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TECHNICAL SUPPORT FOR
ROCKY MOUNTAIN ARSENAL

FINAL
WATER REMEDIAL INVESTIGATION REPORT

(Version 3.3)
Volume I

EBASCO SERVICES INCORPORATED
Applied Environmental, Inc.
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R.L. Stollar & Associates, Inc.

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THIS WATER REMEDIAL INVESTIGATION IS A COMPILATION, INTEGRATION, AND INTERPRETATION OF GROUND WATER AND SURFACE WATER STUDY RESULTS OBTAINED FROM SPECIFIC TASKS AND DESIGNED TO PROVIDE A COMPREHENSIVE ASSESSMENT OF CONTAMINATION BOTH ON- AND OFF-POST.

THE RI IS DIVIDED INTO FIVE VOLUMES:

1. INTRODUCTION TO THE PROJECT, DESCRIPTION OF THE ENVIRONMENTAL SETTING, AND ASSESSMENT OF THE NATURE AND EXTENT OF CONTAMINATION
2. GEOLOGICAL AND HYDROLOGIC DATA, TASK 44 DATA, CHEMISTRY DATA, AND INFORMATION PERTAINING TO HYDROCHEMICAL PROPERTIES AND HYDROLOGIC CALCULATIONS
3. APPENDIX F WHICH IS A DETAILED DESCRIPTION OF GEOLOGY, HYDROLOGY, CONTAMINANT DISTRIBUTION, AND HISTORICAL GROUND WATER AND SURFACE WATER PROGRAMS
4. COMMENTS AND RESPONSES FOR THE DRAFT FINAL RI
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Prepared By

EBASCO SERVICES INCORPORATED
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ACRONYMS AND ABBREVIATIONS

ac-ft	acre-feet
ac-ft/mo	acre-feet per month
ac-ft/yr	acre-feet per year
ACL	alternative concentration limit
Al	A lithologic zone - lower
Am	A lithologic zone - middle
ARAR	Applicable or Relevant and Appropriate Requirement
Army	Department of the Army
As	A lithologic zone - channel
ASTM	American Society for Testing and Materials
ASY	apparent specific yield
atm-m^3/mole	atmosphere-cubic meter per mole
Au	A lithologic zone - upper
AWQC	ambient water quality criteria
12DCLE	1,2 dichloroethane
BTZ	benzothiazole
CC	Contamination Control
CCC	Colorado Climate Center
CCl_4	Carbon Tetrachloride
CDH	Colorado Department of Health
CDM	Camp Dresser & McKee, Inc.
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CF&I	Colorado Fuel and Iron
cfs	cubic feet per second
CH_2Cl_2	Methylene Chloride
cm/sec	centimeters per second
CMP	Comprehensive Monitoring Program
COE	U.S. Army Corps of Engineers
CPMS	chlorophenylmethyl sulfide
CPMSO	chlorophenylmethyl sulfoxide
$CPMSO_2$	chlorophenylmethyl sulfone

ACRONYMS AND ABBREVIATIONS (Continued)

CRL	certified reporting limits
CSU	Colorado State University
CSU-GWFlow	Colorado State University Groundwater Flow Model
CWP	Composite Well Program
CWQ	Clean Water Act
DBCP	Dibromochloropropane
11DCE	1,1-dichloroethylene
11DCLE	1,1-dichloroethane
12DCE	trans-1,2-dichloroethylene
DCPD	Dicyclopentadiene
DIMP	Diisopropylmethyl phosphonate
1,4-DITH	1,4-dithiane
DMDS	dimethyldisulfide
DMMP	dimethylmethyl phosphonate
DOJ	Department of Justice
EA	Endangerment Assessment
EDL	elevated detection limit
EPA	U.S. Environmental Protection Agency
ESE	Environmental Science and Engineering, Inc.
FCP	First Creek Paleochannel
Fm	Formation
FRICO	Farmer's Reservoir and Irrigation Company
FS	Feasibility Study
ft	feet
ft/day	feet per day
ft/ft	feet per foot
ft/sec	feet per second
ft/yr	feet per year
ft^3	cubic feet
FY87	Fiscal Year 1987
gal/ft^2	gallons per square foot
GB	nerve gas comprised of Sarin

ACRONYMS AND ABBREVIATIONS (Continued)

GC	gas chromatograph
G/ml	gram per milliliter
GC/MS	gas chromatography/mass spectrometry
gpd/ft	gallons per day per foot gpd/ft^{2}gallons per day per square foot
gpm	gallons per minute
H	Henry's Law Constant
HCCPD or CL_6CP	hexachlorocyclopentadiene
HGU	Hydrogeologic unit
HLA	Harding Lawson Associates
HSL	Hazardous Substance List
ICAP	inductively-coupled argon plasma
ICS	Irondale Containment System
ID	inside diameter
in/hr	inches per hour
in/mo	inches per month
IRA	Interim Response Action
ISP	Initial Screening Program
K	hydraulic conductivity
K_{oc}	organic carbon partition coefficient
K_d	partition coefficient
K_{ow}	octanol/water partition coefficient
LA	Lignite A
LB	Lignite B
lbs/ft^3	pounds per cubic foot
LC	Lignite C
LD	Lignite D
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
mg/l	milligrams per liter
mi	miles
MIBK	methylisobutyl ketone
MKE	Morrison-Knudsen Engineers, Inc.

ACRONYMS AND ABBREVIATIONS (Continued)

mm	millimeter
mph	miles per hour
msl	mean sea level
NBCS	North Boundary Containment System
NBTP	North Boundary Treatment Plant
NBW	north boundary west
NTC	nontarget compounds
NWBCS	Northwest Boundary Containment System
NWBP	Northwest Boundary Paleochannel
O&M	operation and maintenance
O_3	ozone
PAS	Parties and the State
OCP	organochlorine pesticide
OD	outside diameter
°F	degrees Farenheit
OXAT	oxathiane
OX/DITH	Combined oxathiane and dithiane
PCE	tetrachloroethylene
PI	plasticity index
PID	photoionization detector
PMO-RMA	U.S. Army Program Manager's Office for Rocky Mountain Arsenal Contamination Cleanup
PMSO	Program Manager Staff Office
p,p'-DDE	p,p'-1,1-dichloro-2,2-bis(4-chlorophenyl)-ethylene
p,p'-DDT	p,p'-dichlorodiphenyltrichloroethane
PPLV	Preliminary Pollutant Limit Value
ppm	parts per million
psi	pounds per square inch
PVC	polyvinyl chloride
QA1	Paleochannels in terrace gravels
QA2	Paleochannels in eolian deposits (w/gravels)
QA3	Silty terrace gravels and coarse sand
QA4	Paleochannels in eolian deposits (w/o gravels)

ACRONYMS AND ABBREVIATIONS (Continued)

QAE	Eolian deposits
QA/QC	Quality Assurance/Quality Control
QC	Quality control
QT	Quarternary terrace gravels
RCI	Resource Consultants, Inc.
RCRA	Resource Conservation and Recovery Act
R_f	Retardation factor
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
RIC	RMA Information Center
RMA	Rocky Mountain Arsenal
RMACCPMT	Rocky Mountain Arsenal Control Management Team
ROD	Record of Decision
SACWSD	South Adams County Water and Sanitation District
SAR	Study Area Report
SARA	Superfund Amendments and Reauthorization Act
SCC	Shell Chemical Company
SCS	Soil Conservation Service
SDWA	Safe Drinking Water Act
Shell	Shell Chemical Oil Company
SO_2	Sulfur Dioxide
sq mi	square mile(s)
STP	Sewage Treatment Plant
SW/GW	surface water/groundwater
T	transmissivity
111TCE	1,1,1-trichloroethane
112TCE	1,1,2-trichloroethane
TCLEE	tetrachloroethylene
TIC	tentatively identified compounds
TKd	Denver Formation
TRCLE	trichloroethylene
TSP	total suspended particulates

ACRONYMS AND ABBREVIATIONS (Continued)

1u	number one upper zone in the Denver Fm
ug/g	micrograms per gram
ug/l	micrograms per liter
UFS	Unconfined Flow System
UNK	unknown
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency
USCS	Unified Soil Classification System
UTM	Universal Transverse Mercator
VC	volcaniclastic interval
VCE	clay-rich zone stratigraphically equivalent to VC
VOA	volatile organic aromatics
VOC	volatile organic compounds
VOH	volatile organohalogens
WES	U.S. Army Corps of Engineers Waterways Experiment Station
WRI	Water Remedial Investigation
WY87	Water Year 1987

EXECUTIVE SUMMARY

The purpose of the Water Remedial Investigation Report is to present results of the U.S. Department of the Army's Remedial Investigation for the Rocky Mountain Arsenal (RMA) on-post water media. The Water Remedial Investigation assesses contaminant occurrence and distribution within groundwater and surface water. To accomplish this assessment, the RMA environmental setting was evaluated in terms of geology, hydrology, nature and extent of water-borne contamination, and contaminant migration. The study area is bounded by the southern and eastern boundaries of RMA, Second Creek, and the South Platte River.

The report provides a general overview of contamination in water at RMA. It is not intended to be the only source of information for Feasibility Study. The USATHAMA database, and other detailed investigations also are appropriate sources of information.

Soil, groundwater, and surface water became contaminated locally as a result of past military and industrial activities. With time, contaminants entered the groundwater system and were transported off-post, creating a threat to downgradient water wells. On-post contamination resulted from unintentional spills, waste disposal practices, and sewer-line leakage. The number and concentration of contaminants present in RMA groundwater have changed through time. Groundwater contaminant systems have been installed in three primary contaminant pathways to reduce contaminant migration to off-post areas.

Environmental Setting

RMA is part of the High Plains physiographic province, and is characterized by gently rolling hills with a total change in altitude of 220 feet (ft) and average annual precipitation of approximately 15 inches. Surface water flows within several small drainage basins that are tributaries of the South Platte River. The major drainages within RMA boundaries are First Creek and Irondale Gulch. Manmade structures, including diversion ditches, lakes, and water retention basins, have modified the natural drainage patterns.

The surficial geologic units at RMA consist of unconsolidated alluvial and eolian deposits, and the underlying geologic unit is the Denver Formation. Alluvial and eolian deposits locally attain a thickness of 130 ft but typically are less than 50 ft. Several prominent paleochannels have been identified in the erosional surface of the Denver Formation. Bedding planes in the Denver Formation dip approximately 1° to the southeast. The Denver Formation consists of lenticular sandstone and siltstone bodies interlayered with relatively thick sequences of low permeability shale and claystone. Lignitic beds are laterally more continuous than sandstone layers and commonly are fractured. Total thickness of the Denver Formation at RMA varies from 200 to 500 ft.

Groundwater at RMA occurs under both confined and unconfined conditions. The Unconfined Flow System includes saturated alluvium, eolian deposits, and occasionally, subcropping parts of the Denver Formation. In areas where alluvial and eolian deposits are unsaturated, the Unconfined Flow System consists solely of sandstone and of fractured or weathered rock within shallow parts of the Denver Formation. Saturated thickness varies from less than 10 ft to approximately 70 ft. Hydraulic conductivity estimates from aquifer tests range from 0.3 ft/day in areas where the Denver Formation is unconfined to greater than 900 ft/day in alluvial terrace gravel.

Groundwater in the Unconfined Flow System generally flows toward the north and northwest. Spatial variations in hydraulic gradients can be attributed to variations in saturated thickness, hydraulic conductivity, locations of recharge and discharge, and configuration of the bedrock surface. Hydraulic gradients in areas of saturated alluvium typically are 0.002 to 0.009 ft/ft. Gradients in areas of unconfined Denver Formation typically are larger. Water level fluctuations are generally small; however, seasonal fluctuations as large as 7 ft have been measured beneath South Plants. Historical water level fluctuations have been large in the vicinity of Basin C. Basin C held water during 1957, 1958, 1966, 1967, and the consecutive years beginning in 1969 and ending in 1974. During these years, water levels beneath Basin C rose 20 to 30 ft in response to artificial recharge. Present day recharge to the Unconfined Flow System occurs as infiltration of precipitation and irrigation (off-post), seepage from lakes and streams, seepage from reservoirs, canals and buried pipelines, and flow from the underlying Denver aquifer. Discharge occurs primarily as seepage to lakes and the South Platte River.

Mass balance calculations have been used to estimate rates of hydraulic interchange between lakes and the Unconfined Flow System. Results indicate that Lower Derby Lake, Havana Pond, and Basins A through C are areas of groundwater recharge, whereas Lake

Ladora, Lake Mary, and Basin A receive groundwater in upstream areas and lose it in downstream areas. Recharge-discharge conditions at Upper Derby Lake depend on lake level. Streamflow loss and gain studies indicate that all streams and canals at RMA lose water to the Unconfined Flow System over the course of a water year. However, actual recharge or discharge rates vary substantially in response to changes in stream discharge and aquifer head. During periods of negligible streamflow, First Creek north of the RMA boundary gains groundwater at a small rate.

A numerical model of groundwater flow in the Unconfined Flow System has been developed to evaluate hydrologic concepts and refine hydraulic conductivity estimates. Model calibration consisted of adjusting hydraulic parameters until simulated hydraulic head adequately reproduced measured water levels. With few exceptions, model calibration was achieved without modifications to initial estimates of hydraulic parameters. Model results confirmed that paleochannels and terrace deposits generally convey larger flows than interfluvial zones. Hydraulic conductivity estimates in the Basin A Neck and areas immediately northwest obtained during model calibration were smaller than initial estimates. Sensitivity analyses indicated that the areas of greatest model uncertainty within the boundaries of RMA are near South Plants and Basins A through F.

It should be recognized that the regional groundwater flow model referenced in this report represents only one solution to flow in a very complex system. Due to the fundamental nonuniqueness inherent in all distributed parameter models, values calculated from the regional groundwater flow model are subject to uncertainty, and the model in its present form may not be sufficiently accurate for predictive purposes in all cases. Therefore, until such time as the model is refined and discrepancies resolved, extreme care should be used for modeling mass transport, determining boundary conditions for local models, or evaluating the effectiveness or regional impacts of remediation alternatives.

The Denver aquifer in the vicinity of RMA consists of parts of the Denver Formation where water is under confined conditions. Generally, confined conditions are observed within permeable sandstone or lignitic beds that are separated from the Unconfined Flow System by relatively impermeable shale or claystone. The hydraulic conductivity of the shale and claystone matrix is small, probably 10^{-2} to 10^{-4} ft/d. The hydraulic conductivity for sandstone in the Denver aquifer has been estimated by pumping test analyses to range from 1.1 to 7.7 ft/d. The hydraulic conductivity of fractured lignitic beds may be an order of magnitude greater than the hydraulic conductivity of sandstone.

Hydrogeologic cross-sections and potentiometric surface maps indicate that there is potential for groundwater in the Denver aquifer to move downward and laterally toward the northwest. The smaller hydraulic conductivity of shale relative to sandstone, as well as the stratification of the Denver aquifer, probably restricts the rate of vertical flow while enhancing lateral flow. Water in transmissive strata of the Denver aquifer probably returns to the Unconfined Flow System by lateral flow in areas where the elevation of the bedrock varies appreciably in a short distance and the transmissive strata subcrop. Initial efforts to estimate rates of hydraulic interchange have been based on an assumption that flow from the Denver aquifer to the Unconfined Flow System occurs in all areas of subcropping sandstone.

A cross-sectional numerical model was developed to gain a better understanding of flow mechanisms within the Denver aquifer. The model was constructed approximately along a flow path from Upper Derby Lake to the Basin A Neck. A variety of layered heterogeneous flow systems were hypothesized and simulations for each system were completed. Results indicate that shale and claystone layers have low vertical hydraulic conductivity and provide a high degree of confinement within the Denver aquifer. Hydraulic conductivity of sandstone was estimated during model development to range from 0.3 to 3.0 ft/day and hydraulic conductivity of lignitic beds was estimated to be an order of magnitude greater.

Nature and Extent of Contamination

The nature and extent of contamination is based primarily on analytical results from Third Quarter FY87 sampling. These results have been compared to previous water quality data when appropriate. In this report, individual analytes have been consolidated into composite groups on the basis of analytical methodology. Individual analytes within a group generally have similar physical and chemical characteristics.

Areas where surface water contamination was detected during the Third Quarter FY87 sampling period include South Plants, Basin A, and the sewage treatment plant. Organochlorine pesticides and organosulfur compounds were the most frequently detected analytes. Fewer contaminants were detected from water entering RMA along the Peoria

Interceptor. Comparisons of Third Quarter FY87 data with previously collected data indicate that there is little difference in analyte concentration at a site through time.

Groundwater contaminant pathways have been identified primarily on the basis of plume configuration. Pathways conform to groundwater flow lines that have been inferred from the potentiometric surface map of the Unconfined Flow System. Pathway names are based on proximity to well known fractures and may not indicate the source of a particular contaminant plume. Contaminant pathways include South Plants, Basin A-Basin A Neck, central, Basin F, western tier, and motor pool and railyard. Several secondary pathways and off post pathways also have been named.

The majority of contamination by organic compounds occurs in the Unconfined Flow System. Volatile halogenated organic plumes have been identified along all major pathways with peak concentrations of 39,800 micrograms per liter (ug/l) the Basin F pathway. Peak concentrations of 56,200 ug/l have been detected near Basin A for volatile aromatic organics. Plumes of volatile aromatic organics occur along South Plants, Basin A-Basin A Neck and Basin F pathways. Plumes of organosulfur compounds occur along the Basin A-Basin A Neck and Basin F pathways. Plumes of diisopropylmethyl phosphonate are more extensive than other organic compounds and have been identified along all major pathways. Peak concentration is 5,200 ug/l. Plumes of organochlorine pesticides with peak concentrations greater than 1.0 ug/l have been identified in the South Plants, Basin A-Basin A Neck, central, and Basin F pathways. Organic plumes have also migrated along off-post pathways.

Inorganic contaminants that are areally extensive in the Unconfined Flow System include arsenic, fluoride, and chloride. Arsenic plumes have been delineated in the Basin A-Basin A Neck and Basin F pathways. A 410 mg/l peak concentration of arsenic occurred in the Basin F pathway. Fluoride concentrations greater than 5,000 ug/l were measured in the vicinity of Basin A and Basin F. Chloride concentrations greater than 1,000,000 ug/l were measured along the Basin A-Basin A Neck, central, and Basin F pathways. The distribution of inorganic contaminants is complicated by the natural occurrence of these substances.

Concentrations of organic compounds in the Denver aquifer generally are less than concentrations in the overlying Unconfined Flow System. Volatile aromatic organics and diisopropylmethyl phosphonate have been identified over a more extensive area than other organic groups. Organosulfur compounds are common in upper stratigraphic zones of the Denver aquifer beneath the Basin A-Basin A Neck pathway and beneath Basin C. Organochlorine pesticides generally occur in isolated areas, rather than plumes. Other organic compounds occur only in isolated areas. In Sections 1, 2, 3, 9, 19, 23, 24, 26, 27, 33, 35, and 36 samples from the deepest wells in the Denver aquifer contained measurable concentrations of one or more organic contaminants. Organic analytes detected in water from deeper stratigraphic zones of the Denver aquifer generally have been located in the area between Basin F and off-post Sections 13 and 14 (T2S R67W).

Inorganic analytes above background levels have been detected in water of the Denver aquifer; however, concentrations generally decrease with increasing depth. Concentrations of chloride in the Denver aquifer north and northwest of Basin F are less than 15,000 ug/l. Fluoride concentrations in this area are less than 2,500 ug/l. Chloride concentrations in the Denver aquifer beneath Basin A-Basin A Neck are generally less than 250,000 ug/l. Fluoride concentrations in this area are generally less than 2,000 ug/l.

Contamination Assessment

Changes in contaminant concentrations of groundwater at RMA are due to advective transport, hydrodynamic dispersion, dilution, and several hydrochemical processes. Advection is migration at the average rate of water molecules and is described by the average linear velocity of groundwater flow. Descriptions of migration due to advection along selected flow paths are given later in this section. Hydrodynamic dispersion describes deviations from the average rate of migration. While regional assessments of dispersion have been completed, evaluations along specific flow paths have not been attempted. Changes in concentration due to dilution are important in areas where potentiometric surface maps show converging flow paths. The predominant hydrochemical processes affecting changes in contaminant concentration are sorption, vaporization, and degradation. Distribution coefficients (K_d) for RMA contaminants indicate that organochlorine pesticides are generally strongly sorbed while organosulfur compounds are generally weakly sorbed. Volatile aromatic organics and volatile halogenated organics tend to vaporize readily to the unsaturated zone.

Contaminant migration from the South Plants area occurs along several pathways. Pathways radiate in several directions from a water table mound beneath South Plants.

Numerous contaminants have been detected along a pathway from South Plants toward Basin A. Contaminants include organochlorine pesticides, organosulfur compounds, volatile halogenated organics, volatile aromatic organics, and others. Estimates of groundwater travel time from the center of the water table mound beneath South Plants to the center of Basin A range from 1.6 to 115 years. Volatile halogenated organics and volatile aromatics occur as plumes along a pathway from South Plants through unconfined Denver Formation toward Ladora Lake. Estimates of groundwater travel time from the center of the water table mound to Ladora Lake range from 2.8 to 249 years.

Contaminant migration from Basin A is principally toward the northwest in a small area of saturated alluvium called the Basin A Neck. Secondary pathways trending generally north from the Basin A-Basin A Neck also may exist in unconfined parts of the Denver Formation. Groundwater contaminants that occur in greatest concentrations along the Basin A-Basin A Neck pathway include dithiane, oxathiane, benzene, chlorobenzene, chloroform, diisopropylmethyl phosphonate, fluoride, and chloride. Estimates of groundwater travel time from Basin A to the downgradient end of Basin D range from 1.5 to 44.5 years. Dithiane and oxathiane are weakly sorbing contaminants and have been used to compare average linear velocity and groundwater travel time calculated from available hydraulic information with actual contaminant travel time. The comparison was most favorable when assuming an effective porosity of 0.20 and a hydraulic conductivity of 29 ft/day..

Contaminants moving through the Basin A Neck continue to migrate along one of several central pathways toward the Northwest Boundary Containment System. Other central pathways originate near the Sand Creek Lateral or Basin F and also trend toward the Northwest Boundary Containment System. Hydraulic conductivity is less and hydraulic gradient is greater along the upgradient part of these pathways than along the downgradient part. Estimates of groundwater travel time from the downgradient end of Basin D to the Northwest Boundary Containment System range from 0.2 to 41 years. Calculated groundwater travel time along these pathways compares well with travel time of contaminants that are weakly adsorbed. The comparison with diisopropylmethyl phosphonate was most favorable when assuming an effective porosity of 0.20 and a hydraulic conductivity range between 15 and 20 ft/day.

Contaminant migration from source areas beneath Basin C and the Basin F area occurs in alluvial material and weathered bedrock. The Basin F pathway trends north to the North Boundary Containment System. Most target contaminants occur near Basin F or along the Basin F pathway. Saturated thickness along the pathway typically is less than 10 ft and hydraulic gradients are very low. Saturated thickness and hydraulic gradients in recent years are substantially less than gradients from 1957 to 1971 when Basin C was used as an artificial recharge basin. Assuming an effective porosity value between 0.1 and 0.3, and hydraulic conductivity between 30 and 900 ft/day, present day groundwater travel time from Basin F to the North Boundary Containment System ranges from 1.1 to 99 years. Groundwater travel time during periods when Basin C was used as a recharge basin probably was 3 to 5 times shorter.

Three major pathways of contaminant migration have been identified in the western tier. Trichloroethylene is the primary contaminant detected in all pathways. Dibromochloropropane has been detected along one pathway. Groundwater contained in these pathways occurs in deposits of permeable sand and gravel. Hydraulic conductivity is large and hydraulic gradients are correspondingly small. Average linear velocity along these pathways is the highest of all pathways considered in this report. Groundwater travel time from the motor pool and railyard areas to the Irondale Containment System is estimated to be between 0.44 and 8.6 years. Groundwater travel time from the southern boundary of RMA to the Irondale Containment System is estimated to range from 3.5 to 6.8 years. Average linear velocities are similar along the western tier pathway and off-post western tier pathway.

1.0 INTRODUCTION

1.1 Purpose

The purpose of the Water Remedial Investigation is to present the U.S. Department of the Army's Remedial Investigation results for the Rocky Mountain Arsenal (RMA) on-post water media. This document is a formal Remedial Investigation product prepared in accordance with the Federal Facility Agreement (1989), the RMA Technical Program Plan (TPP), (Program Manager's Office, PMO, 1988/RIC88131R01), and the June 1985 RI Guidance Document (U.S. Environmental Protection Agency, EPA). This report is one of the four Media Remedial Investigation reports (water, air, buildings, and biota) and seven Regional Remedial Investigation Study Area Reports (SARs) prepared to define the nature and extent of contamination and complete a comprehensive Remedial Investigation for the On-Post Operable Unit of RMA as required by the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act (SARA), and the National Contingency Plan (NCP). The Water Remedial Investigation is a compilation, integration, and interpretation of groundwater and surface water study results obtained from specific tasks designed to provide a comprehensive assessment of contaminant occurrence at the site. This report was prepared under contract numbers DAAA15-88-D-0024 and DAAK11-84-D-0016.

The report provides a general overview of contamination in water at RMA. It is not intended to be the only source of information for Feasibility Study. The USATHAMA database, and other detailed investigations also are appropriate sources of information.

1.2 Scope of Work

Recent Media Remedial Investigation efforts have focused on assessing air, biota, buildings, and water contamination at RMA. The Air Remedial Investigation (ESE, 1988d/RIC88263R01) assessed airborne contaminant occurrences and established ambient air quality conditions for RMA. The Biota Remedial Investigation (ESE, 1989a/RIC89054R01) studied the presence and effect of potential contamination on plant and animal communities of RMA. The Buildings Remedial Investigation (Ebasco, 1988c/RIC88306R02) carefully documented structure use history, which, combined with a limited sampling effort, was used to assign contamination classifications to the structures. This report discusses contaminant occurrence and distribution within groundwater and surface water at

RMA. Volume I presents an introduction to the project (Section 1); then describes the environmental setting (Section 2), nature, and extent of contamination (Section 3), and concludes with an assessment of contamination (Section 4). Volume II comprises supporting data for Volumes I and III. These supporting data are presented in Appendices A through E, and include geologic and hydrologic data, Task 44 data, chemistry data, and information pertaining to hydrochemical properties and hydrologic calculations. Volume III comprises Appendix F, which is a detailed description of geology, hydrology, contaminant distribution, and historical groundwater and surface water programs found in Volume 1. Volume 4 contains comments and responses on the Draft Final Water Remedial Investigation Report, Version 2.2. Volume 5 contains Plates 1 through 17, which are referenced in Volumes I and III.

The Water Remedial Investigation assesses contaminant occurrence and distribution within the boundaries of RMA and in areas that are hydraulically downgradient. Hydraulically downgradient areas are northwest of RMA and are bounded on the northeast by Second Creek and on the northwest by the South Platte River. Therefore the study area described in this report is bounded by the southern and eastern boundaries of RMA, Second Creek, and the South Platte River.

1.3 Methodology

In 1985 the Army created a separate office, the Program Manager's Office for the Rocky Mountain Arsenal Contamination Cleanup, to specifically deal with contamination problems at RMA. This office awarded contracts to two consultant teams, Environmental Science and Engineering (now Hunter/ESE) and Ebasco Services Incorporated to define the nature and extent of contamination at the site and to provide litigation support for the U.S. Department of Justice.

Task order contracts were developed for the consultant teams with general objectives to conduct an environmental program to define the nature and extent of contamination and select remedial action alternatives to mitigate contamination problems. Survey elements include the Remedial Investigation, Endangerment Assessment (EA), and Feasibility Study (FS). Twenty-three of the tasks involving water data acquisition or interpretation were utilized in the Water Remedial Investigation report. All tasks were completed in September 1988.

1.4 Overview

RMA occupies over 17,000 acres in Adams County, Colorado (Figures 1.1 and 1.2), and is located approximately 10 miles northeast of downtown Denver. Stapleton International Airport extends into the southern border of the RMA (Figure 1.1). Land use along the remaining boundaries includes residential, light industrial manufacturing, and agricultural. Residential population in the vicinity is concentrated to the west with a total of approximately 1.5 million within 15 miles of the RMA boundary.

Military History: RMA was established in 1942 by the U.S. Department of the Army as a manufacturing facility for the production of chemical and incendiary munitions. During World War II, chemical intermediate munitions, toxic products, and incendiary munitions were manufactured and assembled by the Army. From 1945 to 1950, stocks of Levinstein mustard were distilled, mustard-filled shells were demilitarized, and mortar rounds filled with smoke and high explosives were test-fired. Various obsolete ordnance were also destroyed by detonation or burning during this period.

In the early 1950s, RMA was selected to produce the chemical nerve agent GB (Sarin) under U.S. Army operations. The North Plants manufacturing facility was completed in 1953 and was used to produce agents until 1957. Munitions-filling operations continuing until late 1969. Primary activities between 1969 and 1984 involved the demilitarization of chemical warfare materials.

Industrial Use History: Concurrent with military activities, industrial chemicals were manufactured at RMA by several lessees from 1947 to 1982. In 1947, portions of the site were leased to the Colorado Fuel and Iron Corporation (CF&I) for chemical manufacturing of chlorinated benzenes, DDT, naphthalene, chlorine, and fused caustic. Between 1947 and 1949, Julius Hyman & Company manufactured chlordane. Between 1947 and 1952, Julius Hyman & Company developed and initiated the manufacture of Aldrin and Dieldrin and conducted pilot studies on Endrin. In late 1949, Julius Hyman & Company leased portions of the property previously covered by the CF&I lease. In May 1952, Shell Chemical Corporation (Shell) acquired Julius Hyman & Company and operated this company as a wholly owned subsidiary until 1954 at which time Hyman was integrated into the Shell corporate structure as the Denver Plant and Shell succeeded Hyman as the named lessee by amendment to the original lessee. Shell conducted manufacturing operations at the site until 1982, producing a variety of insecticides, herbicides, nematocides, and other compounds such as adhesives, anti-icers, and lubricating greases.

Litigation History: In May of 1974, diispropylmethyl phosphonate and dicyclopentadiene were detected in surface water at the northern boundary. Later that year, the Colorado Department of Health (CDH) detected diispropylmethyl phosphonate in a well north of the site and issued three administrative orders directed against Shell and/or the Army in April of 1975. These orders, commonly referred to as the "cease and desist orders", directed Shell and the Army to:

- Take steps, as necessary, to cease and desist from all unauthorized discharges to the waters of the state;
- File an application for a discharge permit;
- Establish a groundwater surveillance program;
- Maintain monitoring and sampling records; and
- Report the results of monitoring to the state.

In response to the cease and desist orders, a regional sampling and hydrogeologic surveillance program was initiated requiring quarterly collection and analysis of over 100 on-post and off-post surface water and groundwater samples. This program was carried out under the auspices of the Contamination Control Program, established in 1974 to ensure compliance with Federal and State environmental laws. Since 1975, numerous other programs have been implemented to monitor surface water and groundwater.

