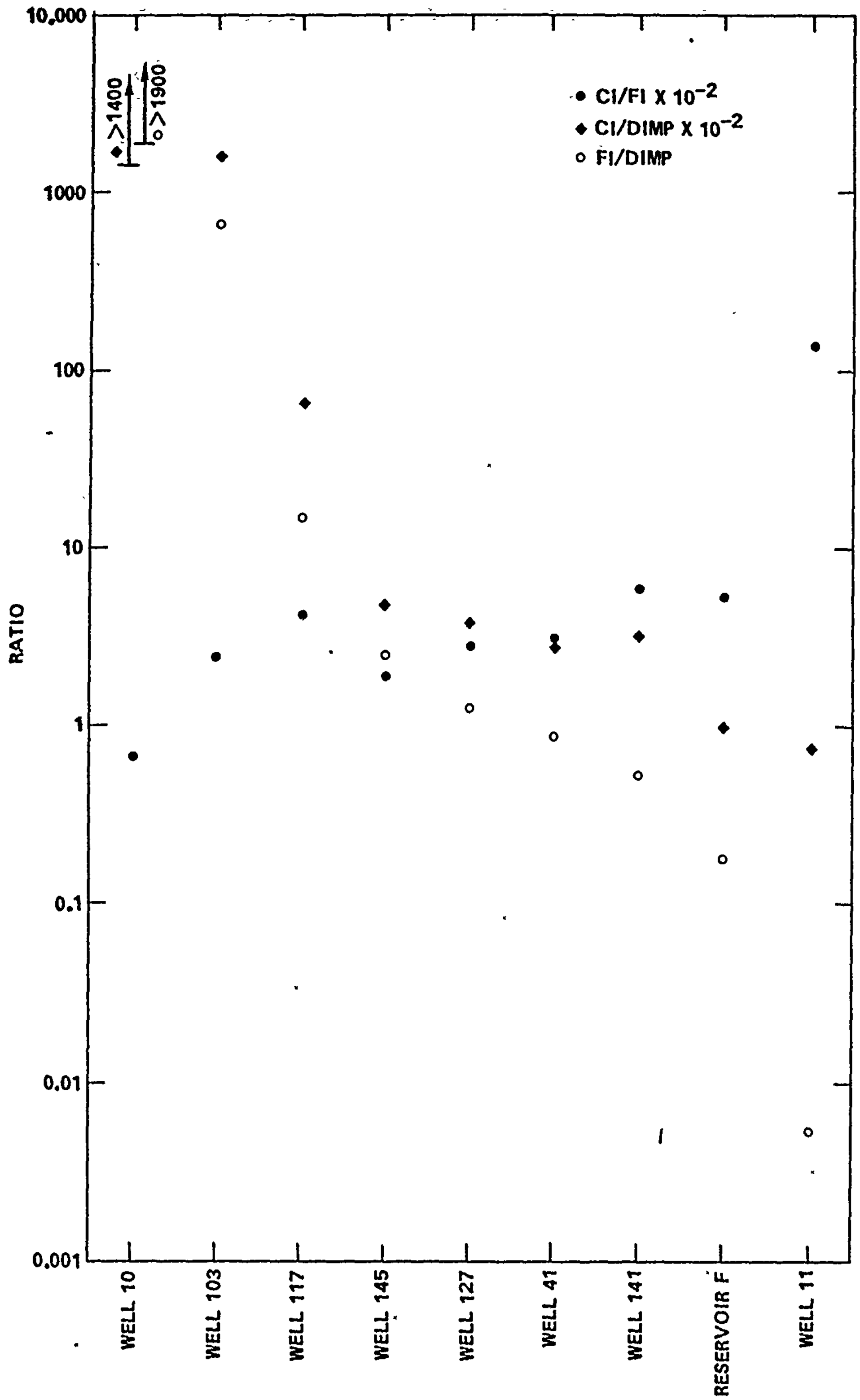


Figure 12.--Concentration ratios for selected wells and Reservoir F.

concentrations (p. 1) due to the influence of uncontaminated ground-water recharge from pond C as is indicated on figures 7, 8, and 9. The higher concentration of DIMP in wells located between well 103 and pond C is thought to be due to a recent source of contamination near pond C.

The water type in well 141 is similar to the water type in Reservoir F. Water with progressively less similarity to Reservoir F water occurs in wells 41, 127, and 145. On this basis, it appears possible for water from Reservoir F to be one source of recent contamination. However, the similarity in water types in wells 141 and 11 permit consideration of another source near pond A. If contaminated ground water near pond A is affecting the ground-water quality near Reservoir F by means of flow through the alluvium, the water type in well 145 should be more similar to that in well 11 than are the water types in wells 141, 41, and 127. However, it may be possible for contaminated ground water to move from near pond A to near Reservoir F through permeable zones in the underlying bedrock without affecting the water quality in the overlying alluvium. The lack of wells perforated in the bedrock in this area prevents an evaluation of this possibility.

There are insufficient data to determine the mechanism responsible for the recent contamination or the exact location of the spirce(s) of contaminants or duration of the discharge. Possibilities to be considered include one or more of the following:

1. A leak in the reservoir liner, a sewer carrying contaminated waste (pl. 1), or other structures associated with Reservoir F.

2. Movement of contaminated ground water through permeable zones in the underlying bedrock formation.

3. Percolation in ponds C, D, or E of contaminated surface runoff from ponds A or B.

4. Release of contaminants previously concentrated in the soil by evaporation or sorbtion.

Use of the Phase I model indicates that a DIMP input near pond C of 1-year duration with a concentration of 3,000 µg/L was adequate to reasonably simulate the 1975 observed concentrations in the aquifer near ponds C, D, and E and Reservoir F.

Every effort should be made to determine and correct the condition responsible for the recent input of DIMP to the ground-water system. This effort should include monitoring ground-water levels and chemical quality in affected areas and a determination of the concentration and rate of leakage of contaminants into the aquifer. Without prompt and appropriate action, long-term ground-water contamination problems will continue to occur at Rocky Mountain Arsenal.

Numerous model simulations indicate that the zone of high DIMP concentration near the north boundary of the arsenal and the zone near pond C are the likely result of two separate periods of contamination. The northern zone is the remnant of contamination that occurred during 1952-56 and the zone near pond C is the result of recent contamination in this area.

The rate of long-term average ground-water flow through various parts of the alluvial aquifer near the arsenal may be calculated using the calibrated Phase I model and the recharge and discharge data in table 1. Results of these calculations are shown on figure 13 and indicate that of the 0.93 ft^3/s (26 L/s) entering the aquifer south of Reservoir F, 0.77 ft^3/s (22 L/s) leaves the arsenal through the alluvial gaps to the west of Reservoir F. The saturated-thickness near all but the northern gap was shown by Konikow (1975) to be less than 10 ft (3 m). If water-level declines approach 10 ft (3 m) in this area the rate of underflow shown on figure 13 would be drastically reduced. As shown in a subsequent model run (Run 11), a reduction in the rate of recharge from pond C can produce significant water-level declines near the gaps resulting in a reduction in the flow of ground water through the area. The distribution of flow shown on figure 13 represents conditions resulting from long-term average recharge and discharge in the area and may not represent flow conditions resulting from other recharge or discharge rates.

The mass of conservative contaminant introduced to the model aquifer will equal the mass removed from the aquifer plus the mass remaining in the aquifer, if the model is completely accurate. An error in a part of the computer algorithm prevented the automatic calculation of the mass balance for the arsenal models. However, a hand calculation of the mass balance indicates that the quantities of mass balance within 1 to 2 percent. A total of about 50 tons (45 t) of DIMP was introduced to the model between 1952 and 1975, of which about 40 tons (36 t) was discharged and about 10 tons (9 t) remained in the aquifer in 1975. About 34 tons (31 t) of DIMP was discharged to the South Platte River and about 6 tons (5 t) was discharged at springs, seeps, and pumping wells.

MODEL SIMULATIONS

The Phase I and Phase II models have been shown to be capable of calculating ground-water level and quality conditions from 1952 to 1975. The models also can be used to calculate water-level and quality conditions in the future; for example, from 1975 to 1995. The projected simulations can be used to test the effects of proposed changes in the operation of the ground-water system on the future water-level and quality distributions in the aquifer. The model thus can be a tool to help evaluate the relative effectiveness of specific management alternatives.

The model simulations proposed by the U.S. Army, in collaboration with the U.S. Geological Survey, primarily emphasize the use of a bentonite barrier trenched into the aquifer in order to control ground-water movement. For purposes of model simulation, it is assumed that the barrier would be impermeable and extend through the full saturated thickness of the aquifer. Ground-water movement also could be controlled by use of a paired line source and sink (a line of recharge wells adjacent to a line of extraction wells, for example). Although no simulations were made to specifically evaluate a paired source and sink configuration, the large-scale water-quality effects of a barrier of the

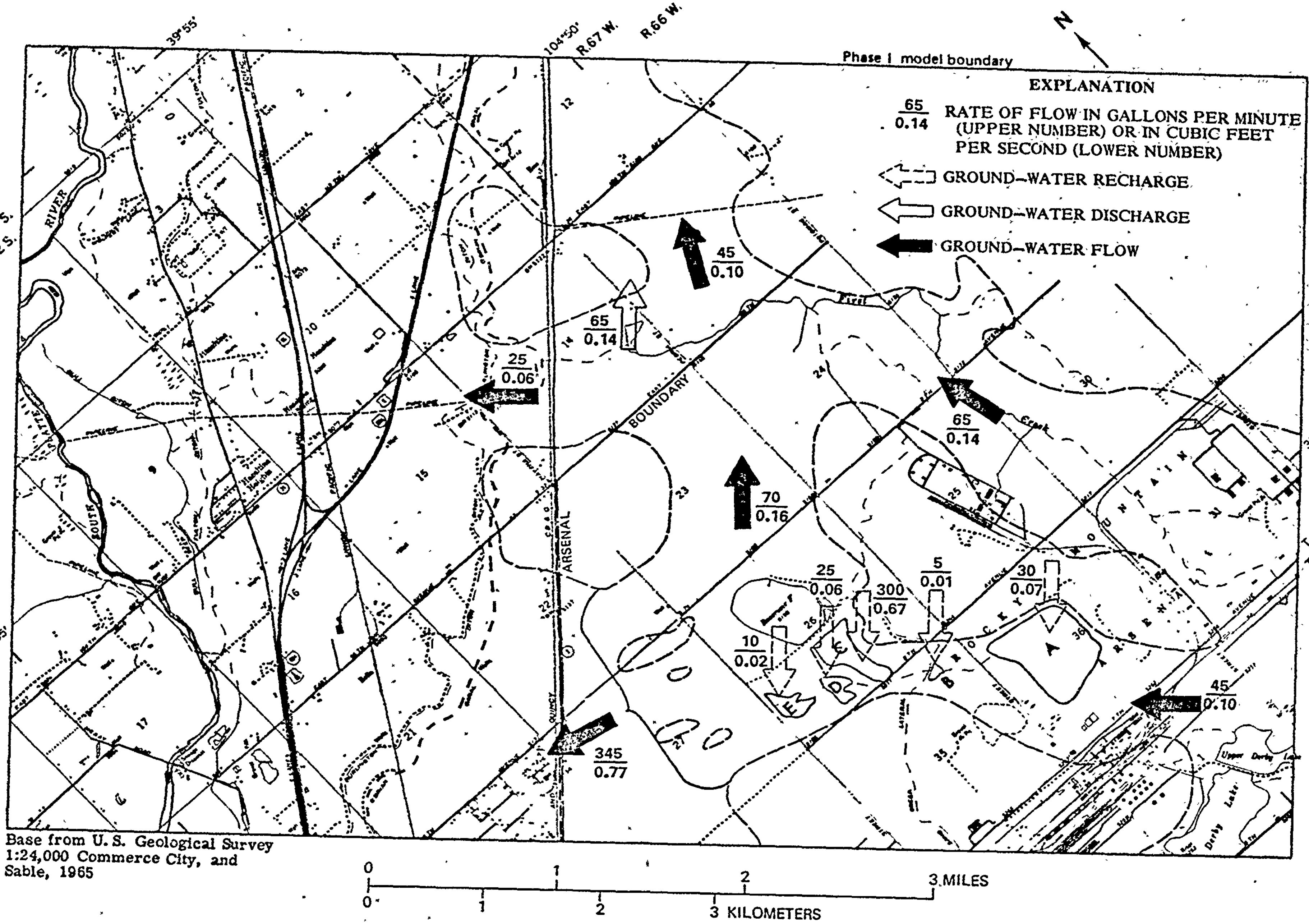


Figure 13.--Mean rates of recharge, discharge, and ground-water flow, 1952-75.

type considered in Run 3 are similar to those that would be produced by the paired source and sink.

The ability of the models to accurately calculate the DIMP concentrations that would occur at a future time are limited by the thoroughness and accuracy of the calibration and by the extent to which the model assumptions and data are representative of future conditions. Because of the number of poorly defined model parameters and the single point in time (1975) calibration, care needs to be exercised when using the model results to avoid reading more accuracy into the results than the data would justify. If DIMP is not a conservative tracer as has been assumed, the model simulations will show too much DIMP movement and tend to present a worst-case concentration distribution. Except as noted, all the model simulations are based on the assumptions that the aquifer and contaminant characteristics will not differ significantly from those used in the model calibration. In particular, it is assumed that: (1) The bedrock highs form no-flow aquifer boundaries, (2) minor changes in water-table elevation will not alter the location of the no-flow boundaries or the aquifer transmissivity, (3) the flow system will remain in near steady-flow conditions, and (4) data such as the rate of recharge or discharge from disposal ponds, canals, irrigated areas, and wells, and the concentration of DIMP in recharge will remain compatible with the data representing 1952-74 conditions as was used in the model calibrations. Initial conditions for each simulation are based on the observed May-July 1975 DIMP concentrations (pl. 1) and projections are made for 1975 to 1995.

Run 1

Objective.--Simulate the results of taking no remedial measures to alter the normal movement of contaminated water.

Approach.--For this simulation, all the preceding model and data assumptions apply and no remedial measures were incorporated into the model. The DIMP concentration in recharge from ponds A, B, C, D, and E was assumed to be zero. It was further assumed that the recent source of contamination near Reservoir F would not be allowed to continue in the future; therefore, no contaminated recharge was simulated near Reservoir F. However, the effects of the existing contaminated ground water near Reservoir F (pl. 1) are incorporated in the simulation.

Results.--The Phase I and Phase II model-calculated DIMP concentrations for 1975 to 1995 are shown on figures 14 and 15. The models indicate that an improvement in water quality would occur over most of the area near the arsenal as can be seen by comparing these figures with the initial conditions (pl. 1). In the area near Barr Lake and the O'Brian Canal north of First Creek, there would not be an improvement in ground-water quality due to the continuing discharge of DIMP-contaminated ground water into First Creek and the O'Brian Canal. The DIMP-contaminated surface water in Barr Lake and the O'Brian Canal, in turn, would recharge the aquifer southeast of Brighton. This would allow DIMP-contaminated ground water to advance to within less than 1 mi (1.6 km) of the southernmost well in the Brighton municipal well field.

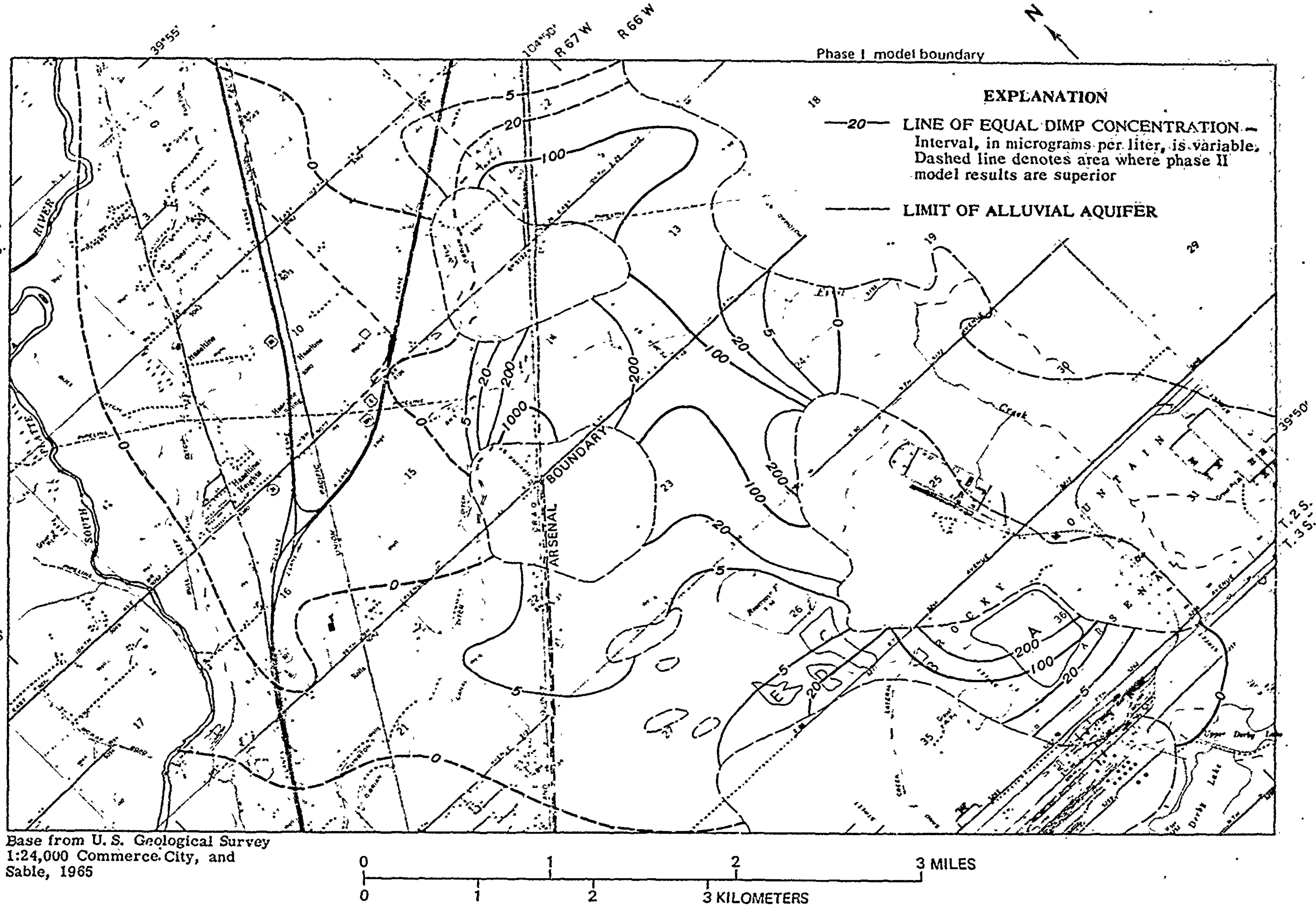
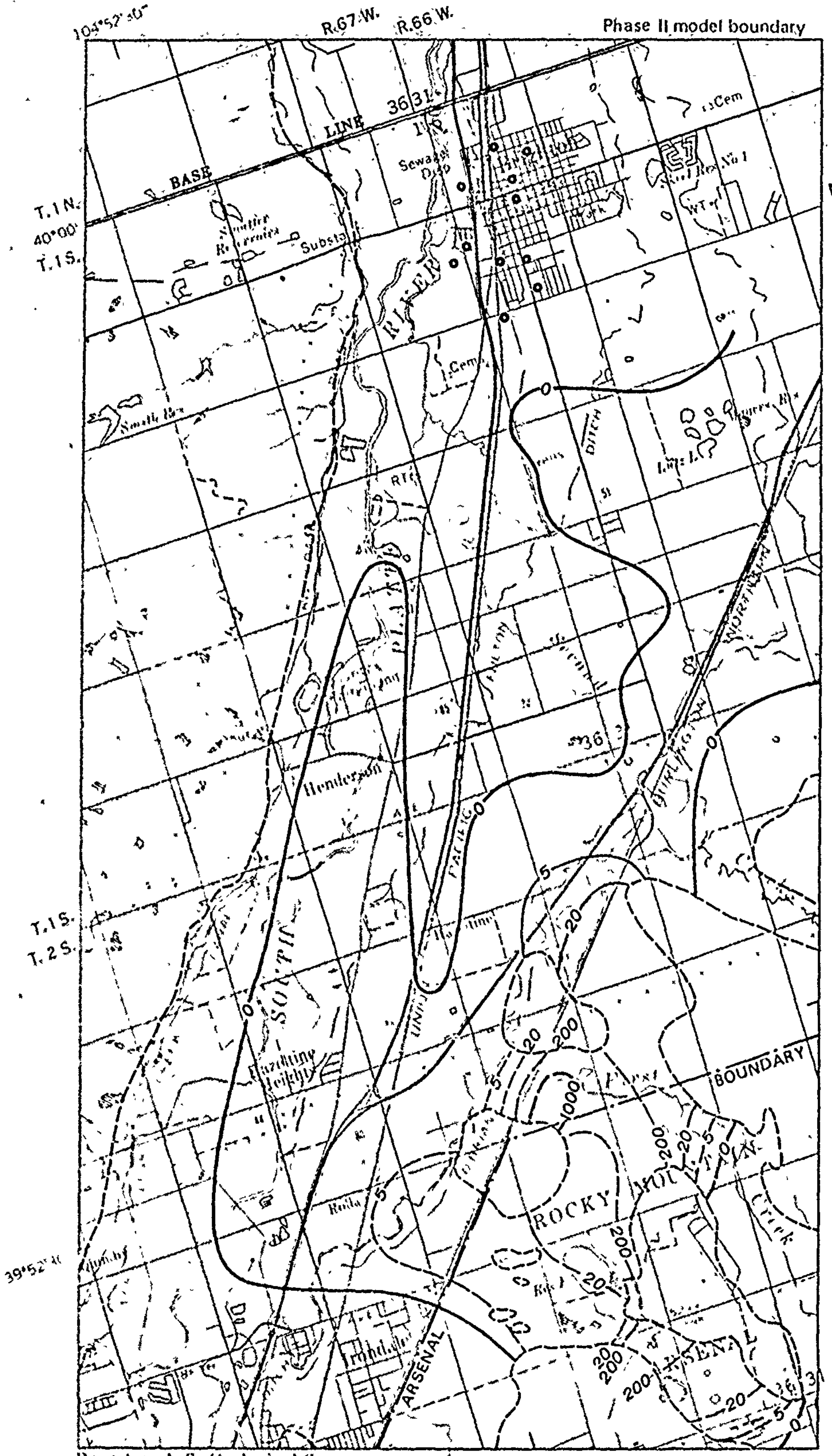


Figure 14.--Phase I model-calculated 1995 DIMP concentrations for Run 1, no remedial measures.



EXPLANATION

—5— LINE OF EQUAL DIMP CONCENTRATION — Interval, in micrograms per liter, is variable. Dashed line denotes area where phase I model results are superior

o CITY OF BRIGHTON MUNICIPAL SUPPLY WELL

—— LIMIT OF ALLUVIAL AQUIFER

Base from U.S. Geological Survey Greater Denver Area sheet of the Front Range Urban Corridor, 1972

0 1 2 3 MILES

0 1 2 3 KILOMETERS

Figure 15.--Phase II model--calculated 1995 DIMP concentrations for Run 1, no remedial measures.

Run 2

Objective.--Consider conditions similar to the previous run in order to evaluate the effects of allowing recent DIMP contamination near pond C to continue at the 1974-75 levels during the next 20 years.

Approach.--This simulation is the same as run 1 with the exception of the recent source of DIMP contamination near Reservoir F which was simulated to continue at 3,000 µg/L concentration for the 20-year simulation period.

Results.--As shown on figure 16, this simulation produces DIMP concentrations in ground water on the arsenal in excess of 2,000 µg/L and concentrations as high as 1,000 µg/L in areas off the arsenal. Although DIMP-contaminated ground water would not move into the Brighton municipal well field by 1995 under either Run 1 or Run 2 conditions, the possibility exists of this occurring after 1995 because, in Run 2 (fig. 16), the ground water with the highest DIMP concentration would not move into the area of First Creek by 1995. The volume of DIMP recharged to and discharged from the ground-water system from 1952 to 1995 under either Run 1 conditions or Run 2 conditions is shown in figure 17. The 12 tons/yr (11 t/yr) of DIMP introduced to the model aquifer between 1952 and 1956 produced a maximum of 6.6 tons/yr (6.0 t/yr) discharge to the South Platte River during 1958-60. The 2 tons/yr (1.8 t/yr) of DIMP introduced to the aquifer in 1974-75 produced a maximum discharge of 0.6 ton/yr (0.5 t/yr) during 1979-83 under Run 1 conditions. This is contrasted by the conditions of Run 2 in which a continuous DIMP source of 2 tons/yr (1.8 t/yr) would cause a continuous discharge of 1.7 tons/yr (1.5 t/yr) into the South Platte River after 1983. The mean annual concentration of DIMP in the South Platte River may be calculated based on the 366-ft^3/s (10.4-m^3/s) mean annual flow in the river at Henderson, Colo. (U.S. Geological Survey, 1974). The mean annual concentration in the river during 1985-95 would be less than 1 µg/L for Run 1 conditions, and about 5 µg/L for Run 2 conditions. The peak DIMP discharge in 1959 would have produced about 30 µg/L DIMP in the river during a year when the mean annual flow was about 200 ft^3/s (5.7 m^3/s).