Two lawsuits were filed in December 1983 as a result of contamination at RMA. The first was brought by the State of Colorado against the United States of America and Shell for natural resource damages both on and off the site, and for response costs under CERCLA. The second was filed by the United States against Shell for response costs and for natural resource damage at RMA. The United States and Shell have entered into a Federal Facility Agreement and a Settlement Agreement that, among other things, establish procedures for assessment, selection, and implementation of response actions resulting from the release or threatened release of hazardous substances at or from the Arsenal and set forth the terms and conditions for payment of response costs by the Army and Shell.

1.5 Problem Definition

As a result of military and industrial activities, on-post soils, groundwater, and surface water became locally contaminated. With time, contaminants entered the groundwater and surface water systems and migrated on-post and to an extent off-post, creating a threat to shallow water wells immediately downgradient of RMA boundaries. Soil and water contamination on-post resulted from routine disposal of waste effluent to unlined and lined basins, leaking sewer lines, and unintentional spills of raw materials, process intermediates, and end products from the manufacturing complexes. Disposal practices at RMA consisted of routine discharge of military and industrial waste effluents to lined and unlined evaporation basins and burial of solid wastes at various locations. Fluctuations in disposal volumes, leaking sewers, and leaking process water distribution and return lines have influenced the groundwater regime by artificially recharging the hydrogeological system, locally raising the water table (causing "mounding") and increasing contaminant transport velocities downgradient.

The number and concentration of contaminants present in RMA groundwater have changed through time. Factors contributing to these changes include variations in operational activities, procedures for handling materials and wastes, and physicochemical properties for contaminants. In addition, environmental and climatic changes have changed the variety and concentration of contaminants.

1.6 Previous Investigations

Numerous investigations have been conducted historically at RMA for the purposes of defining the hydrogeologic system and identifying Arsenal-related toxic constituent(s) in the ground and surface water. In addition, during the course of active operations at RMA, the U.S. Army has undertaken various projects designed to ameliorate the effects of the contamination of ground and surface waters caused by Arsenal-related compounds and to halt further contamination. In June 1954, farmers located north of RMA began complaining of crop damage, the result of purportedly polluted irrigation water drawn from wells drilled into the Alluvial Aquifer. In the summer and fall of 1954, the U.S. Army Corps of Engineers conducted resistivity studies for the purpose of determining the direction of groundwater flow north from RMA and chemical analyses of samples of water from the affected wells. The resistivity studies indicated groundwater flow in the direction of those areas suffering crop damage. Laboratory analyses of water drawn from wells north of RMA revealed high concentrations of chlorides and sulfates. In February 1955, the Corps of Engineers issued contracts to the U.S. Geological Survey (USGS) to investigate the sources and the extent of contamination in the Alluvial Aquifer and to the Ralph M. Parsons Company (Parsons Co.) to undertake a study of waste disposal practices at RMA and to recommend, on the basis of this study, an economical and environmentally safe method for the disposal of large volumes of liquid waste. The Parsons Co. was also tasked with attempting to identify which chemical compounds, if any, in RMA wastes were responsible for the crop damage occurring north of the Arsenal.

The USGS study completed in August, 1956 concluded that unlined solar evaporation ponds at RMA were the probable source of a one-half mile wide flow of highly saline groundwater extending north from the Arsenal to the areas affected by crop damage. However, the USGS study was unable to identify the specific phytotoxicants responsible for the crop damage. The recommendations of the Parsons Co. issued in September 1955 in conjunction with concurrent studies by the U.S. Army Chemical Corps prompted the Army in 1956 to build Basin F, a 93 acre solar evaporation pond lined with a 3/8-inch catalytically blown asphalt membrane, for the disposal of process liquid industrial wastes and to cease forever the use of unlined basins for this purpose. Basin F, completed in the fall of 1956, was used continuously until December, 1981. Except for a short period in the spring of 1957 while repairs were performed on the liner of Basin F, no further utilization of unlined basins for the disposal of liquid waste occurred at RMA. In 1958 and 1959 researchers at the University of Colorado, contracted by the Army in 1956, working in cooperation with personnel from the Army Chemical Research Development Laboratory at Ft. Detrick, identified the chlorate ion and an unknown substance similar to the herbicide, 2,4-D as the phytotoxicants in the groundwater responsible for the crop damage north of RMA. "In 1961, in response both a 1959 U.S. Public Health Service finding of Arsenal culpability for contamination of the Alluvial Aquifer north of RMA and to a need for additional waste disposal capacity, the Army built a deep well designed to provide environmentally safe disposal through pressure injection of treated liquid wastes into sub-surface formations at a depth of 12,045 feet. Beginning in 1962, the deep well was used intermittently along with Basin F for liquid waste disposal until 1966 when public fears of a connection between deep well operations and atypically intense local earth tremors in the Denver area prompted its closing."

Significant studies conducted at RMA between 1955 and 1974 for the purposes of defining the hydrogeologic system and identifying toxic constituents(s) in the surface and ground water include:

- L.R. Petri and R.O. Smith, Water Quality Division, Geological Survey U.S. Department of the Interior, Investigation of the Quality of Ground Water in the Vicinity of Derby, Colorado, August 1, 1956, CSD 017 0591-0684;

- U.S. Army Corps of Engineers, Omaha District, Report on Ground Water Contamination, Rocky Mountain Arsenal, Denver, Colorado, September 1955;

- Ralph M. Parsons, Co., Final Report Disposal of Chemical Wastes, Rocky Mountain Aresenal, September 29, 1955, RNA002 0928-1007.

- E. Bonde, P. Urone, T. Walker, University of Colorado, Research on Phytotoxic Materials (sponsored by the U.S. Army Chemical Corps, Contract DA-05021-CML-10-092), Interim Reports, 1 July, 1 September, 1 December 1956; 1 January thru 1 December 1957; 1 January thru 1 December 1958; 1 January thru 1 May 1959; 1 May thru 31 May 1959; 1 June thru 30 June 1959; 1 July thru 31 July 1959; 1 August thru 31 August 1959; 1 September thru 30 September 1959; 1 October thru 31 October 1959; 1 November thru 30 November 1959; 1 December thru 31 December 1959; Final Report on Research on Phytotoxic Materials, 1 June 1956 thru 31 December 1959;

- Robert L. Weintraub, U.S. Army Biological and Chemical Research Laboratory, Ft. Dedrick, Md., "Toxicity of Rocky Mountain Arsenal Waste," Status Report, 25 May 1959;

- Graham Walton, Engineering Section, Water Supply and Water Pollution, Research Branch, U.S. Department of Health, Education and Welfare, Public Health Aspects of the Contamination of Ground Water in South Platte River Basin in Vicinity of Henderson, Colorado, August 1959, November 2, 1959, RMA 062 0255-9282;

- Public Health Service, Division of Water Supply and Pollution Control, South Platte River Basin Project, U.S. Department of Health, Education and Welfare, Ground Water Pollution in the South Platte River Between Denver and Brighton, Colorado, December 1965, RIC 85007R02; and

- U.S. Army Environmental Hygiene Agency, Water Quality Geohydrological Consultation No. 24-012-74, Rocky Mountain Arsenal 30 July - 3 August 1973, July 10, 1974, RAA 0230734-0821.

In response to the problems highlighted in the cease and desist orders described previously, the Army beginning in 1975 through the Contamination Control Program implemented a regional sampling and hydrogeologic surveillance program requiring collection and analysis of over 100 on-post and off-post surface water and ground water samples. The surveillance monitoring program for Basin F, on-going since at least 1962, was augmented in 1975 with the addition of four wells and expanded study. Shell also implemented a number of ground water monitoring programs on-post, most notably in the South Plants and the Railroad Classification Yards areas. Additional studies, directed by the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) were conducted to identify, control and treat pollutants. To mitigate problems associated with contaminant migration off-post, three ground water treatment systems were installed by the Army and Shell between 1978 and 1984 at the northern and northwestern property boundaries of RMA to intercept and treat contaminated ground water and re-inject the treated water into the subsurface. In 1982, the chemical sewer interceptor lines to Basin F were removed, the Basin was diked to prevent the intrusion of surface run off, and an enhanced evaporation system was installed to aid in the reduction of the ponded liquid contents to manageable volumes prior to removal.

The first overall data assessment was performed by Geraghty & Miller, Inc., in 1981 (Stollar and van der Leeden, 1981/RIC81293R05) and a site-wide hydrogeologic study was recommended as a result of this study. This recommended study was performed by the U.S. Army Corps of Engineers Waterways Experiment Station for the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA).

U.S. Army Corps of Engineers Waterways Experiment Station studied groundwater flow directions and volumes in various geographical areas and identified areas where the shallow Quaternary age alluvium is in direct contact with underlying permeable sandstones of the Cretaceous to Tertiary age Denver Formation. This finding indicates that the alluvium and the Denver Formation are locally in hydrogeologic communication and that there is potential for contaminant transport between the units (May, 1982/RIC82295R01).

In 1982, contaminant source control strategies for RMA and assessment of associated remediation costs were developed by the Army through the Contamination Control Program. The first report issuing from this two and one-half year study, titled, "Selection of a Contamination Control Strategy for RMA" (RMACCPMT, 1983/RIC83326R01), was generated by the RMA Contamination Control Program Management Team (RMACCPMT) in 1983 and delineated the procedures for the development of a contamination control strategy. This report documented the results of a two and one-half year study of potential contamination control strategies that would ensure compliance with state and Federal statutes pertaining to the release of pollutants into the environment. The report also included an extensive technical review and analysis of migratory pathways of hazardous contaminants and their sources; an assessment of applicable environmental laws; development of corrective strategies within available technology; screening and evaluation of alternative strategies; and the selection of a preferred strategy.

A second report titled, "Decontamination Assessment of Land and Facilities at RMA" (RMACCMPT, 1984/RIC84034R01) was developed by the Army for planning purposes. It identified and classified over 150 potential contamination sites and provided a preliminary assessment of the extent, probable use, boundaries, and possible contamination profile of the sites. This report was developed based upon personnel interviews and upon information contained in the first report. Study results were not field verified. The report also discussed environmental laws affecting decontamination activities and evaluated technical approaches for attaining decontamination.

In 1985, as described previously, the Army through the Program Manager's Office for Rocky Mountain Arsenal Contamination Cleanup, inaugurated a services of investigations designed to define the nature and extent of contamination at RMA and to select remedial action alternatives to mitigate contamination problems. The investigations of ground water and surface water conducted under this program form the subject matter of this report.

As a post-Remedial Investigation program to provide long-term hydrogeologic information at RMA, the Comprehensive Monitoring Program was developed. This verification monitoring program was designed to provide both regional monitoring and site and/or source monitoring, as well as long-term hydrogeologic monitoring in both the on-post and off-post areas.

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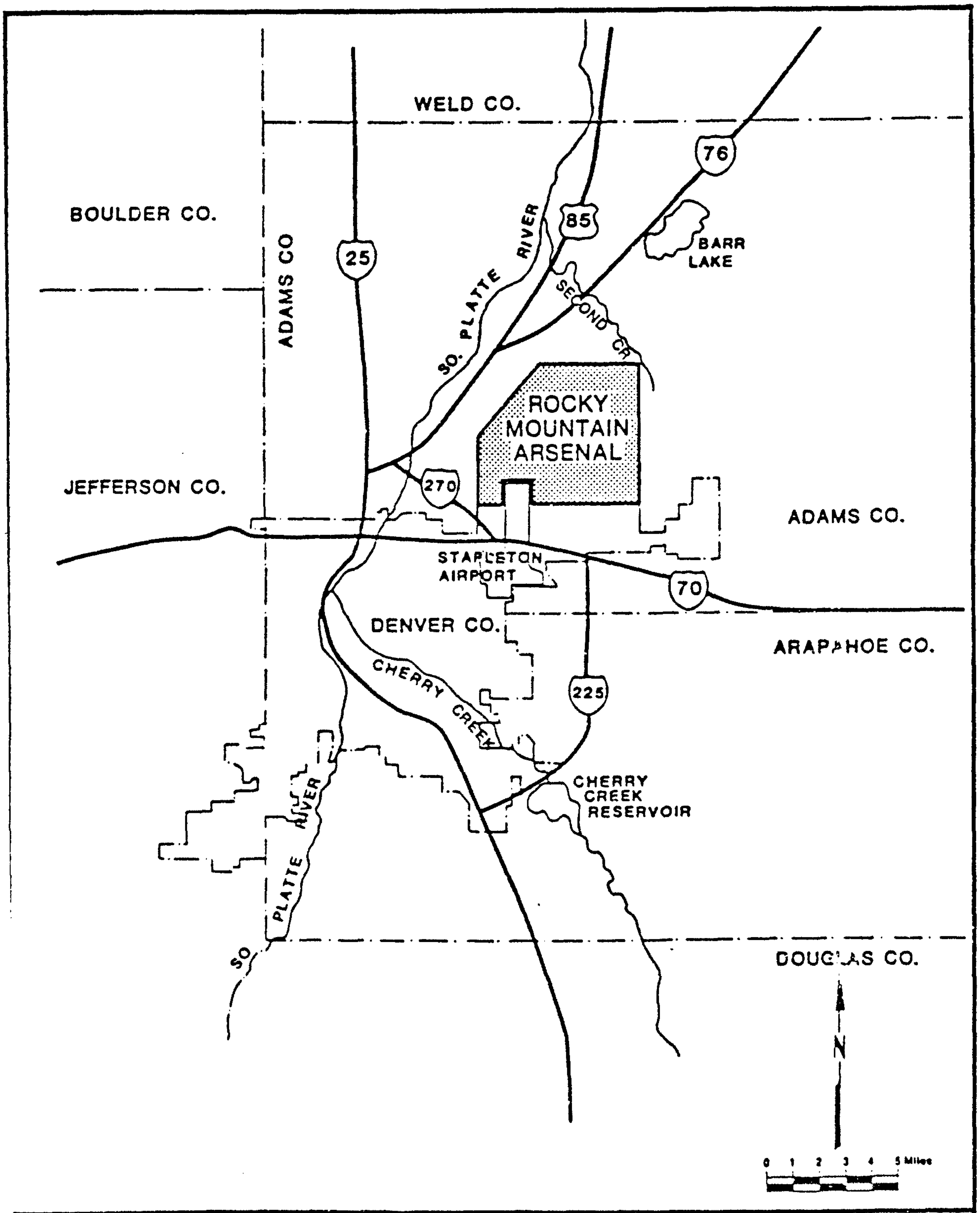


Figure 1.1
LOCATION MAP OF
ROCKY MOUNTAIN ARSENAL
SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

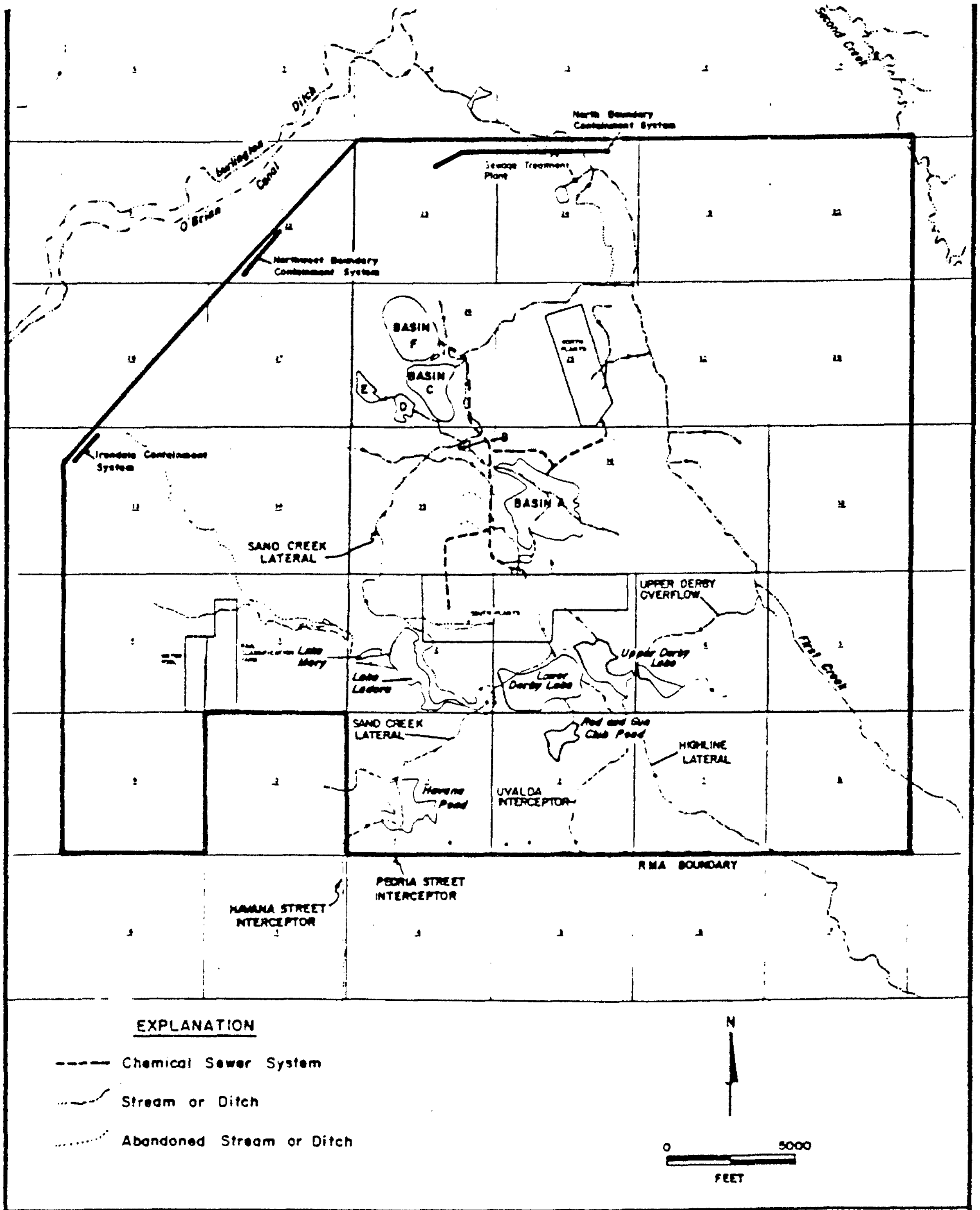
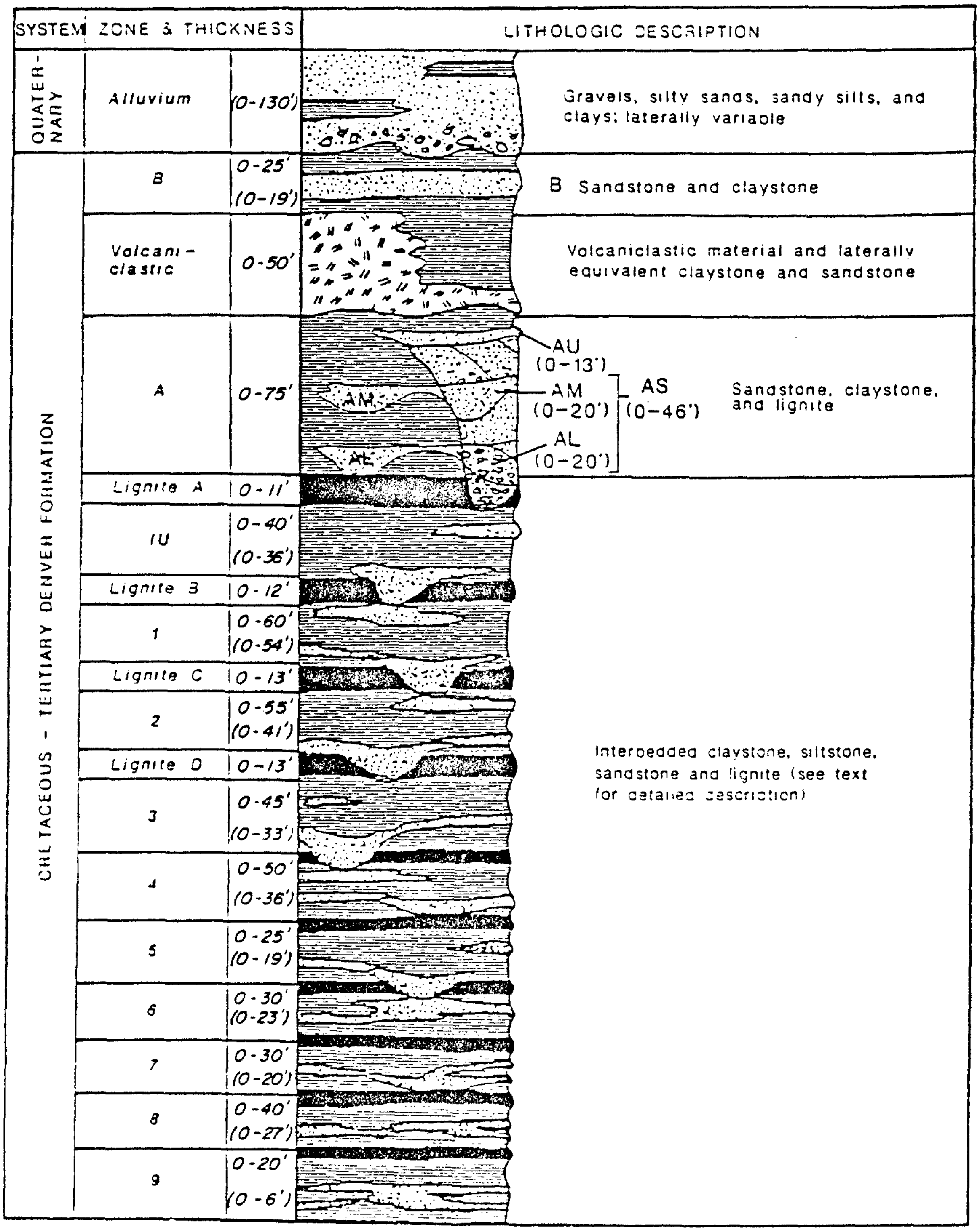


Figure 1.2

SIGNIFICANT FEATURES AT ROCKY MOUNTAIN ARSENAL

SOURCE: R.L. Stoller & Assoc., 1990

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland



NOTE Not to Scale. Net Sandstone Thickness Shown in Parentheses.
Thickness for Zone 5 through Zone 9 based on limited data.

Figure 2.1

RMA STRATIGRAPHIC COLUMN

SOURCE: HLA, Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

2.0 ENVIRONMENTAL SETTING

Contaminant distribution is controlled in part by the physiographic, geologic, and hydrologic characteristics of RMA and vicinity. The purpose of this section of the report is to describe these characteristics in sufficient detail to understand contaminant occurrence and migration. Subsequent sections of the report will describe contaminant occurrence and relate occurrence to physiographic, geologic, and hydrologic characteristics.

2.1 Physiography

RMA is part of the High Plains physiographic province and is characterized by gently rolling hills. The land surface slopes from southeast to northwest with a total change in altitude of 220 ft. Short grass prairie and disturbed grasslands predominate in the northern part of RMA while lakes, wetlands, and small areas of woodland are present in southern and eastern areas.

Average annual precipitation is approximately 15 inches with annual variations from approximately 7.5 to 23 inches. Approximately 50 percent of annual precipitation occurs between April and July. Snow accounts for approximately 30 percent of annual precipitation. Frequent summer thunderstorms result in substantial variations in precipitation over short distances. Average annual potential evaporation is 38.5 inches based on a 27 year average for Cherry Creek Reservoir (COE, 1987). Large seasonal fluctuations in air temperature are common. The lowest recorded temperature was -30°F and the highest recorded temperature was 104°F (1936). Prevailing winds are from the south and southwest.

2.2 Surface Water Hydrology

Surface water at RMA flows within several small drainage basins that are tributaries of the South Platte River (Figures 1.1 and 1.2). The major drainages within RMA are First Creek and Irondale Gulch. Man-made structures including diversion ditches, lakes, and water retention basins have modified the natural drainage patterns. Culverts, sewers, and similar control structures also have been constructed.

First Creek drains an area of approximately 27 square miles upstream of RMA and approximately 12 square miles within the boundaries of RMA. First Creek discharges into O'Brian Canal approximately 0.5 miles north of RMA. Streamflow data for water years 1986 and 1987 indicate that mean monthly discharge of First Creek decreased from 82.2 acre-ft/mo where the stream enters RMA to 69.3 acre-ft/mo where it leaves RMA. Mean monthly discharge of First Creek at Highway 2 was 24.7 acre-ft/mo. There are no major diversions of surface water from First Creek. Streamflow in First Creek varies substantially during the water year. Extended periods with little or no flow are common.

The Irondale Gulch basin drains an area of approximately 11.5 square miles upstream of RMA and 6.5 square miles within the boundaries of RMA. Four lakes and several other impoundments within the basin are located on RMA. The Havana and Peoria Interceptors, North and South Uvalda Street Interceptors, and Highline Lateral deliver water from south of RMA to the lakes and impoundments. Sand Creek Lateral diverts water from Havana Pond and Lower Derby Lake during periods of high lake level, collects additional runoff from the South Plants area, and flows north out of the Irondale Gulch drainage toward First Creek. Natural stream channels are poorly defined or lacking over most of the Irondale Gulch Basin partly as a result of moderate to high rates of soil infiltration. Streamflow statistics for man-made channels in the basin are summarized in Table 2.1. Gaging station locations are shown in Appendix F, Figure 2.3-2.

Lakes, in downstream order at RMA, are Upper and Lower Derby Lakes, Ladora Lake, and Lake Mary. Ladora Lake and Lower Derby Lake were irrigation reservoirs prior to the construction of RMA. In 1942, the Army modified both reservoirs to enlarge their holding capacities and, in addition, built Upper Derby Lake. Lake Mary was constructed in 1960 as a recreational fishing area. Havana Pond receives water from interceptor channels. The Rod and Gun Club Pond receives water from Lower Derby Lake via a ditch bisecting a lake sludge disposal site, although water levels in Lower Derby Lake are generally below the ditch bottom elevation. Storage capacity of the lakes varies from 60 acre-ft for Lake Mary to 970 acre-ft for Lower Derby Lake. Stage fluctuations have been monitored on a regular basis to aid in evaluating hydraulic interchange of surface water and groundwater.

Six basins, designated Basin A through Basin F, were constructed for retention of process waste, wastewater, and storm runoff. Each basin is a natural topographic depression that has been modified by berms and other structures. Of the six basins,

Table 2.1 Streamflow Statistics for Gaging Stations at RMA During Water Years 1986 and 1987

Station	Mean Monthly (ac-ft/mo)	Maximum Instantaneous (cfs)	Minimum Instantaneous (cfs)	WY86 Total** (ac-ft)	WY87 Total** (ac-ft)
Peoria Intercept	11.7	230	0	92	211
Havana Intercept	98.4	677	0	1,088	1,276
Ladora Weir	8.4	16	0	76	141
South Uvalda	52.2	202	0.2	621	
North Uvalda	53.1	55	0	688	659
Highline Lateral	29.6	14.4	0	308	462
South First Creek	82.2	380+	0	1,006	1,003
North First Creek	69.3	213	0	1,068	733
South Plants Ditch	0.0	Trace	0	0	0
Basin A	0.8	5.6	0	9.6	10.4
First Creek at Hwy 2	24.7	23.2	0	*	413

ac-ft	acre foot
ac-ft/mo	acre foot per month
cfs	cubic foot per second
*	no data available
**WY	Water Year defined as October 1 through September 30

Source: ESE, 1988.

Basins A, C, and F had the largest storage capacities. Groundwater levels beneath Basin A are 1 to 4 ft below land surface.

Basin C was built in 1953 and from 1953 to 1956 collected wastewater overflow from Basins A and B, and wastewater diverted from the Sand Creek Lateral. Infiltration of fresh water in Basin C probably affected the historical groundwater flow directions in the area of Basins C and F, these effects are discussed in Section 4. Except for local runoff, Basin C has been dry since 1976.

Basin F, constructed between July and November 1956, was lined with a 3/8-inch catalytically blown asphalt membrane. Basin F was used for the disposal of liquid waste at RMA from 1956 to 1981. Storage capacity of Basin F was 746 acre-feet. An interim response action (IRA) was implemented in 1988 at Basin F to remove liquid and solid wastes to safe, temporary storage and to prevent the further migration of any contamination still present in the area of the basin until final remedial action is initiated. The project consisted of transferring the residual liquid to temporary storage tanks and a lined and covered pond; stabilizing the sludges, asphalt liner and some of the subliner soil, and placing the stabilized material in a double-lined waste pile constructed within the basin; and placing a clay cap over the entire excavation basin to minimize infiltration. Final closeout for this IRA is scheduled for July 1989.

2.3 Geology

The groundwater system at RMA is part of the Denver structural basin that extends from Colorado into Western Nebraska, Kansas, and Eastern Wyoming. Strata in the Denver basin with usable quantities of potable water are the Fox Hills Sandstone, Laramie Formation, Arapahoe Formation, the Denver Formation, and the Dawson Arkose. The Dawson Arkose is present only in the southern part of the Denver basin and is absent at RMA. Unconsolidated alluvial and eolian deposits are at land surface throughout most of RMA. The bedrock immediately underlying these deposits is the Denver Formation.

Alluvial and eolian deposits at RMA locally attain thicknesses of 130 ft; however, the thickness of these deposits is typically much less. Several prominent paleochannels with alluvial thickness varying from approximately 50 to 130 ft have been identified in the erosional surface of the Denver Formation. Thickness of alluvial and eolian deposits in other areas is generally less than 50 ft. Areas with less than 20 ft of alluvial and eolian deposits are common. One of these areas, called the Basin A Neck in Sections 35 and 36, probably has an important influence on contaminant migration at RMA.

Older alluvial units located in areas along the South Platte River west and northwest of RMA generally consist of coarse grained sand and gravel deposited during post-glacial periods. Eolian deposits and younger alluvial units are finer grained than older alluvial units. Coarse grained deposits generally occur within paleochannels, while fine grained material tends to blanket the entire area.

The Denver Formation underlying the alluvium consists of interbedded claystones, siltstones, sandstones, and organic-rich (lignitic) intervals. Water-bearing layers of sandstone and siltstone occur in irregular beds that are dispersed within relatively thick sequences of somewhat impermeable material. Individual sandstone layers are commonly lens shaped and range in thickness from a few inches to as much as 50 ft. Reliable correlation of individual sandstone layers between wells is generally good in areas such as South Plants and Basin A, where a thick lignite bed (LA) is present and provides a recognizable marker horizon. Correlations through other areas of RMA are more tenuous. Lignitic beds typically vary in thickness from 0 to 13 ft, are more continuous laterally than sandstone layers, and commonly are fractured. Low permeability volcaniclastic material is present in the upper part of the Denver Formation. The Denver Formation is 200 to 500 ft thick at RMA.

Stratigraphic zones within the Denver Formation have been identified on the basis of relatively continuous lignitic marker beds (Figure 2.1). Each zone consists of discontinuous sandstones separated by claystone. The interval of volcaniclastic material is identified as a separate stratigraphic zone. Data to map geologic characteristics of each zone are most common where the zone is shallow. Sandstone units in shallower zones vary in thickness from near 0 ft to greater than 50 ft. Sandstone units generally trend north to south.

Bedding planes in the Denver Formation dip approximately 1° to the southeast. Because of this, relatively older stratigraphic zones subcrop against alluvium in northwestern parts of RMA, with progressively younger zones subcropping toward the southeast. Evidence for folding or faulting in the Denver Formation at RMA is inconclusive.