Model Runs 1 and 2 are representative of the best and worst conditions that might reasonably be expected to occur with no remedial action, assuming the model is reasonably valid. Because it is thought to be more probable that the recent source of DIMP contamination will not be allowed to continue, the first run is used as a basis for evaluating the effectiveness of subsequent management alternatives.

Run 3

Objective.--Simulate a barrier to ground-water movement located in the alluvial gap at the north boundary of the arsenal. Ground water moving toward the barrier is to be pumped from the aquifer immediately above the barrier, treated to remove all DIMP, and returned to the aquifer immediately below the barrier so as to maintain existing water levels and ground-water flow in the aquifer above and below the barrier.

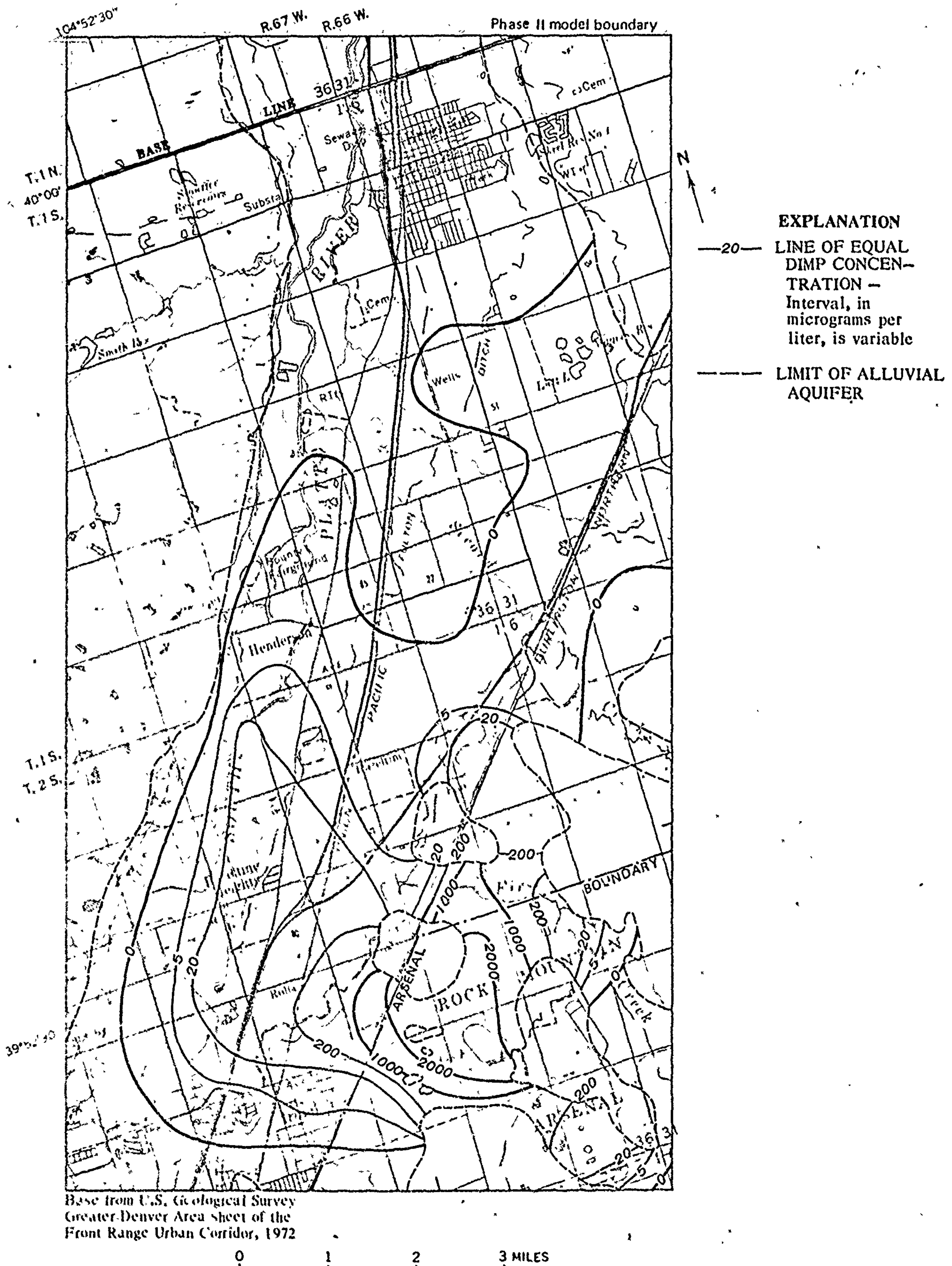


Figure 16.--Phase II model–calculated 1995 DIMP concentrations for Run 2, no remedial measures with continued contamination source near pond C.

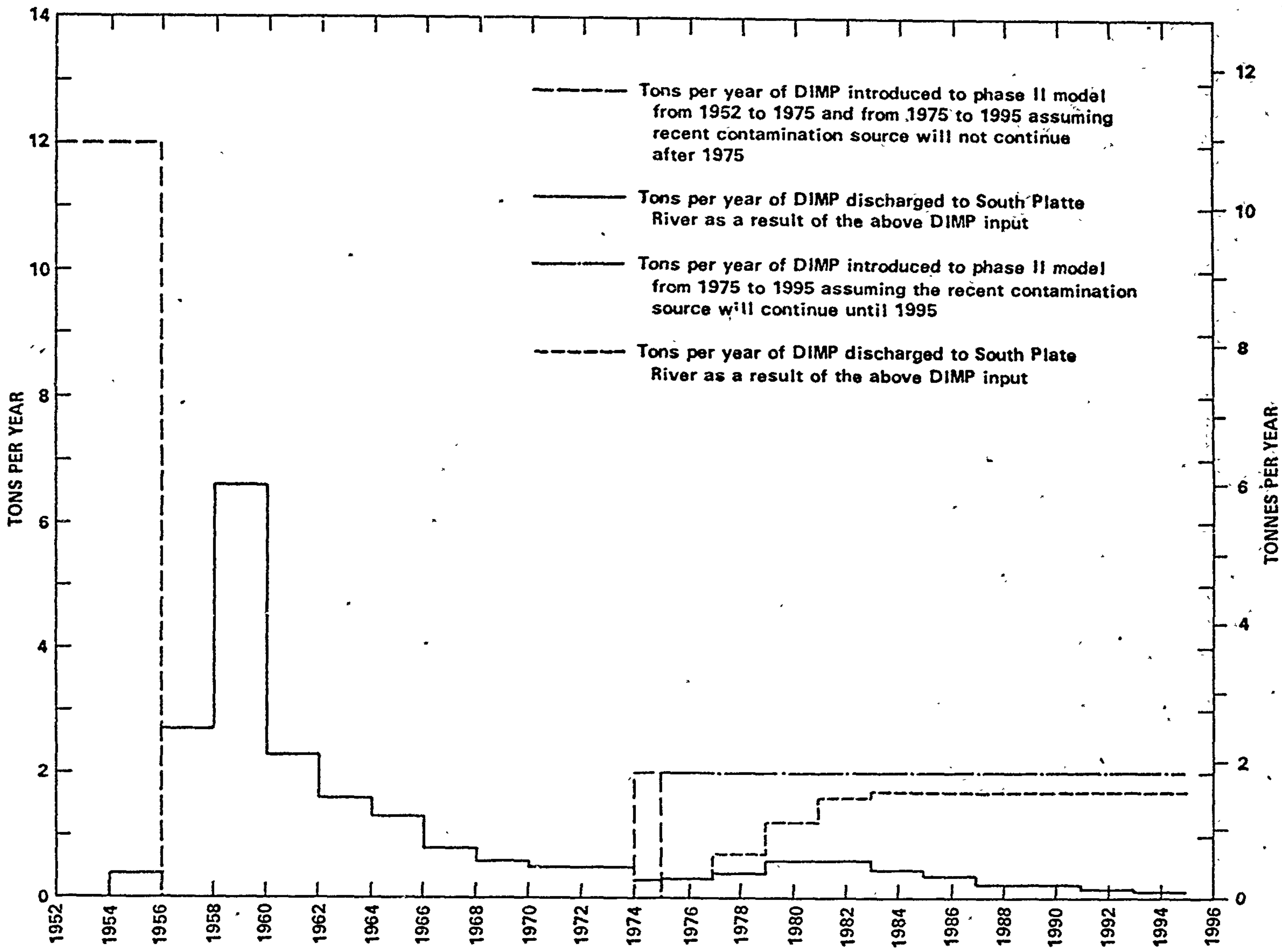


Figure 17.--Change in DIMP recharge to Phase II model and discharge to South Platte River.

Approach.--In this simulation, all the previously discussed model assumptions apply. The DIMP concentration in recharge from ponds A, B, C, D, and E was zero and no recent sources of DIMP contamination were considered. A no-flow boundary was used to simulate the barrier with constant-head nodes above and below the barrier, providing the required recharge and discharge at the barrier.

Results.--By comparing the Phase I model results for Run 1 (fig. 14) with the results of this simulation (fig. 18), the change in water quality produced by this simulation can be seen. A comparison of figures 14 and 18 indicates that by 1995 a significant improvement in water quality would occur immediately north of the barrier. DIMP concentrations would have been reduced as much as 200 µg/L near the barrier with progressively smaller reductions occurring at greater distances below the barrier. The average DIMP concentration in ground water along First Creek between the barrier and the O'Brian Canal was 850 µg/L in 1975 and would decrease to 100 µg/L by 1995. The rate of barrier pumping and recharge would equal the total underflow in the aquifer at the north arsenal boundary (135 gal/min or 85 m^3/s). The ground-water discharge to First Creek would still contain DIMP after 20 years of barrier operation with the Phase II model indicating that in 1995 the DIMP concentrations in the aquifer near Barr Lake and the O'Brian Canal below First Creek would not be significantly different than those shown on figure 15. As would be expected, no change in water quality would be produced above the barrier. These results suggest that a barrier of this type could be an effective means of intercepting contaminated ground water but low ground-water velocities could slow the spread of better quality water below the barrier.

Run 4

Objective.--This simulation is similar to Run 3 in that a barrier to ground-water movement is to be simulated at the north boundary of the arsenal. Ground water is to be pumped from the upgradient side of the barrier at a rate that maintains the original ground-water level near the barrier. The pumped water is to be treated to remove all DIMP and then made available for ground-water recharge in a 23-acre (0.09-km^2) pond about 0.8 mi (1.3 km) south of the barrier. Water in excess of that which can be recharged from the pond is to be returned to the aquifer immediately below the barrier. This management procedure will result in greater flow in the aquifer above the barrier coupled with less flow in the aquifer below the barrier.

Approach.--As in the previous run, a no-flow boundary and constant-head nodes were used to simulate the barrier and the sources of recharge and discharge near the barrier.

Limitations.--The model and data assumptions discussed previously apply to this simulation. The assumption that small changes in water-table elevation will not alter the location of no-flow boundaries or the transmissivity of the aquifer is particularly important in the areas where water-level changes are indicated by the model. Of equal importance is the assumption that the flow system will remain in a near steady-flow condition. This assumption is not rigidly met in this simulation, for model results indicate

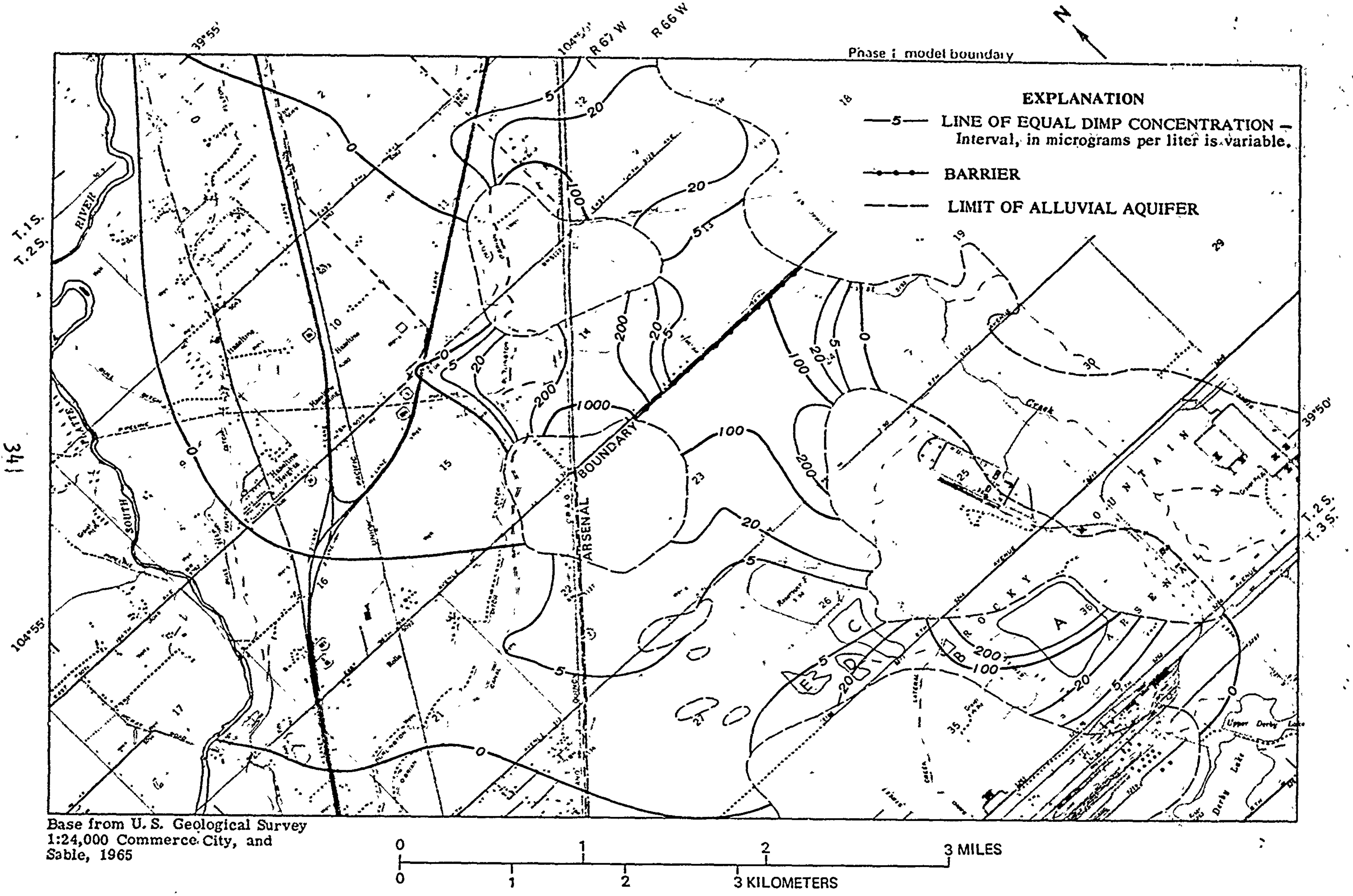


Figure 18.--Phase I model—calculated 1995 DIMP concentrations for Run 3, barrier at north arsenal boundary.

that significant water-level changes would occur over a large area. As a result, transient-flow conditions in the area of water-level changes ar[illegible]ot considered in the steady-flow model. The model results will tend to s[illegible]IMP concentrations that are too high near sources of freshwater recharge in areas of water-level changes (near the recharge pond and immediately north of the barrier, for example).

Results.--A comparison of figures 14 and 19 indicates that by 1995 a greater improvement in water quality would have occurred both above and below the barrier than would have occurred with no remedial action. The water-quality improvement below the barrier would not be as great as that shown in Run 3 due to the reduced rate of recharge below the barrier. The improvement in water quality above the barrier would be due, in part, to the increased flushing of contaminated water to the west of the recharge ponds. As a result, a deterioration in water quality would occur at the arsenal boundary northwest of Reservoir F. Water-level changes produced by this management practice would range from as much as 10 ft (3 m) of decline below the barrier to as much as 15 ft (4.5 m) of rise above the barrier. While this procedure also would be effective in controlling contaminant movement near the north arsenal boundary, it would be more complex than a barrier of the type considered in Run 3.

Run 5

Objective.--For this simulation, barriers are to be located at the north arsenal boundary and in the alluvial gaps to the west of Reservoir F (fig. 20). Ground water is again to be pumped from above the northern barrier in order to prevent the rise in water levels at the barrier. This practice is not to be used at the barriers to the west of Reservoir F, however, and water levels are free to rise to the level necessary to divert ground-water flow toward the northern barrier. Water removed from above the northern barrier is to be treated and used to recharge the aquifer below all barriers so as to prevent water-level declines below the barriers.

Approach.--No-flow boundaries were used to simulate the barriers with constant-head nodes above and below the north arsenal boundary barrier and constant-head nodes below the barrier to the west of Reservoir F. The assumptions discussed in Run 1 also apply to this simulation.

Limitations.--The model assumption that changes in water-table elevation do not affect the location of the aquifer boundaries or the transmissivity of the aquifer should be reemphasized in this situation for large water-level changes are produced in the model (fig. 20).

Results.--Model-calculated water-level elevations are above land-surface elevations in the area indicated on figure 20. Although the model calculations in this area do not represent reality, they do indicate the area in which ground water could discharge to the land surface. Such uncontrolled ground-water discharge would be an undesirable result of this type of barrier configuration. Because of this result, additional model runs were not made using this type of barrier configuration.

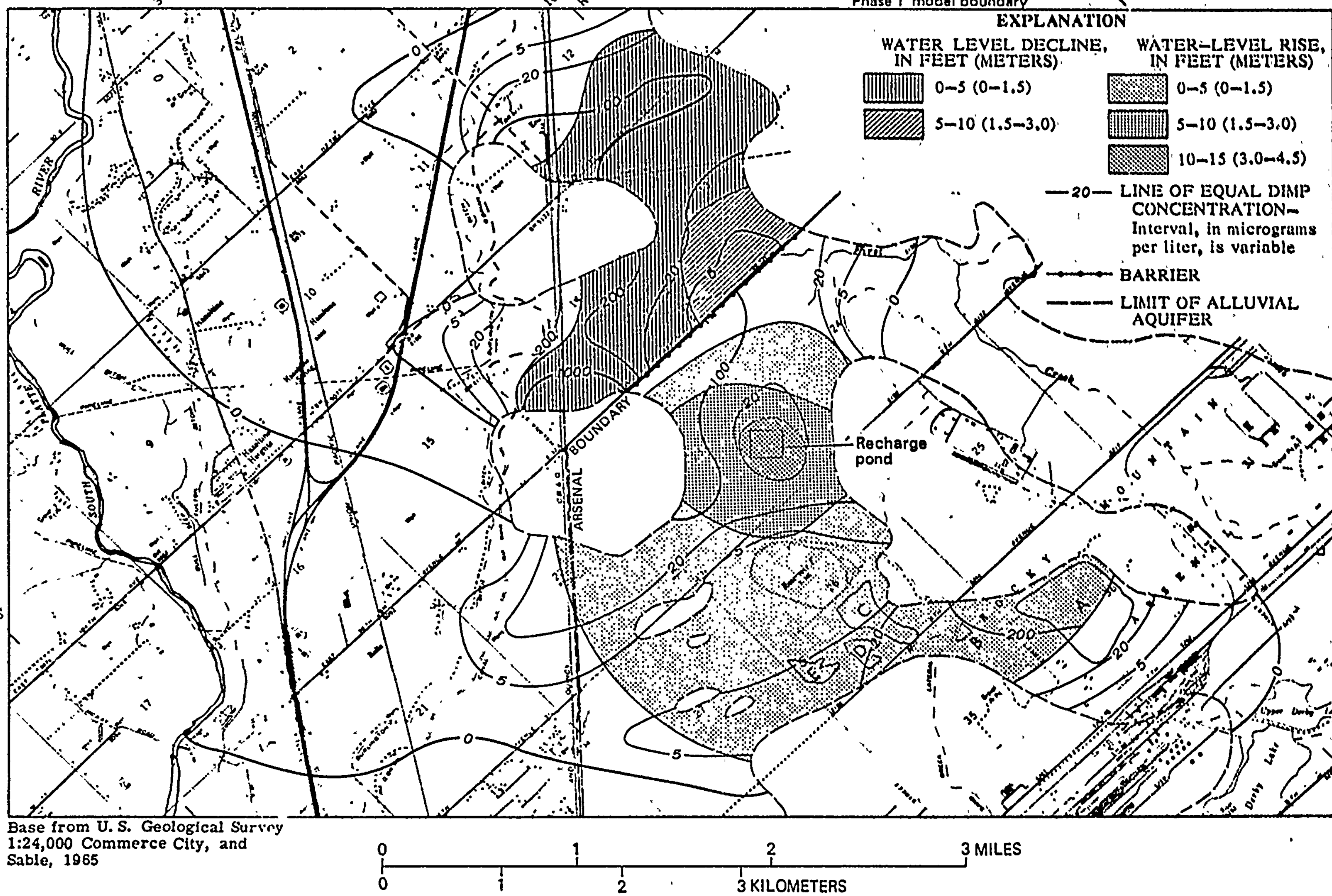


Figure 19.--Phase I model-calculated 1995 DIMP concentrations for run 4, barrier at north arsenal boundary with recharge pond above barrier.

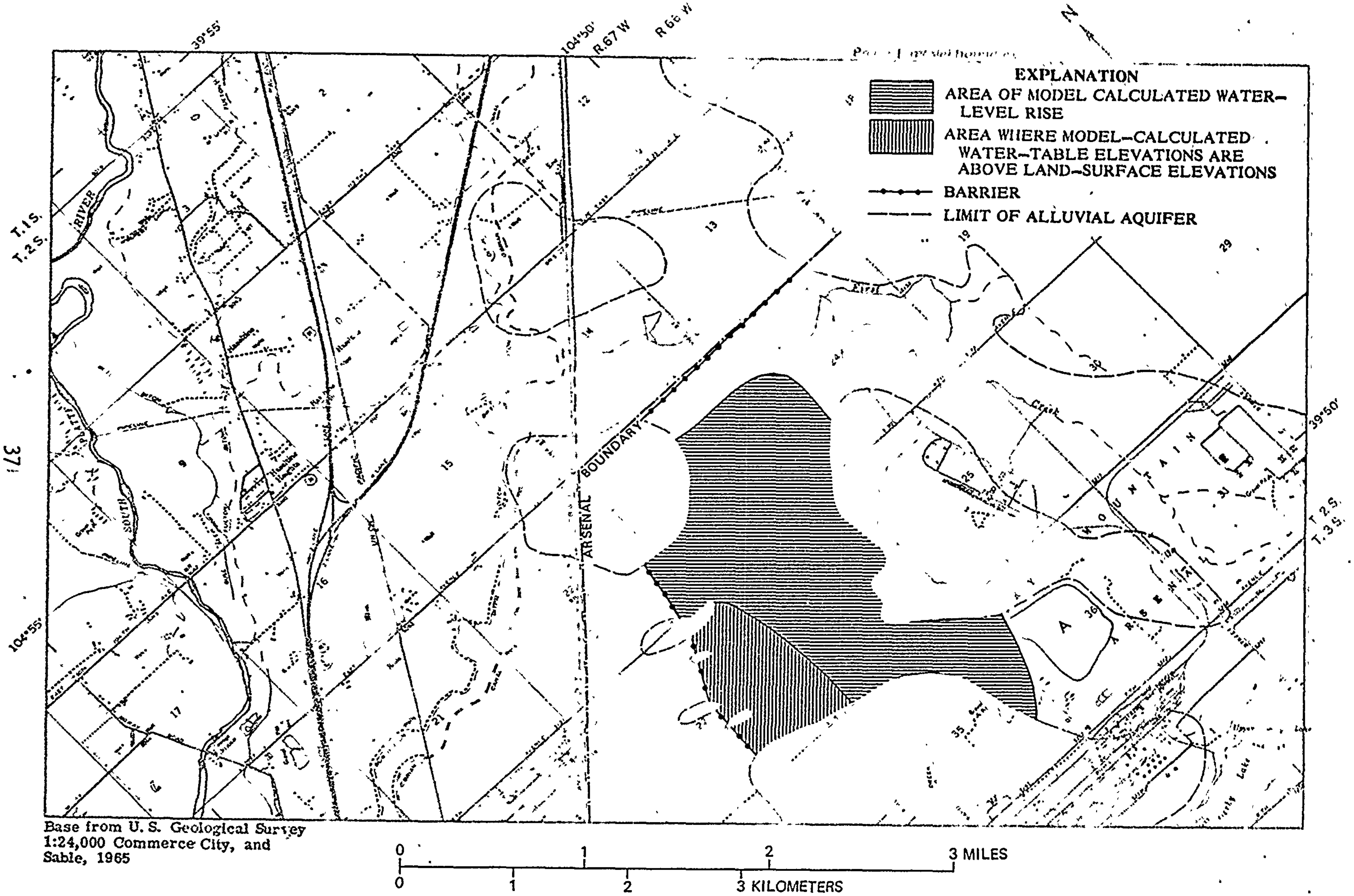


Figure 20.--Phase I model-calculated 1995 change in water-table elevation for Run 5, barriers near north and west arsenal boundaries.