2.4 Unconfined Flow System

Groundwater at RMA occurs under both confined and unconfined conditions. Water in bedrock typically is under confined conditions while water in unconsolidated surficial deposits typically is under unconfined conditions. Exceptions occur in areas where bedrock units are exposed at land surface or overlying unconsolidated deposits are unsaturated. Where these conditions occur, water in shallow bedrock is unconfined.

The Unconfined Flow System includes saturated alluvium, eolian deposits, and subcropping parts of the Denver Formation where lithologic data indicate the presence of sandstone or other relatively permeable material. In areas where alluvial and eolian deposits are unsaturated, the Unconfined Flow System consists solely of sandstone and fractured or weathered rock within the shallow parts of the Denver Formation. This definition does not preclude lateral flow between alluvium and permeable material in subcropping Denver Formation. However, rates of flow within these parts of the Denver Formation may be substantially different from rates of flow in the alluvium due to differences in hydraulic conductivities between these units.

The nature of flow in shallow parts of the Denver Formation is substantially more complex than the nature of flow in alluvial and eolian deposits. Transmissive rock of the Denver Formation is discontinuous and extremely heterogeneous. These local-scale complexities may have important implications for flow and transport and may result in local areas where water in the shallow Denver Formation is under confined conditions. These complexities also may result in steep vertical gradients in some areas where the Unconfined Flow System consists of Denver Formation. Consequently, there is a greater degree of uncertainty when characterizing flow in the Denver Formation than occurs when characterizing flow in alluvial and eolian deposits.

The bottom of the Unconfined Flow System is delineated by the following criteria. Where no sandstone of the Denver Formation subcrops, the bedrock-alluvium interface is the bottom of the Unconfined Flow System. If subcropping sandstone is present, the sandstone in the area of subcrop is included as part of the Unconfined Flow System. If alluvium is unsaturated or absent, the bottom of the Unconfined Flow System is defined by the depth of weathered rock in the Denver Formation. Based on these criteria, the Unconfined Flow System extends throughout RMA and vicinity.

The saturated thickness of the Unconfined Flow System varies from less than 10 ft to approximately 70 ft (Figure 2.2). Thickness is greatest in paleochannels and typically varies from 20 to 50 ft. Thickness beneath Basins A through F and South Plants is typically 20 ft or less. Large areas with thickness less than 7 ft have been identified in Sections 20, 26, and 29.

2.4.1 Hydraulic Properties

The Unconfined Flow System has been divided into seven hydrogeologic units on the basis of lithologic descriptions and aquifer test results (Figure 2.3). Six of the hydrogeologic units are located within unconsolidated Quaternary deposits. Unconfined parts of the Denver Formation are grouped as the seventh unit. Aquifer test results (Appendix B) were used to estimate hydraulic conductivity for each hydrogeologic unit (Table 2.2). A complete lithologic description of each hydrogeologic unit is presented in Appendix F.

For hydrogeologic units with a substantial number of aquifer tests, typical values given in Table 2.2 are the median values of those tests. These units are QT, QA1, QA2, and QA3. Aquifer-test data for the remaining units, particularly data from multiple well tests are more limited. In these cases, the range of estimates is based on test results, while the typical value reflects the judgement of the hydrogeologists who compiled the information.

Hydraulic conductivity of unconfined Denver Formation generally is one to two orders of magnitude smaller than the eolian unit and two to three orders of magnitude smaller than alluvial gravel and coarse grained sand units. Estimates of hydraulic conductivity in the Denver Formation range from 0.03 to 3 ft/day. Estimates in the eolian unit range from 10 to 100 ft/day, and estimates in gravel and coarse grained sand units range from 60 to 3,000 ft/day. Estimates of hydraulic conductivity were obtained from results of 16 aquifer tests with observation wells, nine aquifer tests without observation wells, and 75 slug tests.

Specific yield estimates obtained from aquifer test results correlate qualitatively with hydrogeologic units. In eolian and fine-grained alluvial units, specific yield estimates range from 0.01 to 0.05. Specific yield estimates in coarser material are typically 0.23 to 0.25. Aquifer-test results in the Denver Formation have not provided reliable estimates of specific yield.

Table 2.2 Hydraulic Conductivity Estimates for Hydrogeologic Units of the Unconfined Flow System

Hydrogeologic Unit and Symbol	Hydraulic Conductivity Typical Value (ft/day)	Hydraulic Conductivity Range of Estimates (ft/day)
Terrace gravel (QT)	900	300 to 3,000
Paleochannels in terrace gravels (QA1)	900	300 to 3,000
Gravel-filled paleochannels in eolian deposits (QA2)	300	100 to 1,000
Silty terrace gravels and coarse sand (QA3)	200	60 to 600
Paleochannels without gravel in eolian deposits (QA4)	100	30 to 300
Eolian deposits (QE)	60	10 to 100
Unconfined Denver Formation (TK_d)	0.3	0.03 to 3

2.4.2 Potentiometric Surface

Potentiometric surface data (Figure 2.4) obtained in 1987 indicate that groundwater in the Unconfined Flow System generally flows toward the north and northwest. Spatial variation in hydraulic gradients can be attributed to variations in saturated thickness, hydraulic conductivity, and locations of recharge and discharge. Where saturated thickness is small, hydraulic gradients are also influenced by the configuration of the bedrock surface. In areas where the Unconfined Flow System is primarily alluvium, hydraulic gradients vary from approximately 0.0001 to 0.01 ft/ft. In areas where the Unconfined Flow System is primarily Denver Formation, hydraulic gradients are generally larger (0.007 to 0.02 ft/ft) and subject to greater uncertainty.

As a result of the 10 ft contour interval selected for mapping the potentiometric surface, some detail has been lost. More detailed maps are available within Study Area Reports and other more site-specific documents. Flow paths inferred from Figure 2.4 are generally correct; however, more detailed maps must be used in areas of rapidly diverging flow. More detailed maps also show several groundwater mounds in parts of the Unconfined Flow System that correspond to unconfined Denver Formation. When total head change across these mounds is less than 10 ft, the mound may not appear on Figure 2.4. Examples of low magnitude groundwater mounds occur in the area of unsaturated alluvium northwest of Basin F and north of Basin A.

Hydraulic gradients in the Unconfined Flow System are small in areas where saturated thickness and hydraulic conductivity are large. Small hydraulic gradients (0.004 ft/ft) include the RMA western tier and the South Platte River. Other areas with small hydraulic gradients are near First Creek (0.006 ft/ft), south-central parts of RMA (0.009 ft/ft), and between the RMA northern boundary and the South Platte River (0.008 ft/ft).

Hydraulic gradients in the Unconfined Flow System generally are large in areas where hydraulic conductivity is relatively small, or where saturated thickness is small and the elevation of the bottom of the Unconfined Flow System changes substantially. These conditions exist northwest of Basin F, in parts of Sections 27, 34, and 35, and in areas where flow in the Unconfined Flow System occurs through rocks of the Denver Formation.

A small hydraulic gradient (0.0001 ft/ft) occurs from Basin F to the RMA northern boundary. Saturated thickness generally is small (less than 20 ft) and a substantial part of the Unconfined Flow System in this area consists of the Denver Formation. Reasons for the small gradient include a probable small quantity of water moving between Basin F and the RMA northern boundary, and hydraulic head control near the RMA northern boundary where water flowing from the vicinity of Basin F mixes with a larger volume of water flowing through material with high hydraulic conductivity beneath First Creek. Installation and operation of the North Boundary Containment System has had a secondary influence on the hydraulic gradient from Basin F to the northern boundary of RMA.

Water levels beneath the South Plants area indicate the presence of a groundwater mound, and water flows radially away from this groundwater high beneath South Plants. The mound has existed since 1957 and perhaps earlier. The Unconfined Flow System beneath the South Plants area is predominately claystone and volcaniclastic material of the Denver Formation and has relatively small hydraulic conductivity. Where saturated, surficial deposits are silt and clay with small hydraulic conductivity. The Unconfined Flow System in areas adjacent to the mound consists of material with larger hydraulic conductivity. Assuming uniform recharge from precipitation in the South Plants and adjacent areas, the spatial differences in hydraulic conductivity are sufficient to cause water table mounding.

Recharge beneath South Plants has been enhanced in the past and contributed substantially to the height of the groundwater mound. Enhanced recharge occurred as a result of leaking pipes and sewer lines, collection of water in low lying areas and other activities within the South Plants area. A major leak in the sewer system was identified and corrected in 1980. Water levels beneath South Plants have declined 1 to 2 feet since 1982.

2.4.3 Water Level Fluctuations

Historical water level fluctuations have been large in the vicinity of Basin C. Elsewhere, historical water level fluctuations have been small. Fresh water was stored in Basin C during the late 1950s. Water level data collected during 1957 (Smith et al., 1963/RIC84324R02) indicate that hydraulic heads beneath Basin C and Basin F were 20 to 30 ft higher than present-day heads. Basin C also was used extensively for storage of fresh water from 1969 through 1975. Water level data for this period were not available.

Water level data for the composite period 1955 through 1971 (Konikow, 1975/RIC84324M01) show water levels beneath Basin C, Basin F and Basin A Neck were approximately 10 ft higher than present-day water levels. Basin C has not been used extensively since 1976 and water level data collected since 1978 reflect the present-day potentiometric surface generally with deviations of less than 5 ft.

The present-day water level beneath Basin C, Basin F, and adjacent areas is at or slightly below the contact between Denver Formation and overlying alluvium. Relatively small increases in water level would cause the alluvium to become saturated. Because hydraulic conductivity of the alluvium probably is one to two orders of magnitude larger than hydraulic conductivity of the Denver Formation, flow paths and travel times for contaminant migration may be substantially lower today than when Basin C contained water.

Seasonal water level fluctuations as large as 7 ft have been measured near South Plants between 1982 and 1986. Seasonal fluctuations elsewhere at RMA tend to be less than 2 ft. The magnitude of changes in the South Plants area may be a reflection of smaller hydraulic conductivity and specific yield beneath South Plants compared with adjacent areas, or it may be a reflection of changes in recharge.

2.4.4 Recharge and Discharge

Recharge to the Unconfined Flow System occurs as infiltration of precipitation and irrigation, seepage from lakes and streams, and seepage from reservoirs, canals, and buried pipelines. Water also enters the Unconfined Flow System by underflow of groundwater from areas south and east of the study area. Water in transmissive strata of the Denver aquifer flows laterally into the Unconfined Flow System where the elevation of the bedrock varies appreciably in a short distance and the transmissive strata subcrop. Rates of recharge vary seasonally, have caused relatively minor changes in water levels and groundwater flow paths, and will not be discussed in detail.

Recharge rates for the Unconfined Flow System (Table 2.3) have been estimated from a number of investigations during the period 1981-1987. Descriptions of each recharge component are given in Appendix F. Estimates of many recharge components shown in Table 2.3 are based on assumptions that could not be evaluated quantitatively with available information. As a result, estimation accuracy and reliability could not be quantified. The recharge rates shown in Table 2.3 were used as initial estimates in developing a regional model of flow in the Unconfined Flow System. This model is described in Section 4.3 of this report.

Discharge from the Unconfined Flow System occurs as seepage to Lake Ladora, Lake Mary, Rod and Gun Club Pond, and the South Platte River. Additional groundwater discharge probably occurs by evapotranspiration from the water table in areas such as Upper Derby Lake where the water table is within 5 ft of the land surface. In some areas, water flows vertically from the Unconfined Flow System into the underlying Denver aquifer. Vertical flow probably occurs through fractures in areas where the subcropping strata are predominantly shale or claystone. Historically, vertical flow may have been greater when the water table was substantially higher than presently observed. Initial discharge rates to Lake Ladora and Lake Mary were obtained by calculating water budgets for each lake. A water budget for Rod and Gun Club Pond was not constructed but discharge was assumed to be less than 25 acre-ft/yr. Total discharge to these three lakes is estimated to vary from 82 to 385 acre-ft/yr. Estimates of groundwater discharge to the South Platte River, based on calculations with Darcy's law, are sensitive to uncertainty in estimates of hydraulic gradients and hydraulic conductivity. Discharge estimates range from 28,400 to 56,600 acre-ft/yr. Discharge also varies seasonally. For example during periods of negligible streamflow, the Unconfined Flow System discharges to First Creek north of RMA at a small rate.

Table 2.3 Estimated Recharge to the Unconfined Flow System

Source of Recharge	Estimated Recharge (acre-feet/year)
Precipitation	740
First Creek, on-post	300
First Creek, off-post	316
Basin A	10 to 20
Basin B	4
Basin C	2
Basin D	0
Basin E	0
Sewage Treatment Plant	0
Lower Derby Lake	480
Upper Derby Lake	unknown
Havana Pond	1,300
Uvalda Interceptor	360
Rail Classification Yard	13
Sand Creek Lateral	20
Fulton Ditch	4,020
Burlington Ditch*	5,300
O'Brian Canal*	10,400 to 15,800
Highline Lateral	489 to 900
North Bog	190
Irrigation	6,550
TOTAL	30,500 to 36,300

* Estimates are for the entire length of the canal.

Note: Recharge estimates are for the area bound by Sand Creek, South Platte River, Second Creek and Highline Canal.

2.5 Denver Aquifer

The Denver aquifer in the vicinity of RMA consists of parts of the Denver Formation where water is under confined conditions. Generally, confined conditions are observed within permeable sandstone or lignite that is separated from permeable material of the Unconfined Flow System by relatively impermeable shale or claystone. Because upper stratigraphic intervals of the Denver Formation are included in the Unconfined Flow System where water is unconfined, there is no direct correlation between rock of the Denver aquifer and stratigraphic intervals of the Denver Formation. The bottom of the Denver aquifer is delineated by 30 to 50 ft of claystone and shale, informally called the Buffer Zone, that separates the Denver from the underlying Arapahoe aquifer. The Arapahoe Formation underlies RMA at a depth of approximately 250 to 400 ft below ground surface (May, 1982/RIC82295R01).

Flow in the Denver aquifer is substantially more complex than flow in the Unconfined Flow System. Transmissive rock in the Denver aquifer is discontinuous and heterogeneous. The distribution of hydraulic head in the Denver aquifer indicates the presence of a complex three-dimensional flow system. Consequently, understanding of flow in the Denver aquifer is less certain than understanding of flow in the Unconfined Flow System.

2.5.1 Hydraulic Properties

Hydraulic conductivity estimates vary spatially and reflect variations in lithology. Hydraulic conductivity of the shale and claystone matrix generally is small; probably 10^{-2} to 10^{-4} ft/day. In contrast, hydraulic conductivity for sandstone in the Denver aquifer has been estimated by slug-test analyses to range from 0.03 to 4 ft/day. Values less than 0.3 ft/day are typical of silty sandstone. Values from aquifer tests range from 1.1 to 7.7 ft/day. Estimates of hydraulic conductivity for lignitic beds that have been fractured are not available. However, flow model analyses indicate that hydraulic conductivity of lignitic beds may be an order of magnitude greater than hydraulic conductivity of sandstone.

Contaminant migration in the Denver aquifer probably depends on the occurrence of interconnected sandstone lenses and fractured lignitic beds. Thickness and areal extent of sandstone in stratigraphic zones of the Denver Formation is described by a series of maps in Appendix F. Sandstone varies in thickness from a few inches to 50 ft. The maps identify thicker areas of sandstone that generally trend south to north with substantial deviations in trend within each stratigraphic zone.

2.5.2 Distribution of Hydraulic Head

Head in the Denver aquifer decreases with depth at most locations in the vicinity of RMA. Increasing head with depth has been observed at relatively few isolated locations (Appendix F, Figure 2.4-11). Decreasing head with depth at RMA is consistent with regional potentiometric surface maps for deep aquifers in the Denver basin (Robson, 1987). Prior to 1885, head increased with depth in deep aquifers beneath RMA and heads in the Denver, Arapahoe, and Laramie-Fox Hills aquifers were large enough to cause flowing wells in the valley of the South Platte River. Groundwater withdrawals from 1885 to the present have caused water level declines greater than 300 ft in the Denver area. As a result, the vertical gradient at RMA currently is downward.

Hydrogeologic cross-sections constructed from the South Plants area to the RMA northwestern boundary (Plate 1) and to the RMA northern boundary (Plate 2) indicate that there is potential for groundwater flow toward the northwest as well as downward potential. Similar results are obtained by constructing potentiometric surface maps for stratigraphic zones in the Denver aquifer (Figures 2.5 through 2.10). While these maps indicate potential for flow, rates of flow are also dependent on hydraulic conductivity.

2.5.3 Recharge and Discharge

Recharge to the Denver aquifer occurs by vertical leakage from the overlying Unconfined Flow System in areas where the subcropping bedrock is predominantly shale or claystone. Head differences between the Unconfined Flow System and confined sandstone strata of the Denver aquifer indicate a potential for downward leakage. Rates of leakage per unit area are small but probably are enhanced by movement through fractures. Rates of leakage are a function of head difference and vertical hydraulic conductivity. A single estimate of vertical hydraulic conductivity (4.1×10^{-5} ft/day) is available from a pumping test conducted near the North Boundary Containment System. Recharge to the Denver aquifer also occurs by underflow from areas south and east of RMA.

Discharge from the Denver aquifer occurs by lateral flow into the Unconfined Flow System where transmissive strata of the Denver aquifer subcrop and the elevation of the bedrock varies appreciably over a short distance. Discharge from the Denver aquifer also may occur by leakage to the Arapahoe aquifer. No production wells obtain water from the Denver aquifer at RMA.

Recharge and discharge of water in the Denver aquifer is controlled on a local scale by variations in hydraulic conductivity, the potentiometric surface of the Unconfined Flow System, and bedrock surface. Locations where sandstone or other permeable material are in contact with the Unconfined Flow System are likely areas for local recharge and discharge. Recharge and discharge probably occur on a local scale, where the elevation of the bedrock surface varies appreciably in a short distance. For example, within the cross-section shown in Plate 1, localized recharge through shale probably occurs in Section 35 where head gradients indicate downward flow. The recharge water moves perpendicular to the lines of equal potential through Denver sands A, 1U, and 1. Localized discharge to the Unconfined Flow System probably occurs where Denver sand subcrops near the boundary between Section 26 and Section 35. A similar local condition probably occurs in Section 27. The groundwater mound in the Unconfined Flow System near the South Plants area probably functions as an area of recharge to the Denver aquifer.

Quantitative estimates of recharge and discharge rates in the Denver aquifer are not available. Because recharge and discharge in the Denver aquifer are closely related to variations in hydraulic conductivity and the potentiometric surface of Unconfined Flow System and bedrock surface, reliable estimation probably would require cross-sectional or three-dimensional flow modeling in areas of suspected recharge and discharge.

2.6 Surface Water - Groundwater Interaction

Mass balance calculations have been used to estimate groundwater recharge and discharge beneath lakes. Water entering and leaving each lake was measured. Lake evaporation was estimated on the basis of pan evaporation data collected from Cherry Creek Dam south of Denver. Changes in lake storage were estimated from lake level data and stage-volume relations. The residual of the mass balance calculation was estimated to be groundwater recharge or discharge. Estimates could be in error due to uncertainties or possible errors in the stage-volume relations used, or as a result of assuming that the residual of the mass balance calculation is entirely groundwater recharge or discharge. Therefore estimates should be considered initial values subject to revision or refinement as additional information become available. A description of the analysis for each lake is presented in Appendix F, Section 2.0.

Upper Derby Lake loses water to the Unconfined Flow System at an estimated rate of 3.5 acre-ft/mo when the lake contains water, but functions as a groundwater discharge area when the lake is empty. Groundwater discharge estimated at the rate of 2.5 acre-ft/yr occurs by evapotranspiration from the water table. The water table generally is within two feet of the lake bottom.

Lower Derby Lake functions as a groundwater recharge area. Lake losses were estimated to average 39.7 acre-ft/mo during water years 1986 and 1987.

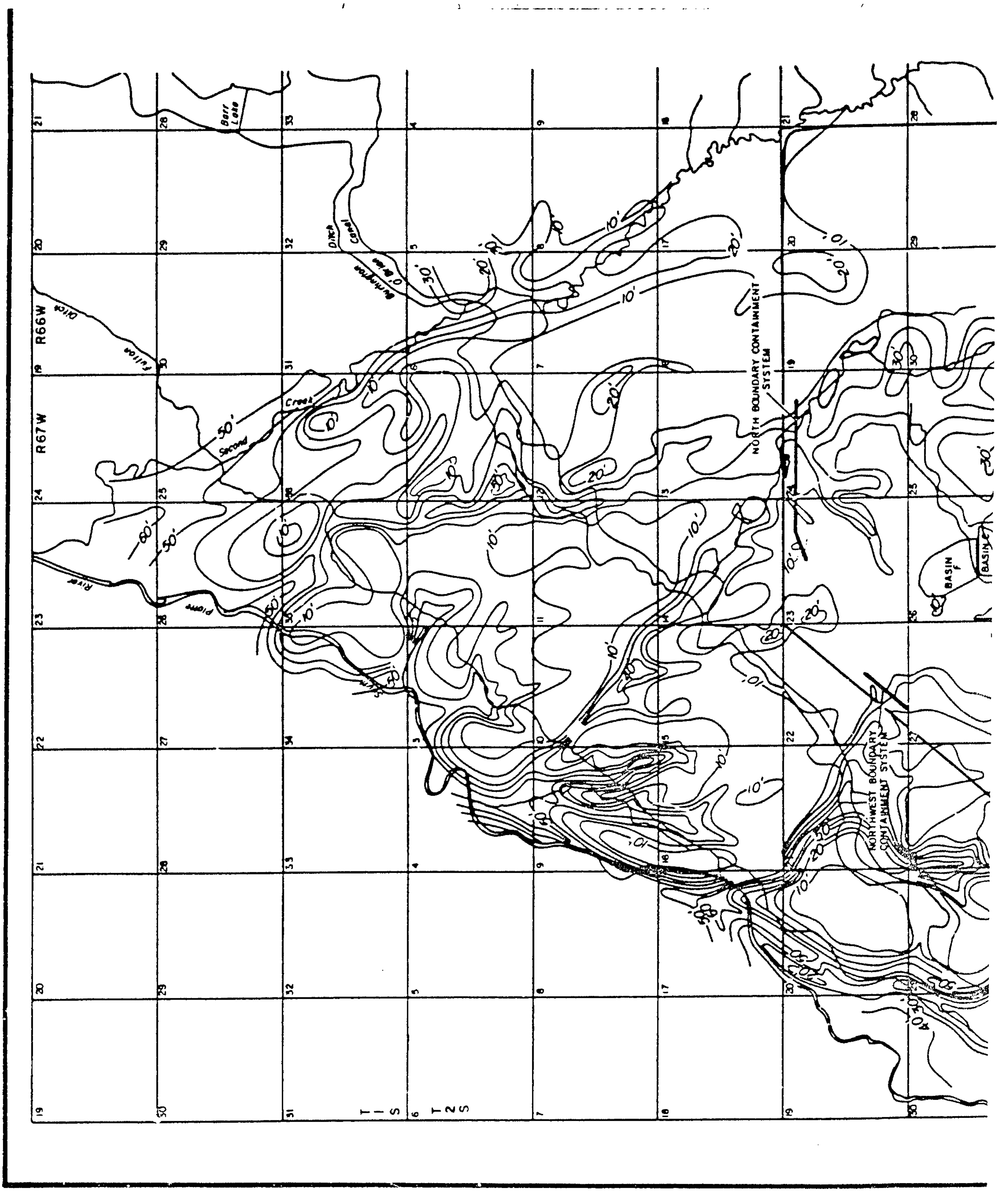
Lake-aquifer head relations indicate that both Lake Ladora and Lake Mary receive groundwater in upstream areas and lose water in downstream areas. However, mass balance calculations indicate net gains of water for both lakes. Net groundwater discharge is estimated to be 14 acre-ft/mo from Lake Ladora and 1.4 acre-ft/mo from Lake Mary during water years 1986 and 1987.

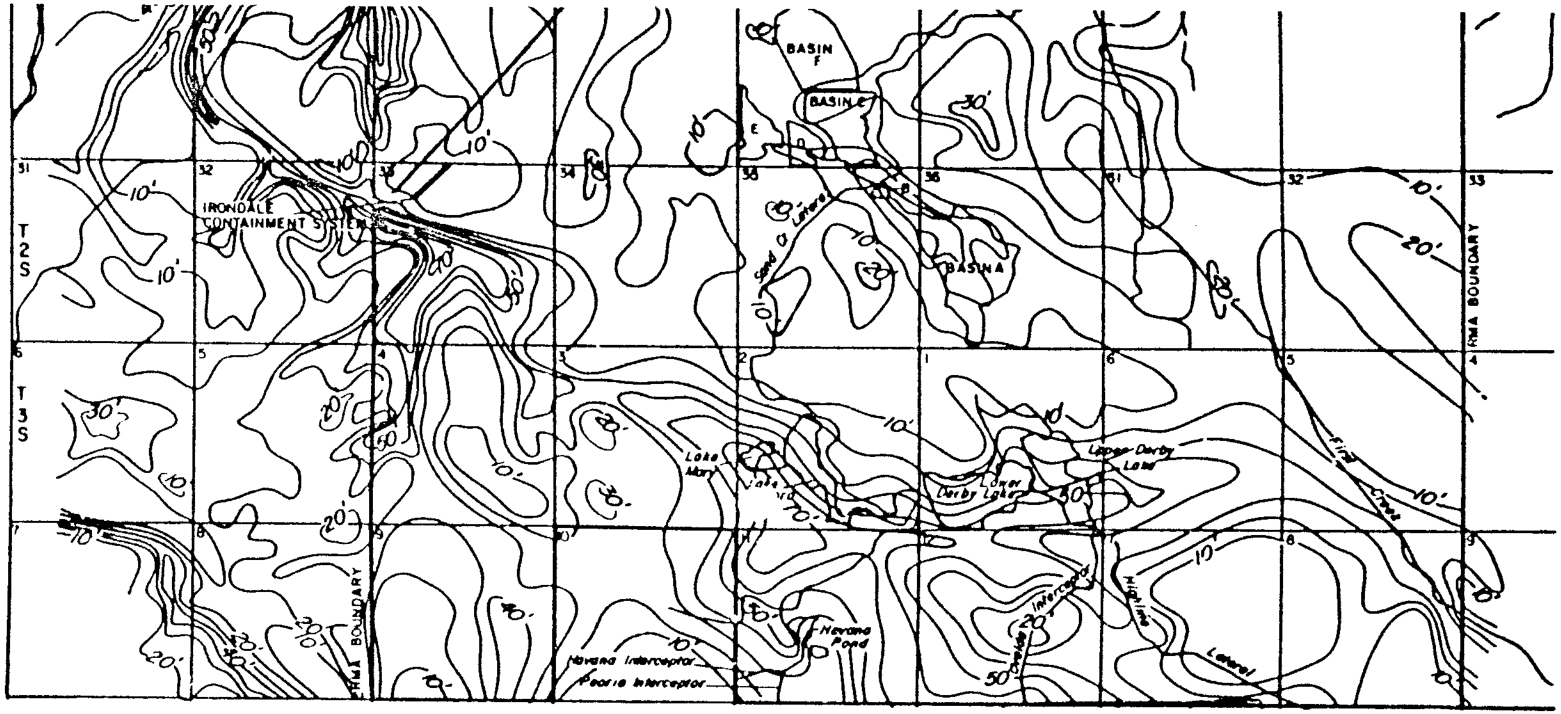
Mass balance calculations for Havana Pond indicate that virtually all water entering the pond becomes groundwater recharge. Average recharge is estimated to be 108.3 acre-ft/mo during water years 1986 and 1987.

Basins A through F exchange water with the Unconfined Flow System at very low rates. A detailed discussion of each basin is presented in Appendix F.

Historically, groundwater recharge in the vicinity of Basins A through F was different from present conditions. Konikow (1977) estimated rates of groundwater recharge during four periods from 1943 through 1972. The estimates were obtained as part of flow-model calibration. From 1943 through 1956, total recharge from Basins A, B, C, D, and E was estimated to be 0.88 ft^3/seconds. From 1957 through 1960, Basins A, B, D, and E were treated as empty and recharge from Basin C was estimated to be 1.08 ft^3/seconds. From 1961 through 1967, recharge from Basins B, C, D, and E was estimated to be 0.42 ft^3/seconds. From 1968 through 1972, recharge from Basin C was estimated to be 1.08 ft^3/seconds, while Basins A, B, D, and E were assumed to be empty. A water budget analysis of Basin C for the years 1969 through 1975 (MKE, 1988, written communication) indicates that average recharge from fresh water storage was approximately 0.95 ft^3/seconds.

Streamflow loss-and-gain studies have been used to estimate stream-aquifer relations at RMA. Results have been compared with stream-aquifer head relations where possible. Calculations indicate that Uvalda Interceptor loses approximately 30 acre-ft/mo. Highline Lateral is estimated to lose 75 acre-ft/mo. First Creek loses approximately 2.9 acre-ft/mo within the boundaries of RMA and an additional 44.6 acre-ft/mo north of the RMA. These estimates represent averages during the 1986 and 1987 water years. Actual values for a given time deviate substantially in response to changes in stream discharge and aquifer head. During periods of negligible streamflow, First Creek north of the RMA boundary gains groundwater at a small rate (0.06 cfs).


Barr Lake
Ditch
Canal
Burlington
O'Brien
R66W
R67W
Fulton
Ditch
Second
Creek
River
Platte
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F
BASIN
T 1 S
T 2 S
10'
20'
30'
50'
60'



EXPLANATION

Contour Interval Equals 10 Feet

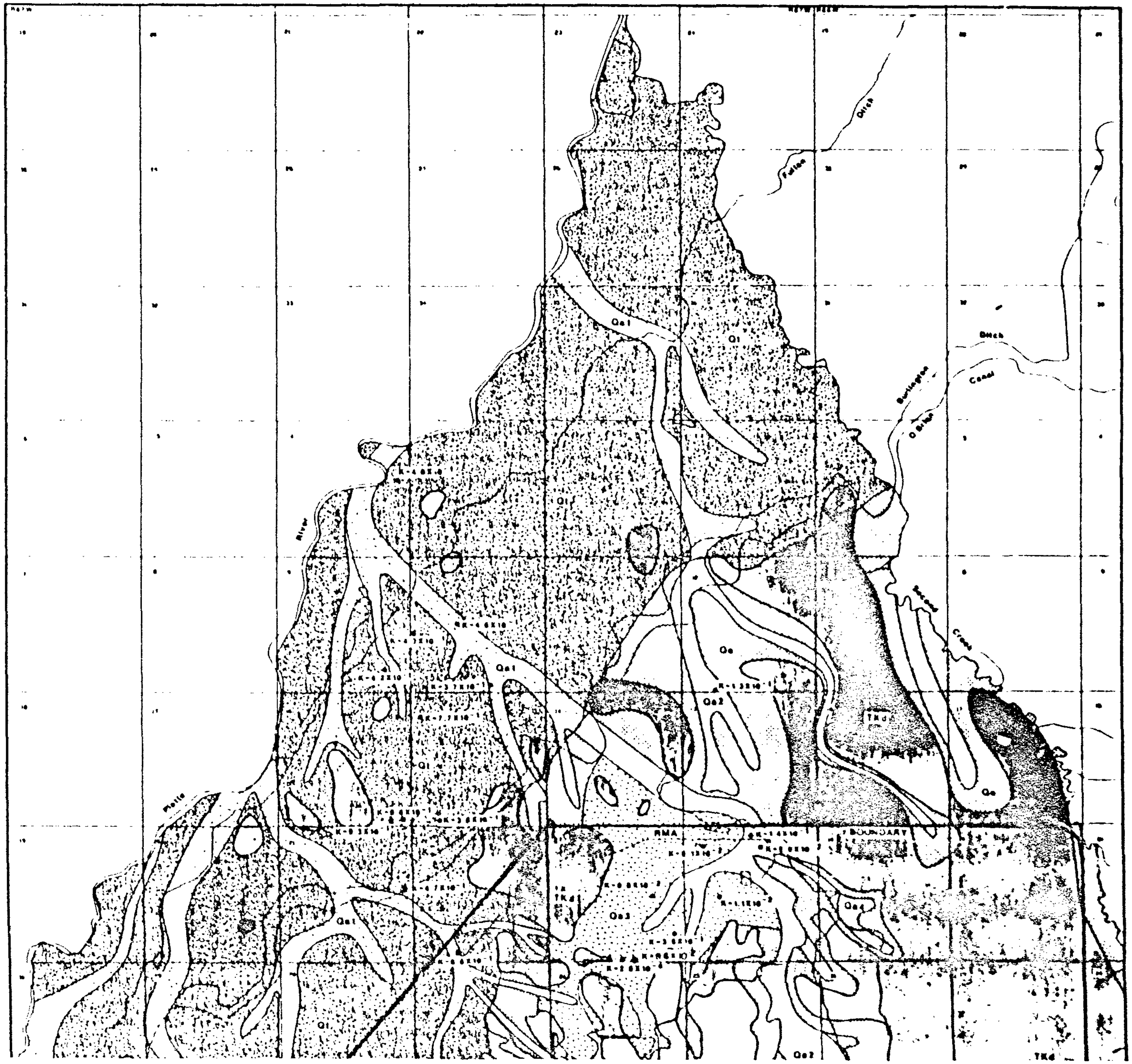
Figure 2.2

SATURATED THICKNESS MAP FOR UNCONFINED FLOW SYSTEM

SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland

Fulton Ditch
Burlington Ditch
O'Brian Canal
Second Creek
Platte River
Qa1
Ql
Qe
Qa2
Qa3
TKd
RMA BOUNDARY

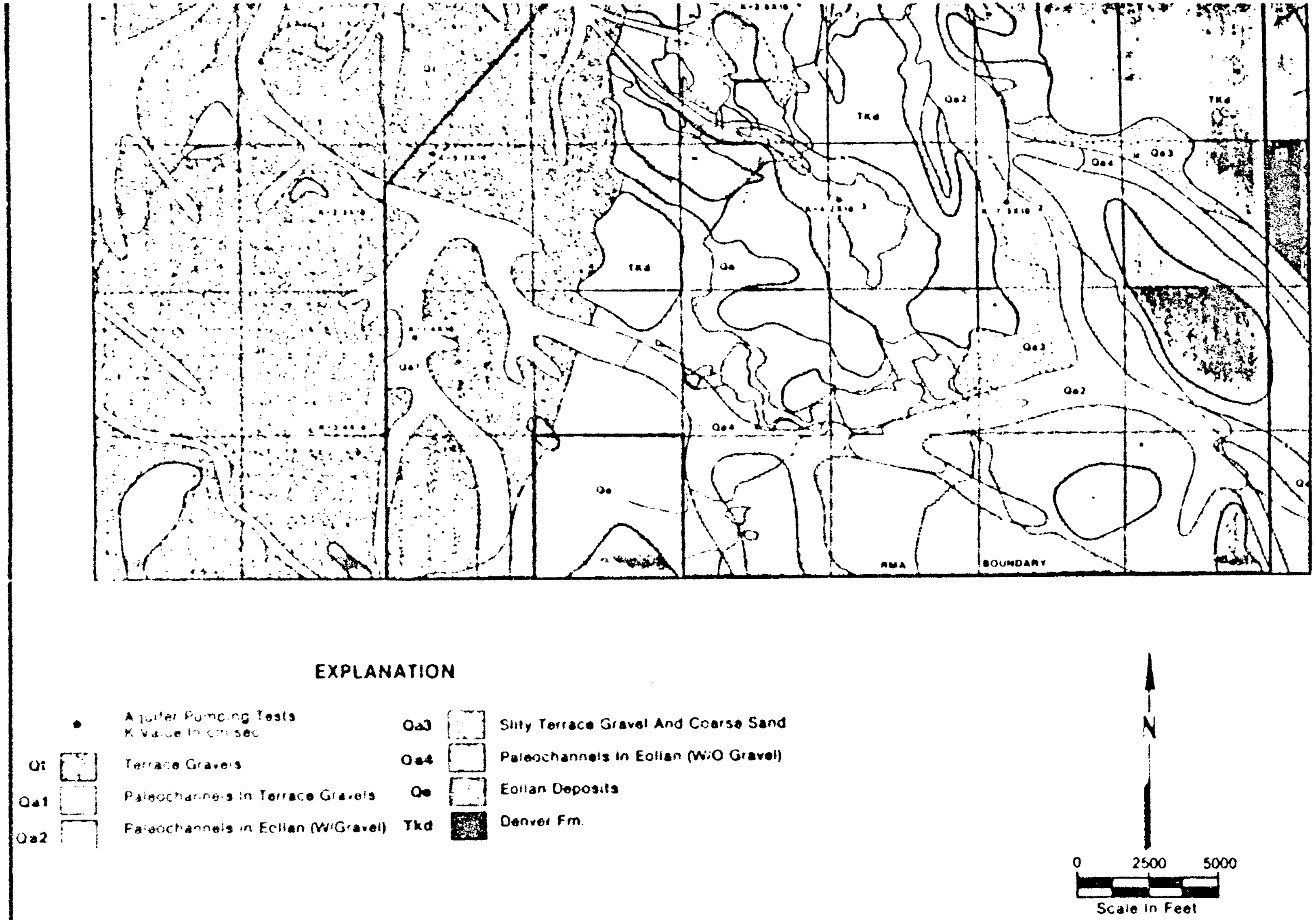


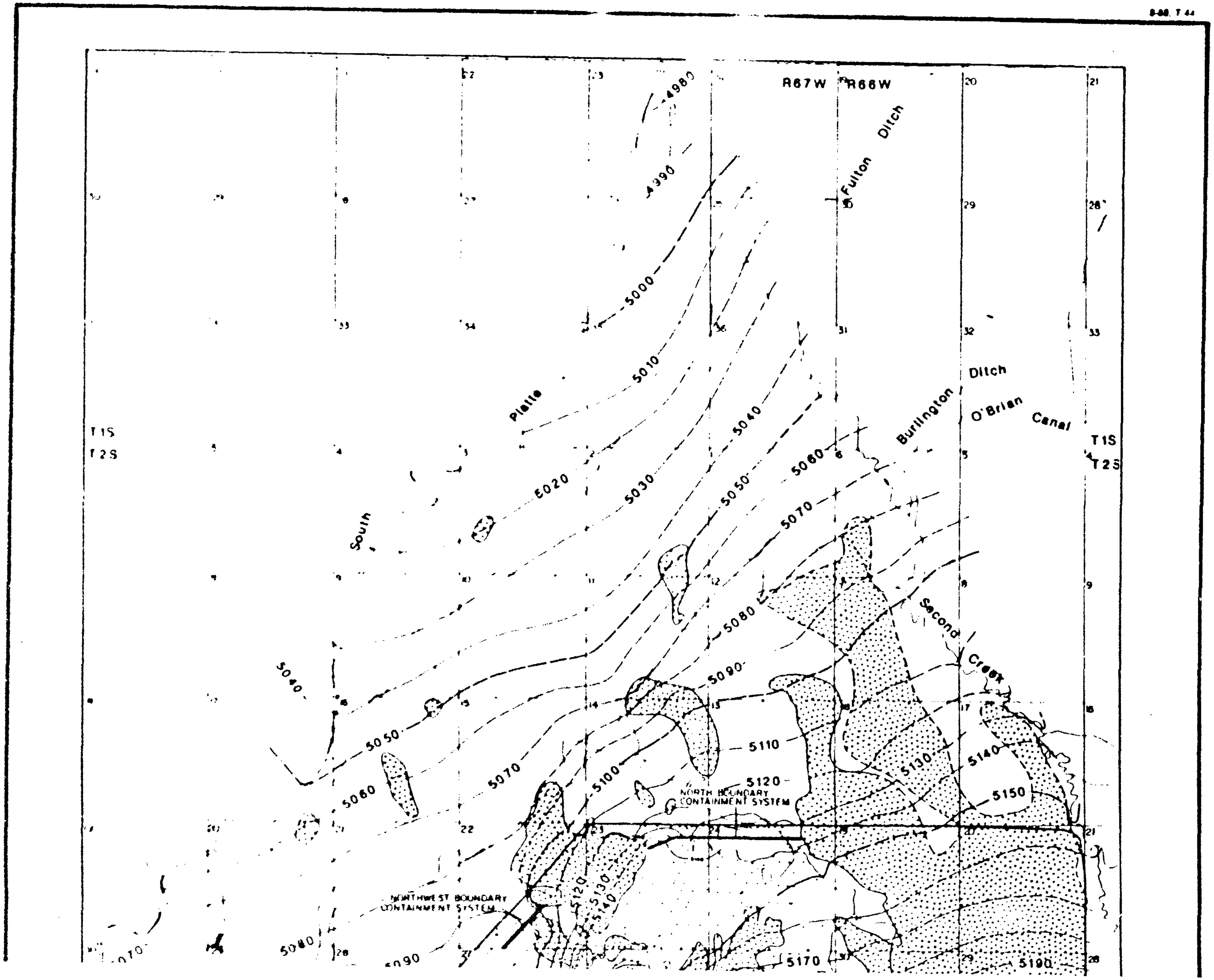
Figure 2.3

HYDROGEOLOGIC UNIT MAP FOR UNCONFINED FLOW SYSTEM

SOURCE HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T1S
T2S
Fulton Ditch
Burlington Ditch
O'Brien Canal
Second Creek
South Platte
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
4980
4990
5000
5010
5020
5030
5040
5050
5060
5070
5080
5090
5100
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5130
5140
5150
5170
5190