Run 6

Objective.--The Phase II model is used to simulate the effects of barriers to the movement of ground water located in the alluvial gaps west of Reservoir F and off the arsenal in the alluvial gaps in secs. 12 and 14, T. 2 S., R. 67 W. (fig. 21). Barriers in these locations are downgradient of the zones of high DIMP concentration (pl. 1) and are intended to halt movement of contaminated water into adjacent areas of low concentration.

Approach.--Ground water would be pumped from above each barrier to prevent water-level changes above the barrier. The pumped water is not returned to the aquifer, thus the model calculates the water-level declines and concentration changes that would occur as a result of halting all ground-water discharge from the areas of high concentration near the arsenal.

Limitations.--The assumption is again made that no change in aquifer boundaries or transmissivity will result from water-level changes. The assumption that the flow system will remain in near steady-flow conditions is not rigidly met. However, the effect of this noncompliance on the concentration distribution is not significant because no recharge is simulated at the barriers.

Results.--A comparison of figures 15 and 21 indicates that this management practice would have minimal effect on the DIMP concentrations above the barriers but would produce a significant improvement in water quality in the area northwest of the arsenal. Because the barriers have minimal effect on the ground water discharging to First Creek, the area of contamination near Barr Lake and the O'Brian Canal would not be significantly different than that resulting from Run 1 (fig. 15). Water-level declines below the barriers would be as much as 15 ft (4.6 m). The area affected by water-level declines would exceed 9 mi^2 (23 km^2) although declines in most of this area would be less than 5 ft (1.5 m). Barriers in these locations could be effective in controlling the spread of contaminated water; however, the legal problems associated with adversely affecting the water level in large areas off the arsenal and constructing and operating barriers on private property would have to be considered.

Run 7

Objective.-- Contaminated water must be prevented from entering the O'Brian Canal if the zone of high DIMP concentration near the canal and Barr Lake is to be eliminated. In this simulation, contaminated ground water that normally discharges from springs and seeps into First Creek is to be intercepted in order to prevent this discharge.

Approach.--The quantity of water intercepted (0.14 ft^3/s or 4 L/s) was comparable to the spring discharge to the creek and no significant water-level changes were produced. The intercepted discharge was not returned to the model aquifer and no other remedial measures were simulated.

Results.--The Phase II model shows that 6 years after the contaminated

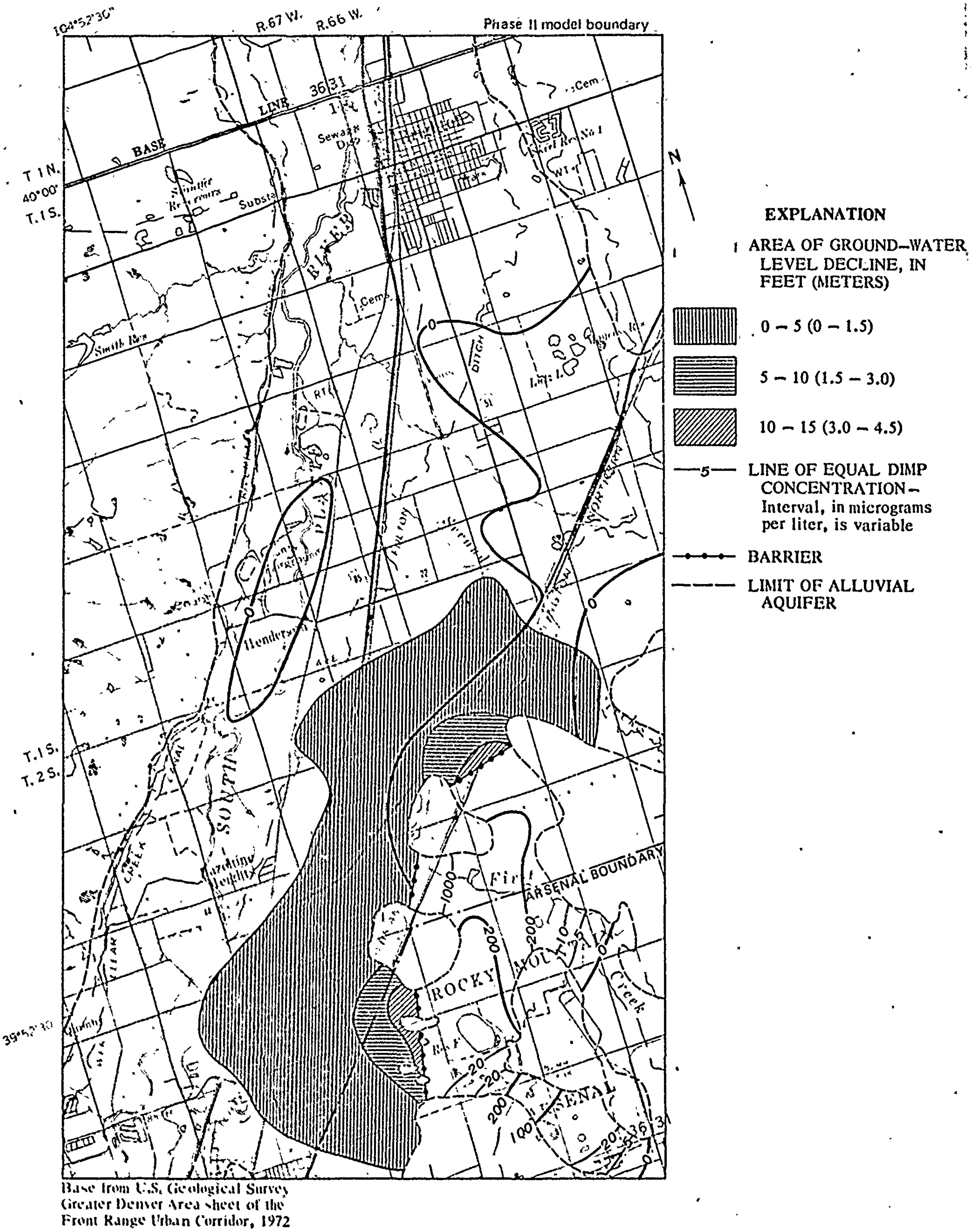


Figure 21.--Phase II model–calculated 1995 DIMP concentrations and water–level decline for Run 6, three barriers near arsenal.

discharge to First Creek is intercepted the aquifer near the O'Brian Canal and Barr Lake would no longer have DIMP concentrations greater than the 0.5-µg/L simulation limit. In other areas, the model-calculated concentrations are identical to those calculated for Run 1 (fig. 15). The rapid improvement in ground-water quality near Barr Lake would be due to the cessation of contaminated surface-water recharge. Without a continuing source of contamination, the concentration of DIMP in the previously contaminated ground water would be reduced by the continuing processes of dispersion, dilution, and withdrawal.

Run 8

Objective.--The effects of halting the movement of contaminated water from near pond A into adjacent areas to the north is to be calculated in this simulation.

Approach.--A barrier to ground-water movement is simulated between ponds B and C. Ground water removed from above the barrier is treated and recharged in pond C at a rate (0.18 ft^3/s or 5.1 L/s) which prevents water-level changes either above or below the barrier. Recharge from ponds A, B, C, D, and E is not considered a source of DIMP and no recent sources near Reservoir F are considered.

Results.--The resulting 1995 concentration distribution (fig. 22) indicates that the water quality would improve below the barrier and northwest toward the South Platte River. However, this reduction in DIMP concentration occurs in an area that would have relatively low DIMP concentrations by 1995 without use of remedial measures. The barrier would not have a significant effect on concentrations in other parts of the aquifer.

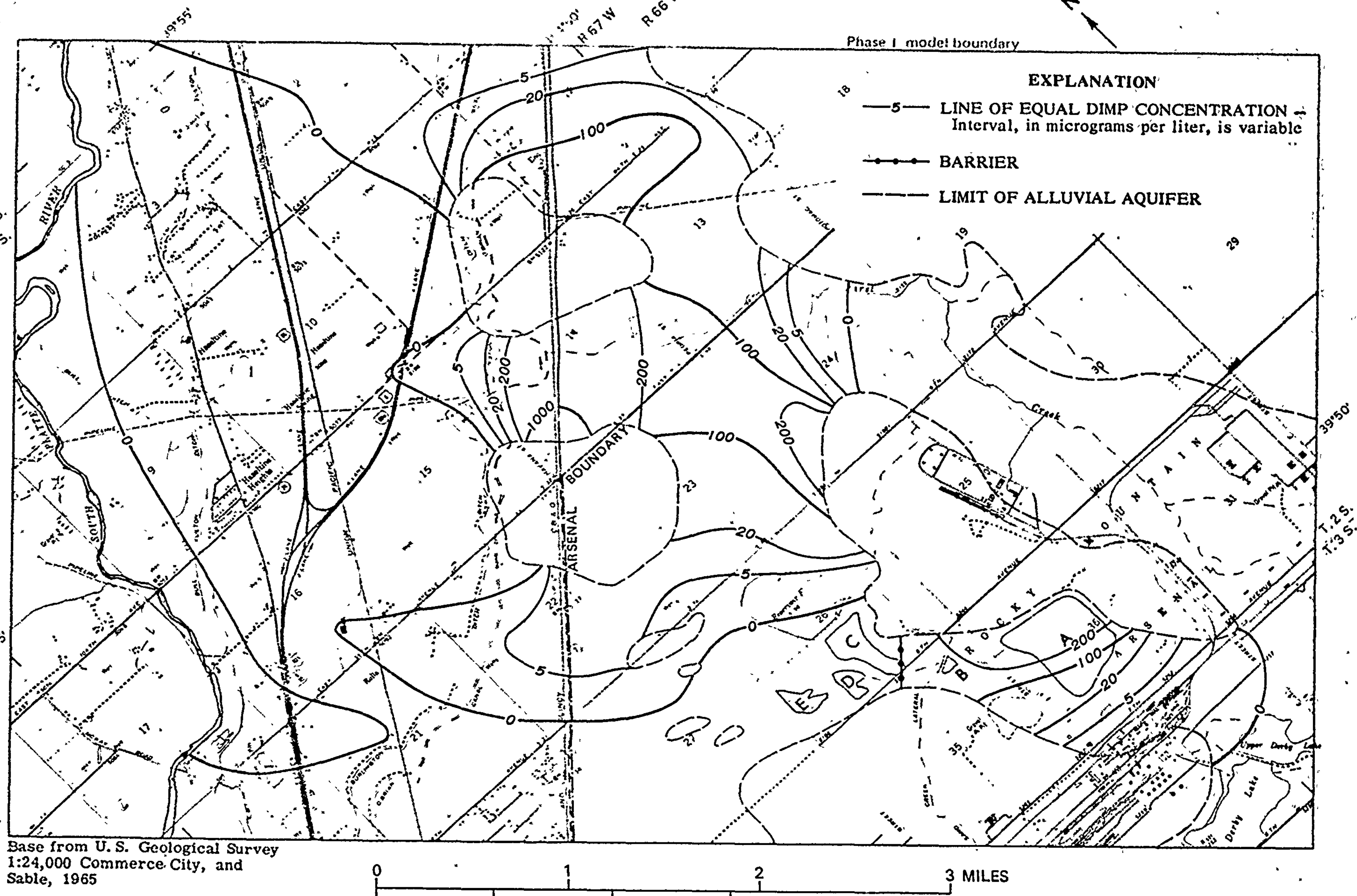
Run 9

Objective.--For this simulation, a barrier is to be located upgradient (south) of pond A in order to prevent ground-water movement into the area near pond A.

Approach.--Uncontaminated ground water is removed from above the barrier in order to maintain water levels in this area. Instead of recharging the aquifer immediately below the barrier, the recharge is simulated to occur in pond C. As in previous runs, ponds A, B, C, D, and E are not considered to be sources of DIMP although recharge still occurs at the ponds.

Limitations.--The assumption that water-level changes will not alter the aquifer boundaries or transmissivity is significant in the areas where water-level changes occur. The assumption that the flow system will remain in near steady-flow conditions is not met. The effect of this noncompliance on the concentration distribution will likely be minor in this simulation.

Results.--As shown on figure 23, this management practice would dewater the aquifer over an area of about 0.5 mi^2 (1 km^2) immediately below the barrier. The aquifer downgradient of pond A is not dewatered due to the recharge



Base from U. S. Geological Survey 1:24,000 Commerce City, and Sable, 1965

Figure 22.--Phase I model--calculated 1995 DIMP concentrations for Run 8, barrier between ponds B and C.

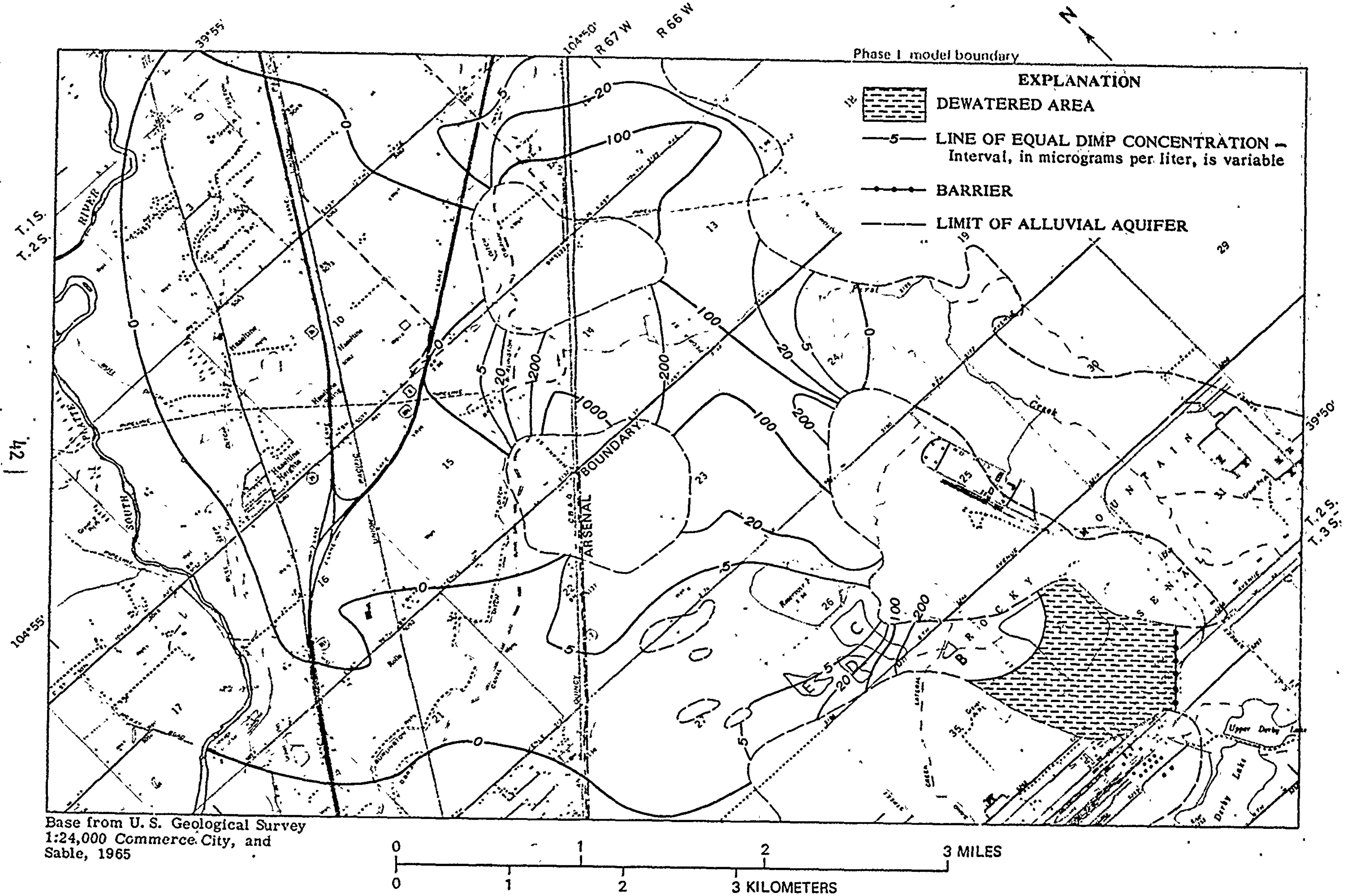


Figure 23.--Phase I model—calculated 1995 DIMP concentrations for Run 9, barrier upgradient from pond A.

occurring in ponds A and B. This recharge was simulated at the same rate as during 1952-75 (table 2) and provides the ground-water flow which continues to transport DIMP away from ponds A and B. As a result, the concentrations in most of the aquifer would not be significantly different from those calculated for Run 1 (fig. 14).

Run 10

Objective.--Barriers both north and south of pond A at the locations shown on figures 22 and 23 are to be considered in this simulation.

Approach.--: Ground water is removed from above each barrier so as to maintain the water levels in the aquifer above the barriers. The water is treated to remove DIMP, if necessary, and recharged to the aquifer at pond C.

Results.--The results of this simulation are similar to those shown on figures 22 and 23, in that the DIMP concentrations below the northern barrier would be the same as those shown on figure 22, and the aquifer would be dewatered in an area below the southern barrier similar to that shown on figure 23.

Run 11

Objective.--Model Run 11 is intended to show the effects of halting all ground-water recharge from pond C under a ground-water-management approach similar to that considered in Run 1.

Approach.--The ground-water recharge from pond C is set to zero for this simulation and no remedial measures are considered. None of the other ponds are considered sources of DIMP and no recent DIMP sources near Reservoir F are modeled.

Limitations.--Because of the loss of 0.67 ft^3/s (19 L/s) of recharge from pond C, water-level declines will occur in much of the Phase I model area necessitating a reduction in aquifer transmissivity and change in location of aquifer boundaries. In addition, the assumption that the flow system will remain in near steady-flow conditions will not be rigidly met in this simulation. A transient-state solute-transport model would normally be used for this type of simulation. In most transient-state models, the flow computation algorithm can compute a new transmissivity distribution compatible with a lower rate of recharge. In the models of the arsenal, however, the flow algorithm was not able to compute the new transmissivity distribution due to the extreme sensitivity of the flow computations to transmissivity changes in some of the alluvial gaps between bedrock highs. In order to circumvent this problem, parts of the transmissivity distribution were modified on the basis of hand calculations and a steady-flow model was used for the simulation. Because the modified data cannot be checked by means of a calibration procedure, it must be understood that the new transmissivity value, model boundaries, and the resulting water-level and concentration distributions are thought to be reasonable but are likely of lower accuracy than the more fully calibrated model simulations. The steady-flow model used for this simulation does not consider the effects of transient-flow conditions on the concentration distribution. Because a source of uncontaminated recharge is not associated with areas which experience transient flow, the resulting concentration distribution should not be seriously affected.

Results.--The loss of recharge from pond C would produce water-level declines that extend over most of the area of the arsenal and cause dewatering of part of the aquifer north and northeast of Reservoir F (fig. 24). Although water-level declines would exceed 5 ft (2 m) in part of the area west of Reservoir F, no significant dewatering would occur in this area. As a result, underflow through this area would not be stopped by the loss of recharge from pond C. The water-level declines would be associated with marked reductions in the rate of ground-water flow through the aquifer near Reservoir F. A total flow of 0.26 ft^3/s (7.4 L/s) would move out of this area, with 0.01 ft^3/s (0.3 L/s) moving through the alluvial gap northeast of Reservoir F and 0.25 ft^3/s (7.1 L/s) moving through the alluvial gaps west of Reservoir F.

A comparison of figures 14 and 25 indicates that this management practice generally would result in less reduction in DIMP concentrations in ground water both on and off the arsenal than obtained in Run 1. Only in the area north of First Creek would DIMP concentrations be reduced by this management practice.

Run 12

Objective.--This model run is intended to show the effects of doubling the rate of ground-water recharge from pond C under a ground-water-management approach similar to that considered in Runs 1 and 11.

Approach.--The rate of ground-water recharge from pond C is increased from 0.67 to 1.32 ft^3/s (19 to 37 L/s) for this simulation and no other remedial measures are considered.

Limitations.--The increased recharge will cause water-level rises in the model aquifer necessitating a corresponding increase in the aquifer transmissivity. The procedures used to adjust the model transmissivity in this run were similar to those used in Run 11. The effects of using a steady-flow model to simulate transient conditions are more serious in this simulation than in Run 11 due to uncontaminated recharge in an area subject to significant transient flow. The model results will show DIMP concentrations that are too high near the uncontaminated recharge in pond C.

Results.--A steady-flow model simulation indicated that the increased recharge from pond C coupled with the increased transmissivity of the aquifer would produce a 1995 concentration distribution that was not significantly different from the results of Run 1 (fig. 14). Although the error introduced by the method of estimating transmissivity is probably acceptable, the error associated with the use of a steady-flow model for this simulation is not. Consequently, the results of this model simulation are considered to be invalid.

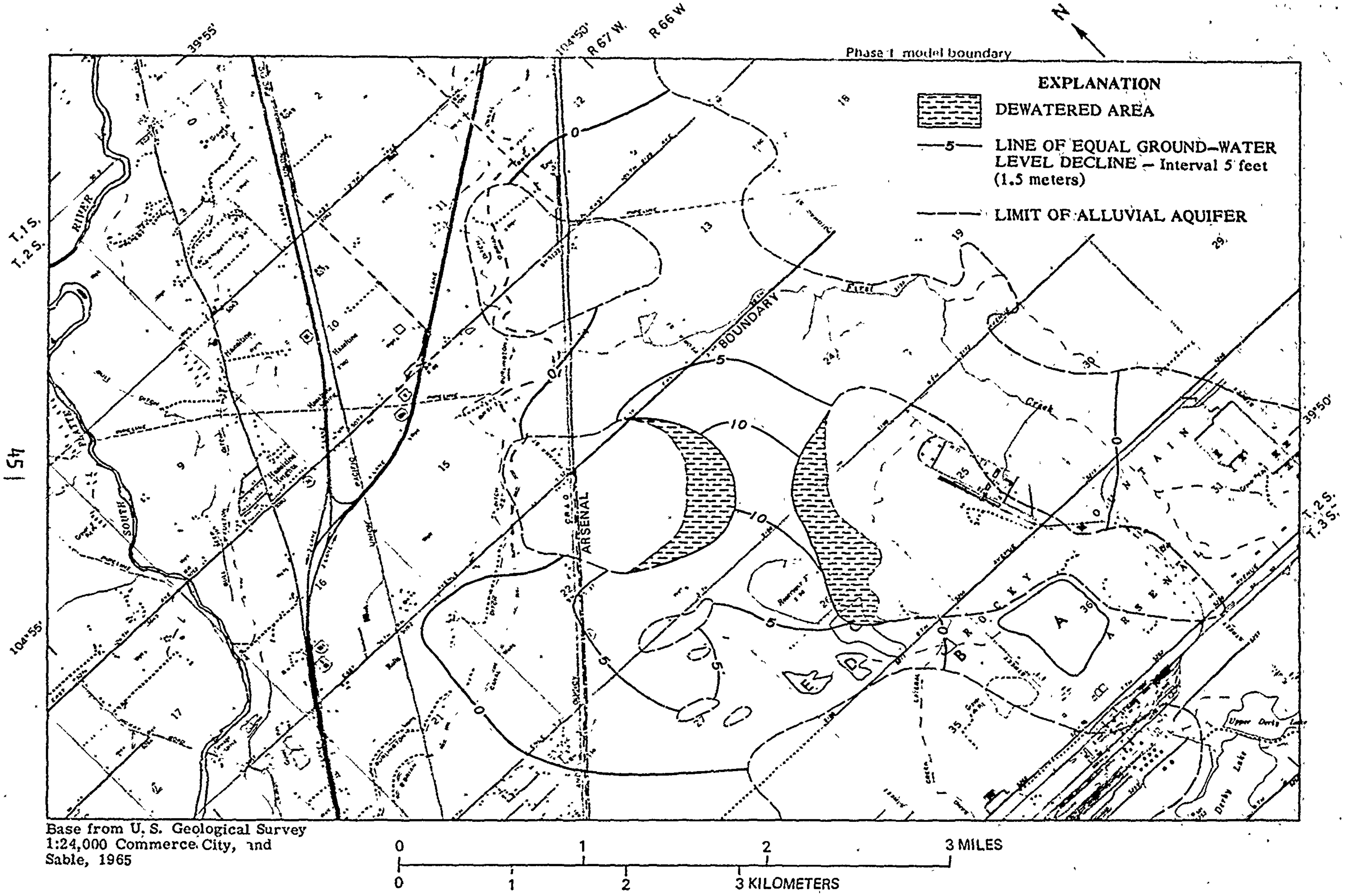
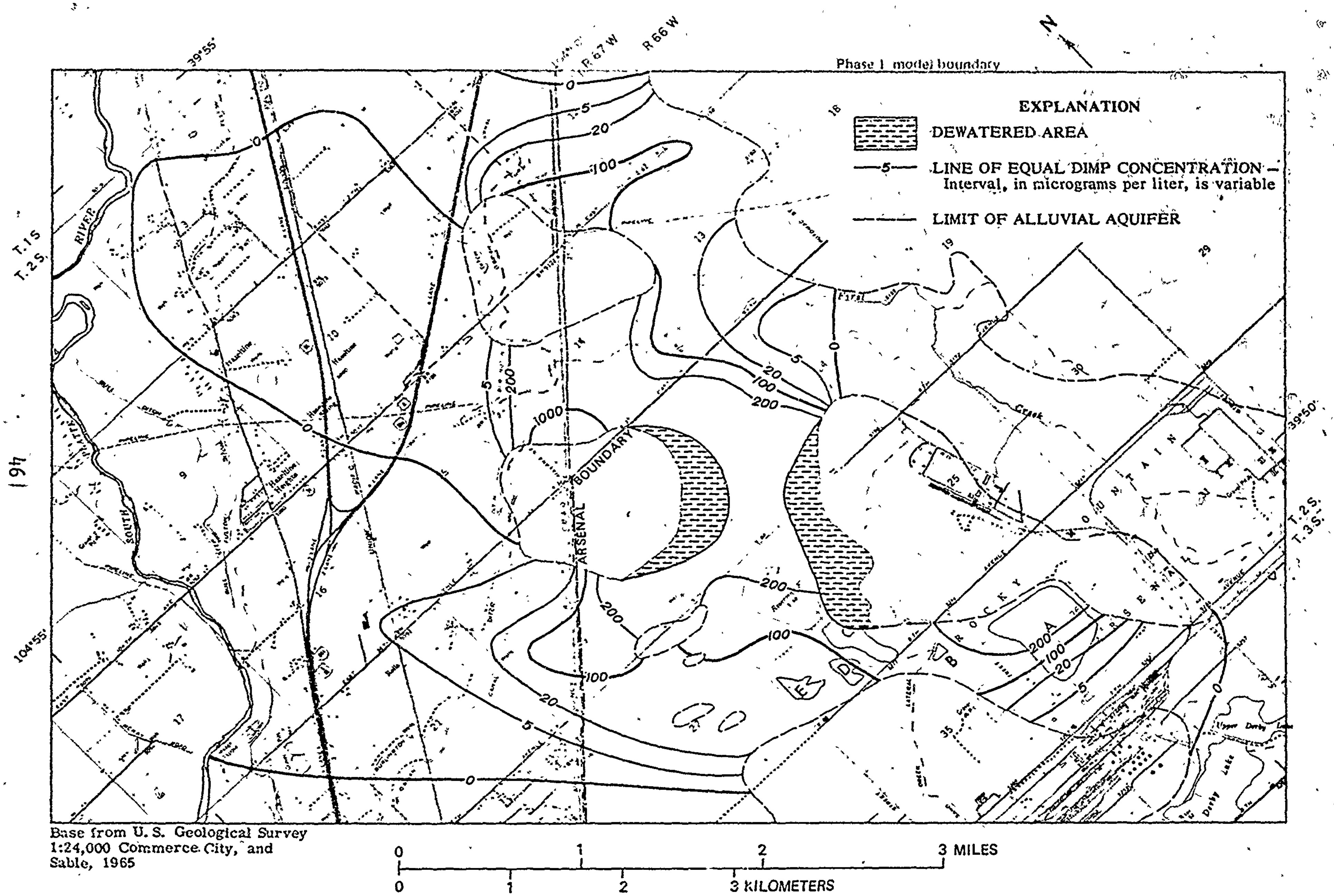


Figure 24.--Phase I model—calculated 1975–95 water–level decline for Run 11, zero recharge, pond C.



Base from U. S. Geological Survey
1:24,000 Commerce City, and
Sable, 1965

Figure 25.--Phase I model--calculated 1995 DIMP concentrations for Run 11, zero recharge pond C.

Run 13

Objective.--This simulation is intended to show the effects of halting all ground-water recharge from Upper Derby Lake.

Approach.--Upper Derby Lake is located on the southern boundary of the Phase I model. This precludes a direct model calculation of the head changes that would result from the loss of recharge from the lake. The model still can be used to investigate the loss of recharge if the hydrology of the lake is first examined.

Results.--Upper Derby Lake and Derby Lake are sources of ground-water recharge and are situated such that the bottom elevation in Upper Derby Lake is near the normal pool elevation in Derby Lake. By permanently draining Upper Derby Lake, the ground-water elevation in the area might decline at least 5 ft (1.5 m). A water-level decline greater than about 5 ft (1.5 m) would dewater the alluvial gap between pond A and Upper Derby Lake, forming a natural barrier to ground-water movement near the location of the artificial barrier shown on figure 23. The effects of the natural barrier on water levels and quality near pond A would be very similar to those produced by the artificial barrier, making the model results for Run 9 (fig. 23) a reasonable simulation of the water levels and DIMP concentrations that would result north of Upper Derby Lake.

Run 14

Objective.--A water-quality management procedure has been proposed by Rocky Mountain Arsenal that involves intercepting ground-water flow in a cutoff trench near First Creek in secs. 5 and 7, T. 3 S., R. 66 W. (pl. 3). The water from the trench would be used to recharge the aquifer below a barrier at the north arsenal boundary. Contaminated water pumped from immediately above the barrier to prevent waterlogging would not be returned to the ground-water system. Upper Derby Lake also would be drained and no longer a source of ground-water recharge. The specific information sought from this simulation is: (1) The effect of the management procedure on DIMP concentrations north of the arsenal, (2) the effect within the arsenal, and (3) the change in water levels and ground-water flow across the arsenal.

Approach.--This plan cannot be simulated with the model developed in this study because Upper Derby Lake and the cutoff trench are both outside the model area. However, the three objectives of the simulation can be partly or fully met by results of previous simulations. The assumptions made in these simulations are the general assumptions discussed on page 27.

Results.--This management practice would cause a reduction of underflow past the southern model boundary. The resulting decline in ground-water levels on the arsenal would likely create a natural barrier to ground-water movement between pond A and Upper Derby Lake. The effect of the reduced underflow on DIMP concentrations on the arsenal would will not be great because most of the change in flow would occur along the uncontaminated area near First Creek. The changes in DIMP concentration and dewatered area that would be produced by the natural barrier south of pond A are depicted on figure 23. The effect of the management practice on DIMP concentrations north of the arsenal is illustrated by the results of run 3 (fig. 18), which simulated a barrier of the type proposed in this run. The long-term average pumping rate above the barrier would be less than that required in Run 3, although the exact rate cannot be determined. The recharge rate below the barrier would be about 0.3 ft^3/s (8.5 L/s) if no water-level declines are to be produced below the barrier. If the flow is maintained in the aquifer below the barrier, contaminated ground water would continue to discharge to First Creek and thus affect the quality of water in the O'Brian Canal and Barr Lake. DIMP concentrations in ground water in excess of 200 µg/L still would exist near First Creek after 20 years of barrier operation (fig. 18). The advantages of this management plan include (1) the reduction in underflow on the arsenal caused by the upgradient cutoff trench and the loss of recharge from Upper Derby Lake, and (2) the barrier at the north arsenal boundary that effectively prevents further off-arsenal movement of contaminated ground water. Two shortcomings of the plan involve the lack of control on (1) DIMP concentrations in First Creek and the O'Brian Canal, and (2) ground-water flow off the arsenal in the alluvial gaps west of Reservoir F.

Run 15

Objective.--The conditions for this simulation are the same as those for Run 14 with the exception of a recharge trench located in the alluvial gap in the southeast corner of sec. 22, T. 2 S., R. 67 W. Freshwater is to be supplied to this trench in order to dilute the ground-water discharge through this gap to less than 5 µg/L of DIMP. An estimate of the quantity of freshwater required to achieve this dilution is needed.

Approach.--If the pumping rate from above the barrier at the north arsenal boundary is regulated so as to maintain existing water levels in the aquifer above the barrier, future discharge through the alluvial gap in sec. 22, T. 2 S., R. 67 W., would occur at a rate of about 0.27 ft^3/s (7.6 L/s). The maximum DIMP concentration in this gap between 1975 and 1995 occurred in 1975 (pl. 1) at a concentration of about 800 µg/L.

Results.--About 43 ft^3/s (1,200 L/s) or 19,000 gal/min (1.2 m^3/s) of freshwater would be needed to dilute 0.27 ft^3/s (7.6 L/s) of water at a maximum DIMP concentration of 800 µg/L to a concentration of 5 µg/L. If pond C were not considered to be a source of recharge, the flow through the gap ultimately would be reduced to about 0.02 ft^3/s (0.6 L/s), and about 3.2 ft^3/s (91 L/s) or 1,400 gal/min (0.09 m^3/s) of freshwater would be required to dilute this flow to 5 µg/L. In either instance, the volume of freshwater required to achieve the required dilution would be large. The results of Run 5 (fig. 20) indicate that it would not be feasible to use the recharge trench to create a barrier to the movement of contaminated ground water, unless the water level in the aquifer above the trench is controlled to prevent surface discharge.

SUMMARY OF MODEL SIMULATIONS

Of the management alternatives simulated in these model runs, a physical barrier to the movement of ground water appears to be the best means of controlling the movement of contaminants in the aquifer. A hydraulic barrier consisting of a paired line source and sink was not simulated in these model runs but should produce results comparable to those of the physical barrier. In order to be most effective, a physical barrier would need to be located immediately downgradient from the area of contamination rather than within the area of contamination (near pond A, for example). If adverse water-level changes are to be avoided near the physical barrier, contaminated ground water needs to be withdrawn above the barrier and uncontaminated water recharged to the aquifer below the barrier. Model results also indicate that a barrier of this type would be slow to control the discharge of DIMP-contaminated ground water to First Creek. As a result, it may be necessary to use a supplemental means of controlling this discharge if the low-level DIMP contamination near Brighton and Barr Lake is to be rectified in the near future. The reduction of underflow onto the arsenal would not have a marked effect on the DIMP concentrations on the arsenal but would be beneficial by eventually reducing the rate of pumping above any barriers that may be installed, subsequently reducing the volume of contaminated water to undergo treatment or disposal.

The results of model Runs 1 and 2 indicate that two courses of action are available to the Rocky Mountain Arsenal under the constraints of the Cease and Desist Order. One course is to take immediate and effective steps to control the recent source of ground-water contamination near Reservoir F and thus assure that only low levels of DIMP will move off the arsenal through the alluvial gaps west of Reservoir F. The second course would be to delay or abstain from any remedial action. Barriers to ground-water movement constructed along the west, as well as the north arsenal boundaries, would be one means of preventing the off-arsenal movement of the resulting contaminated ground water near Reservoir F. The option of allowing ground-water contamination to continue on the arsenal and using barriers to prevent off-arsenal movement would not resolve the problem, for failure of a barrier or ground-water movement through previously undetected permeable zones in the bedrock could allow contaminated fluids to escape.

CONCLUSIONS

The conclusions reached in this study deal with: (1) The character of the alluvial aquifer, (2) the nature of contaminant movement, and (3) the effectiveness of water-quality management alternatives.

Saturated alluvium is as much as 60 ft (18 m) thick in the area and is the primary geologic unit involved in the movement of contaminated ground water. Although water-bearing zones are known to exist in the underlying bedrock, the transmissivity of these zones is small and is not significant in comparison to the transmissivity of the alluvium, which is as much as 20,000 ft^2/d (1,900 m^2/d). Ground water moves downslope from the southeast to northwest across the Rocky Mountain Arsenal and, ultimately, either discharges to the South Platte River northwest of the arsenal or discharges to First Creek near the north arsenal boundary. Ground-water velocities range from less than 1 ft/d (0.3 m/d) on parts of the arsenal to more than 15 ft/d (4.6 m/d) northwest of the arsenal. Long-term estimates of mean annual flow indicate that 0.24 ft^3/s (6.8 L/s) of ground water enters the arsenal from the southeast to be augmented by 0.83 ft^3/s (24 L/s) of recharge from five unlined ponds on the arsenal. About 0.77 ft^3/s (22 L/s) of water leaves the arsenal to the west of Reservoir F, and 0.30 ft^3/s (8.5 L/s) of water crosses the north arsenal boundary, of which 0.14 ft^3/s (4.0 L/s) is estimated to discharge to First Creek.

Ground-water contamination by DIMP resulted from leakage out of unlined industrial waste-disposal ponds during 1952-56 and by 1975 had spread to an area in excess of 28 mi^2 (73 km^2). In May-July 1975, DIMP concentrations in ground water ranged from the 0.5-μg/L analytical-detection limit to as much as 44,100 μg/L. Model simulations of DIMP movement in the aquifer indicate that the contaminated ground water readily moves from the area of the disposal ponds to the northwest and begins discharging into the South Platte River about 4 years after the first introduction of the contaminant to the aquifer. DIMP-contaminated ground water also moves to the north of Reservoir F, where part of it enters First Creek from springs and seeps. The contaminated surface water either flows into Barr Lake or returns to the aquifer between First Creek and Barr Lake, thus affecting the ground-water quality near Brighton.

Both model results and field data indicate that a recent and continuing source of ground-water DIMP contamination probably exists near Reservoir F, although the exact location of the source cannot be determined at this time. Prompt efforts should be made to define and correct the condition responsible for the recent contamination and to gather data which ultimately may be needed to model the movement of the new contaminated zone. Three areas with DIMP concentration in excess of 1,000 μg/L were present in the aquifer in 1975. The areas near First Creek and pond A are shown by the models to be the remnants of the contaminated recharge which occurred during 1952-56, while the area near Reservoir F is thought to be due to the recent source of contamination near this area. Phase II model results indicate that an estimated 12 tons/yr (11 t/yr) of DIMP were introduced to the ground-water system from the unlined disposal ponds during 1952-56. This resulted in a peak DIMP discharge to the South Platte River of 6.6 tons/yr (6.0 t/yr) during 1958-60, giving a mean annual concentration in the river of 30 μg/L. Modeling indicates that mean annual DIMP concentrations in the river have decreased since 1958-60 to levels less than 1 μg/L in 1976.

Fifteen water-quality-management alternatives have been evaluated with the aid of model-simulation techniques. Two simulations indicate that DIMP-contaminated ground water would not reach the Brighton municipal well field by 1995, even if no remedial measures are taken to check the movement of contaminated ground water or to prevent the further contamination of the aquifer from the recent source near Reservoir F. Model results indicate that a physical barrier to ground-water movement would be is the most effective of the evaluated alternatives for limiting contaminant movement in the aquifer, if the barrier is located in or downgradient of the contaminated zone and ground water is withdrawn above the barrier and recharged below the barrier so as to control water-level changes in the area. The barriers simulated in this study did not readily reduce the DIMP concentration in surface flow in First Creek.

However, a management practice that intercepts all contaminated ground water that would normally discharge to First Creek shows that within 6 years the zone of contaminated ground water near Brighton and Barr Lake would be reduced to less than the 0.5-µg/l analytical-detection limit. Measures in addition to a ground-water barrier may be required if the low-level DIMP contamination near Brighton is to be reduced in the near future.

Management techniques that result in a reduction in underflow onto the arsenal have little effect on the concentration distribution on the arsenal but are of value due to the reduced pumping and treatment rates that would be required to maintain proper water-level conditions above any barriers to be installed. Barriers to ground-water movement that are not operated so as to control water levels in the aquifer both above and below the barrier are shown by the model to produce excessive water-level rises or declines near the barrier.

REFERENCES

Bredehoeft, J. D., and Pinder, G. F., 1973, Mass transport in flowing groundwater: Water Resources Research, v. 9, no. 1, p. 194-210.

Brookman, J. A., 1969, Colorado ground-water levels, spring 1969: Fort Collins, Colorado State Univ. Expt. Sta., CER 68-69J839.

Hurr, R. T., Schneider, P. A., Jr., and others, 1972, Hydrogeologic characteristics of the valley-fill aquifer in the Brighton reach of the South Platte River valley, Colorado: U.S. Geol. Survey open-file report, 3 p., 6 pls. [1973].

Konikow, L. F., 1975, Hydrogeologic maps of the alluvial aquifer in and adjacent to the Rocky Mountain Arsenal, Colorado: U.S. Geol. Survey Open-File Rept. 74-342, 1 sheet.

_____1976, Modeling solute transport in ground water, *in* International Conference on Environmental Sensing and Assessment, 1975: Inst. Elec. Electronics Engineers, Inc., U.S.A. Annals no. 75CH1004-I 20-3, 6 p.

McConaghy, J. A., Chase, G. H., Boettcher, A. J., and Major, T. J., 1964, Hydrogeologic data of the Denver Basin, Colorado: Colorado Water Conserv. Board Basic-Data Rept. 15, 224 p.

Petri, L. R., and Smith, R. O., 1956, Investigation of the quality of ground water in the vicinity of Derby, Colorado: U.S. Geol. Survey open-file report, 77 p.

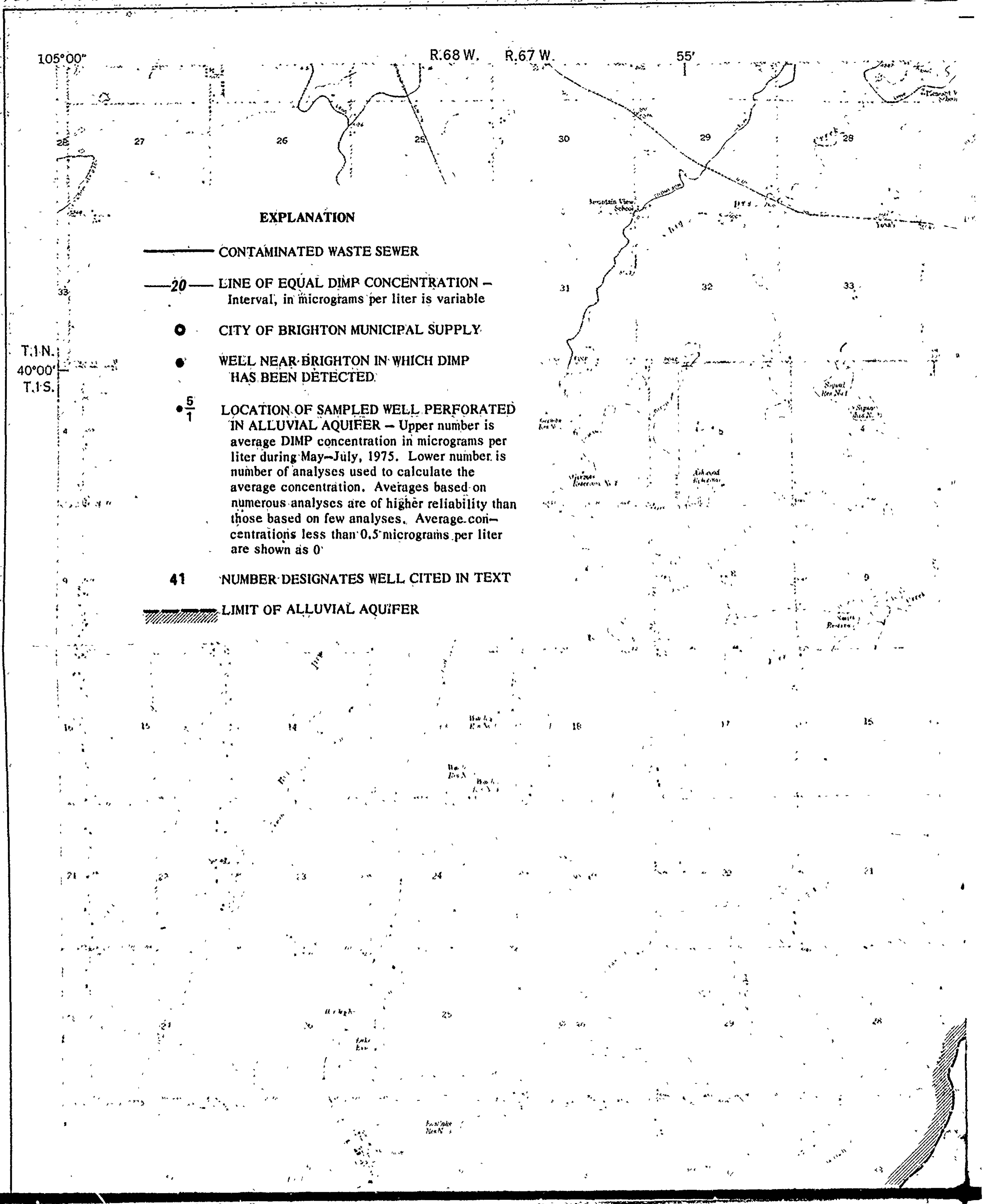
Reynolds, J. W., 1975, Rocky Mountain Arsenal off-post contamination control plan: U.S. Dept. Army, Rocky Mountain Arsenal, 34 p.

Smith, R. O., Schneider, P. A., Jr., and Petri, L. R., 1964, Ground-water resources of the South Platte River basin in western Adams and southwestern Weld Counties, Colorado: U.S. Geol. Survey Water-Supply Paper 1658, 132 p.

U.S. Geological Survey, 1974, Water resources data for Colorado, Part 1. Surface water records: U.S. Geol. Survey ann. rept., 396 p.