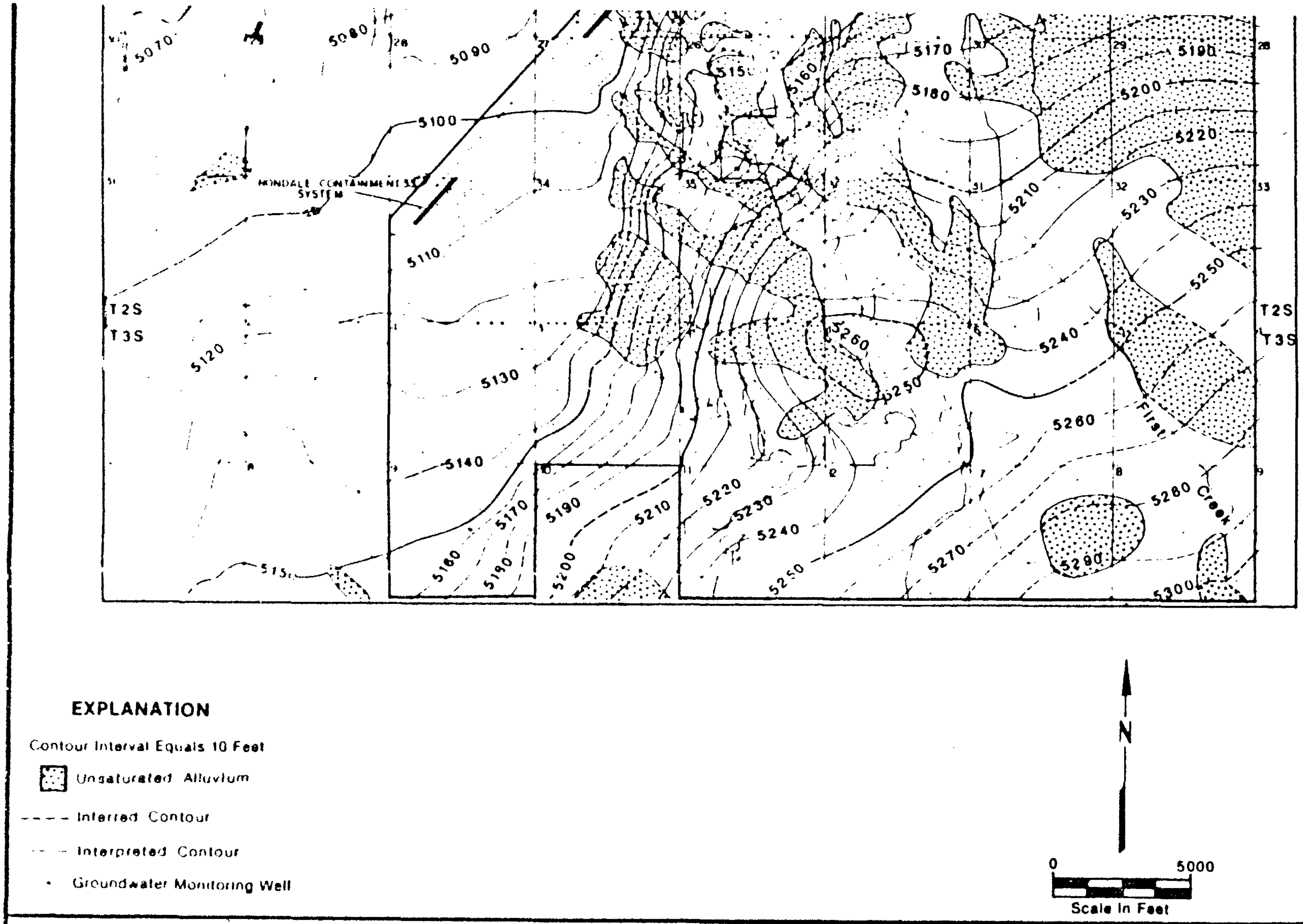


Figure 2.4

POTENTIOMETRIC SURFACE OF THE UNCONFINED FLOW SYSTEM, THIRD QUARTER FY 1987

SOURCE HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland

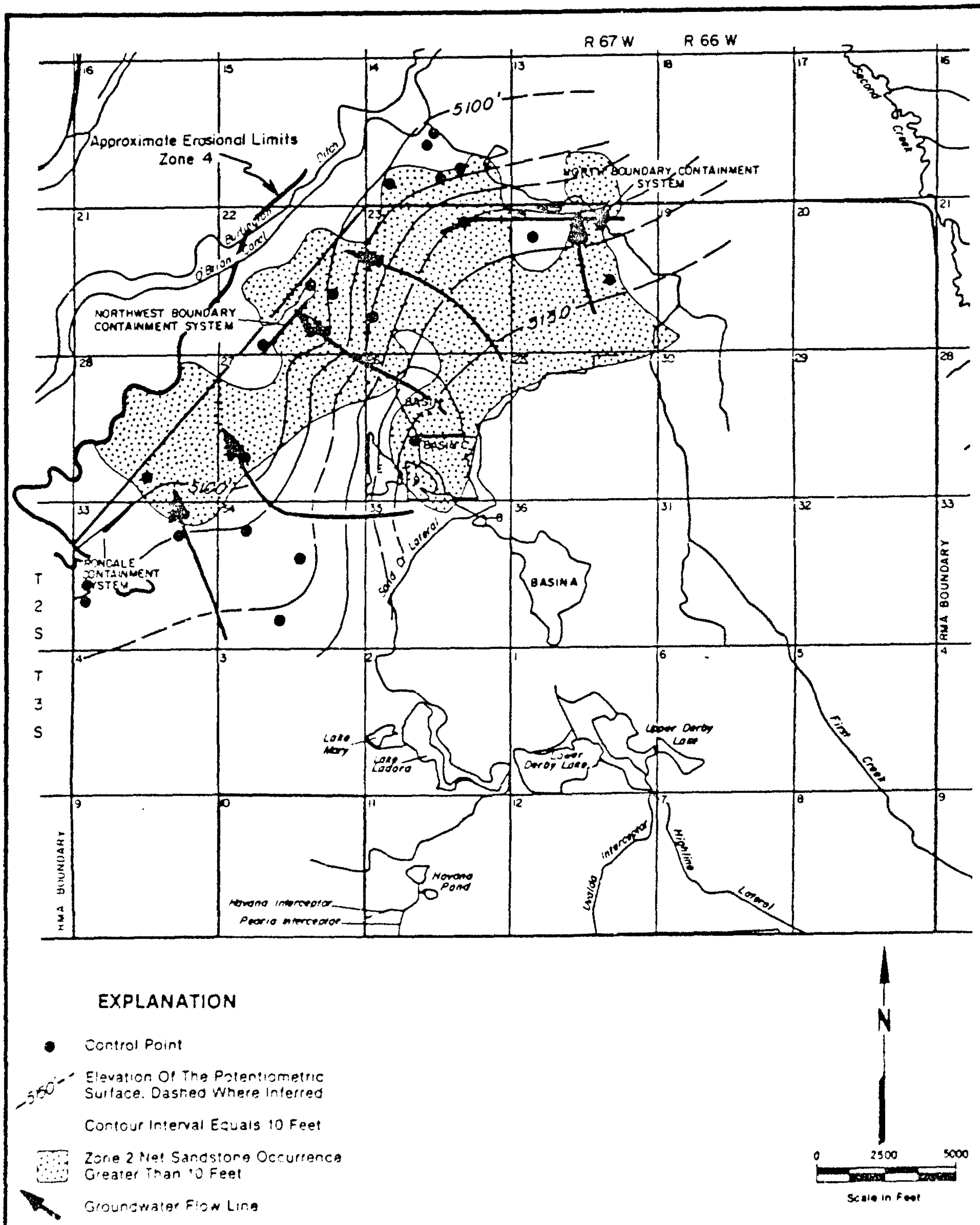


Figure 2.5

POTENTIOMETRIC SURFACE OF DENVER ZONE 4, 3RD QUARTER FY 1987

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

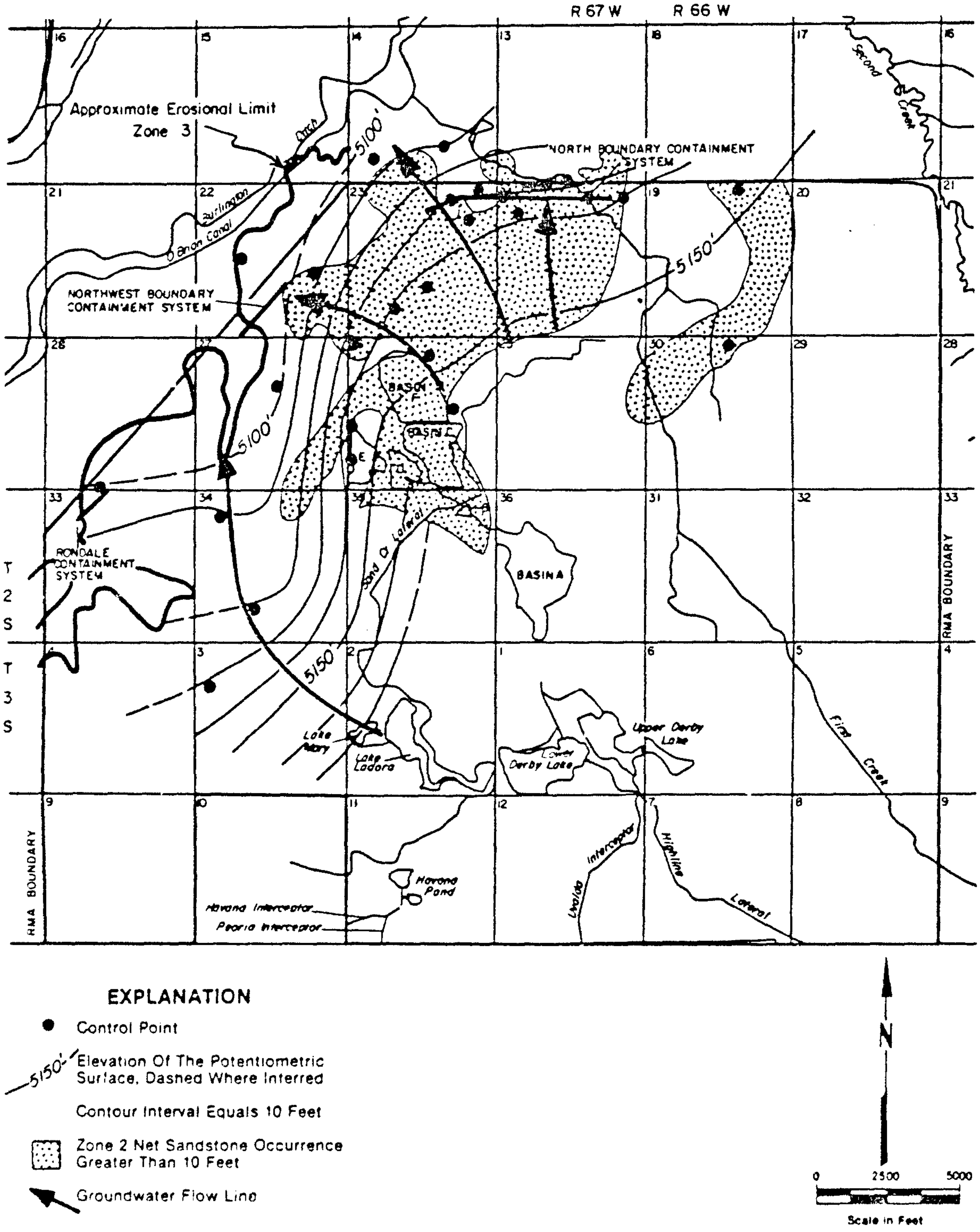


Figure 2.6

POTENTIOMETRIC SURFACE OF DENVER ZONE 3, 3RD QUARTER FY 1987

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

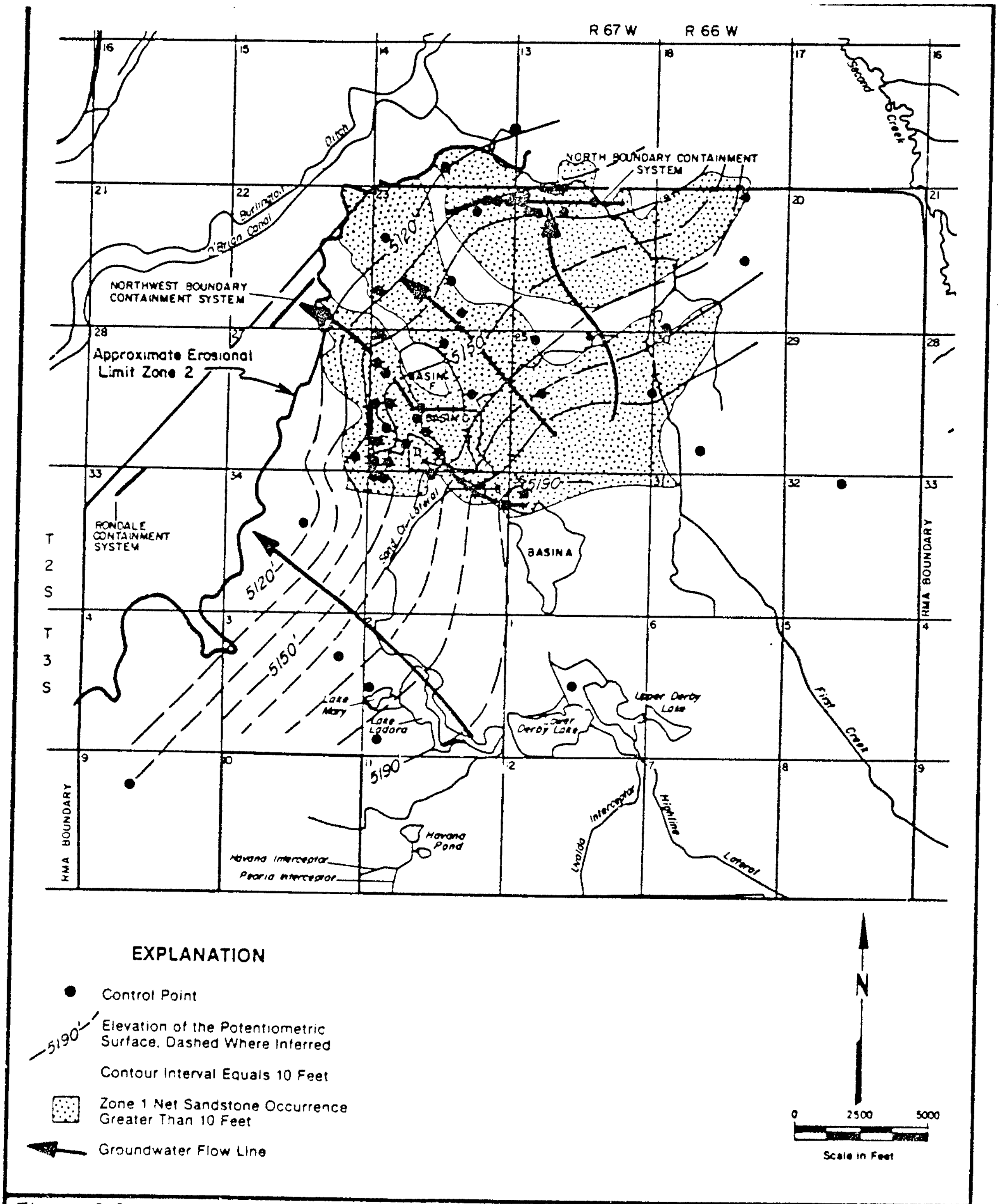


Figure 2.7

POTENTIOMETRIC SURFACE OF DENVER ZONE 2, 3RD QUARTER FY 1987

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

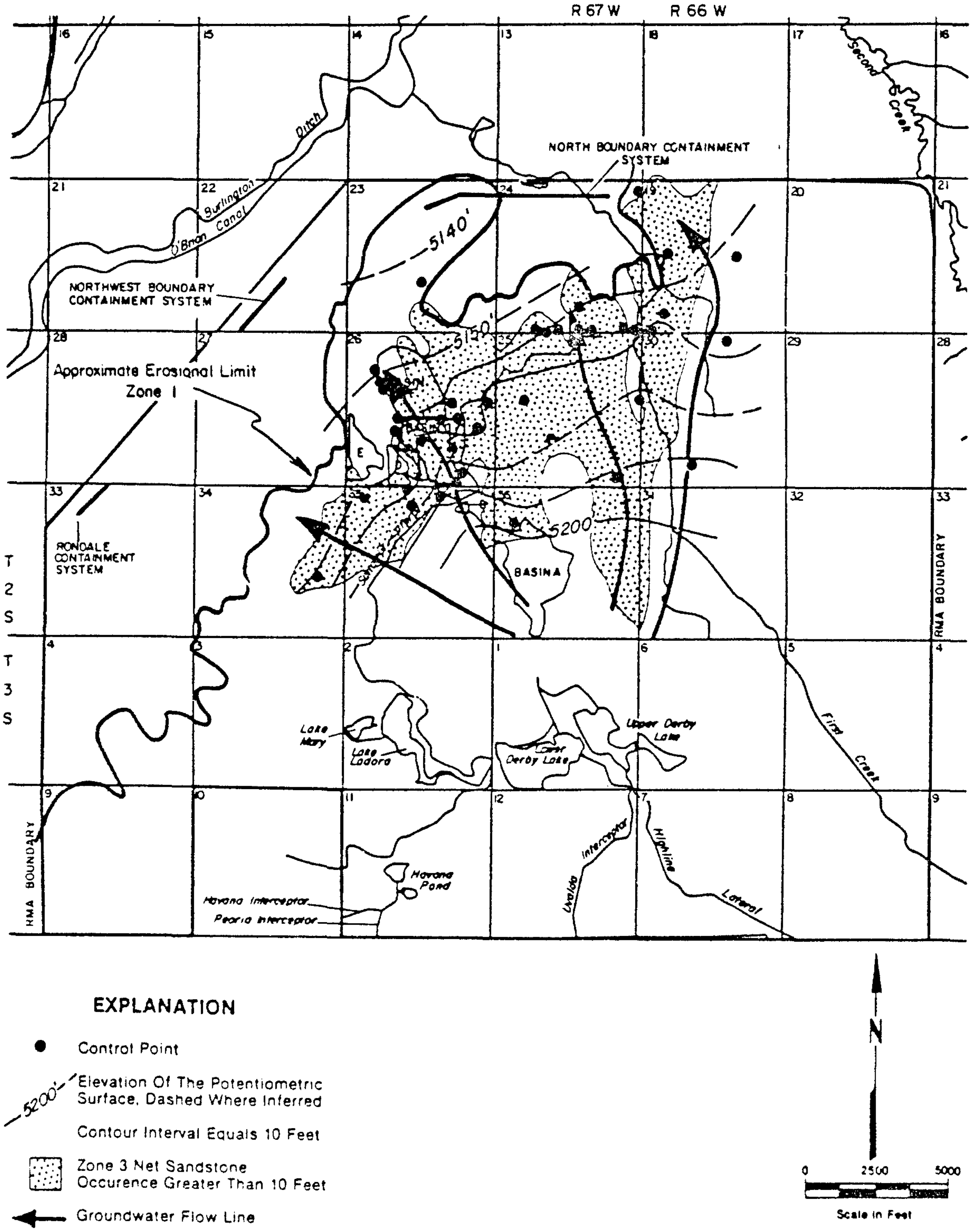


Figure 2.8

POTENTIOMETRIC SURFACE OF DENVER ZONE 1, 3RD QUARTER FY 1987

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

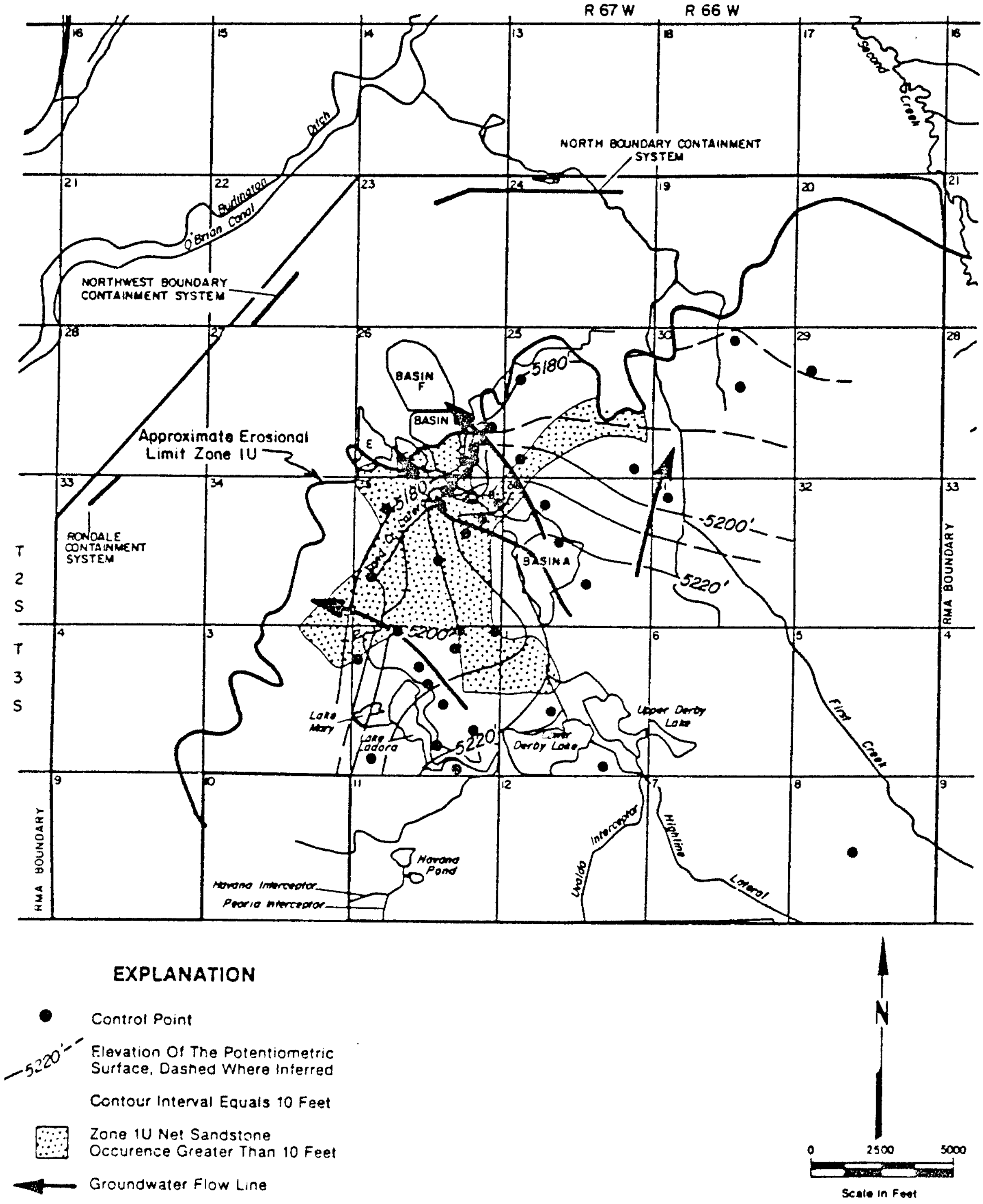


Figure 2.9

POTENTIOMETRIC SURFACE OF DENVER ZONE 1U, 3RD QUARTER FY 1987

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

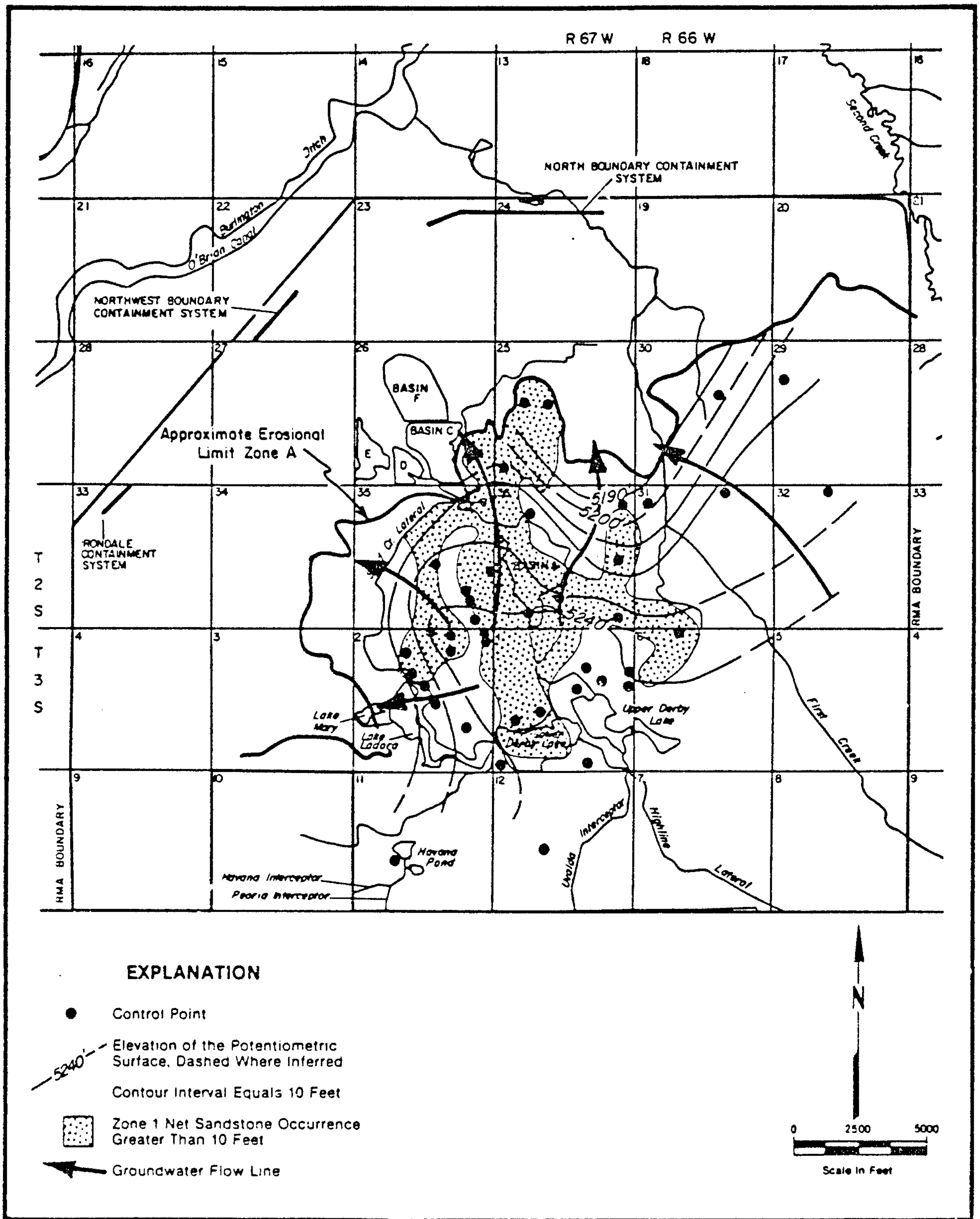


Figure 2.10

POTENTIOMETRIC SURFACE OF DENVER ZONE A, 3RD QUARTER FY 1987

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

3.0 NATURE AND EXTENT OF CONTAMINATION

Numerous surface water and groundwater sampling programs have been conducted at RMA to assess the nature and extent of contamination on a regional and site-specific basis. Assessments of contaminant distribution in surface water and groundwater at RMA were achieved by integrating analytical data from recent and historic sampling programs with the hydrogeologic framework established in previous sections of this report. The descriptive assessment of water quality in the Unconfined Flow System and in the Denver aquifer within the Water Remedial Investigation study area is based primarily on the analytical results from the Third Quarter FY87 sampling period. The Third Quarter FY87 sampling program was selected because it contained the greatest number of sample sites and was the most recent comprehensive sampling event. Where necessary, the historic database was used to corroborate or complement Third Quarter data.

Historic programs mentioned here that predate 1985 include the 360° Monitoring Program, the Basin F Monitoring Program, North and Northwest Boundary Containment Systems Monitoring, Irondale Boundary Control System Monitoring, and the U.S. Army Corps of Engineers Waterways Experiment Station Regional Monitoring Program. The major groundwater programs undertaken since 1985 include Tasks 4, 25, 36, 38, 39, and 44 (Appendix F, Section 3.0).

Unconfined Flow System and Denver aquifer groundwater contaminant plume maps for the Third Quarter FY87 were constructed using well construction data to differentiate Unconfined Flow System and confined Denver Formation wells. Third Quarter FY87 data were supplemented with historical data from lab records, notebooks, USATHAMA database files, and EPA monitoring programs to help establish plume configurations. Hydrogeologic and geologic information was also used in conjunction with these chemical data to further aid in establishing probable plume configurations. The locations of alluvial and Denver Formation wells included in the Third Quarter FY87 monitoring network are shown on Plates 3 and 4. Wells included in the Third Quarter FY87 sampling network are listed in Table 4.2-1 (Appendix F).

The lowest contour interval value for each plume map represents the highest certified reported limit for that analyte or group of analytes when multiple laboratories analyzed samples during a particular sampling period. If only one laboratory was used to analyze a particular analyte or group of analytes, the Certified Reporting Limit (CRL) for that laboratory is equal to the lowest contour line value on plume maps.

The number and types of contaminants analyzed under various groundwater and surface water sampling programs have evolved over time as a result of changes in environmental concerns, improved analytical methods, changing RMA activities, and increased knowledge of contaminant fate and migration. The current analytical list was derived from various sources that included:

- An evaluation of contaminant source characteristics at RMA and compounds attributable to activities at these sites;
- A review of historical chemical data and recognition of compounds previously detected; and
- Additional input from the Parties and State.

Table 3.3-1 (Appendix F) is a comparison of analytical suites from selected historic programs with those of recent Remedial Investigation tasks.

For the purposes of this report, individual analytes have been consolidated into composite groups. Groupings are made primarily on the basis of analytical methodology, although subdivisions within groups reflect similarities in origin, history, and environmental fate. Compounds within a group generally exhibit similar physical and chemical characteristics. As a result, compounds within a group generally display similar behavior with respect to fate and transport in the environment. Brief descriptions of the origin and use of RMA contaminants are presented as part of the discussion of groundwater quality (Section 3.2). Compound characteristics and mechanisms for migration and attenuation are described in Section 4.4.

Primary and secondary contaminant pathways were identified by contaminant occurrence and plume configuration. These pathways were named to standardize contaminant distribution discussions (Figure 3.1). Names of pathways were determined based on proximity to well known features, and were not meant to imply a source-plume relationship. A complete discussion of pathway identification, including selection criteria, is presented in Section 4.5.

Several analytes including chloride, diisopropylmethyl phosphonate, dithiane/oxathiane, aldrin, dieldrin, endrin, dicyclopentadiene, dibromochloropropane (DBCP), chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone are key in assessing the nature and extent of contamination. The relative significance of these contaminants is based on their occurrence, use in RMA industrial or military operations, concentration, and environmental fate and impact.

3.1 Surface Water Quality

The present surface water quality sampling network is essentially an expansion of the 360° Monitoring Program initiated in 1976. Figure 3.2 shows the surface water sampling locations where multiple detections of analytes occurred in samples collected from fall 1985 through fall 1987. Analytes detected only once at sites sampled several times during this time period were not included, to place emphasis on those analytes within multiple detections. Detections that occurred at sites sampled only once during this time period were included since data to confirm or deny the occurrences were unavailable. All analyte detections at surface water sampling sites for the periods fall 1985 through fall 1987 and Third Quarter FY87 are presented in Tables 4.1-3 and 4.1-2 (Appendix F). A comparison of Tables 4.1-2 and 4.1-3 shows that there is little difference between analyte concentration at given sites through time, although a smaller variety of analytes were detected during the Third Quarter FY87 sampling period than had been detected historically.

Areas where surface water contamination was detected during the Third Quarter FY87 sampling period include South Plants, Basin A, and the sewage treatment plant. Also, surface water samples collected during the Third Quarter FY87 sampling period from water entering RMA from the Peoria Interceptor contained benzothiazole, tetrachloroethylene, and 1,1,1-trichloroethane.

3.2 Groundwater Quality

In general, the variety, areal extent and concentrations of contaminants found in the Unconfined Flow System are greater than those found in confined portions of the Denver aquifer. Several compounds or compound groups occur as definable groundwater plumes in the Unconfined Flow System, including volatile halogenated organics, dicyclopentadiene, volatile aromatic organics, organosulfur compounds, diisopropylmethyl phosphonate, DBCP, organochlorine pesticides, arsenic, fluoride, and chloride. Only a limited number of contaminants occur as definable plumes within the Denver aquifer, including oxathiane/dithiane, chlorobenzene, benzene, dieldrin, fluoride, and chloride. Individual or composite groups of analytes discussed here are included because of their possible toxic effects, historic significance, and relatively widespread distribution in groundwater. Plume maps were constructed for compounds having ten or more detections for a particular analyte or analyte group. Compounds with too few detections to be presented in plume maps are included in Appendix D as point plot maps.

3.2.1 Volatile Halogenated Organics

The volatile halogenated organics group includes chloroform, trichloroethylene, tetrachloroethylene, methylene chloride, carbon tetrachloride, 1,1-dichloroethylene, trans-1,2-dichloroethylene, 1,1-dichloroethane, 1,2-dichloroethane, 1,1,1-trichloroethane, and 1,1,2-trichloroethane. Volatile halogenated organics are commonly used as industrial solvents and degreasers. Although used in the past at RMA, they are also in widespread use elsewhere. Composite concentrations for volatile halogenated organics were calculated by summing the volatile halogenated organic concentrations for each sample, with concentrations below the certified reporting limits set equal to zero. The most frequently detected and widespread volatile halogenated organics at RMA are chloroform, trichloroethylene, and tetrachloroethylene.

Historic water quality data for volatile halogenated organics prior to the Initial Screening Program are very limited, as volatile halogenated organics analysis was not performed regularly until the 1980s. MKE distribution maps for the alluvial and Denver Formation aquifers (MKE, unpublished data, 1986) indicate alluvial occurrences of chloroform and carbon tetrachloride in the South Plants area in Section 1, extending into Sections 2 and 36. In the Denver Formation, chloroform and carbon tetrachloride were detected in the South Plants area; chloroform was also detected in Sections 2, 35, and 36. Initial Screening Program data collected from September 1985 to March 1986 for alluvial wells indicated detections of volatile halogenated organics in several locations, including the Basin A-South Plants area, the Basin F area, the Northwest Boundary Containment System area in Sections 22 and 27, the central south pathway in Sections 34 and 35, the western tier pathway and the motorpool and railyard areas of Sections 3, 4, 9, and 33 extending to the western off-post area. Initial Screening Program data for the Denver Formation for the same time period indicate that volatile halogenated organics occurred mainly as isolated detections in Sections 4, 25, 26, 27, and 35.

A summary of volatile halogenated organic detections from the Third Quarter FY87 sampling period is presented in Appendix F, Table 4.2-5. Concentrations greater the 10,000 ug/l were detected in Sections 23, 26, and 36. The highest concentration, 40,000 ug/l, was detected in the Basin F pathway. Using these data, plumes were delineated (Figure 3.3) in the South Plants-Basin A/Basin A Neck pathways, the central pathway, the north off-post First Creek pathways, the Basin F-Basin F east pathways, the western tier pathway and the motor pool and railyard pathway.

Isolated occurrences of volatile halogenated organics were detected during the Third Quarter FY87 in the confined Denver Formation (Appendix F, Table 4.2-5). These occurrences are presented in point plot maps in Appendix D (Figures D-99 through D-134). Single compound or composite volatile halogenated organic occurrences were noted in Denver Formation zones A, 1u, 1, 2, 3, 4, 5, and 6. Geographically these detections occurred in Sections 1, 2, 23, 24, 35, 36, and off-post.

3.2.2 Dicyclopentadiene

Dicyclopentadiene is a raw material that was used as a chemical feedstock for production of pesticides in the South Plants complex. Its distribution is associated directly with RMA activities.

Historically, dicyclopentadiene has been detected in both alluvial and Denver Formation groundwater at RMA. Historical data collected prior to the Initial Screening Program indicate that dicyclopentadiene occurs from Basin F to the northern RMA border; widespread dicyclopentadiene distribution was detected in Sections 1, 35, and 36, and isolated areas of Sections 18, 22, 27, 33, and 34. These patterns were not confirmed by the Initial Screening Program data. Comparison of the Initial Screening Program alluvial groundwater distribution to the historical data indicated discrepancies in the dicyclopentadiene distributions. Comparison of the Spaine report (1984/RIC85133R04) data to the Initial Screening Program alluvial data shows wider distribution and significantly higher concentrations of dicyclopentadiene in groundwater samples analyzed during the 1984 investigation.

A summary of Third Quarter FY87 analytical results for dicyclopentadiene is presented in Table 4.2-17 (Appendix F). The distribution of dicyclopentadiene in the Unconfined Flow System is shown in Figure 3.4. Three plume areas were identified. The largest plume is in the Basin F pathway north from Basin F to the North Boundary Containment System and along the First Creek Off-Post pathway. A second plume extends from northwestern Basin A through the Basin A Neck to the southeastern edge of Basin C. The third plume, extending from South Plants into the middle of Basin A, could not be confirmed by FY87 data due to a lack of sampling in the area. Historical data were reviewed to delineate this plume. A small area south of South Plants with dicyclopentadiene concentrations in excess of 100 ug/l also has been identified (MKE, 1988, unpublished data). The highest concentration of dicyclopentadiene, 1,200 ug/l, was located immediately downgradient of Basin F in Section 23.

Analytical results for dicyclopentadiene samples collected from confined Denver Formation wells during Third Quarter FY87 are presented in Table 4.2-17 (Appendix F, Figures D-140 and D-141). Dicyclopentadiene was not detected in any confined Denver Formation wells.

3.2.3 Volatile Aromatics

The volatile aromatic organics include benzene, chlorobenzene, toluene, ethylbenzene, meta-xylene, and ortho- and para-xylenes. They comprise a significant fraction of hydrocarbon fuels, particularly gasoline, and are in common use as industrial solvents. Although used extensively at RMA, they cannot be identified as unique to RMA activities. Composite concentration values reported below were calculated by summing the detected volatile aromatic organics concentrations for each sample. Concentrations below the certified reporting limits were taken to be zero. Volatile aromatic organics are presented as a group in order to provide an overview of their occurrence in RMA groundwater. Chlorobenzene and benzene are the most commonly detected volatile aromatic organic compounds within the Unconfined Flow System and Denver Formation and exert the most influence over the total aromatic plume configurations.

Historical data for volatile aromatic organics prior to 1985 are scarce because earlier analytical programs did not include volatile aromatic organics as target analytes. Data from the Initial Screening Program report (ESE, 1987a/RIC87253R01) for the period September 1985 to March 1986 indicated the presence of toluene, benzene, ethylbenzene, and xylene in alluvial groundwater in excess of 1,000 ug/l in the South Plants-Basin A area and north-northeast of Basin F in Section 23. For the same time period, Denver Formation occurrences in excess of 10 ug/l were noted in Sections 1, 22, 23, 26, and 35 with isolated, relatively low-level detections in Sections 2, 3, 4, 6, 19, 25, and 32.

A summary of Third Quarter FY87 analytical results is presented in Table 4.2-5 (Appendix F). Volatile aromatic organics were detected in the Unconfined Flow System in the South Plants-Basin A area northward to the Basin A Neck pathway, in the Basin F pathway, and off-post in the northern, First Creek, and Quincy Street pathways. The distribution of summed volatile aromatic compounds is shown in Figure 3.5. The highest detected concentration of volatile aromatic organics was 56,000 ug/l in the southwestern portion of Section 36. Elevated concentrations of benzene and other volatile aromatic compounds have been detected during recent sampling in the South Plants area by MKE. The results of this sampling event are presented in the South Plants Study Area Report. The areal extent of the plumes is indicated in Figure 3.5.

The volatile aromatic compounds occur more extensively in the confined Denver Formation than any other organic compound groups identified at RMA. Volatile aromatic organics were detected in confined Denver Formation zones A, 1u, 1, 2, 3, 4 and 5. Geographically, these detections occurred in Sections 1, 23, 24, 26, 35, 36, and off-post in Sections 13 and 14, downgradient of the North Boundary Containment System (Appendix D, Figures D-75 through D-98).

3.2.4 Organosulfur Compounds

Organosulfur compounds detected at RMA include chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, chlorophenylmethyl sulfone, dithiane, oxathiane, and benzothiazole. The organosulfur compounds chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone are presented as a composite group because the individual compounds have similar chemical and physical properties, and are derived from the manufacture of Planavin in the South Plants complex, and have similar distributions and concentrations. Dithiane and oxathiane have distributions similar to those of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone but result from degradation of mustard agent and will be discussed separately. Mustard was manufactured, handled, and demilitarized in the North and South Plants complexes. Benzothiazole is a relatively recent addition to the RMA analyte list and will be discussed separately.

Historically, chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone have been detected in both the Unconfined Flow System and Denver Formation aquifers. The distributions of these compounds identified during the Initial Screening Program confirmed general historical distributions identified prior to the Initial Screening Program. In general, the distribution of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone detected in the Unconfined Flow System during the Initial Screening Program indicated an association with several recognized source areas at RMA, including the South Plants area, Basin A, and Basin F. Total concentrations ranged from 10 to 100 ug/l or greater. These compounds were also detected in the Unconfined Flow System along the north boundary of RMA (Sec. 23 and 24) in concentrations in excess of 10 ug/l.

The distribution of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone in the confined Denver Formation was largely restricted to the vicinity of Basins B, C, and D in Section 26, and the northern portion of Section 35. Total concentrations generally ranged from 1.3 to 10 ug/l in this area.

During the Initial Screening Program, dithiane and oxathiane were detected in both alluvial and Denver Formation groundwater at RMA. Distributions in the alluvial aquifer were in the vicinity of Basins A through F, and north from Basin F to the north boundary of RMA. Also during the Initial Screening Program, dithiane and oxathiane were detected in confined Denver Formation groundwater in the vicinity of Basins B, C, and D in Section 26, and in the northern portion of Section 35. Analytical data from 1974 through 1985 indicate the presence of these compounds in Basins C, D, and E, north-northeast of Basin F, and in isolated areas of Section 36.

Benzothiazole is a heterocyclic aromatic compound associated with the manufacture of pesticides. Historically, analyses for benzothiazole were not routinely performed on RMA groundwater samples. Benzothiazole analyses were reported on an occasional basis between 1975 and 1984. Based on the results of analyses, benzothiazole was recognized as a possible constituent in RMA groundwater and was added to the RMA target analyte list during Second Quarter FY87.

A summary of Third Quarter FY87 composite analytical results for chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone is presented in Appendix F, Table 4.2-10. Two plumes were identified in the Unconfined Flow System (Figure 3.6), in the areas of the Basin F pathway and the South Plants-Basin A/Basin A Neck pathways. Total concentrations of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone within these plumes range from 6.2 to 2,100 ug/l on-post and 5.2 to 160 ug/l off-post. The highest on-post concentration was noted approximately 600 ft northeast of Basin F. The highest off-post concentration was noted approximately 2,500 ft north of the RMA boundary in west-central Section 13.

A summary of Third Quarter FY87 analytical results for dithiane and oxathiane is presented in Appendix F, Table 4.2-8. The areal distribution of these compounds is shown on the plume map presented in Appendix F, Figure 4.2-5. Dithiane and oxathiane distribution in the Unconfined Flow System is very similar to the distribution of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone, occurring in an apparently continuous plume along the South Plants/Basin A pathway, through the Basin F east and Basin F pathways, and north to the North Boundary Containment System. The plume extends off-post along the First Creek pathway. Greatest concentrations of dithiane and oxathiane occur in the South Plants/Basin A area, ranging from 57 to 9,300 ug/l.

The distribution of benzothiazole in the Unconfined Flow System based on Third Quarter FY87 analyses (Appendix F, Table 4.2-9) is shown on the plume map in Appendix F, Figure 4.2-7. Plumes were identified in the Basin F pathway and in the Basin A pathway. The highest concentration, 15 ug/l, was detected in the Basin A pathway.

Chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone were detected in Third Quarter FY87 samples collected from confined Denver Formation wells completed within zones A, 1u, 1 and 2 (Appendix F, Table 4.2-10). The distribution of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone in confined Denver Formation groundwater was primarily confined to the vicinity of Basins B, C, and D in Section 26 and the northern portion of Section 35 (Appendix D, Figures D-63 through D-74). The highest concentrations were observed in isolated wells in Section 2 (48 ug/l) and Section 26 (64 ug/l).

Dithiane/oxathiane was observed in samples collected from confined Denver Formation wells completed within zones 1u, 1, 2 and 4 (Appendix F, Table 4.2-8). These detections are located in the vicinity of Basin C, Basin A Neck pathway, and the Basin F North pathway. The locations of wells completed within these zones and detected dithiane/oxathiane concentrations are shown on the point plot maps in Appendix D (Figures D-40 through D-55). The highest concentration detected was 310 ug/l, in the vicinity of Basin C.

Benzothiazole was detected in confined Denver Formation wells completed within zones 1U, 1, 4, and 5 (Appendix F, Table 4.2-9). The locations of wells completed within each of these zones and detected benzothiazole concentrations are shown on point plot maps in Appendix D (Figures D-56 through D-62). Benzothiazole was detected in the Basin A Neck area near the eastern margin of Basin C and in isolated wells in Sections 3 and 4. The highest concentration, 3.4 ug/l, was detected in the Basin A Neck area.

3.2.5 Diisopropylmethyl Phosphonate

Diisopropylmethyl phosphonate is a by-product of the manufacture of the nerve agent GB (Sarin) in the North Plants complex. This compound is directly associated with RMA activities.

Historically, diisopropylmethyl phosphonate has been detected in both alluvial and confined Denver Formation groundwater at RMA. During the Initial Screening Program, diisopropylmethyl phosphonate was detected in the alluvial aquifer from the Basin A/Basin A Neck pathway to Basins B through F, to the north and northwestern RMA boundaries in Sections 23 and 24. Diisopropylmethyl phosphonate was detected in confined Denver Formation wells in an area extending from the Basin A Neck through Basin B to the northern portion of Basin C.

A summary of analytical results for diisopropylmethyl phosphonate analyses in the Unconfined Flow System during Third Quarter FY87 is presented in Table 4.2-18 (Appendix F). The distribution of diisopropylmethyl phosphonate in the Unconfined Flow System is shown in Figure 3.7. The diisopropylmethyl phosphonate plume occurs in an area extending from Basin A through Basin A Neck, northward through the Basin F pathway to the north RMA boundary, continuing off-post along the First Creek and the Northern off-post pathways to near the South Platte River. The highest concentration detected was 5,200 ug/l, in Section 26.

A summary of analytical results for diisopropylmethyl phosphonate in groundwater samples from confined Denver Formation wells for third Quarter FY87 is presented in Appendix F, Table 4.2-18. Diisopropylmethyl phosphonate was detected in samples collected from confined Denver Formation wells completed in zones A, 1u, 1, 2, 3 and 5. The locations of wells completed in each of these zones and detected diisopropylmethyl phosphonate concentrations are shown on point plot maps in Appendix D (Figures D-142 through D-148). The highest concentration detected was 5,400 ug/l, in a well completed in zone 1u in Section 35.

3.2.6 DBCP

DBCP is a nematocide and soil fumigant. It was manufactured by Shell in the South Plants complex and shipped in tank cars that were stored in the rail classification yard.

Historically, DBCP has been detected in both the Unconfined Flow System and confined Denver Formation groundwater systems at RMA. According to Initial Screening Program data, the highest concentrations of DBCP in the Unconfined Flow System were observed in the South Plants area, the southern portion of Basin A, an area extending from southeastern Section 4 to the Irondale Boundary Control System, and an area north of Basin F in Sections 23 and 26. Within the confined Denver Formation, DBCP was detected only twice, in Sections 2 and 6. DBCP was detected between 1979 and 1983 in samples from the alluvial aquifer in the South Plants-Basin A area through Basins A, B, C, D, E, and F to the Northwest Containment System and North Boundary Containment System. Analyses performed on Denver Formation samples between 1978 and 1983 detected DBCP in Sections 26 and 35 near Basins B, C, and D (MKE, unpublished data, 1986).

A summary of Third Quarter FY87 analytical results for DBCP is presented in Appendix F, Table 4.2-16. Plume configurations for DBCP in the Unconfined Flow System are shown in Figure 3.8. Plumes were identified in the Basin F pathway from Basin F to the northern RMA boundary, in the Northern Off-Post pathway in Section 11, in the Basin A pathway and along the Basin A Neck pathway through Sections 26 and 27 to an area near the Northwest Containment System, and in the motor pool and railyard pathway extending northward to the Irondale Boundary Control System.

A summary of analytical results for confined Denver Formation wells analyzed for DBCP during Third Quarter FY87 is presented in Appendix F, Table 4.2-16. DBCP was detected in confined Denver Formation wells completed in zones A, 2, and 4. The locations of wells completed within each of these zones and detected DBCP concentrations are shown on point plot maps presented in Appendix D (Figures D-135 through D-139). DBCP was detected in confined Denver Formation wells in Sections 1 and 23, and off-post immediately downgradient of the North Boundary Containment System. The highest concentration detected, 0.78 ug/l, was noted in confined Denver Formation zone 2.

3.2.7 Organochlorine Pesticides

Organochlorine pesticides were manufactured in the South Plants complex, and have been used on-post and in farming land adjacent to RMA. The distribution of organochlorine pesticides is largely the result of dieldrin and endrin occurrences and, to a much lesser extent, aldrin and isodrin. For this reason, plume maps were generated only for dieldrin and endrin and will be discussed below.

Historically, organochlorine pesticides have been detected in alluvial and Denver Formation aquifers. Based on Initial Screening Program data, concentrations in excess of 1.0 ug/l were observed locally in alluvial groundwater in Sections 1, 2, 23, 24, 26, 35 and 36. Isolated detections of organochlorine pesticides in Denver Formation groundwater were observed in Sections 2, 4, 19, 25, 26 and 36.

Summaries of Third Quarter FY87 analytical results for dieldrin and endrin are presented in Tables 4.2-6 and 4.2-7 (Appendix F). The distribution of dieldrin and endrin in the Unconfined Flow System is shown on plume maps presented in Figure 3.9 and Appendix F, Figure 4.2-4, respectively. Six major plumes were identified in the following pathways:

central pathway south, central pathway north, South Plants/Basin A, Basin A Neck pathways to Section 27, Basin F pathway, and Basin F northwest pathway. Within downgradient off-post areas, dieldrin was detected north and northwest of the RMA boundary; endrin was detected only north of the RMA boundary. Contaminant trends in and around the North Boundary Containment System and Northwest Boundary Containment System are discussed further in Task 36 (ESE, 1988g/RIC88344R02), Task 25 (ESE, 1988h, RIC#89024R02) and Task 39 (ESE, 1989b/RIC89024R01).

Based on Third Quarter FY87 analytical results, dieldrin and/or endrin were detected in confined Denver Formation wells completed in zones A, 1, 2, and 3 (Appendix F, Tables 4.2-6 and 4.2-7). The locations of wells completed within each of these zones and detected concentrations are shown on the point plot maps in Appendix D (Figures D-28 through D-34).

3.2.8 Arsenic

Arsenic is a naturally occurring element. It was also a component of Lewisite as well as a by-product of Lewisite manufacture (Ebasco, 1988a/RIC88357R01). Historically, arsenic has been detected in groundwater samples in Sections 1, 2, 4, 19, 23, 24, 26, 27, 32, 35, and 36. Although arsenic may be found naturally, there has been no value recognized by RMA investigators or regulators as representative of background levels of arsenic in groundwater at RMA. Therefore, a plume is defined here by concentrations of arsenic in excess of 3.07 ug/l, which is the highest certified reporting limit for Third Quarter FY87 data for arsenic.

In considering background levels of arsenic in RMA groundwater, it is worthy to note that arsenic detections, even very close to the CRL, were largely limited to known RMA source areas. This indicates that background levels of arsenic are probably very low in the RMA area.