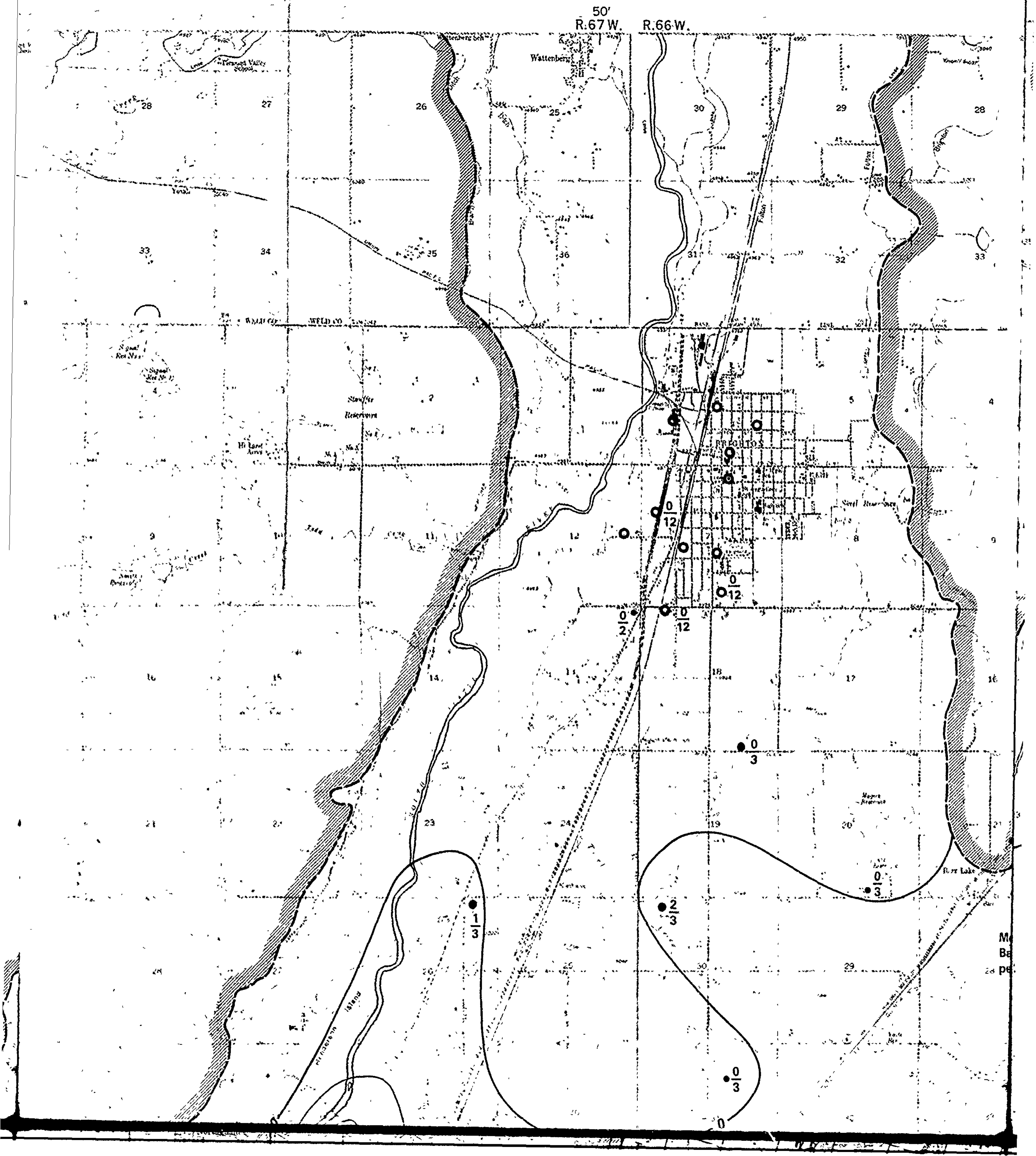
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

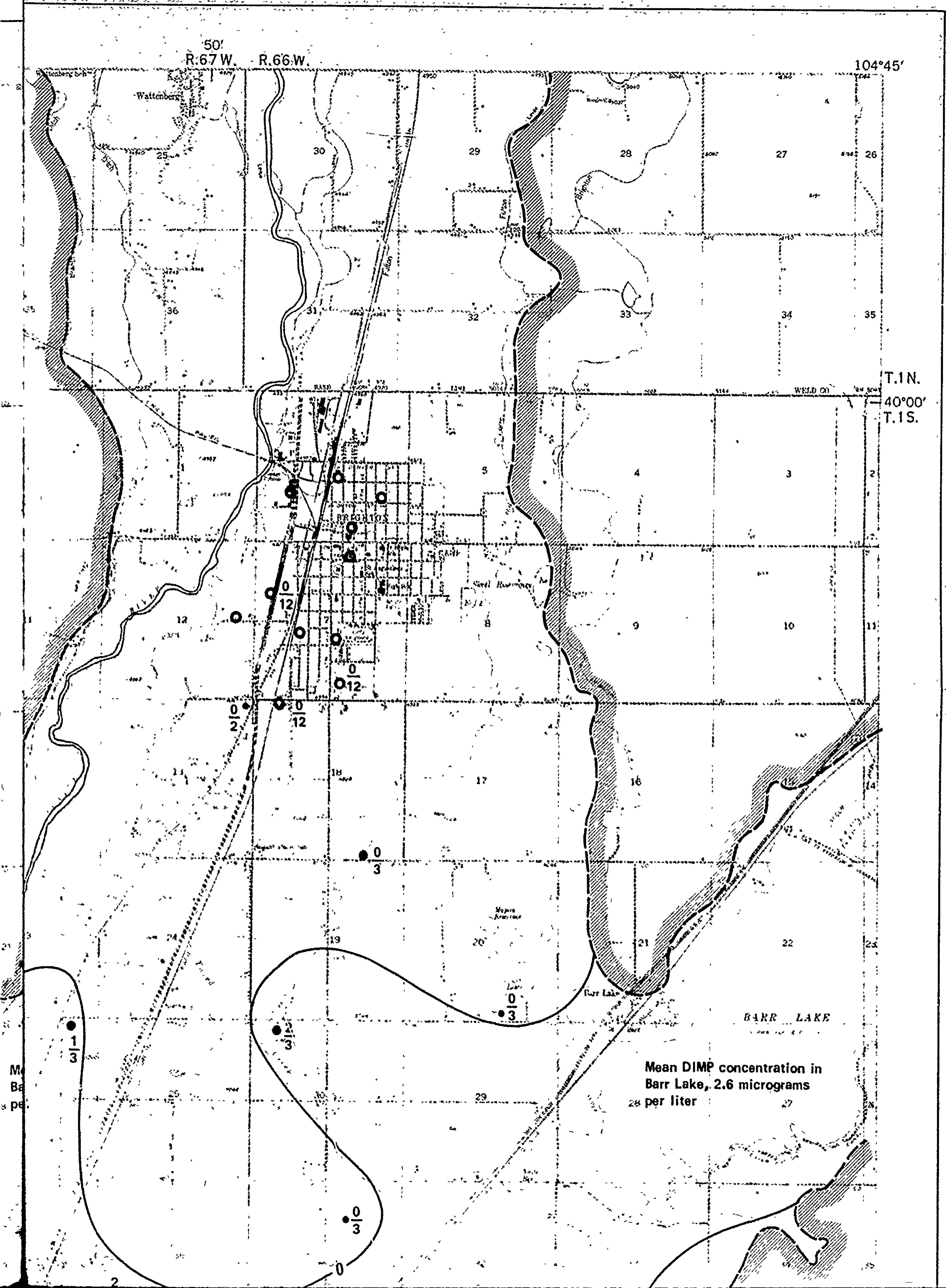
UNITED STAT
ROCI

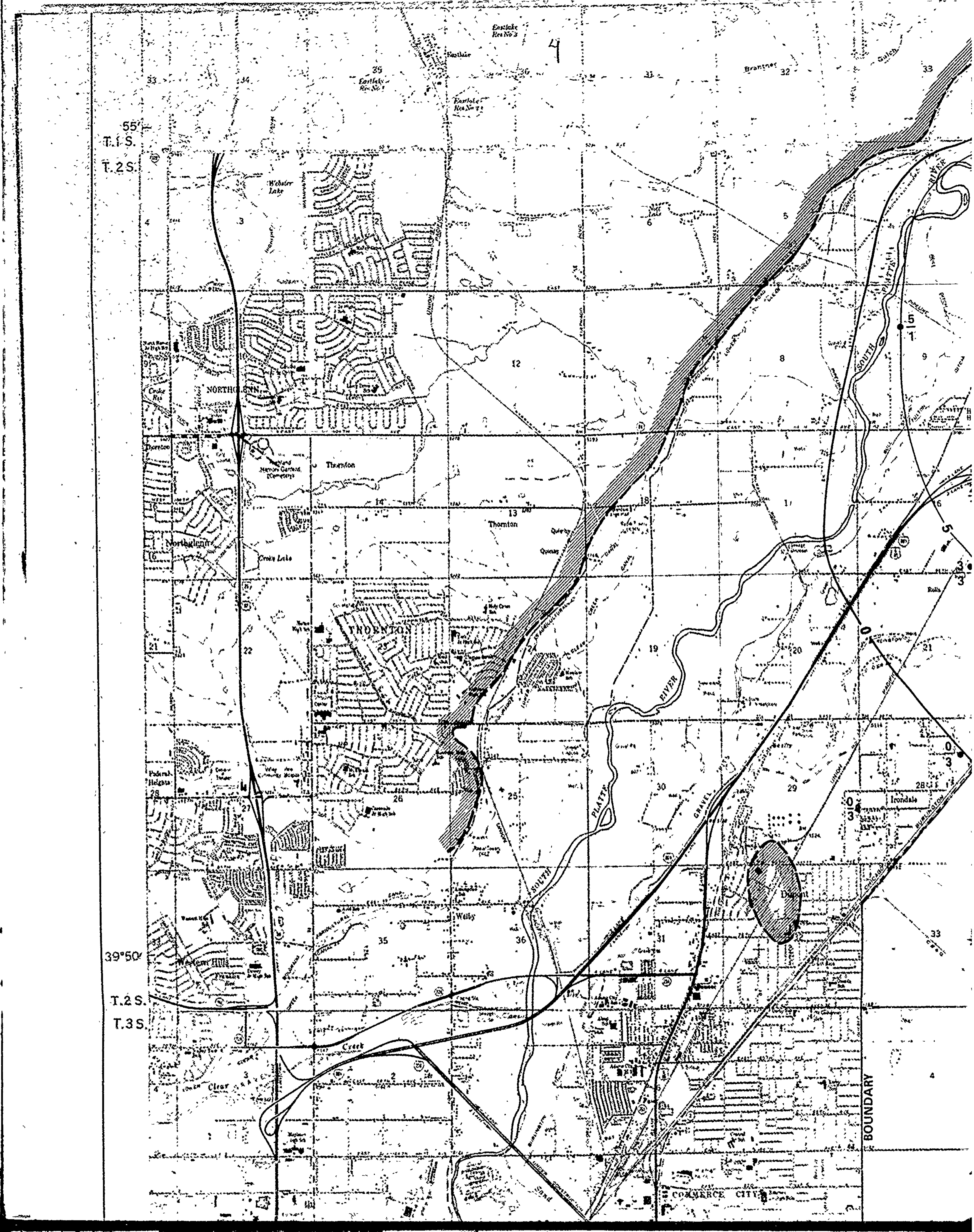


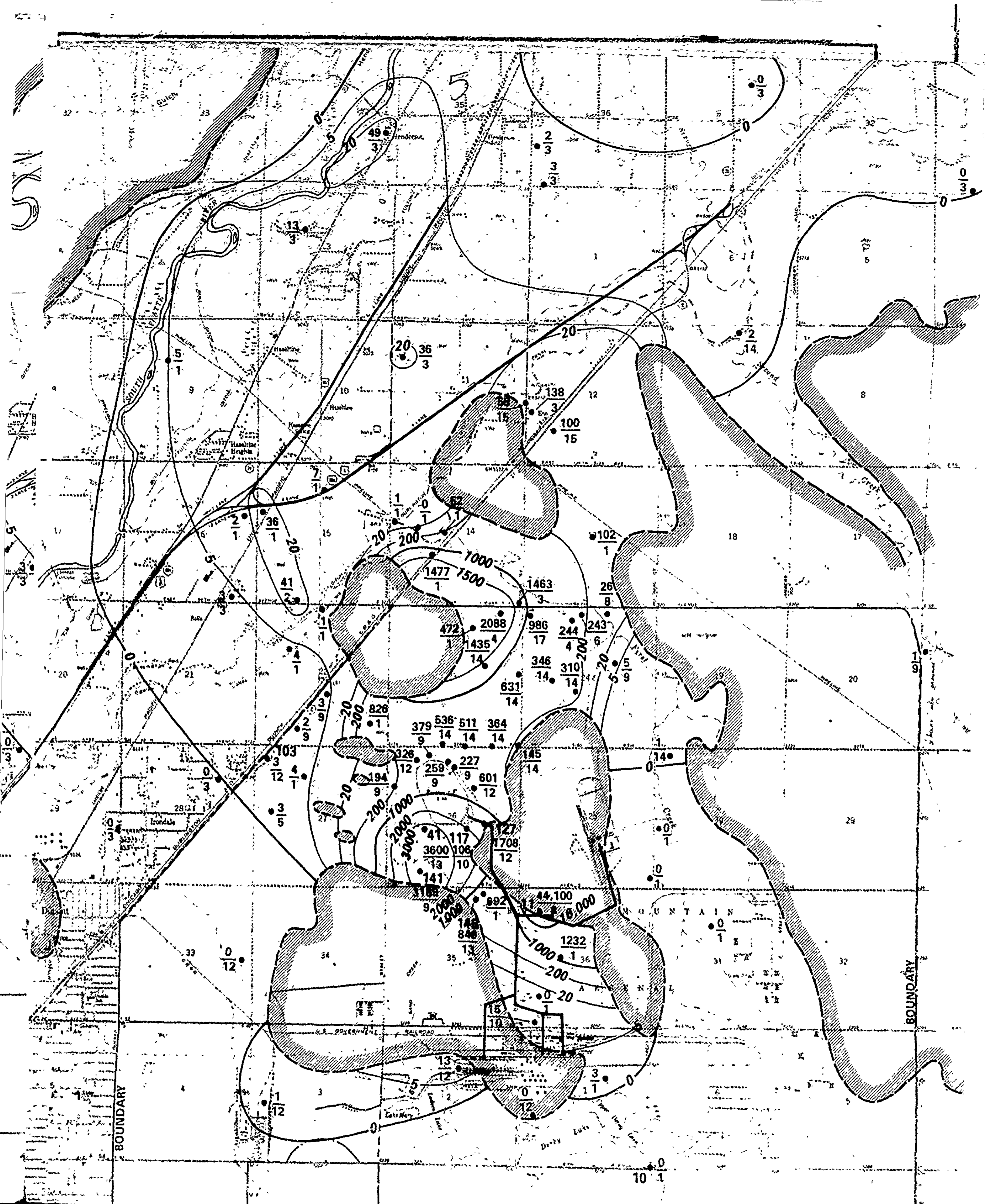
2

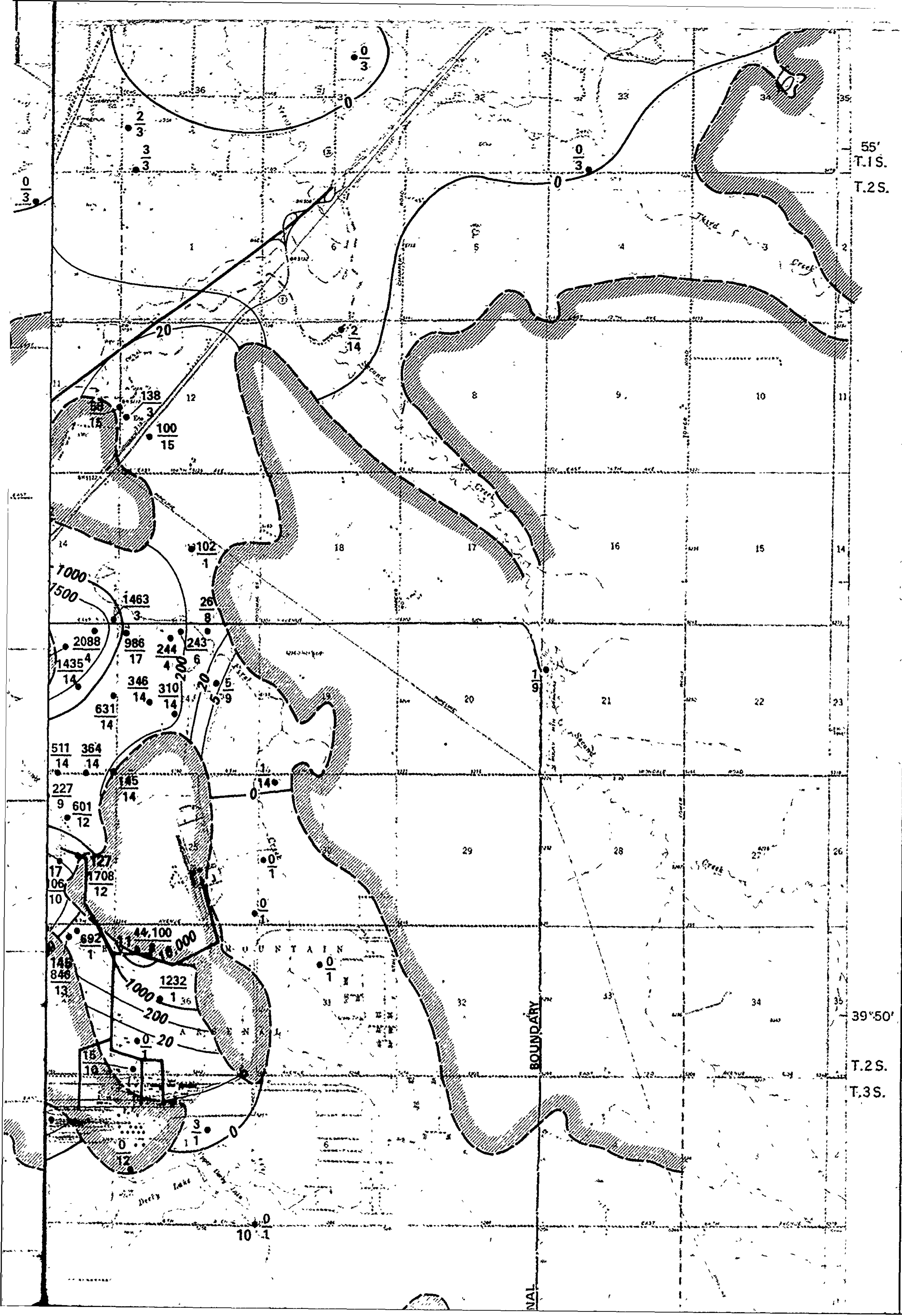
Prepared for the
UNITED STATES DEPARTMENT OF THE ARMY
ROCKY MOUNTAIN ARSENAL



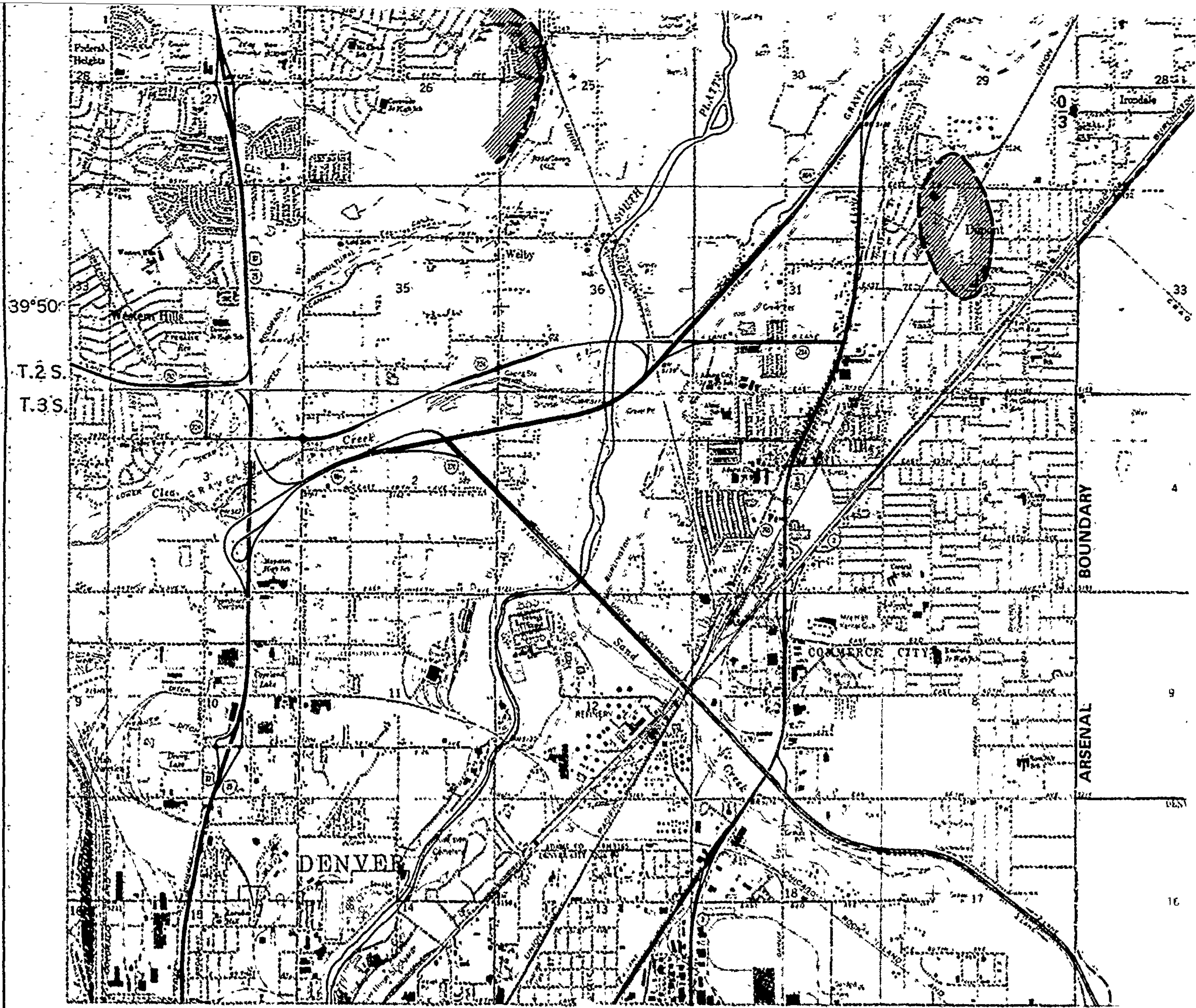

50'
R.67 W.
R.66 W.
104°45'
T.1 N.
40°00'
T.1 S.
Wattenberg
BRIGHTON
BARR LAKE
Barr Lake
Mean DIMP concentration in Barr Lake, 2.6 micrograms per liter


4
Eastlake
Brantner
Gulch
55'
T.1 S.
T.2 S.
Webster Lake
NORTHGLENN
Thornton
Northglenn
THORNTON
Welby
SOUTH PLATTE RIVER
Irondale
Derby
39°50'
Western Hills
T.2 S.
T.3 S.
Clear Creek
BOUNDARY
COMMERCE CITY


BOUNDARY
BOUNDARY
MOUNTAIN
ARSENAL
Irondale
Derby
Hazeltine Heights
U.S. GOVERNMENT RAILROAD
SOUTH PLATTE RIVER

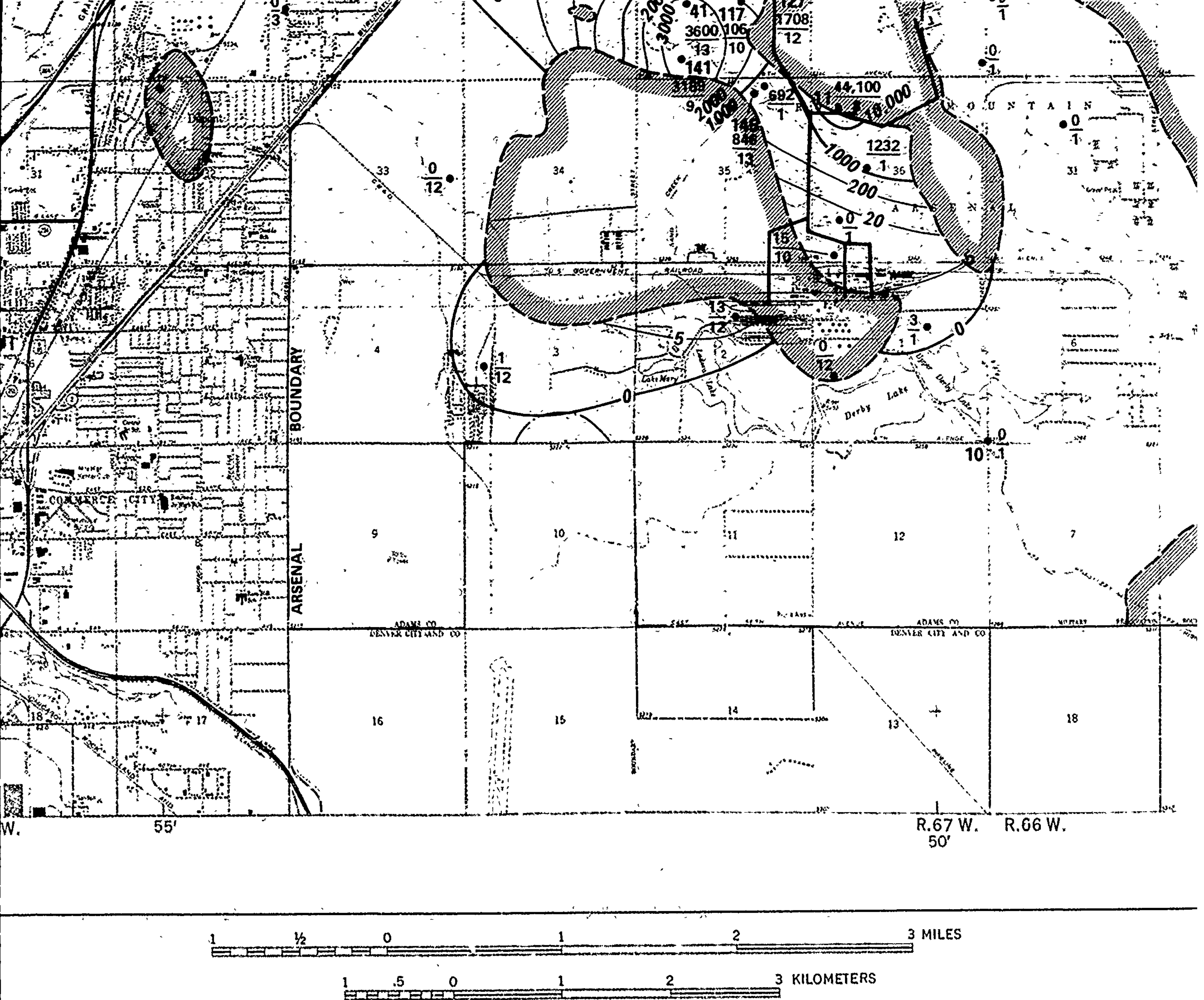


55'
T.1 S.
T.2 S.
39°50'
T.2 S.
T.3 S.
BOUNDARY
Third Creek
First Creek
Second Creek
MOUNTAIN
ARSENAL
44,100
10,000
1000
200
20
0



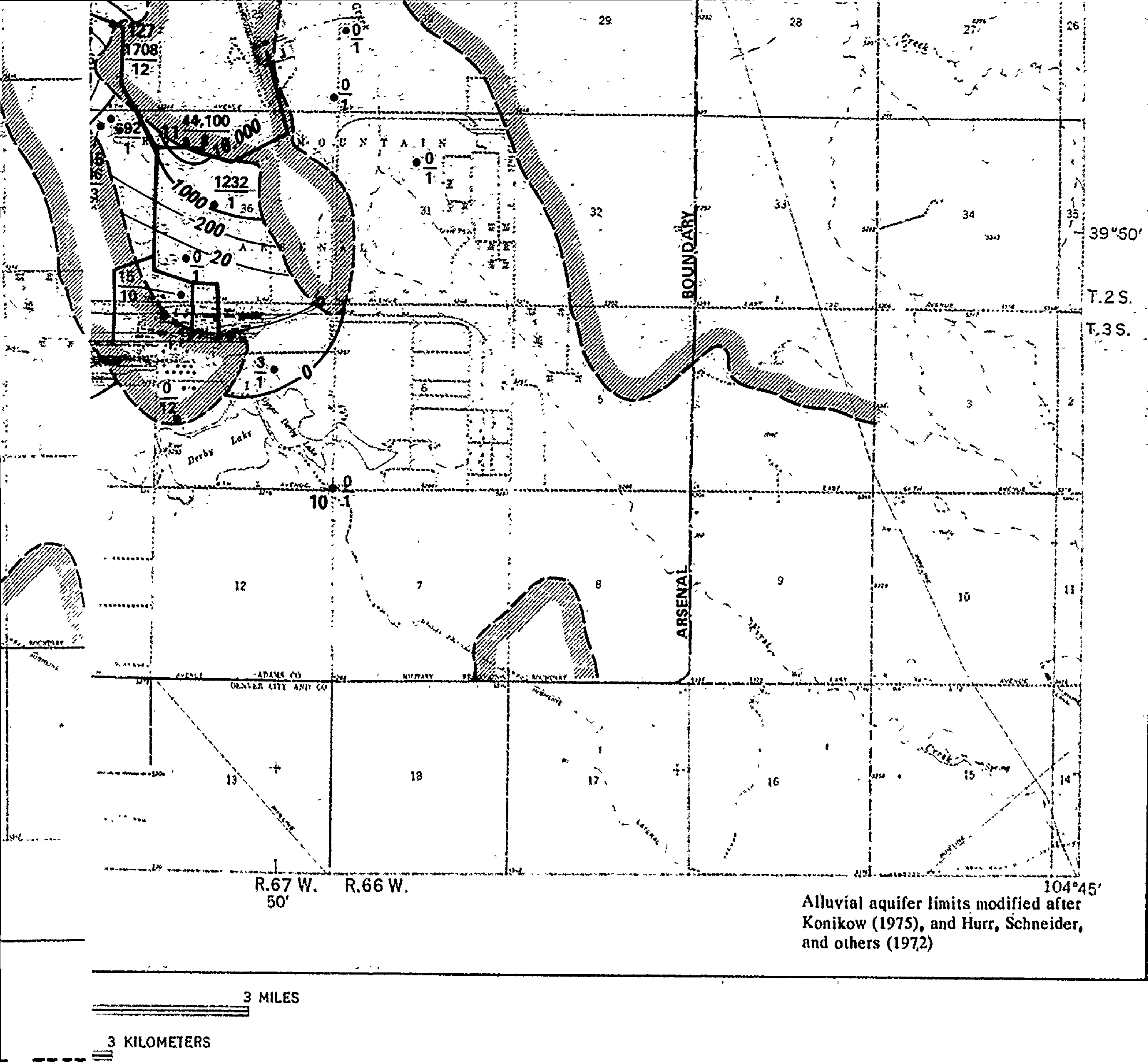
Base from U. S. Geological Survey
1:24,000 Eastlake, Brighton, Commerce
City, and Sable, 1965

MAP SHOWING CONCENTRATION C
ROCKY MOUNTAIN ARSEN



ɪG CONCENTRATION OF DIMP IN GROUND-WATER DURING MAY-J
ⱪY MOUNTAIN ARSENAL AND VICINITY NEAR DENVER, COLORAD

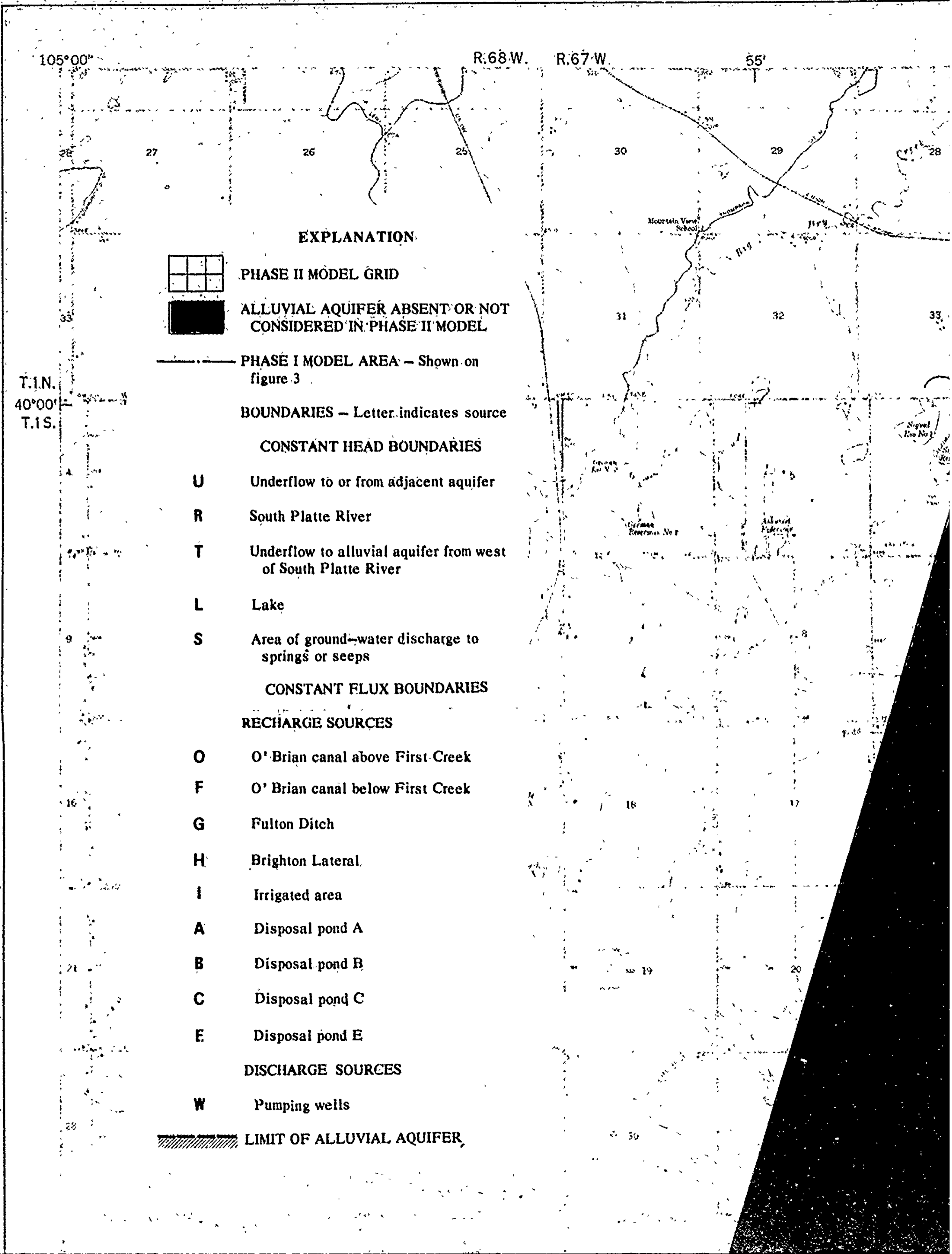
8



-JUI
ADO

-WATER DURING MAY-JULY 1975,
EAR DENVER, COLORADO

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY



UNITE

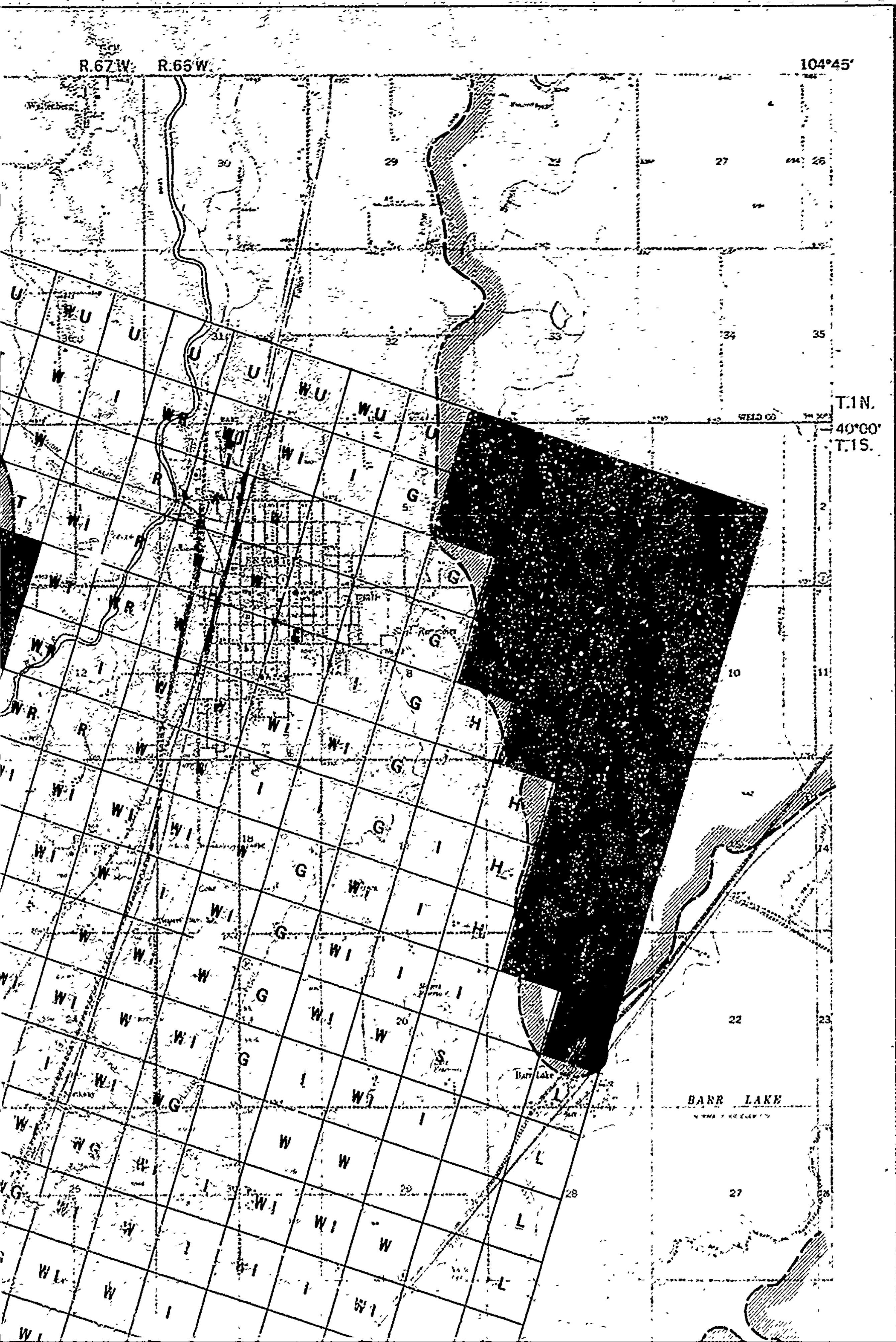
Prepared for the

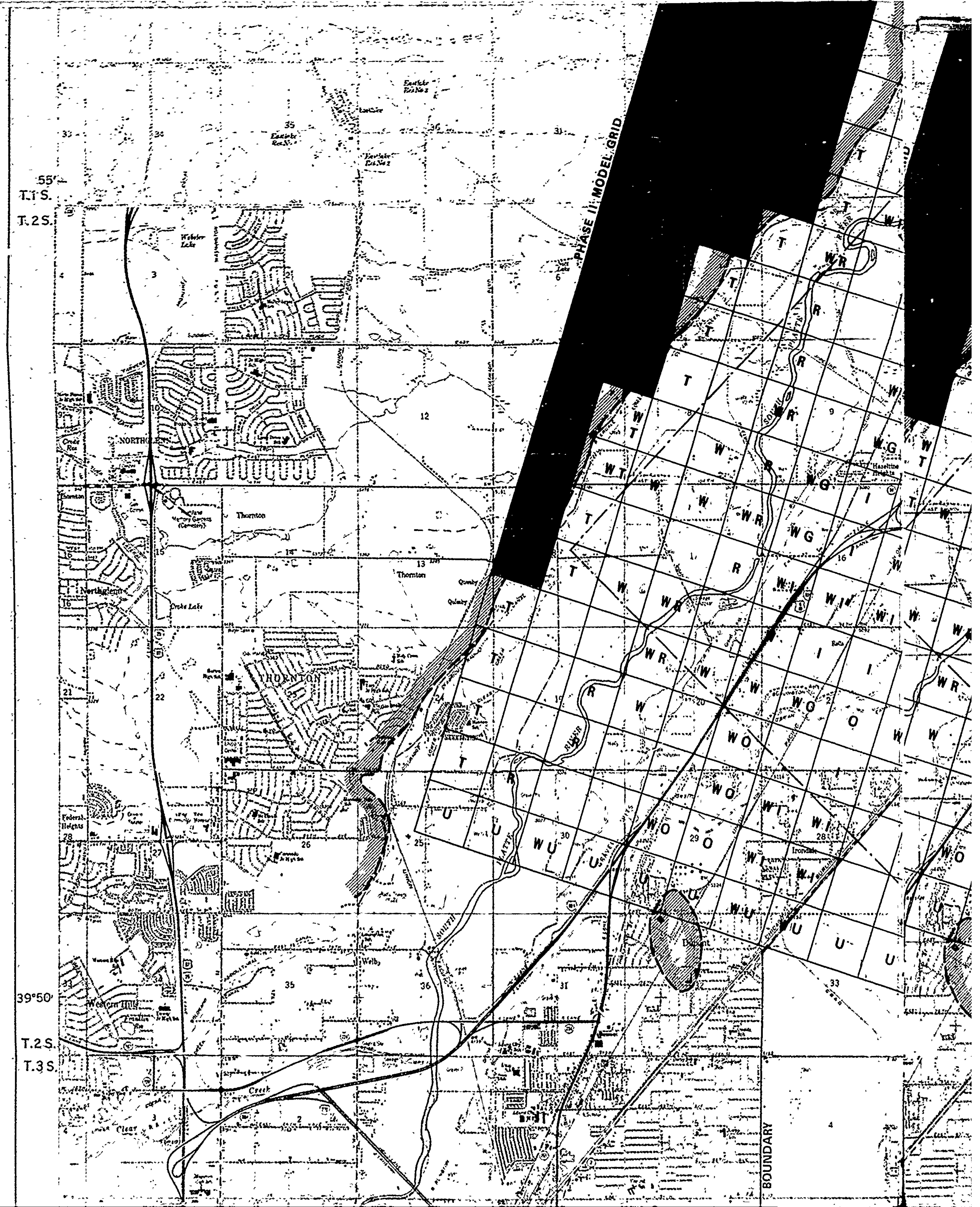
UNITED STATES DEPARTMENT OF THE ARMY

ROCKY MOUNTAIN ARSENAL

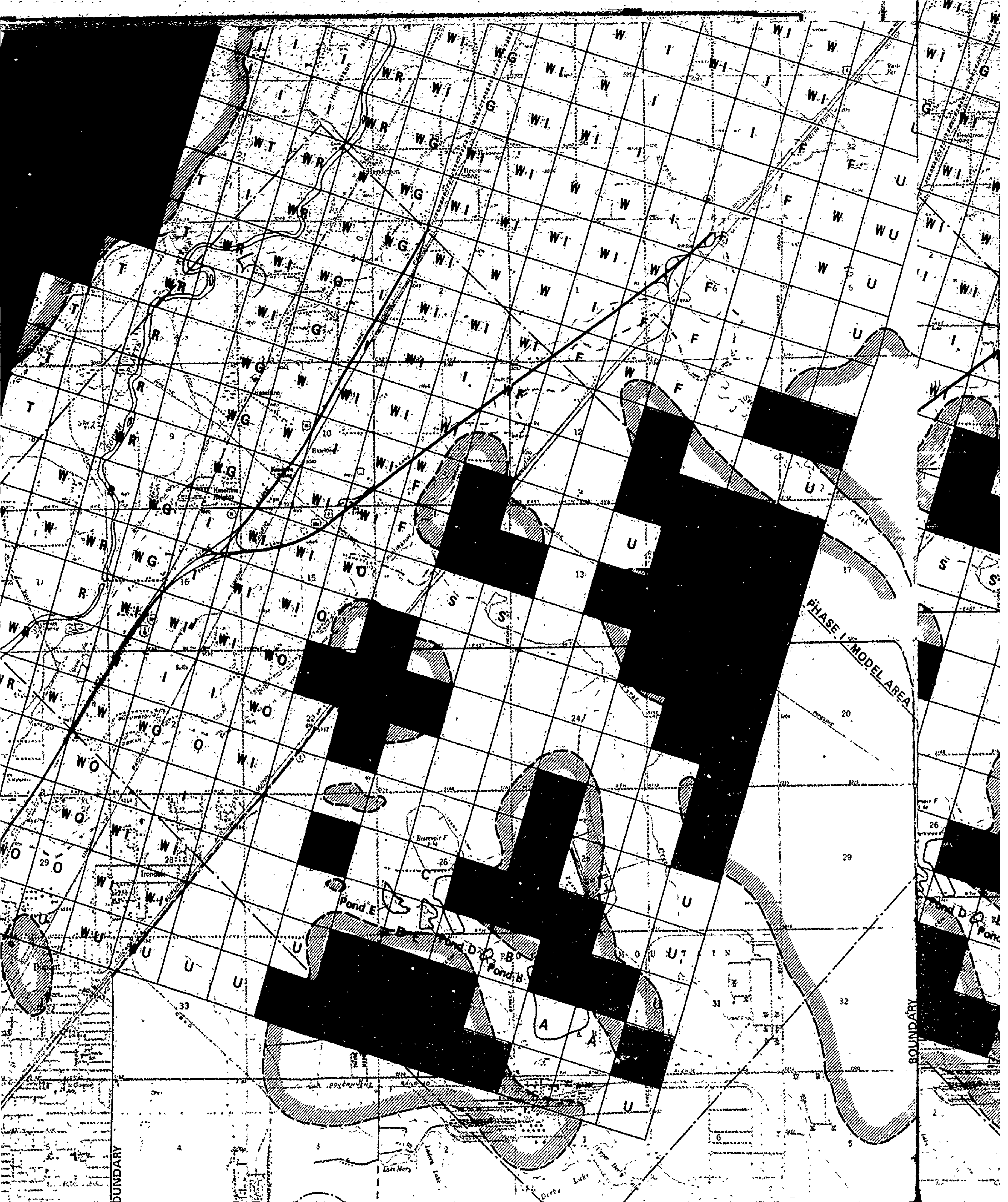
3

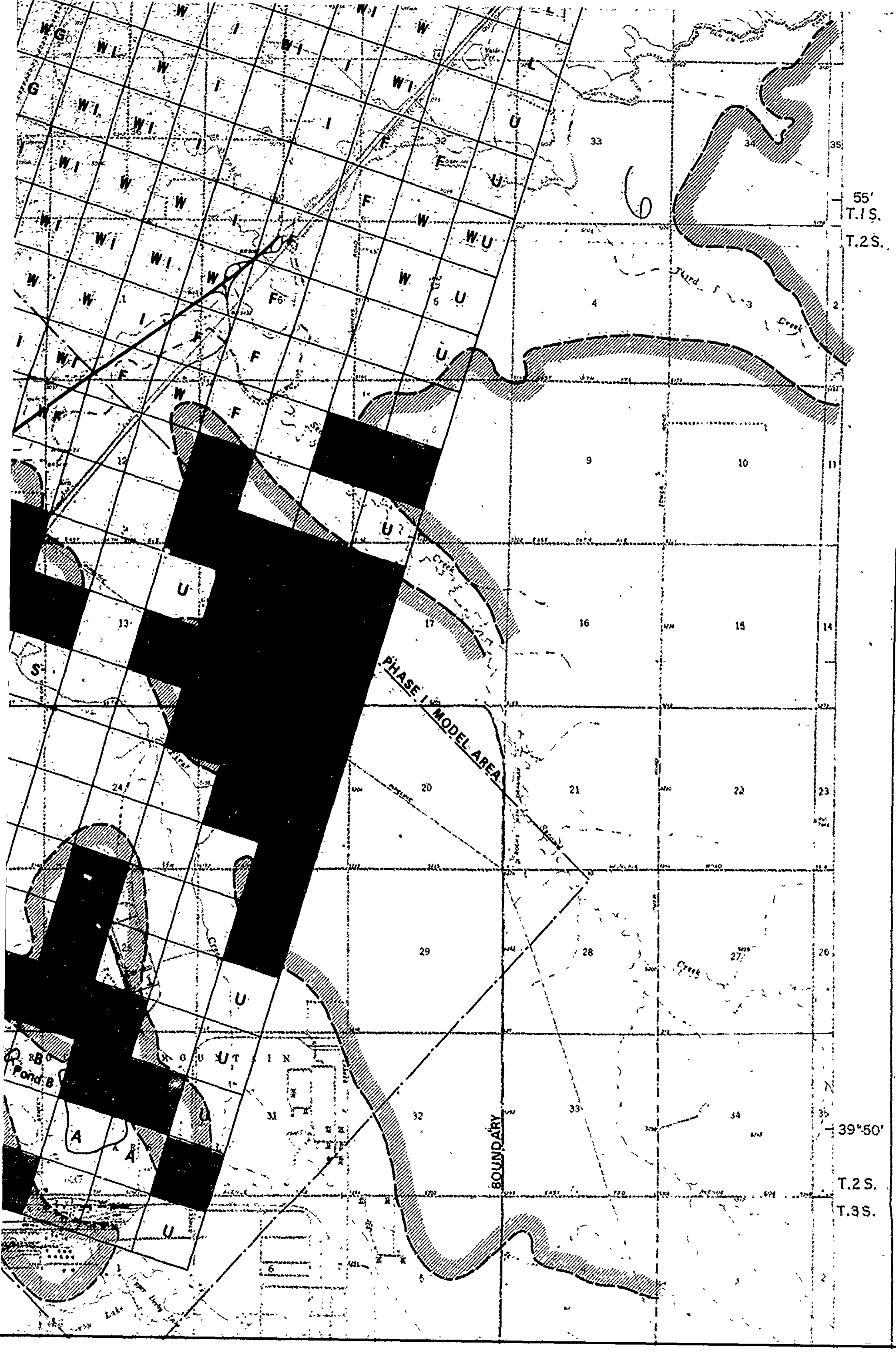
ADMINISTRATIVE REPORT
PLATE 2

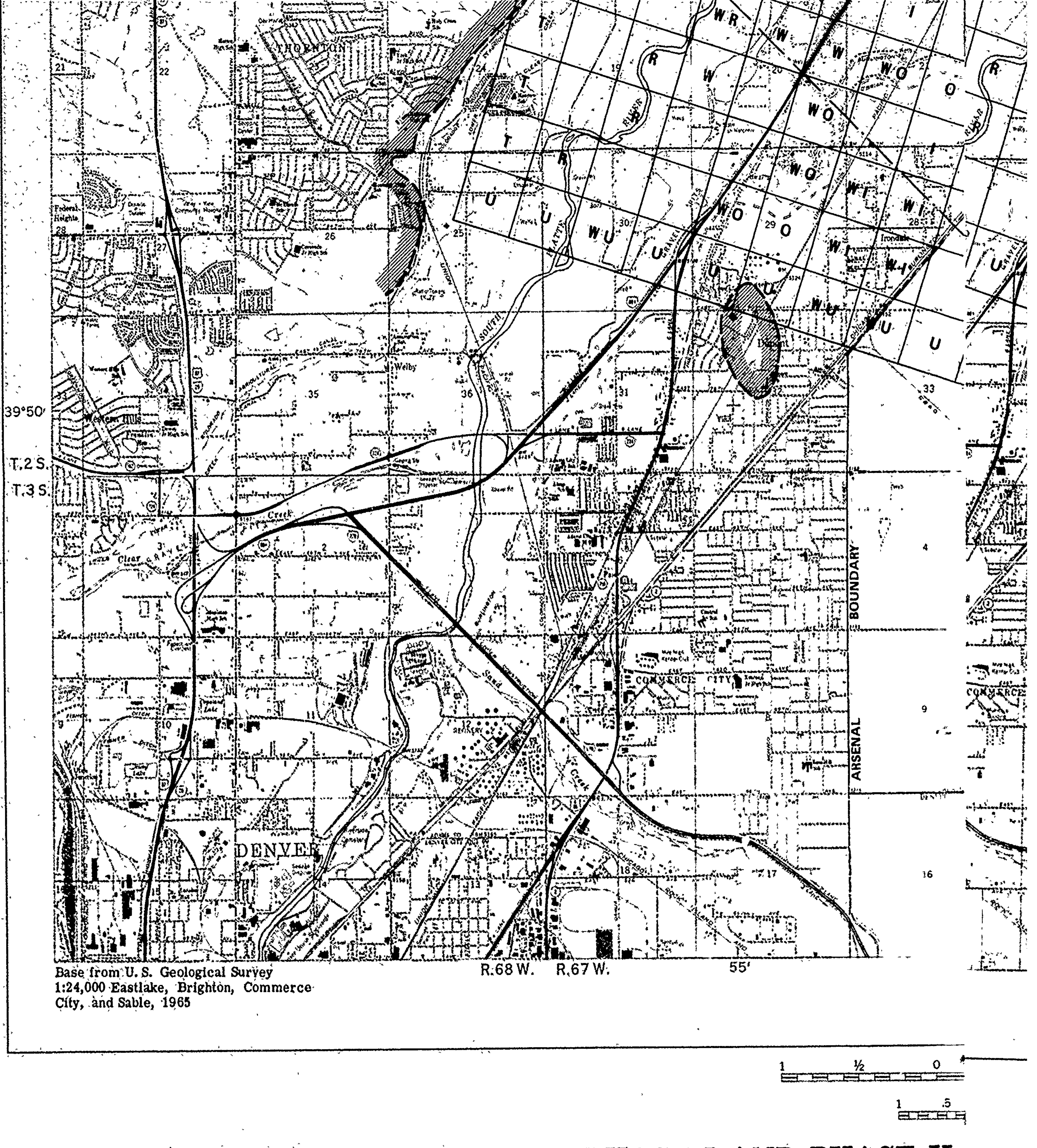




PHASE II MODEL GRID
55'
T.1 S.
T.2 S.
T.3 S.
39°50'
Webster Lake
NORTHGLENN
Northglenn
Thornton
THORNTON
Croke Lake
Federal Heights
Western Hills
Welby
Dupont
Irondale
Hazeltine Heights
BOUNDARY