A summary of Third Quarter FY87 analytical results for total arsenic in alluvial and Denver Formation wells completed within the Unconfined Flow System is presented in Appendix F, Table 4.2-19. Arsenic plumes were delineated in the Basin A/Basin A Neck pathway and the Basin F pathway, with minor occurrences in the First Creek off-post pathway and the Quincy Street pathway (Appendix F, Figure 4.2-21). The highest concentration detected was 410 ug/l, in the Basin F pathway plume.

Arsenic was detected within wells screened in the confined Denver Formation during the Third Quarter FY87 sampling period. A summary of analytical results for these samples is presented in Appendix F, Table 4.2-19. Arsenic was detected in samples from wells screened in confined Denver Formation zones A, lu, 1, 2, 4, and 5 (Appendix D, Figures D-162 through D168). These detections occurred in Sections 3, 4, 6, 8, 22, 24, 26, 35, and 36. The highest detected concentration was 27 ug/l, in zone A in Section 36.

3.2.9 Fluoride

Fluoride is a naturally occurring anion. It was used at RMA in the elemental form of fluorine in the manufacture of nerve gas (Ebasco, 1988a/RIC88357R01). In addition, large volumes of solium fluoride were contained in GB Plant liquid waste discharge from 1953 through 1957. Drinking water standards for fluoride are temperature dependent and range from 1,400 to 2,400 ug/l. During the Initial Screening Program, fluoride in the alluvial groundwater system was detected at concentrations up to 310,000 ug/l. Concentrations above 5,000 ug/l were observed in the area of Basin A, north of Basin F, and in the vicinity of the North Boundary Containment System. Within the Denver Formation, fluoride was observed during the Initial Screening Program at concentrations in excess of 1,200 ug/l over an area encompassing most of the western two-thirds of RMA. The distribution of fluoride within the deeper Denver Formation, in wells with screen tops greater than 50 ft below the bedrock contact, was less widespread than the overall Denver distribution. A comparison of Initial Screening Program data for fluoride analyses to the historical USATHAMA database and data obtained from the Spaine report (1984/RIC85133R04) confirms general distribution trends of fluoride in the alluvial aquifer, principally associated with the primary source areas.

A summary of Third Quarter FY87 analytical results for fluoride (as a dissolved anion) in alluvial and Denver Formation wells completed within the Unconfined Flow System is presented in Appendix F, Table 4.2-20. The distribution of fluoride in the Unconfined Flow System is shown in Appendix F, Figure 4.2-22. Background levels for fluoride have not been defined for the RMA area; however, values for fluoride in upgradient wells shown in Table 3.1 range from 570 to 1,000 ug/l. For the purposes of this report, based

Table 3.1 Representative Concentrations for Naturally Occurring Constituents in RMA Upgradient Unconfined Wells (Values are in ug/l)

Analyte	Unconfined Well (approximately 0.5 miles south east of RMA)[1]	Well Number[2]			Concentration Range From Upgradient Wells
		12001	11001	08002	
Chloride	*	34,000	52,000	60,000	34,000-60,000
Fluoride	1,000	690	570	960	570-1,000
Sulfate	48,000	63,000	132,000	43,000	43,000-138,000
Calcium	51,000	67,000	139,000	112,000	51,000-139,000
Potassium	*	*	*	*	NA
Sodium	36,000	44,000	68,000	60,000	36,000-68,000
Magnesium	9,200	*	*	*	9,200
Nitrogen	8,300	3,500	700	22,900	700-22,900
Zinc	*	*	*	*	NA
Cadmium	*	*	*	*	NA
Lead	*	*	*	*	NA
Chromium	*	*	*	*	NA
Copper	*	*	*	*	NA
Arsenic	*	*	*	*	NA
Mercury	*	*	*	*	NA
pH	*	*	*	7.5	
Conductivity	*	*	*	875	

1 Irrigation well, 70 ft deep, in Section 17, T3S, R66W (McConaghy et al., 1964).
2 Alluvial wells near southern boundary of RMA, samples collected 1975 and 1976 (Army, RIC#82160R12).
* Not analyzed.

Source: HLA, 1988.

largely upon the highest CRL value for fluoride in FY88 monitoring, fluoride plumes have been defined here as those areas where concentrations are in excess of 1,220 ug/l. Three plumes were identified; the largest extends from the South Plants/Lower Lakes area through Basins A through F to beyond the RMA north and northwestern boundaries; a second plume extends from west-central Section 35 to the northwest corner of Section 34; and a third plume extends a short distance within Section 2. The highest concentration detected during Third Quarter FY87, 220,000 ug/l, was adjacent to the north side of Basin F.

Based on Third Quarter FY87 analytical results, fluoride was detected in samples collected from confined Denver Formation wells completed within every zone except the VC/VCE zone (Appendix F, Table 4.2-20). Plumes were constructed based on fluoride concentrations within Denver Formation zones A, 1u, 1, 2, 4, and 5 (Appendix F, Figures 4.2-23 through 4.2-28). Concentration point plot maps were generated for the remaining Denver Formation zones and are presented in Appendix D (Figures D-157 through D-161). Fluoride plumes were delineated in Sections 1, 2, 3, 4, 22, 23, 25, 26, 35, and 36. The highest concentration detected was 7,900 ug/l, in north-central Section 4.

3.2.10 Chloride

Chloride is a naturally occurring anion that is also prevalent in salts and solvents associated with several processes that were conducted at RMA (Ebasco, 1988a/RIC88357R01). The drinking water standard for chloride is 250,000 ug/l. Historically, widespread occurrences of chloride have been detected in both the Unconfined Flow System and confined Denver Formation at RMA. The distribution of chloride detected in the Unconfined Flow System in concentrations greater than 250,000 ug/l during the Initial Screening Program extends from the South Plants area to the northern and northwestern RMA boundaries. Initial Screening Program data also indicate that chloride was detected in the Denver aquifer at concentrations in excess of 250,000 ug/l in three areas; the South Plants area, Basins C through F, and Sections 22 and 23 near the northern RMA boundary.

Historical groundwater data collected prior to the Initial Screening Program show more widespread chloride distributions in both the Unconfined Flow System and confined Denver Formation than Initial Screening Program data indicate. Based on historical data, chloride extends further east, west, and south than chloride distributions indicated by Initial Screening Program data. Within the Denver Formation, historical data imply a continuous distribution of elevated chloride concentrations extending from the South Plants Area to the northwestern RMA boundary.

A summary of Third Quarter FY87 analytical results for chloride in the Unconfined Flow System is presented in Appendix F, Table 4.2-21. Table 3.1 lists inorganic parameters values for several unconfined upgradient wells. For the purpose of this report, this well was used to represent typical background chloride concentrations. The upgradient chloride range is from 34,000 to 60,000 ug/l. Drinking water standards established by the EPA indicate that 250,000 ug/l is the maximum allowable concentration. In light of this, 150,000 ug/l was used as the lowest contour interval, to be sure that all potentially anomalous occurrences were considered in plume mapping. The distribution of chloride in the Unconfined Flow System is shown in Appendix F, Figure 4.2-29. Third Quarter FY87 data for chloride compare more closely with Initial Screening Program data than with historical data. Chloride concentrations in the Unconfined Flow System ranged from 5,700 to 28,000,000 ug/l. Concentrations in excess of 1,000,000 ug/l were observed along the Basin A/Basin A Neck pathway, through Basins B, C, D, and F, and along the Basin F pathway north to the North Boundary Containment System. The highest chloride concentration in Unconfined Flow System wells analyzed was located in Section 26, just northeast of Basin F.

A summary of chloride analyses from groundwater samples collected from confined Denver Formation wells during the Third Quarter FY87 sampling program is presented in Appendix F, Table 4.2-21. Chloride was detected in samples collected from confined Denver Formation wells completed in every zone except the VC/VCE. Plume maps were constructed based on chloride concentrations within zones A, 1, 2, 3, and 4 and are presented in Appendix F (Figures 4.2-30 through 4.2-34). The locations of wells and detected chloride concentrations in the remaining confined Denver Formation zones are shown on point plot maps in Appendix D (Figures D-151 through D-156). The greatest chloride concentration detected in the confined Denver Formation was 7,300,000 ug/l, in zone A in northern Section 2.

3.2.11 GC/MS Analysis

Gas chromatograph/mass spectrometry (GC/MS) was conducted on samples analyzed under Task 4 (3rd and 4th Quarters FY86) and Task 44 (3rd Quarter FY87) to confirm identification of target analytes using other analytical techniques and to tentatively identify nontarget compounds.

A detailed discussion of GC/MS analytical methods, criteria for well selection for GC/MS analysis, QA/QC procedures, and target and nontarget analytical results can be found in Appendix F, Section 4.3. In addition, all analytical data for groundwater analyses performed by GC/MS are contained in Appendix D.

3.2.12 Vertical Extent of Contamination

The purpose of this section is to describe depths of groundwater contaminants that have been detected at RMA. The mechanisms by which contaminants migrated in the Unconfined Flow System and eventually to deeper zones (approximately 200 ft) of the Denver Formation are discussed in Section 4.0. Data used to assess the depth of groundwater contamination in the Denver Formation were generated from the Initial Screening Program through the summer 1987 sampling periods. Data from several sampling periods were used, in order that the reproducibility and associated reliability of the data could be assessed. To aid in this assessment, composite maps were generated that delineate the extent of organic and inorganic analytes from Denver Formation zones A, B, and 1 through 7 (Figure 3.10-3.27).

The composite organic plume maps (Figures 3.20-3.27) show that most organic analytes detected in deeper zones of the Denver Formation (zones 2-7) are located in the area between Basin F and off-post Sections 13 and 14, which are adjacent to and north of the north boundary containment system. Organic analytes have been detected in this area at depths of approximately 160 ft below ground surface. Near the southeast corner of Basin F, dieldrin and endrin have been detected at concentrations of 1.2 ug/l and 0.16 ug/l at a depth of 146 ft (zone 3). In the vicinity of the north boundary, chloroform at 3.1 ug/l (zone 6), chlorobenzene at 7.74 ug/l (zone 5), and diisopropylmethyl phosphonate at 27 ug/l (zone 5) have been detected from depths of approximately 150 to 180 ft.

Chloroform has been detected in the deepest screened well in the South Plants at a depth of 210 ft below ground surface. Detected concentrations of chloroform exceed 100 ug/l in the Unconfined Flow System at South Plants but are less than 10 ug/l in the deepest well. Several wells were installed during autumn 1988 in the South Plants to further assess the extent of vertical contamination in the South Plants area. Results of water samples obtained from these wells will be included in the FY89 annual report of the Comprehensive Monitoring Program.

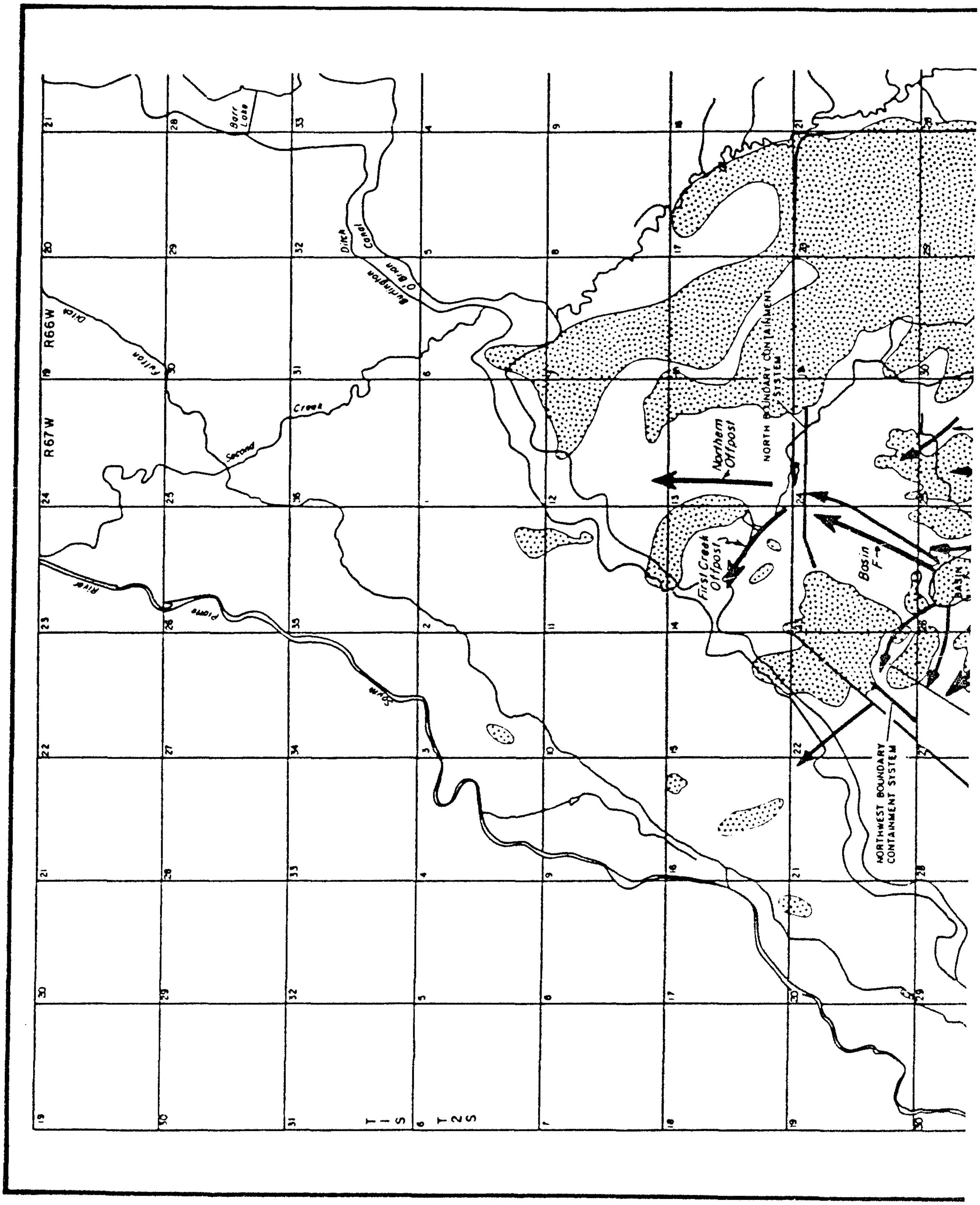
North of the South Plants in the Basin A/Basin A Neck areas, organic analytes have been detected at depths of approximately 100 ft below ground surface. These analytes include oxathiane, dithiane, benzothiazole, chlorophenylmethyl sulfide, chlorobenzene, trichloroethylene, and benzene. All of these analytes were detected at lower concentrations at depth than in the overlying Unconfined Flow System. For example, oxathiane was detected at a concentration of approximately 50 ug/l in the Unconfined flow System and at 17 ug/l in Denver Formation zone 1U. Organic analytes have also been detected in deeper zones of the Denver Formation in what appear to be isolated occurrences in Sections 3, 4, and 9 at depths of 150 to 200 ft; in Section 27 at depths of 100 to 150 ft and in Section 33 at depths of 50 to 100 ft below ground surface. The deepest wells in these sections should be resampled to confirm prior analyses.

Concentrations of fluoride, chloride, and arsenic above background levels have been detected in deeper zones of the Denver Formation both north and northwest of Basin F (Figures 3.16 - 3.18). These inorganic analytes have been detected along the northern and northwestern portion of RMA at depths of approximately 160 ft below ground surface. As with organic analytes, the concentration of inorganic analytes decreases with depth. For example, concentrations of chloride in the Unconfined Flow System north and northwest of Basin F range from 150,000 to over 1,000,000 ug/l. Concentrations of chloride in the deeper zones of the Denver Formation (zones 6 and 7) are less than 15,000 ug/l. Similarly, fluoride concentrations in the Unconfined Flow System range from 1,220 to over 10,000 ug/l, but are less than 2,500 ug/l in the deeper Denver Formation zones.

Most detections of inorganic analytes from deeper zones of the Denver Formation beneath South Plants occur at depths of 145 ft or less. However, inorganic analytes have been detected above background levels (chloride at 62,600 ug/l; fluoride at 1,720 ug/l) in the deepest well (Well 01048) at South Plants at a depth of 210 ft. Concentrations of chloride in the Unconfined Flow System in South Plants range from 150,000 to over 500,000 ug/l and range from approximately 28,000 to 88,000 ug/l at depths of 145 ft.

Inorganic analytes have been detected above background levels in the Basin A/Basin A Neck area at depths of approximately 145 ft. Concentrations of chloride above 1,000,000 ug/l are common in the Unconfined Flow System in this area but are generally less than 250,000 ug/l in deeper zones of the Denver Formation. Fluoride concentrations generally range from 2,000 to 5,000 ug/l in the Unconfined Flow System in this area and generally are less than 2,000 ug/l in deeper Denver Formation zones.

Inorganic analytes have also been detected above background levels in isolated locations within Sections 3, 4, 8, 9, 25, 32, 33, and 34.


R66W
R67W
T 1 S
T 2 S
Barr Lake
Burlington O'Brien Canal
Ditch
Fulton Ditch
Second Creek
South Platte River
Northern Offpost
First Creek Offpost
Basin F
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM

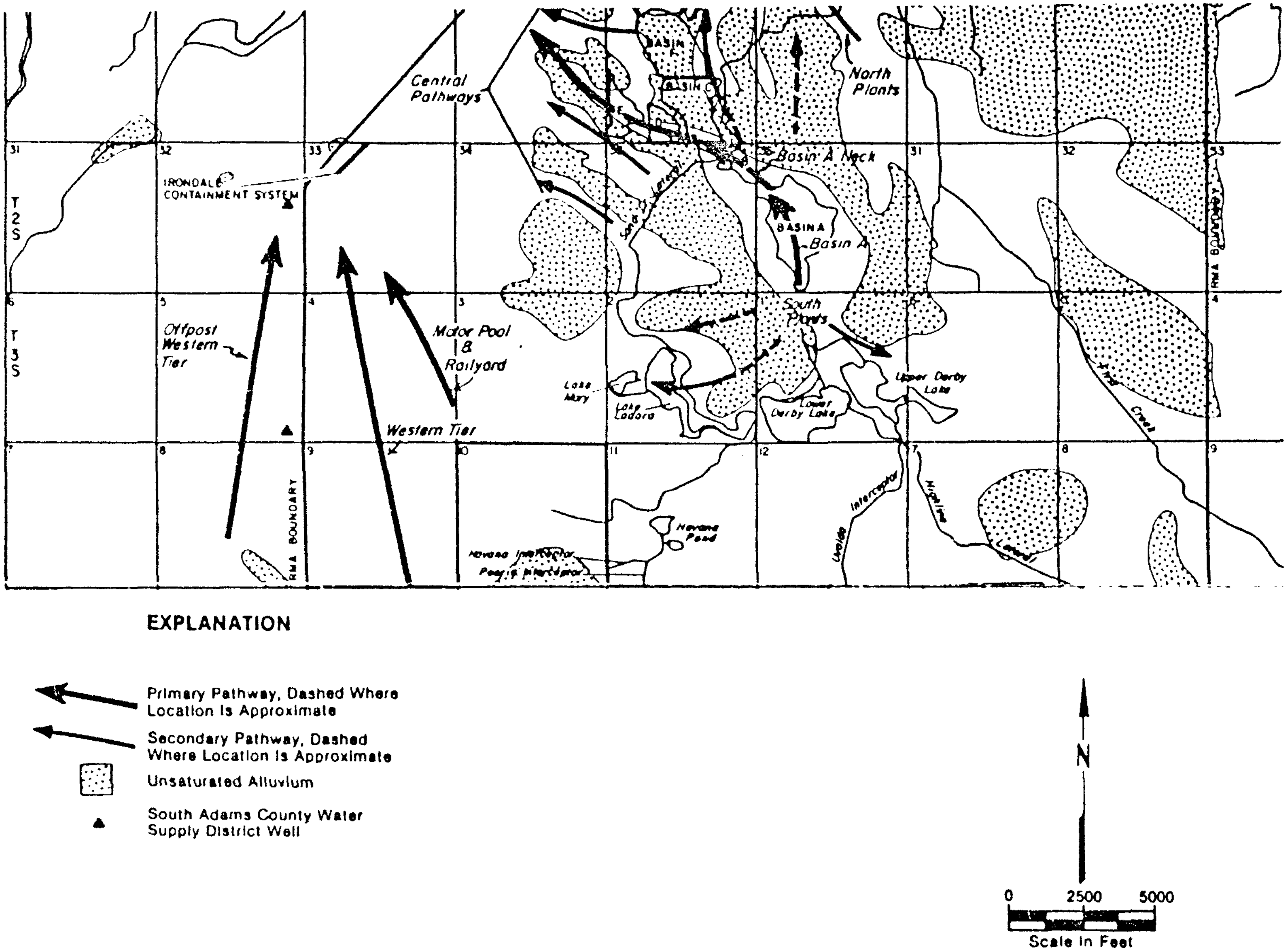


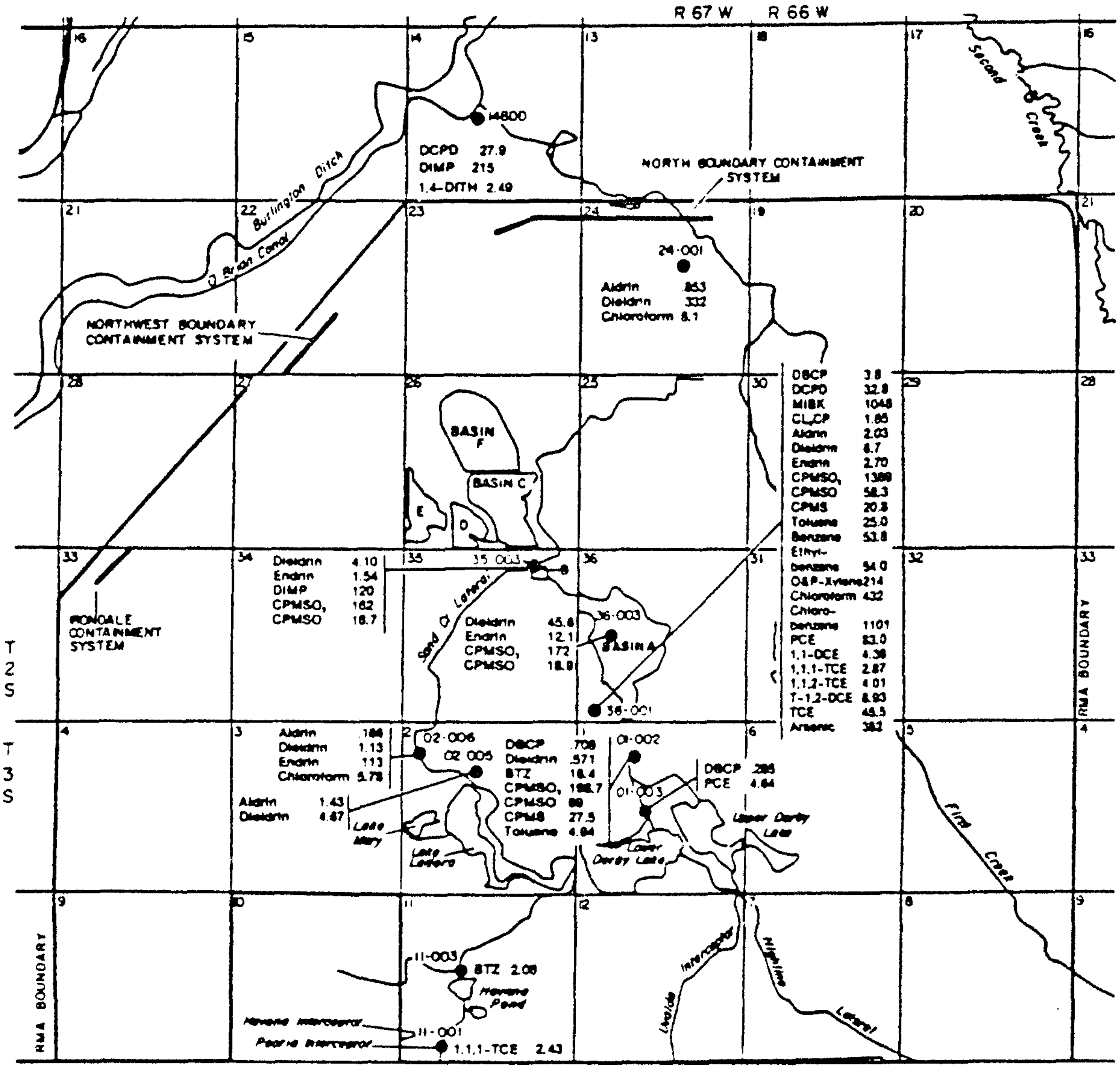
Figure 3.1

RMA CONTAMINANT MIGRATION PATHWAYS

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland



EXPLANATION

BTZ	Benzothiazole
CPMS	Chlorophenylmethyl Sulfide
CPMSO$_2$	Chlorophenylmethyl Sulfone
CPMSO	Chlorophenylmethyl Sulfoxide
DBCP	Dibromochloropropane
1,1-DCE	1,1 Dichloroethylene
T-1,2-DCE	Trans-1,2 Dichloroethylene
DCPD	Dicyclopentadiene
DIMP	Diisopropylmethyl Phosphonate
1,4-DITH	1,4 Dithiane
CL$_6$CP	Hexachlorocyclopentadiene
MIBK	Methylisobutyl Ketone
PCE	Tetrachloroethylene
1,1,1-TCE	1,1,1 Trichloroethane
1,1,2-TCE	1,1,2 Trichloroethane
TCE	Trichloroethylene

Median Concentrations For Compounds Detected During More Than One Sampling Event, Between Fall 85 And Fall 87.

All Concentrations Are In Micrograms/Liter

Arsenic Concentrations Less Than 50 ug/l Were Not Reported.

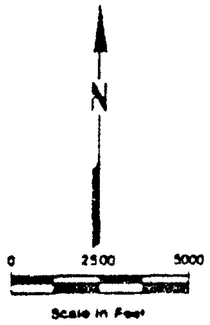
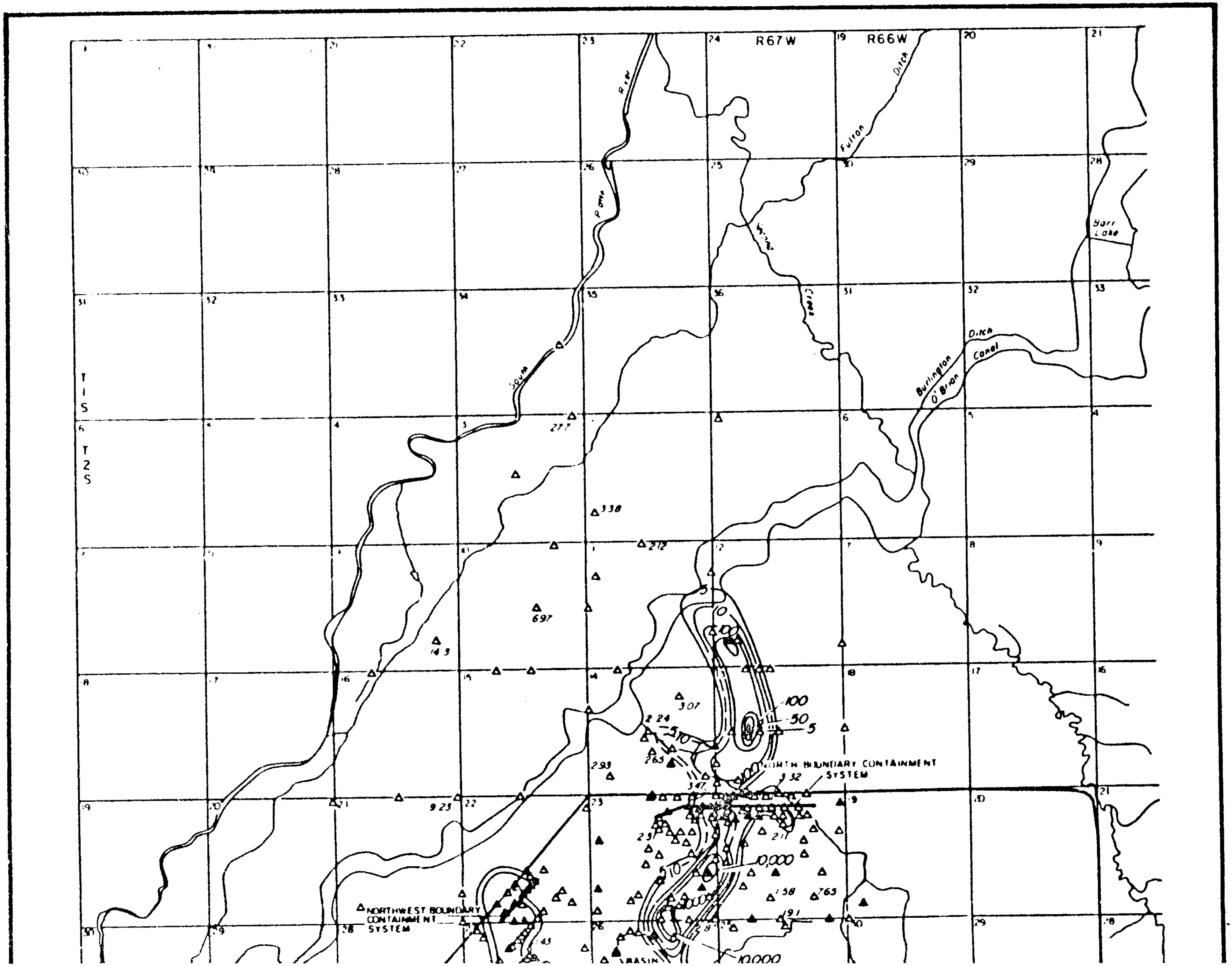
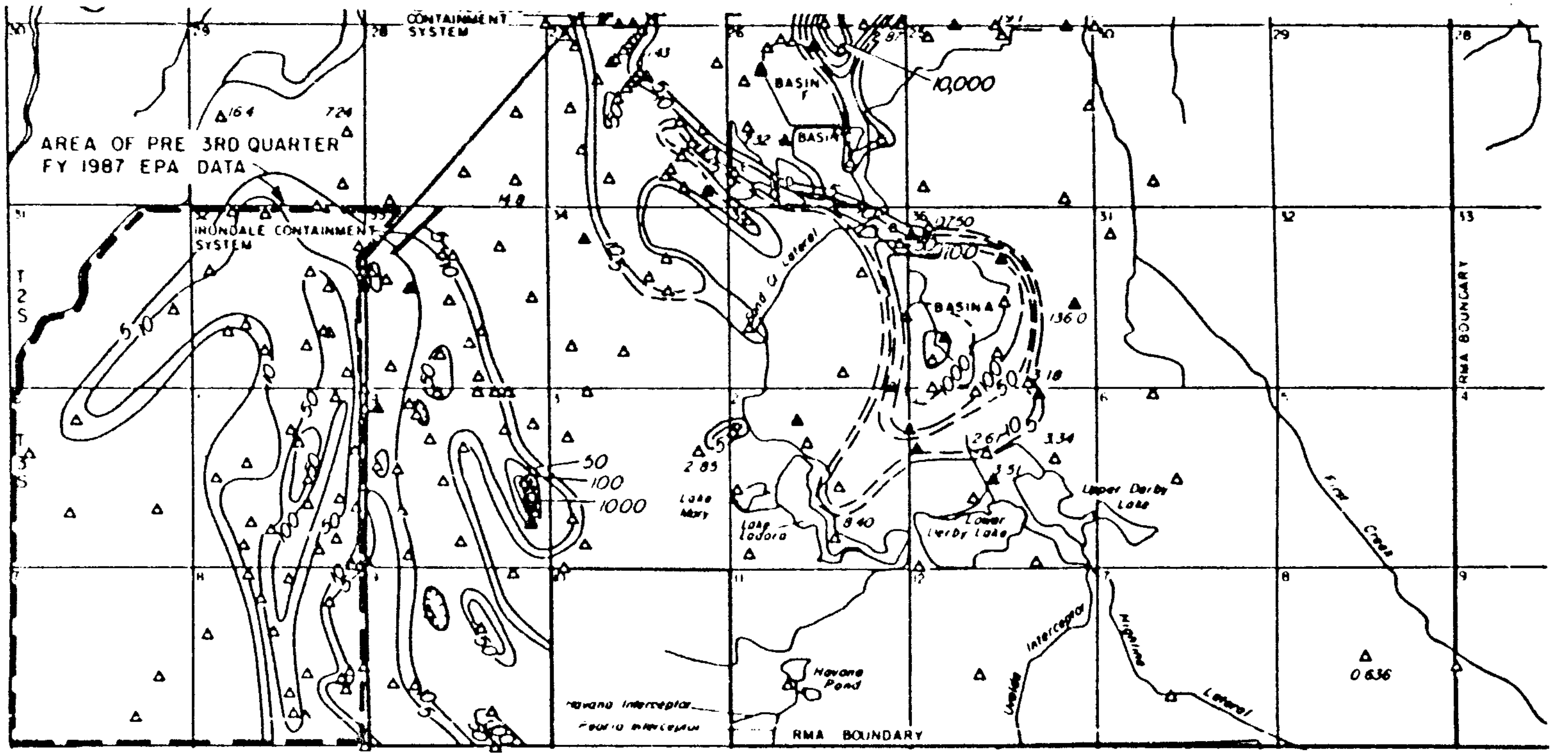


Figure 3.2
SURFACE WATER QUALITY FALL 85 - FALL 87; MULTIPLE DETECTED COMPOUNDS

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland


R67W
R66W
T1S
T2S
South Platte River
Fulton Ditch
Second Creek
Burlington Ditch
O'Brian Canal
Barr Lake
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN
100
50
5
10
10,000
277
338
212
697
14.3
307
2.24
2.65
2.93
3.47
3.32
9.23
211
158
765
191
10,000



EXPLANATION

△ Alluvial Well

▲ Unconfined Denver Formation Well

Isoconcentration Line, Dashed Where Inferred

$\triangle^{2.85}$ Isolated Detection Or Detection Less Than Highest CRL, In ug/l

Contour Interval Varies

NOTE: Summed Volatile Halogenated Organics Include: Chloroform, Trichloroethylene, Tetrachloroethylene, Methylene Chloride, Carbon Tetrachloride, 1,1-Dichloroethylene, Trans-1,2-Dichloroethylene, 1,1-Dichloroethane, 1,2-Dichloroethane, 1,1,1-Trichloroethane, and 1,1,2-Trichloroethane.