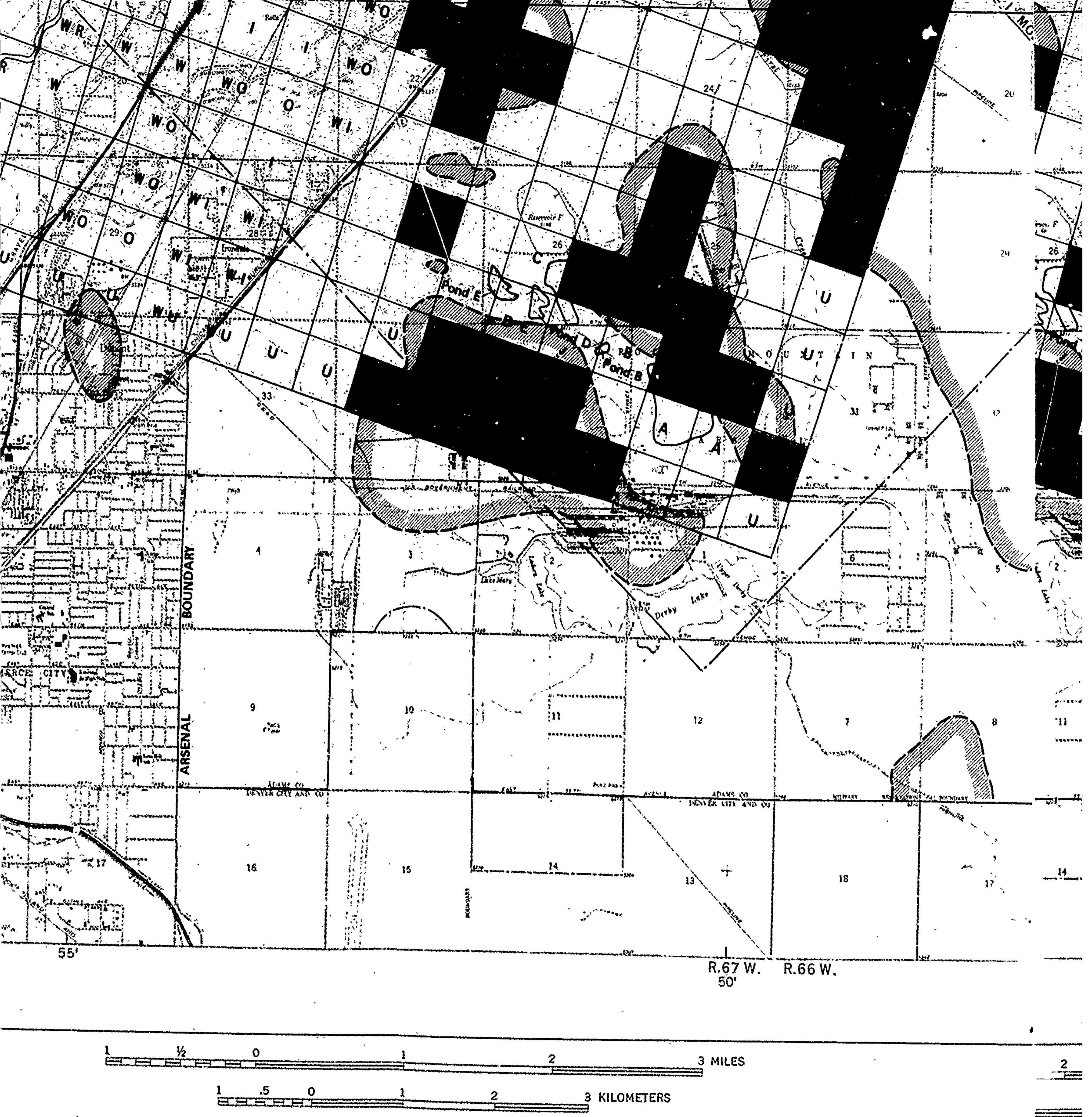

PHASE I MODEL AREA
BOUNDARY
BOUNDARY
Pond E
Pond D
Pond B
Pond D
Reservoir F


55′
T.1 S.
T.2 S.
Third Creek
PHASE I MODEL AREA
BOUNDARY
39°50′
T.2 S.
T.3 S.
Pond B
33
34
35
4
3
2
9
10
11
12
13
16
15
14
17
20
21
22
23
24
29
28
27
26
31
32
33
34
35
6
5

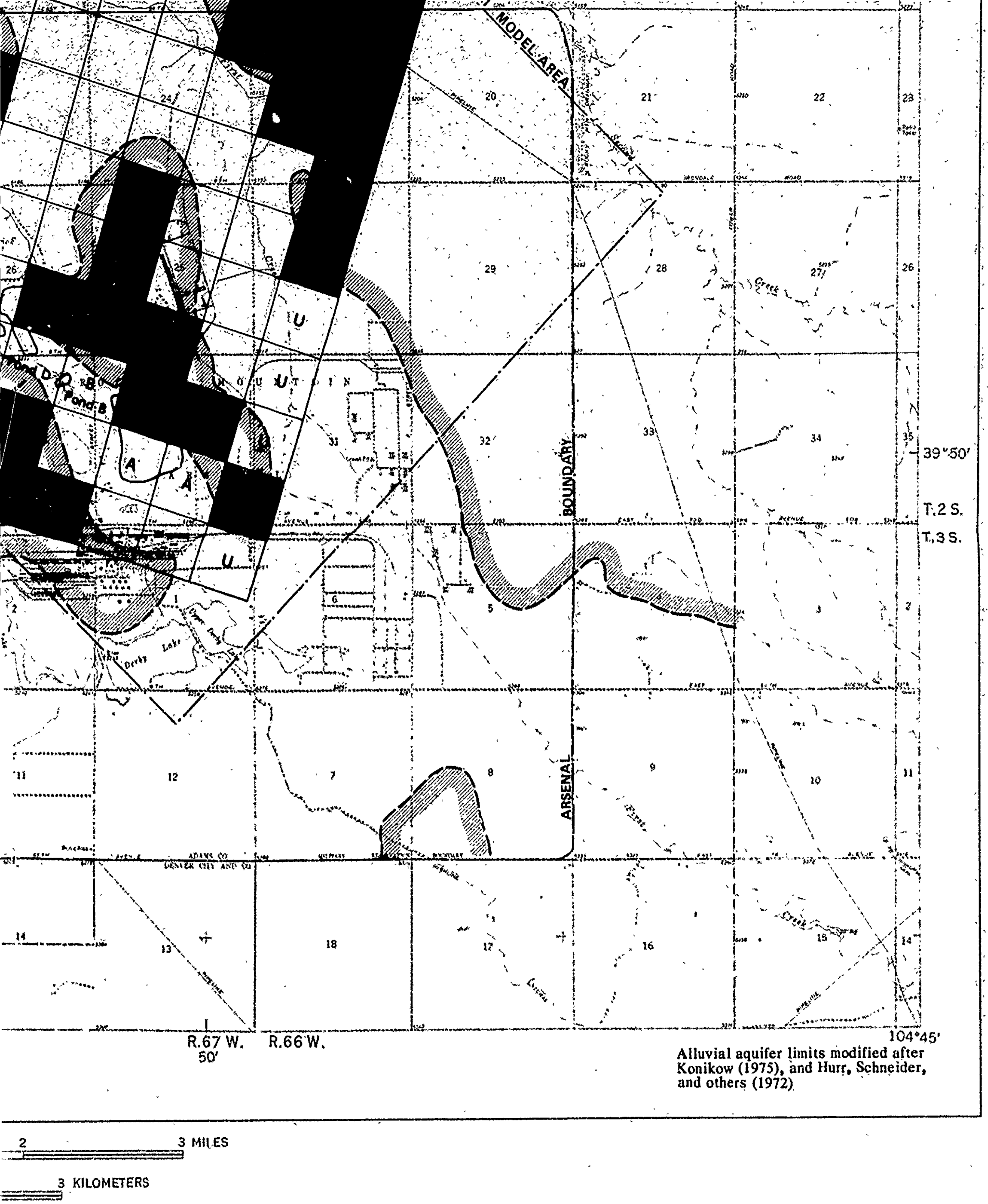


MAP SHOWING LOCATION OF PHASE I AND PHASE II AND CONSTANT-HEAD NODES, ROCKY MOUN

7



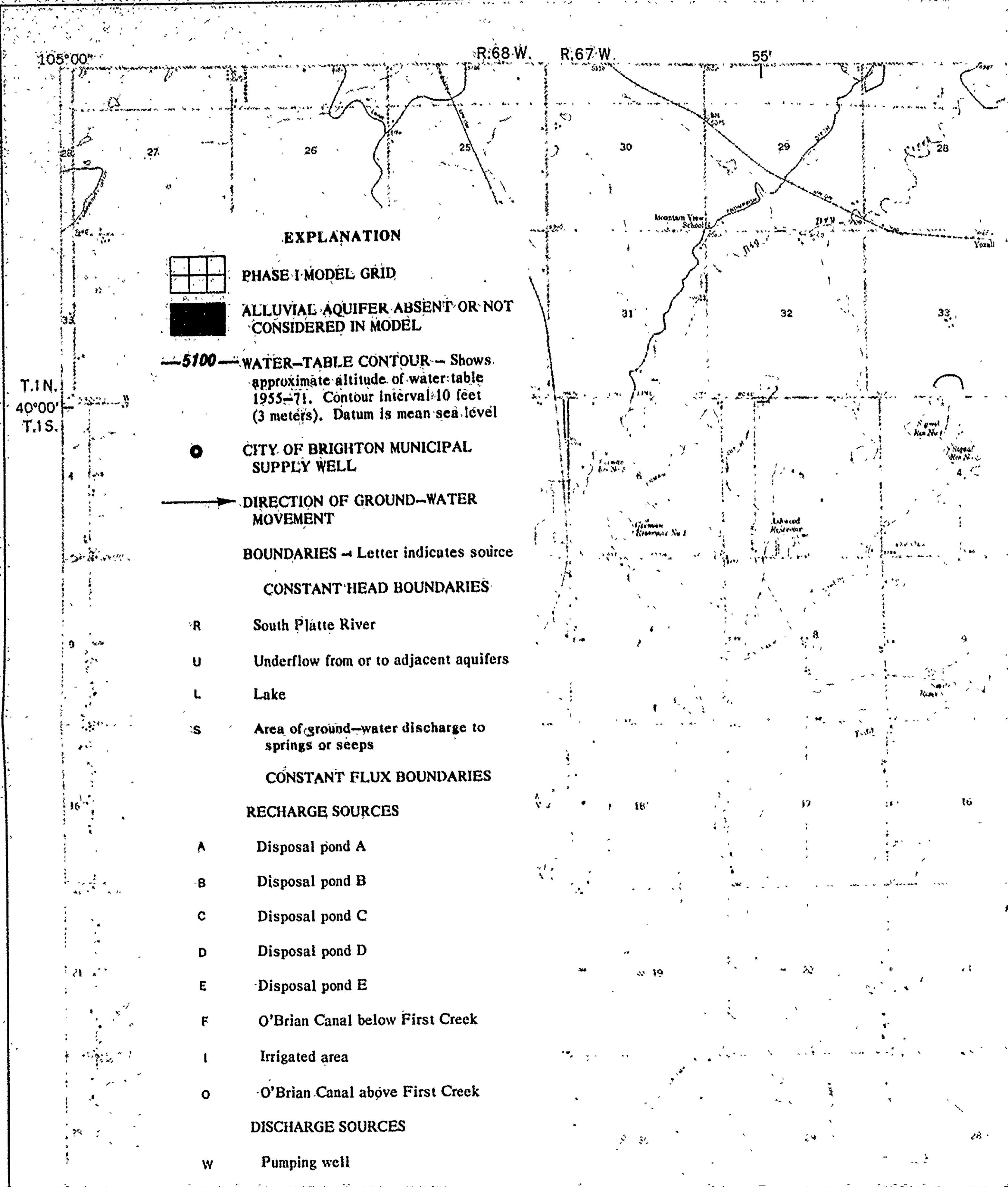
E I AND PHASE II MODEL AREAS AND PHASE II MODEL GRID, RECIAN
DES, ROCKY MOUNTAIN ARSENAL AND VICINITY NEAR DENVER, AI



AND PHASE II MODEL GRID, RECHARGE, DISCHARGE,
AND VICINITY NEAR DENVER, COLORADO

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

UNITED



EXPLANATION

PHASE I MODEL GRID

ALLUVIAL AQUIFER ABSENT OR NOT CONSIDERED IN MODEL

—5100— WATER–TABLE CONTOUR – Shows approximate altitude of water table 1955–71. Contour interval 10 feet (3 meters). Datum is mean sea level

CITY OF BRIGHTON MUNICIPAL SUPPLY WELL

DIRECTION OF GROUND–WATER MOVEMENT

BOUNDARIES – Letter indicates source

CONSTANT HEAD BOUNDARIES

R South Platte River

U Underflow from or to adjacent aquifers

L Lake

S Area of ground–water discharge to springs or seeps

CONSTANT FLUX BOUNDARIES

RECHARGE SOURCES

A Disposal pond A

B Disposal pond B

C Disposal pond C

D Disposal pond D

E Disposal pond E

F O'Brian Canal below First Creek

I Irrigated area

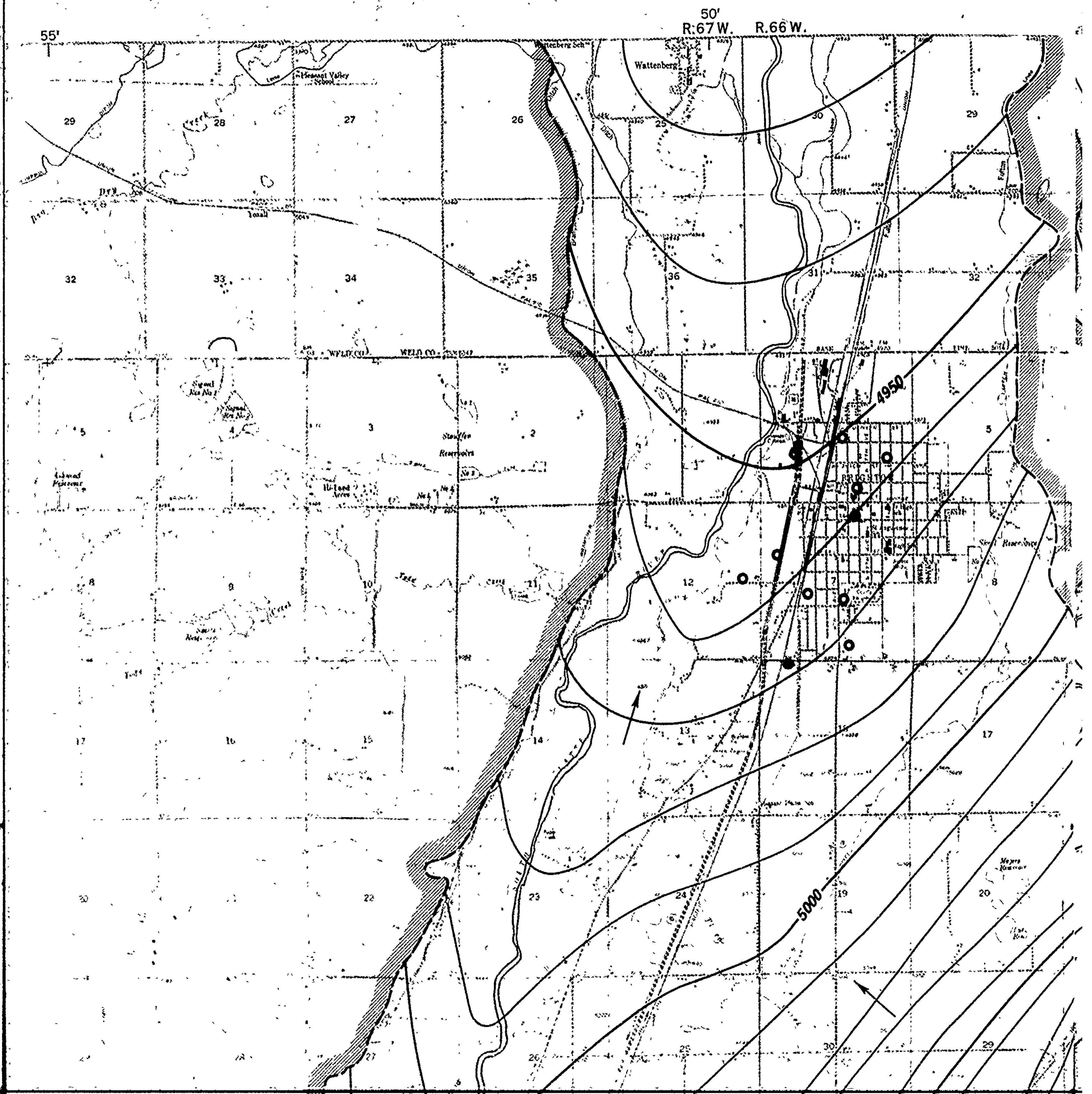
O O'Brian Canal above First Creek

DISCHARGE SOURCES

W Pumping well

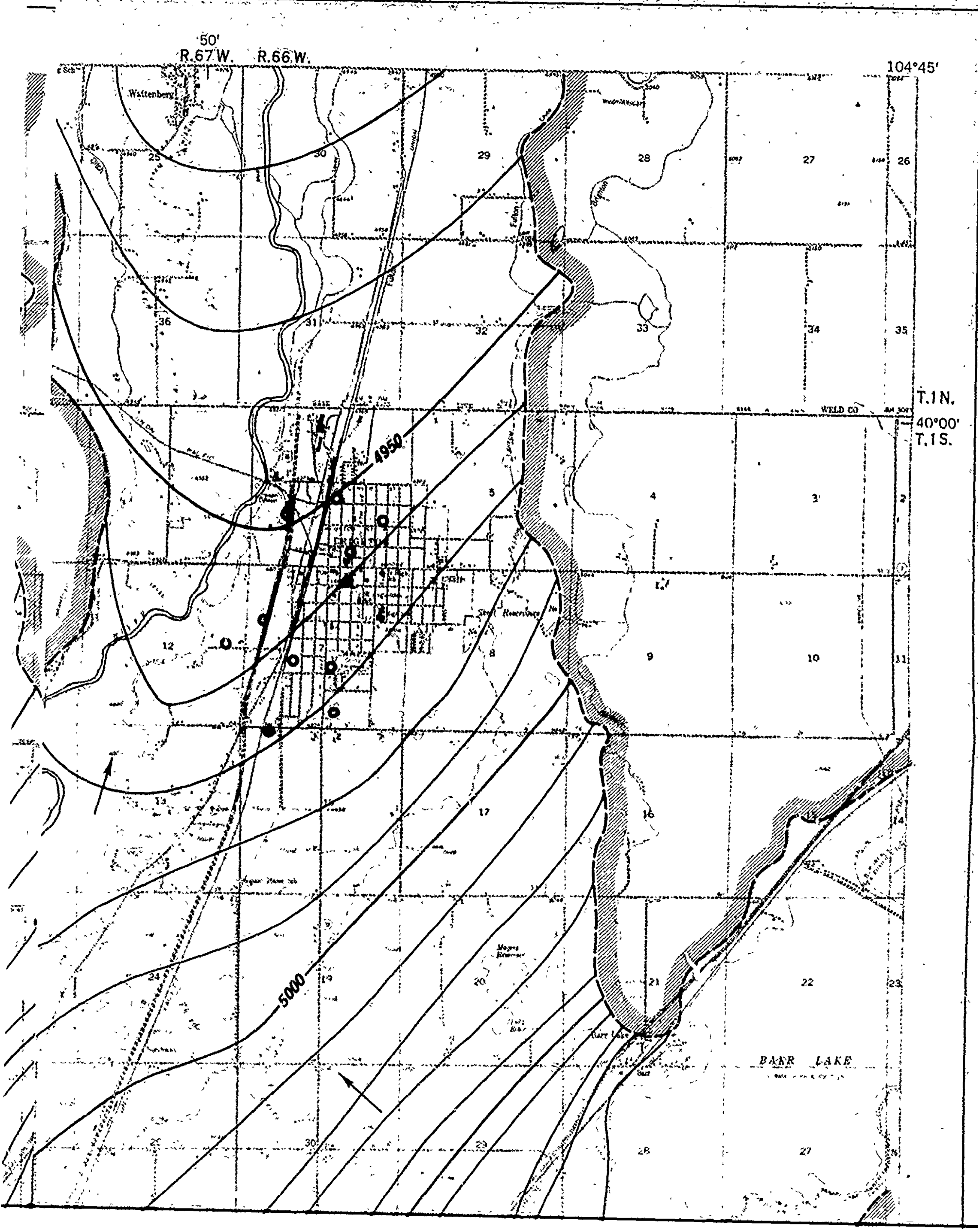
2

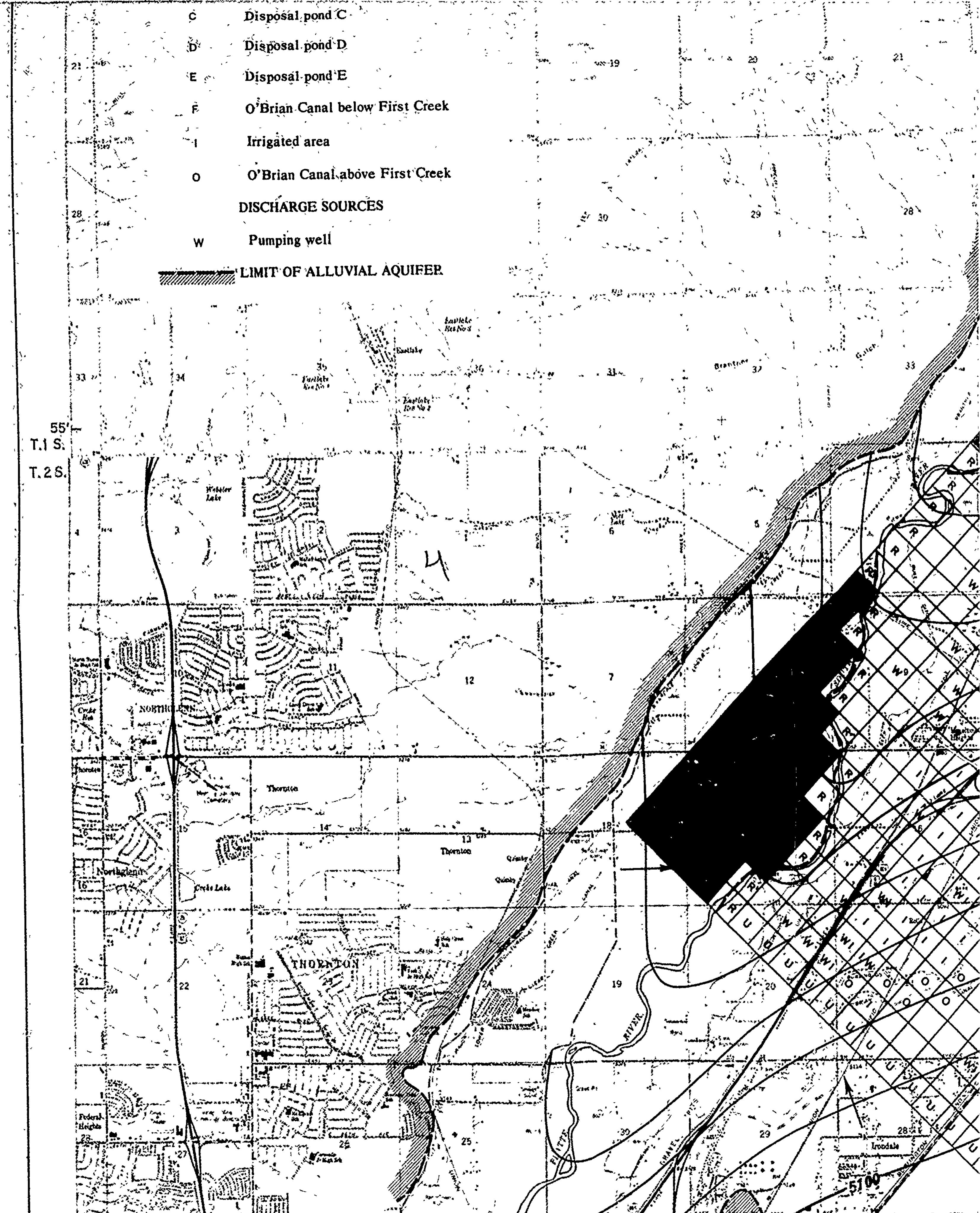
Prepared for the
UNITED STATES DEPARTMENT OF THE ARMY,
ROCKY MOUNTAIN ARSENAL

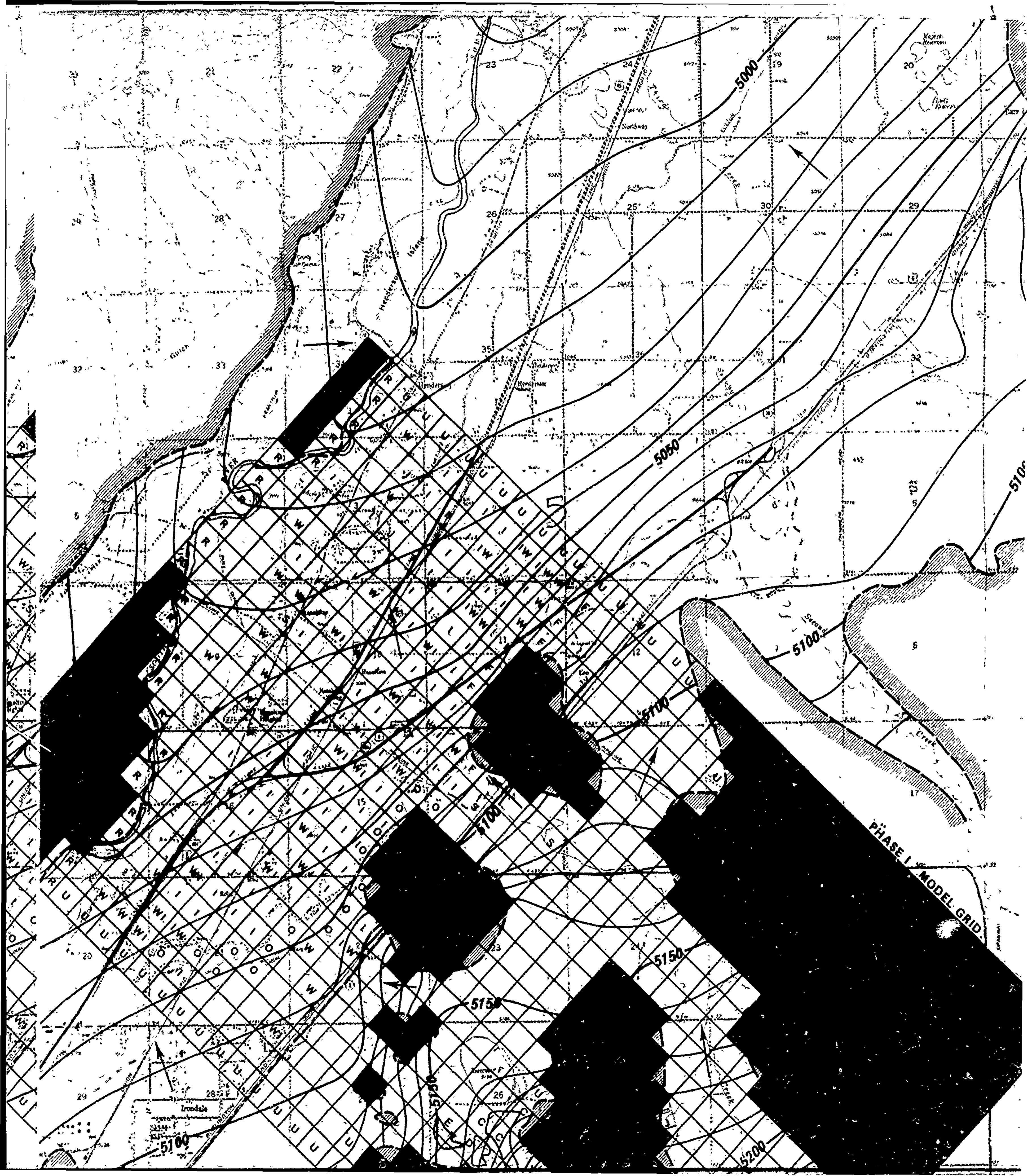


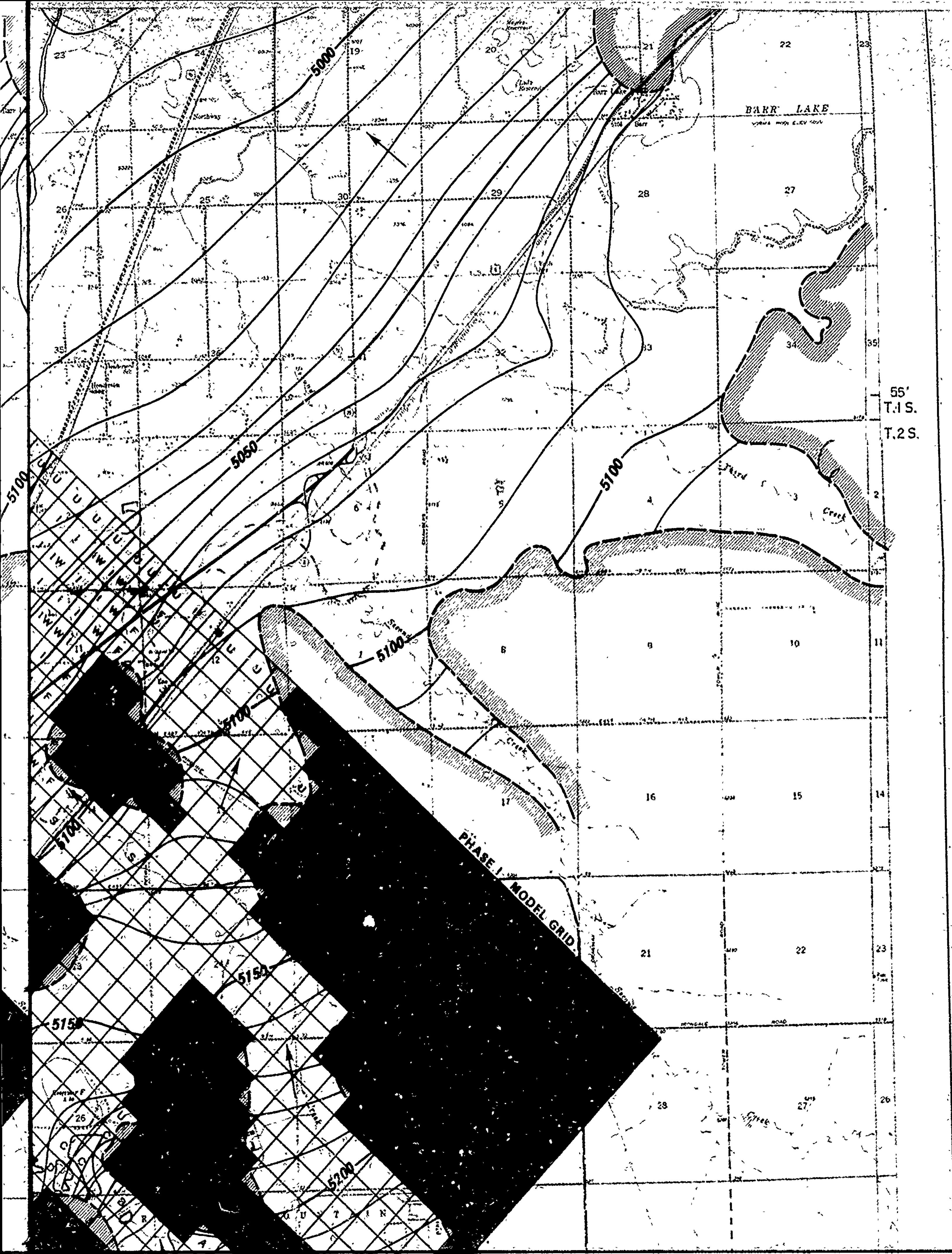
3

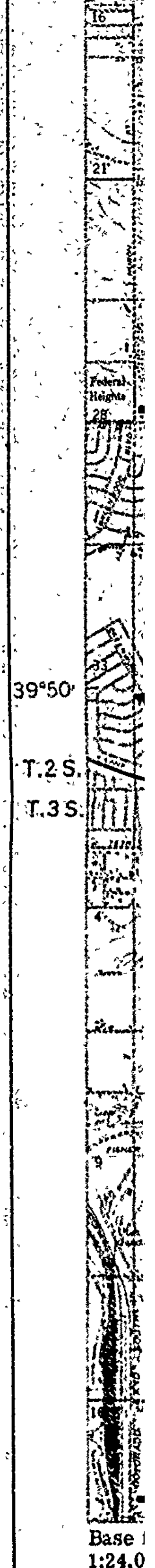
ADMINISTRATIVE REPORT
PLATE 3



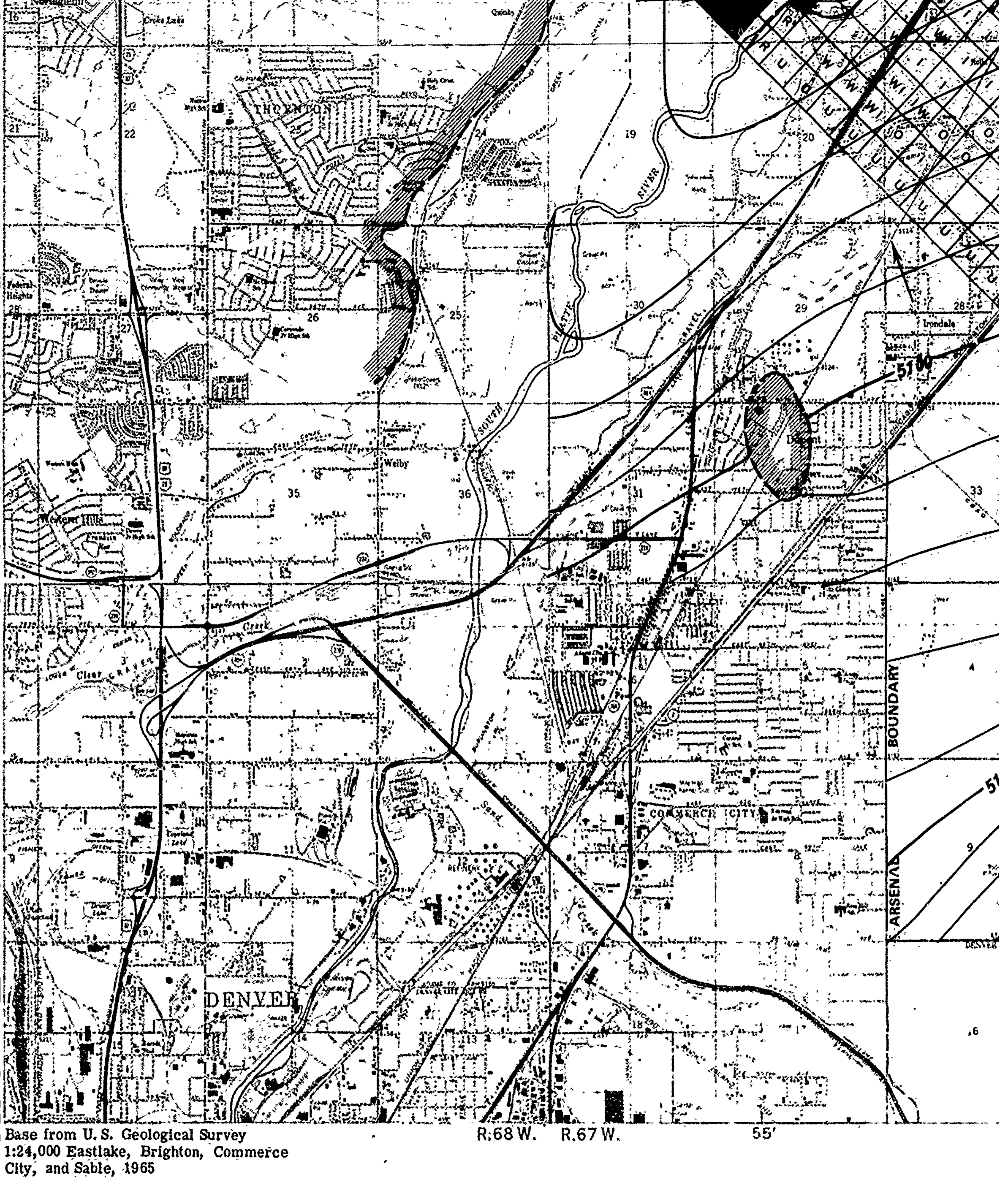

C Disposal pond C
D Disposal pond D
E Disposal pond E
F O'Brian Canal below First Creek
I Irrigated area
O O'Brian Canal above First Creek
DISCHARGE SOURCES
W Pumping well
LIMIT OF ALLUVIAL AQUIFER
55'
T.1 S.
T.2 S.
Thornton
THORNTON
Northglenn
Irondale
RIVER
5100


PHASE I MODEL GRID
5000
5050
5100
5150
5200
Irondale


5000
BARR LAKE
55′
T.1 S.
T.2 S.
5050
5100
5150
5200
PHASE I MODEL GRID


39°50′
T.2 S.
T.3 S.
Base
1:24,0
City,

MA



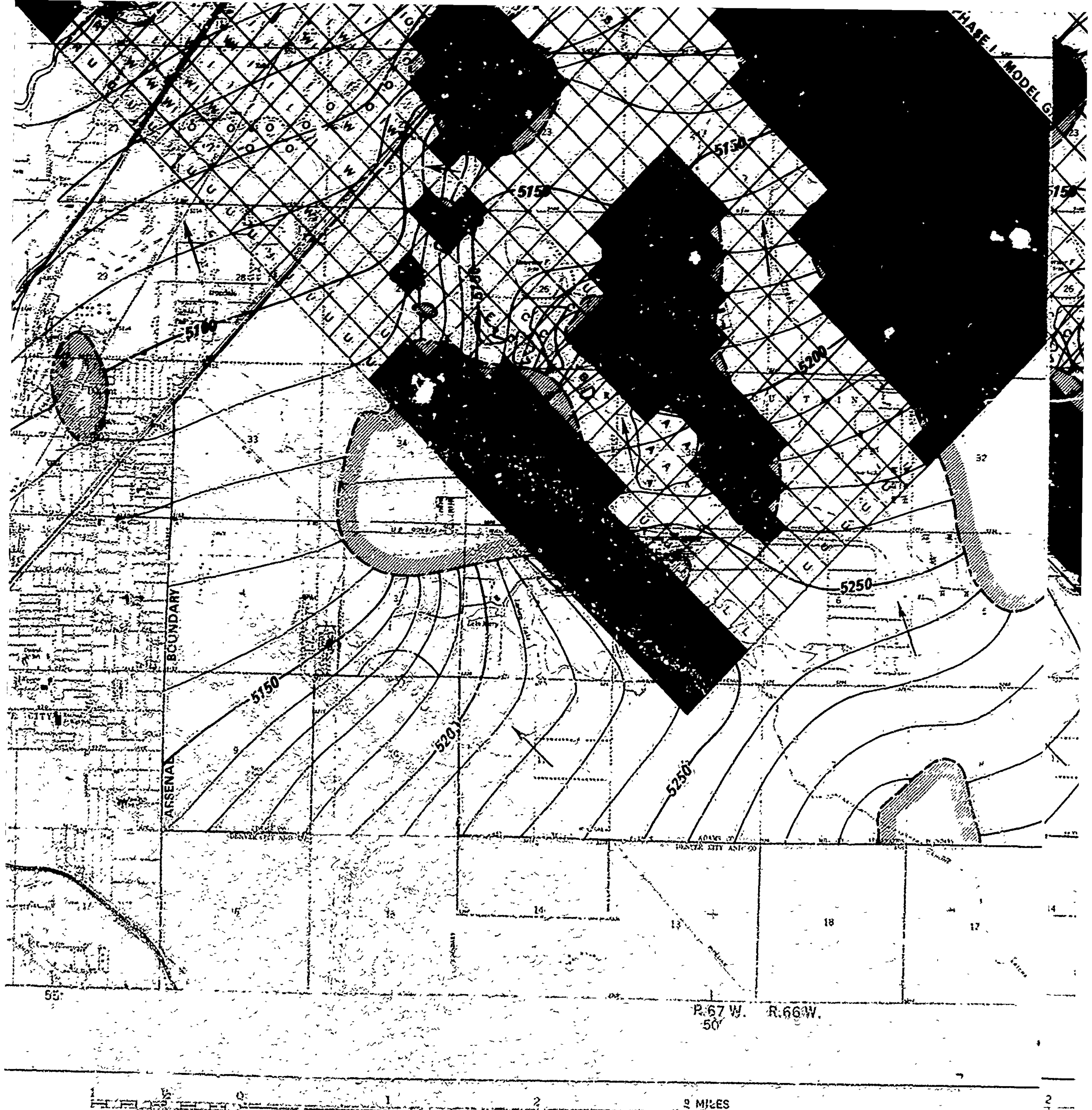
Base from U. S. Geological Survey 1:24,000 Eastlake, Brighton, Commerce City, and Sable, 1965

1 ½ 0

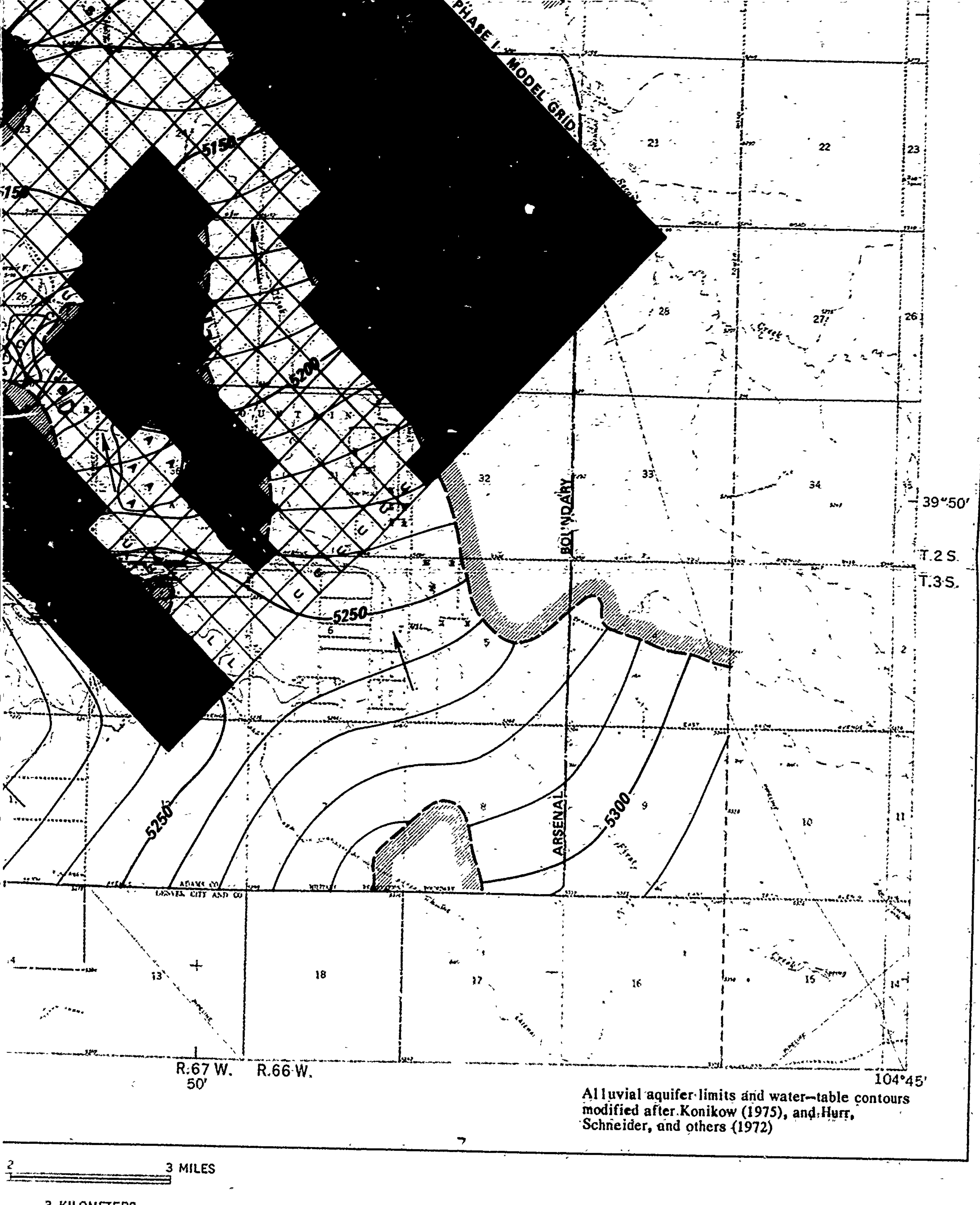
1 .5

MAP SHOWING PHASE I MODEL GRID, LOCATION OF RE
WATER-TABLE CONTOURS, ROCKY MOUN

7



OCATION OF RECHARGE, DISCHARGE, AND CONSTANT-HEAD NOD
S, ROCKY MOUNTAIN ARSENAL AND VICINITY NEAR DENVER, CO



RGE, AND CONSTANT-HEAD NODES, AND STEADY-FLOW
ND VICINITY NEAR DENVER, COLORADO