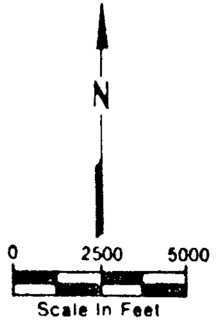


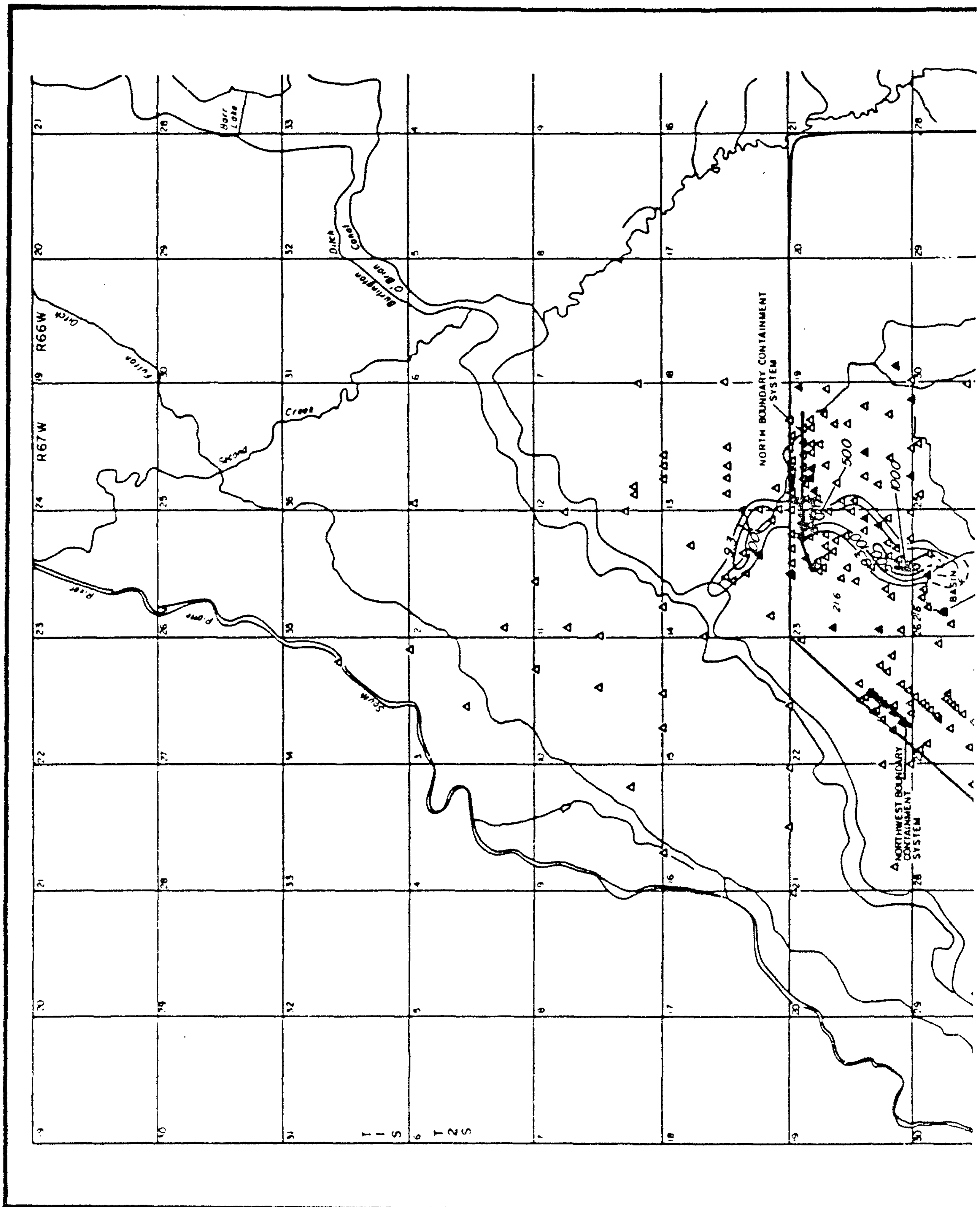
Figure 3.3

SUMMED VOLATILE HALOGENATED ORGANICS PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM, 3RD QUARTER FY 1987

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland



R66W
R67W
T 1 S
T 2 S
Barr Lake
Burlington O'Brien Canal
Ditch
Fulton Ditch
Second Creek
Platte River
South
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN
500
1000
216

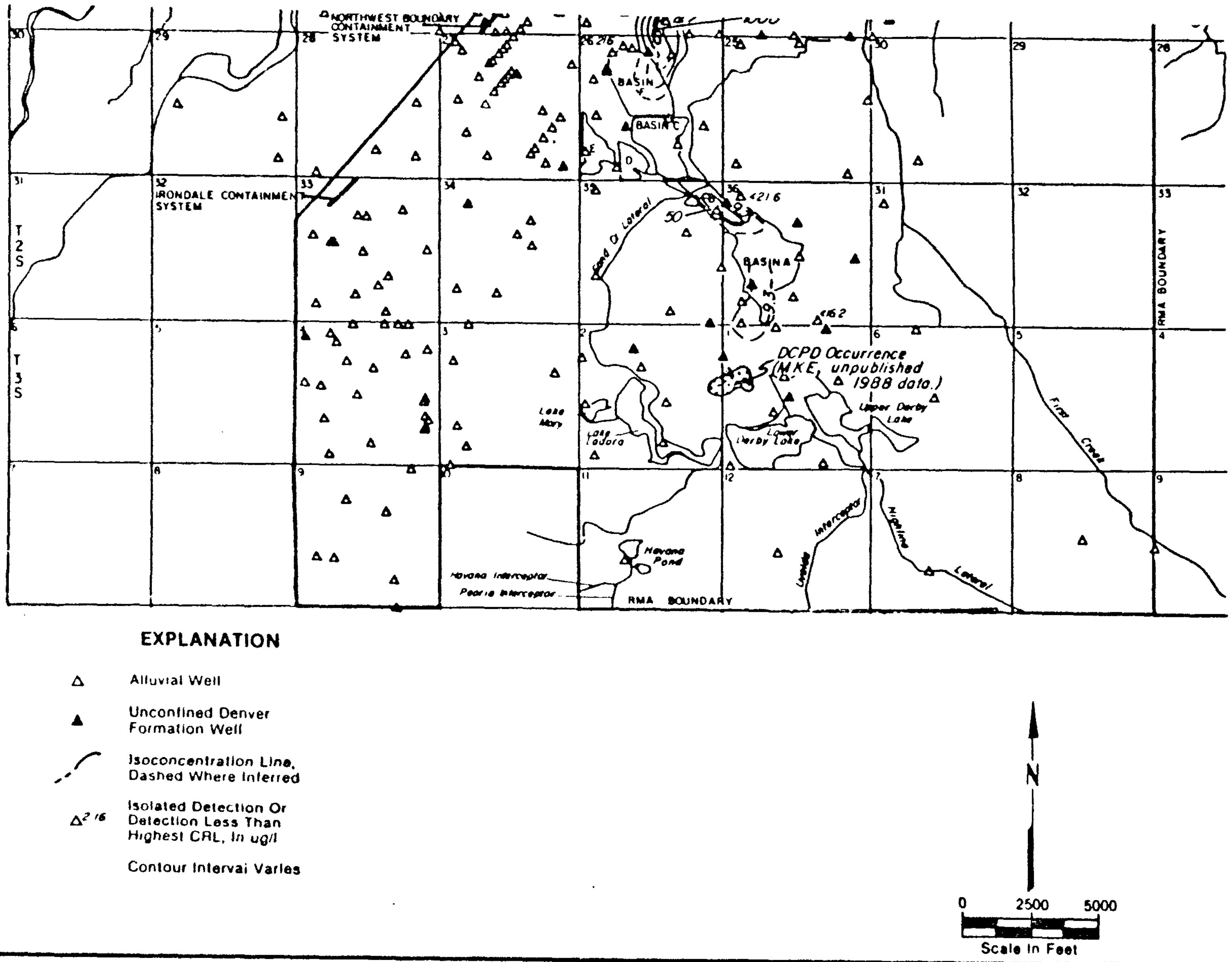


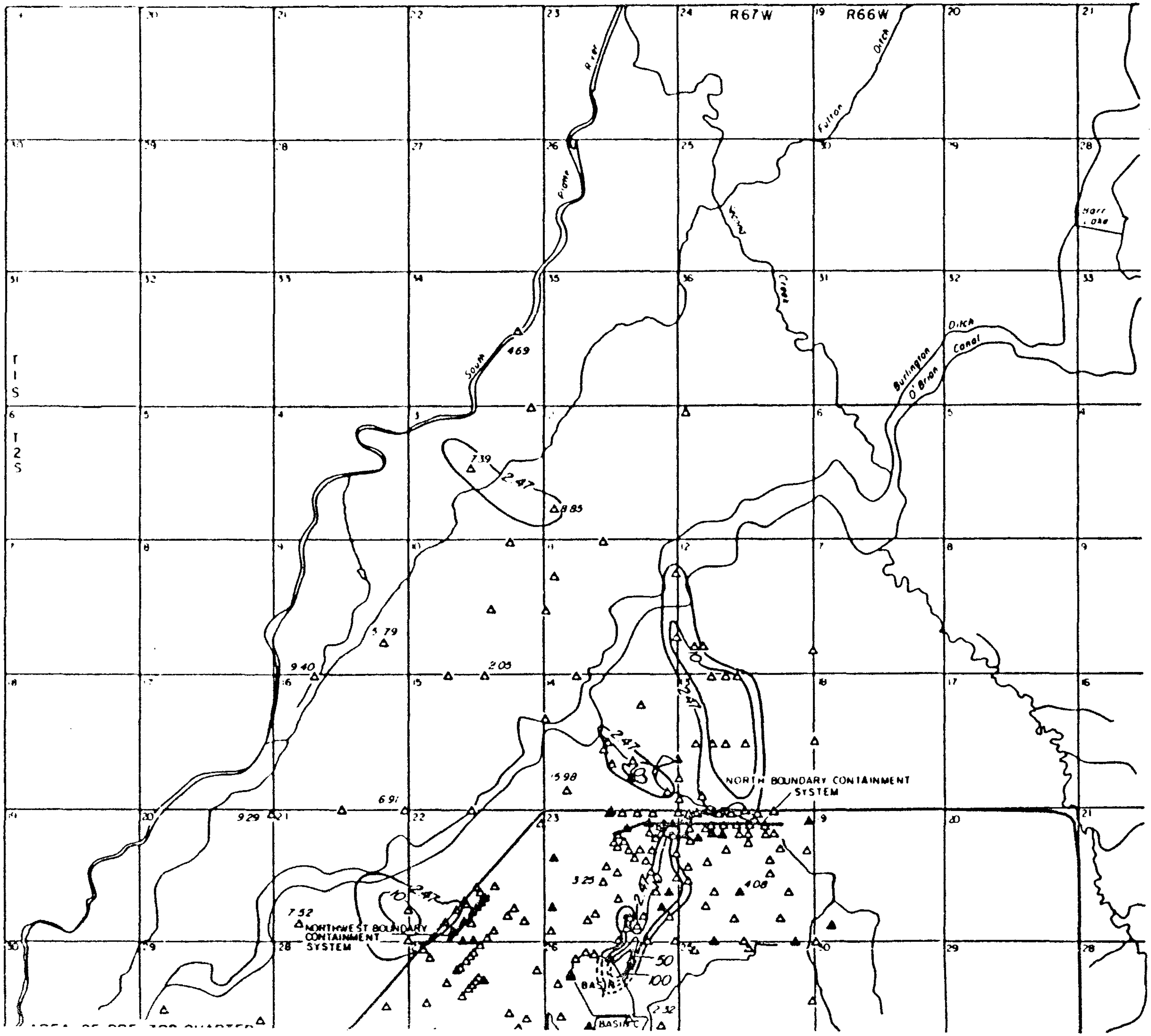
Figure 3.4

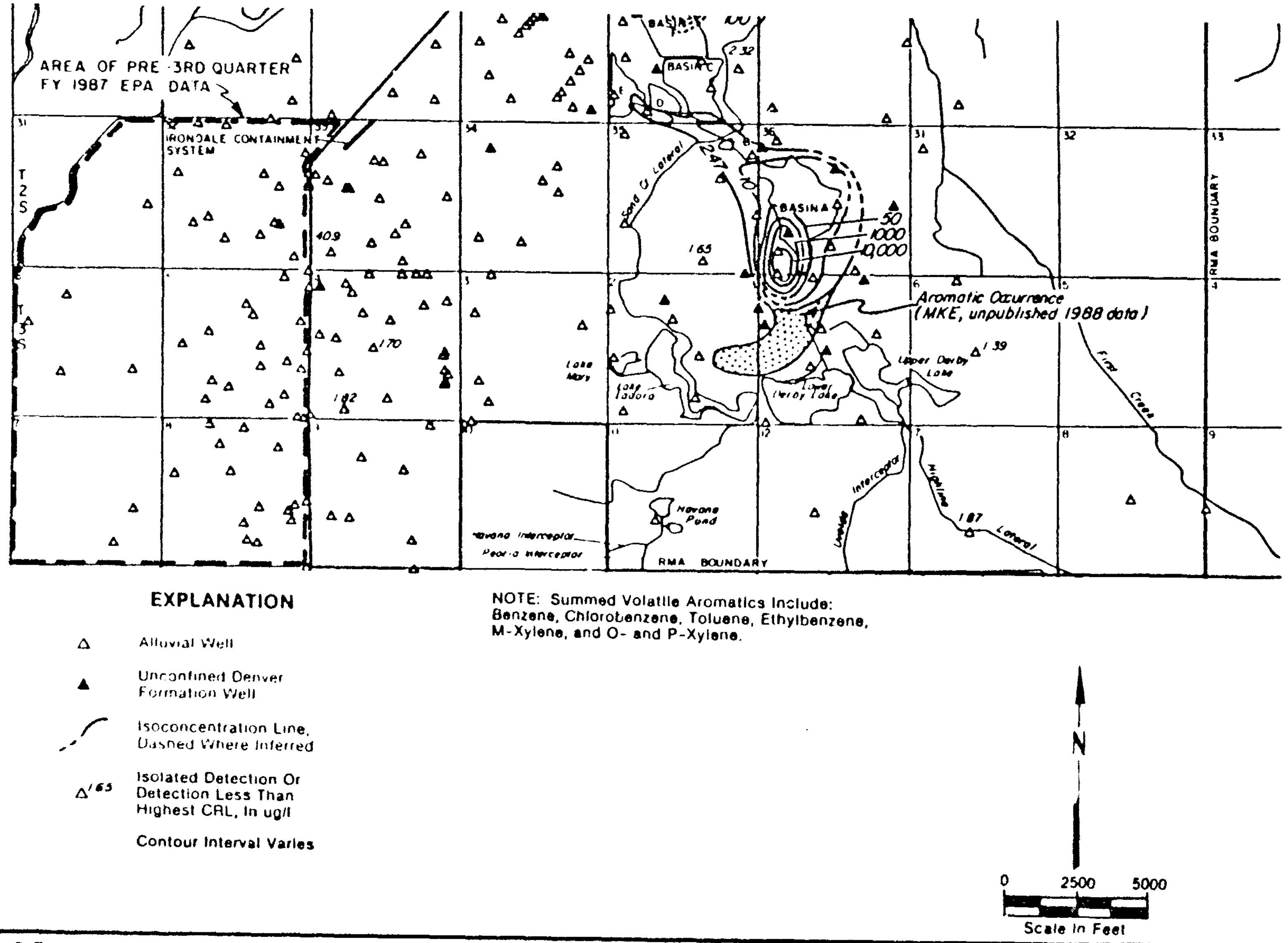
DICYCLOPENTADIENE PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM, 3RD QUARTER FY 1987

SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T 1 S
T 2 S
South Platte River
Fulton Ditch
Burlington Ditch
O'Brian Canal
Barr Lake
Creek
4.69
7.39
2.47
8.85
5.79
9.40
2.05
10
2.47
15.98
6.91
9.29
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
7.52
3.25
4.08
50
100
2.32
BASIN
BASIN C



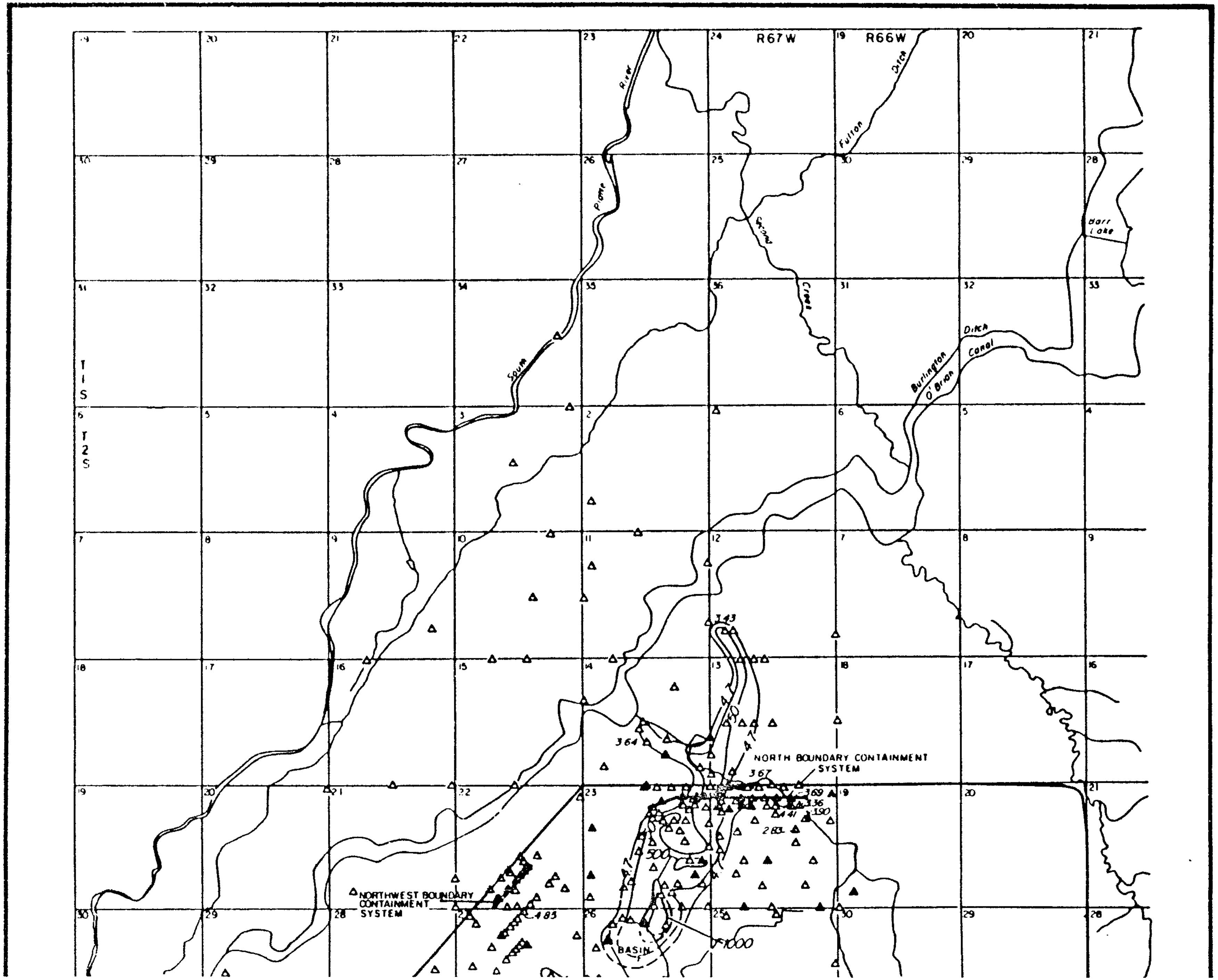
NOTE: Summed Volatile Aromatics Include: Benzene, Chlorobenzene, Toluene, Ethylbenzene, M-Xylene, and O- and P-Xylene.

Figure 3.5

SUMMED VOLATILE AROMATICS PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM, 3RD QUARTER FY 1987

SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland


R67W
R66W
T1S
T2S
South Platte River
Fulton Ditch
Second Creek
Burlington Ditch
O'Brian Canal
Barr Lake
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F
343
364
367
369
336
441
390
283
47
50
500
485
1000

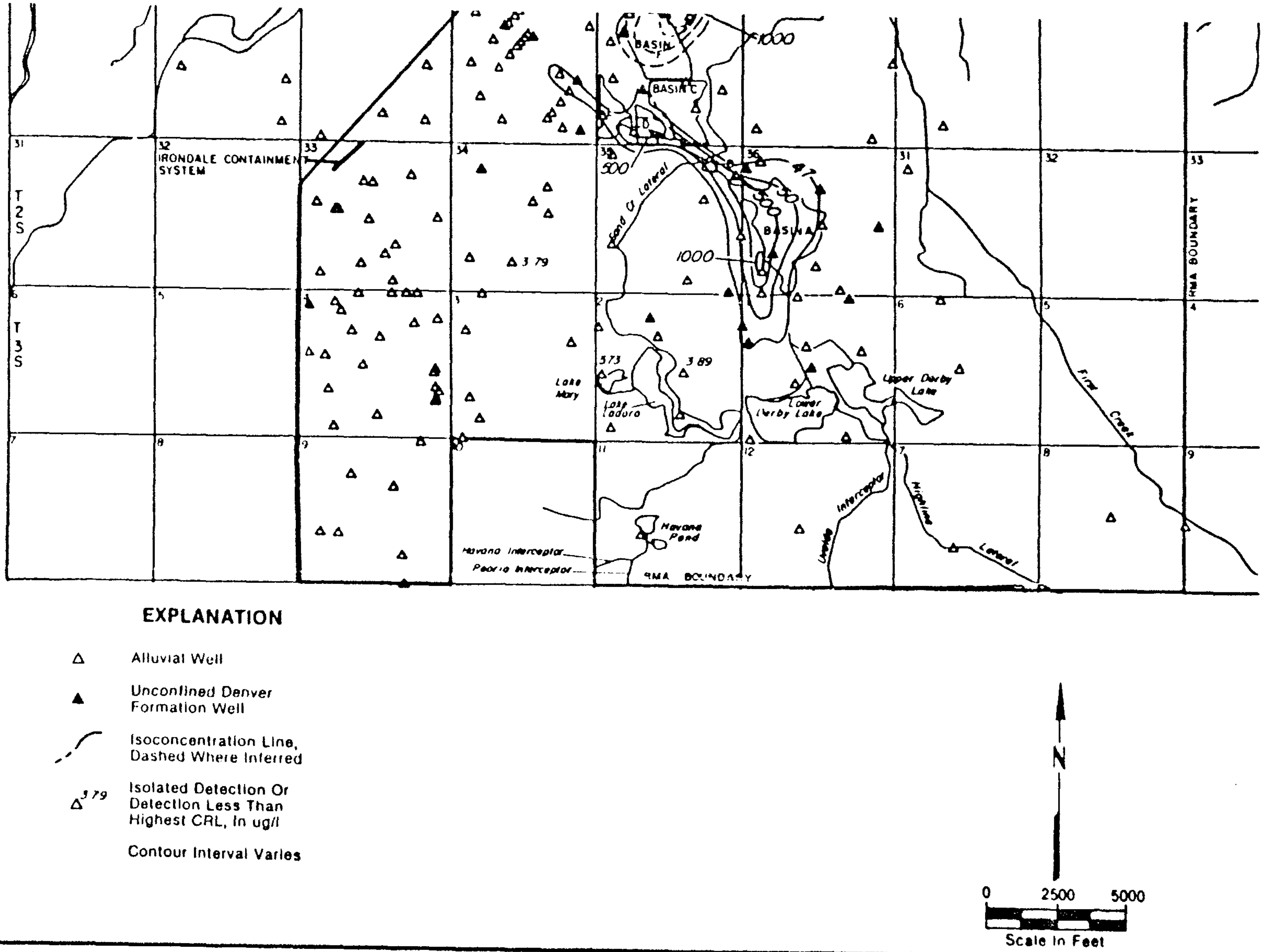


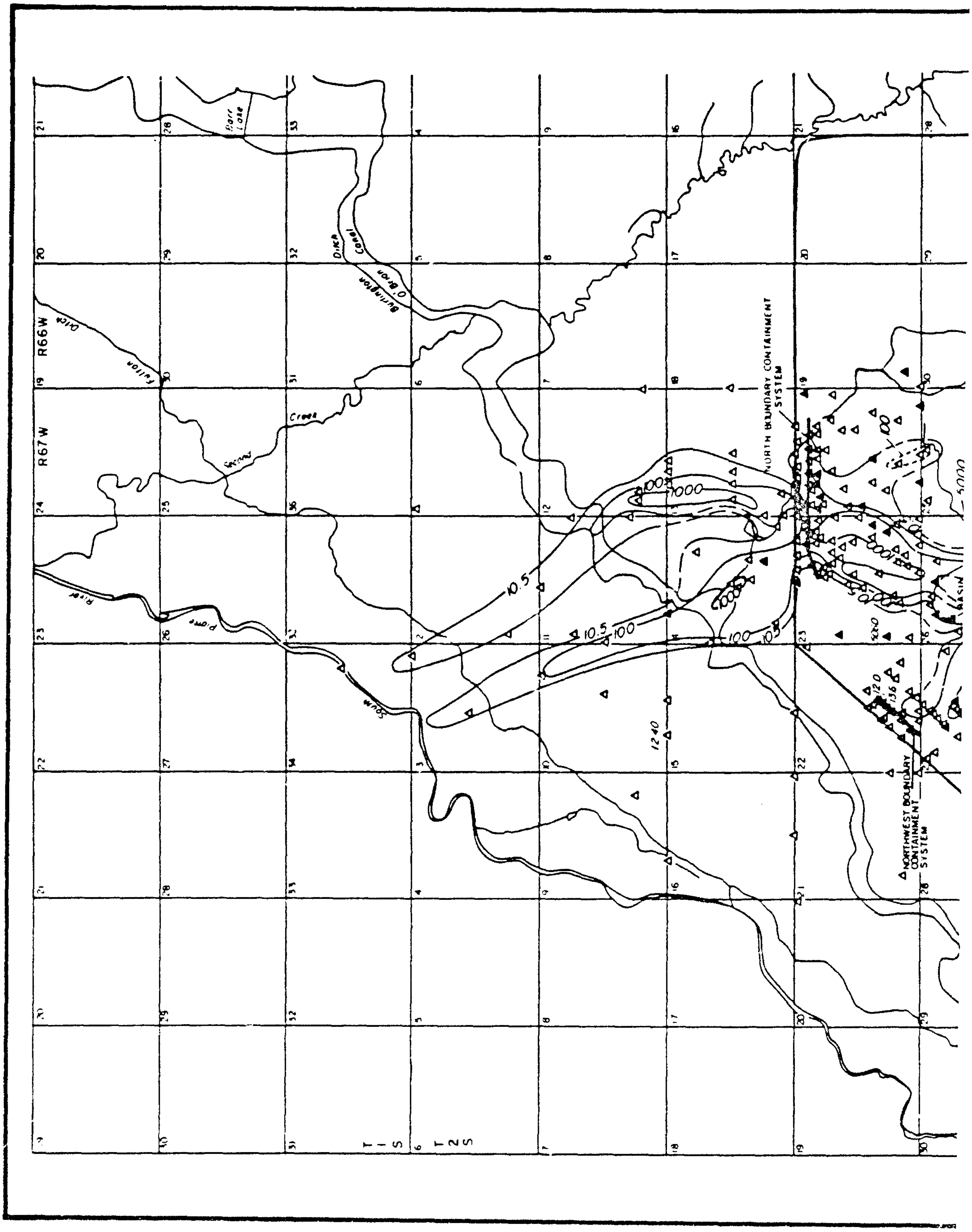
Figure 3.6

ORGANOSULFUR COMPOUNDS (CPMS, CPMSO, CPMSO$_2$) PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM, 3RD QUARTER FY 1987

SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R66W
R67W
T1S
T2S
Barr Lake
Burlington O'Brian Canal
Dike
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN
10.5
100
1000
5000
120
136
1240

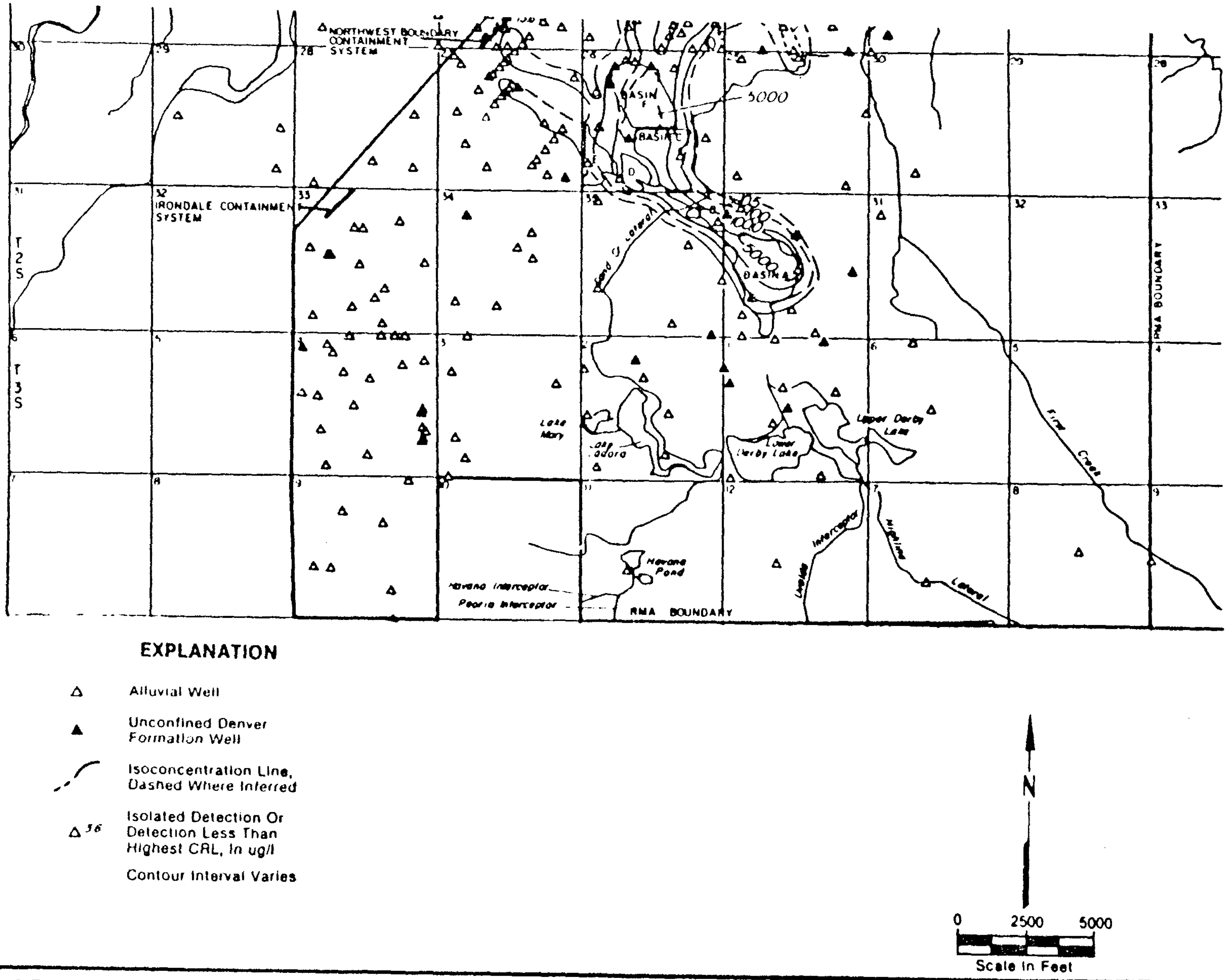


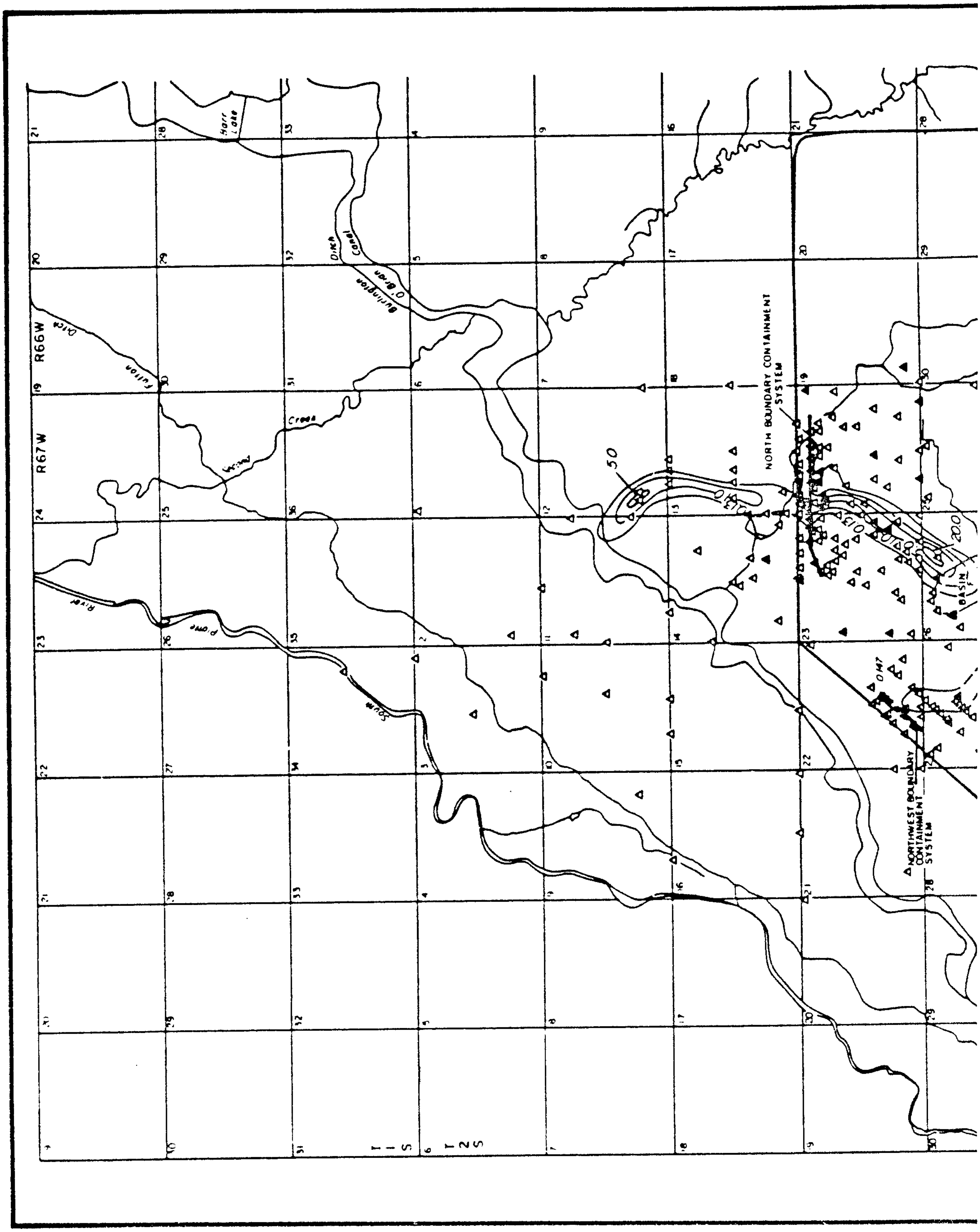
Figure 3.7

DIISOPROPYLMETHYLPHOSPHONATE PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM, 3RD QUARTER FY 1987

SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland



R66W
R67W
T 1 S
T 2 S
Barr Lake
Burlington O'Brian Canal
Ditch Canal
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F
50
200

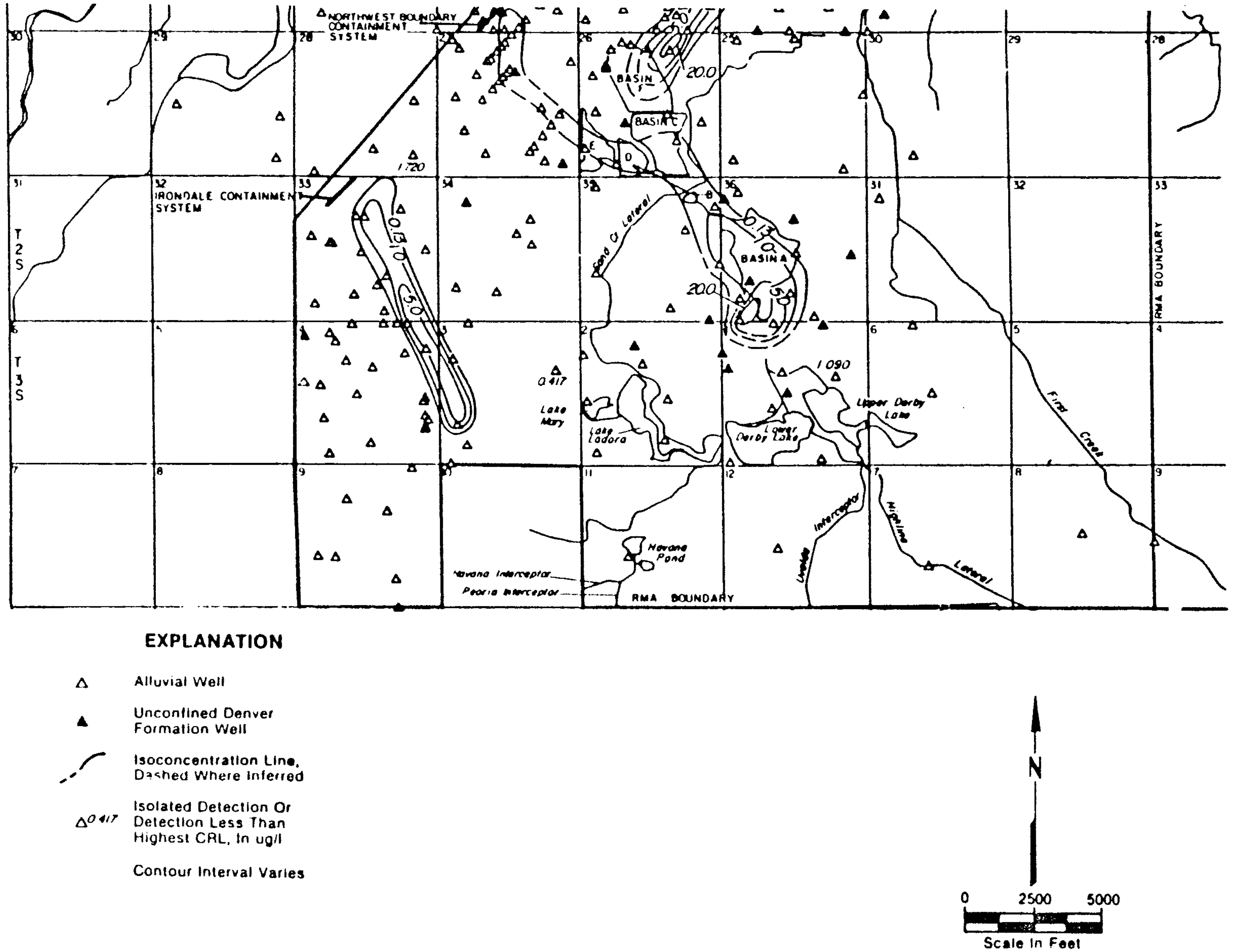


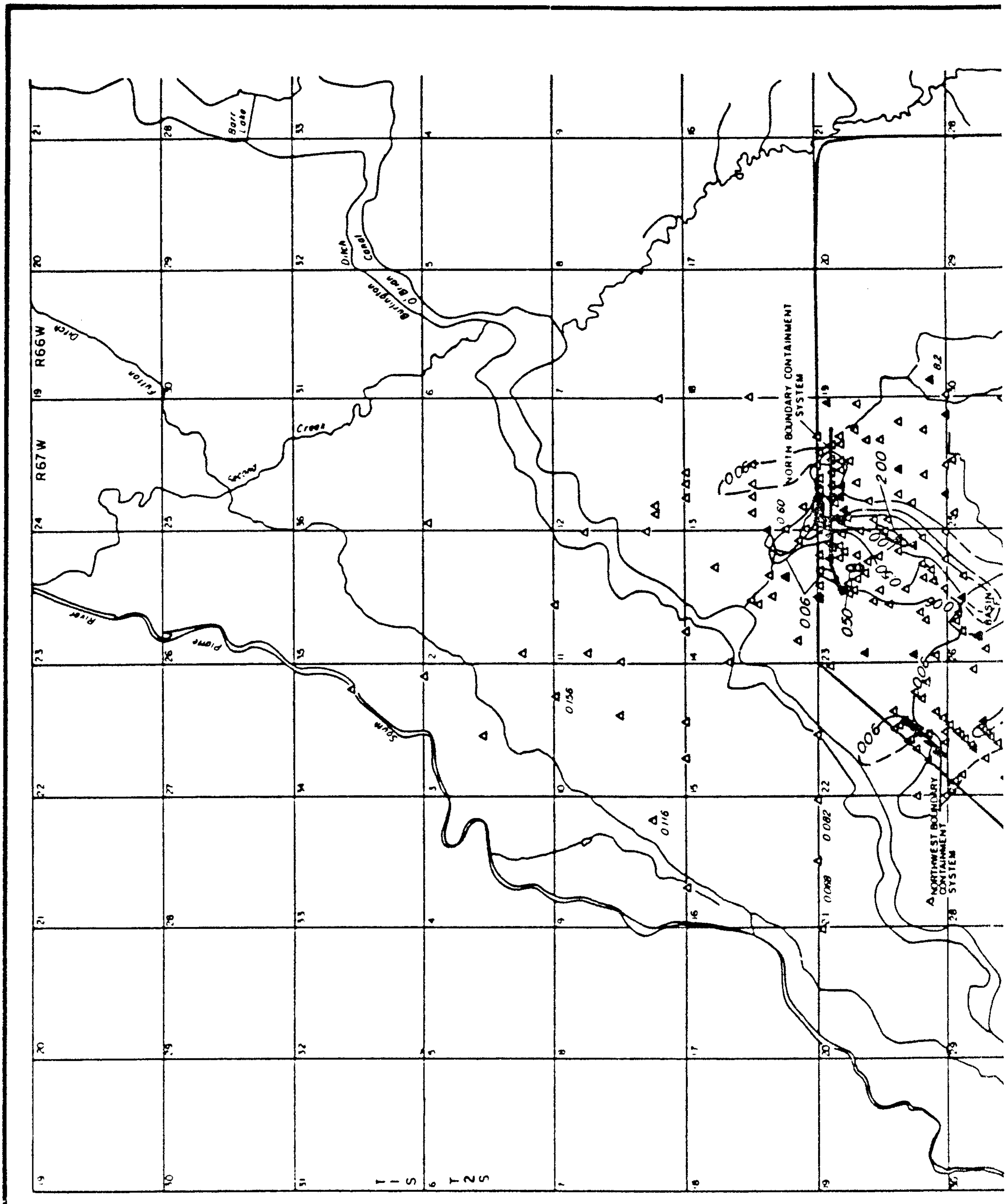
Figure 3.8

DIBROMOCHLOROPROPANE PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM, 3RD QUARTER FY 1987

SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R66W
R67W
T1S
T2S
Barr Lake
O'Brian Canal
Burlington Ditch
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F
0.156
0.116
0.082
0.008
0.060
0.60
2.00
0.50
0.06
82

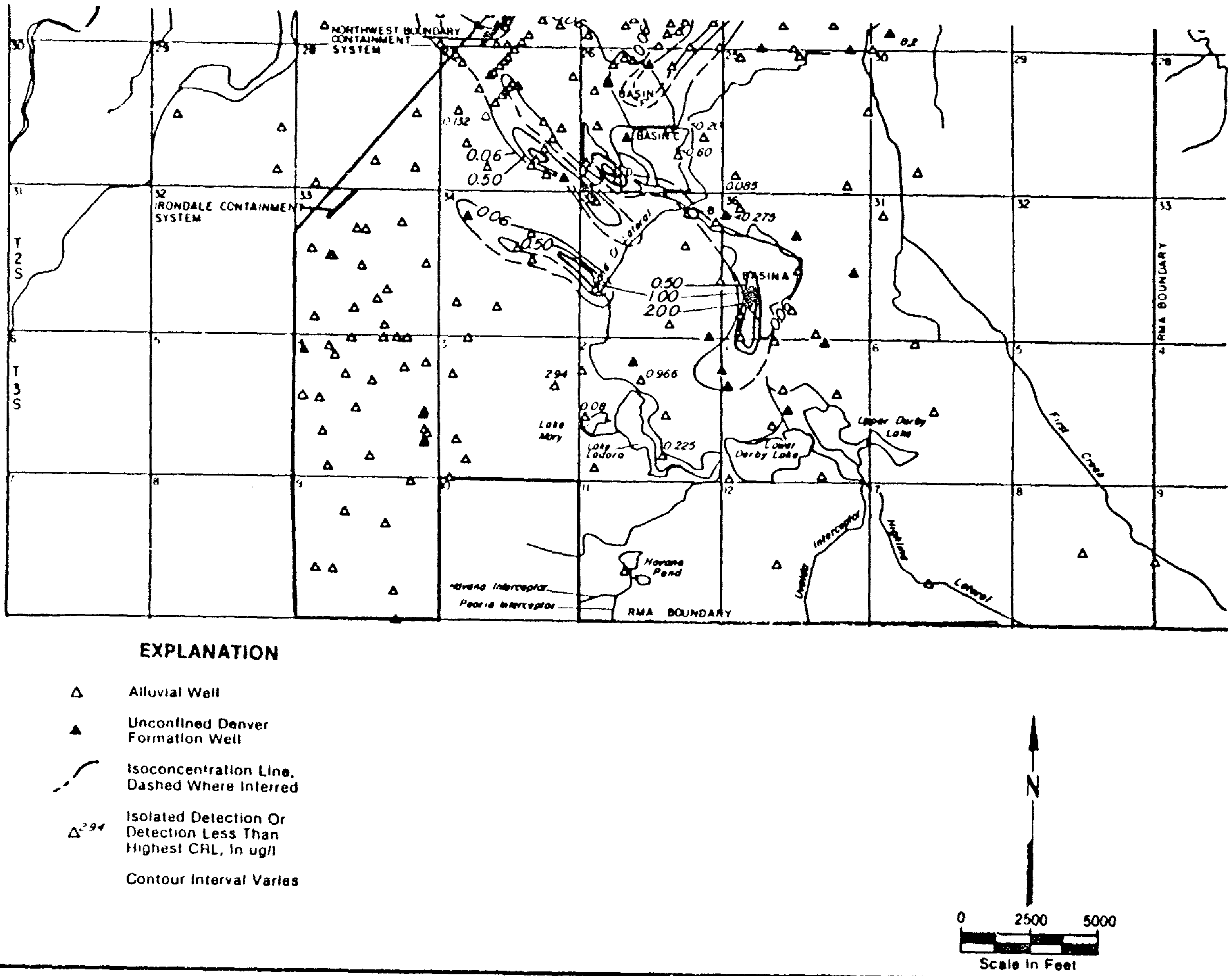


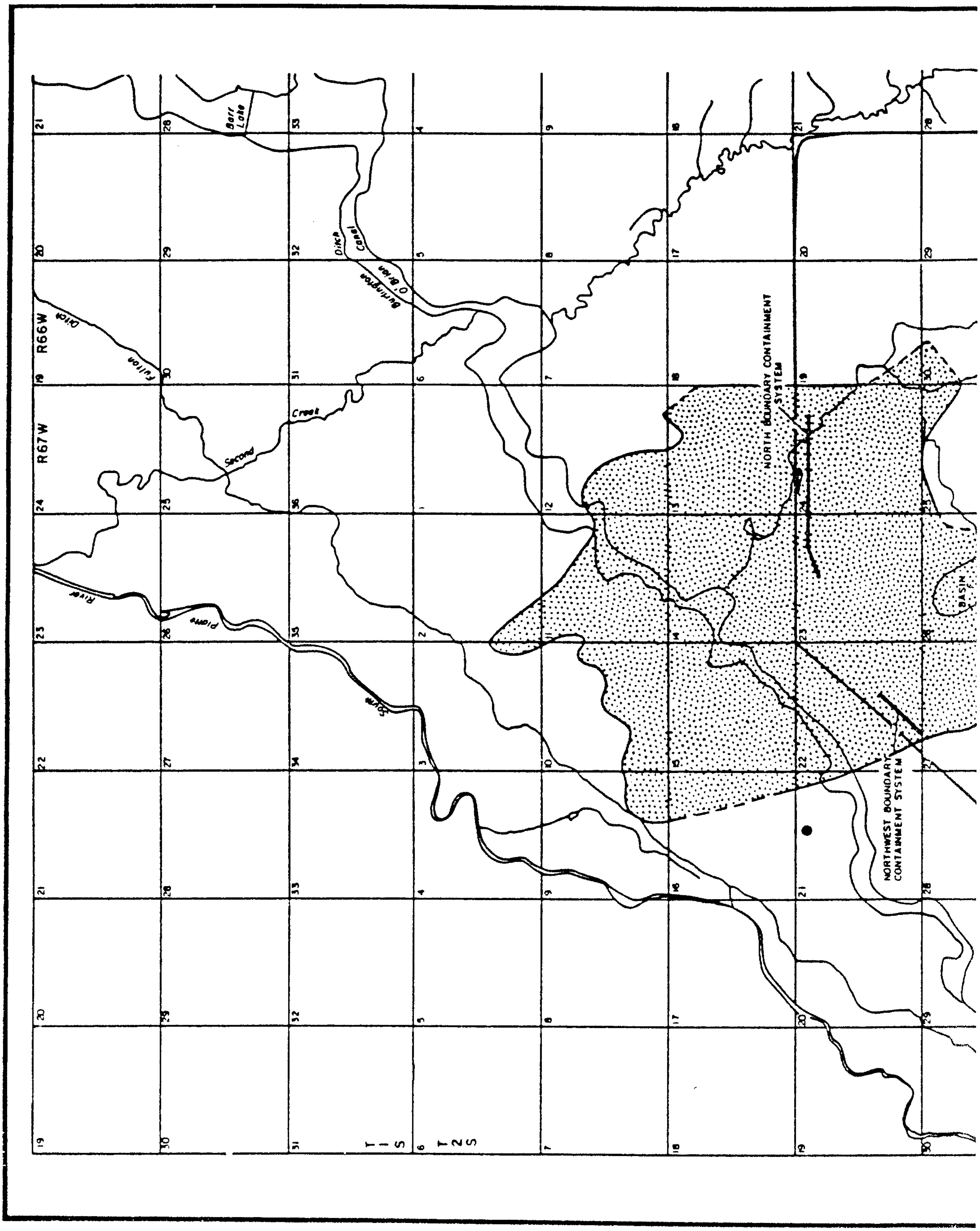
Figure 3.9

DIELDRIN PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM
3RD QUARTER FY 1987

SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland



R66W
R67W
T 1 S
T 2 S
Barr Lake
Burlington O'Brian Canal
Ditch
Fulton Ditch
Second Creek
Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F

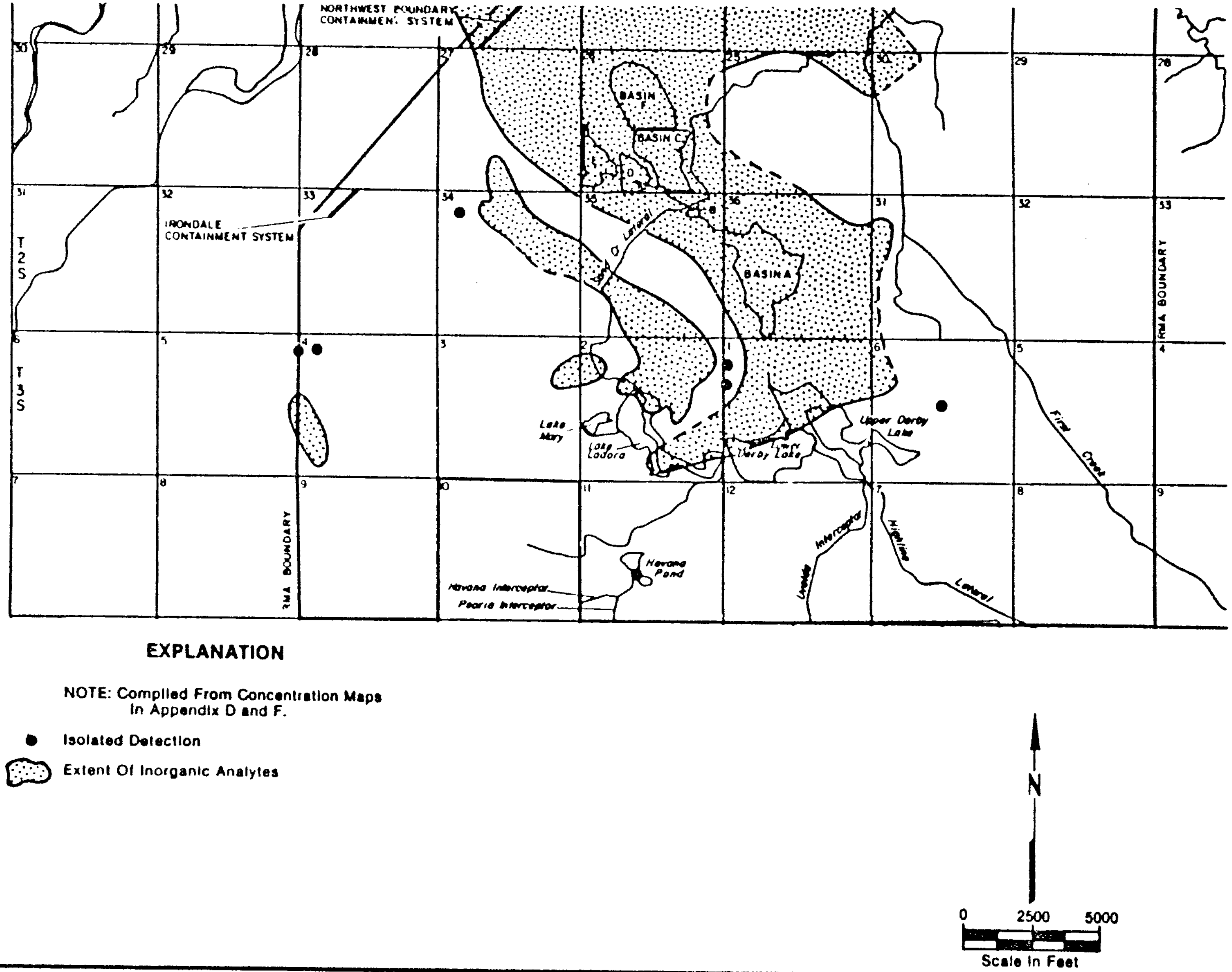
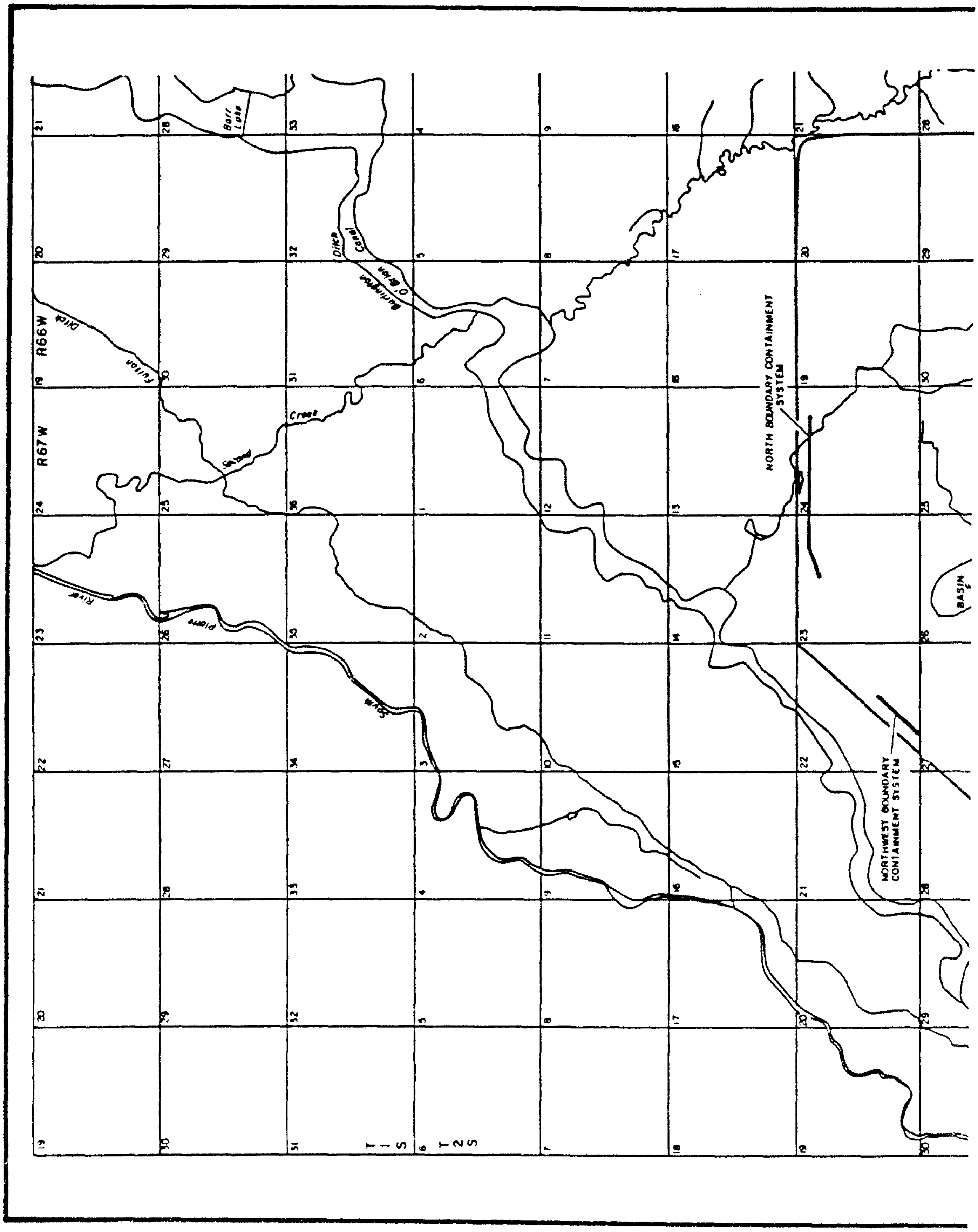


Figure 3.10
AREAL EXTENT OF INORGANIC ANALYTES IN THE UNCONFINED FLOW SYSTEM

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T 1 S
T 2 S
Barr Lake
Burlington Ditch
O'Brian Canal
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F

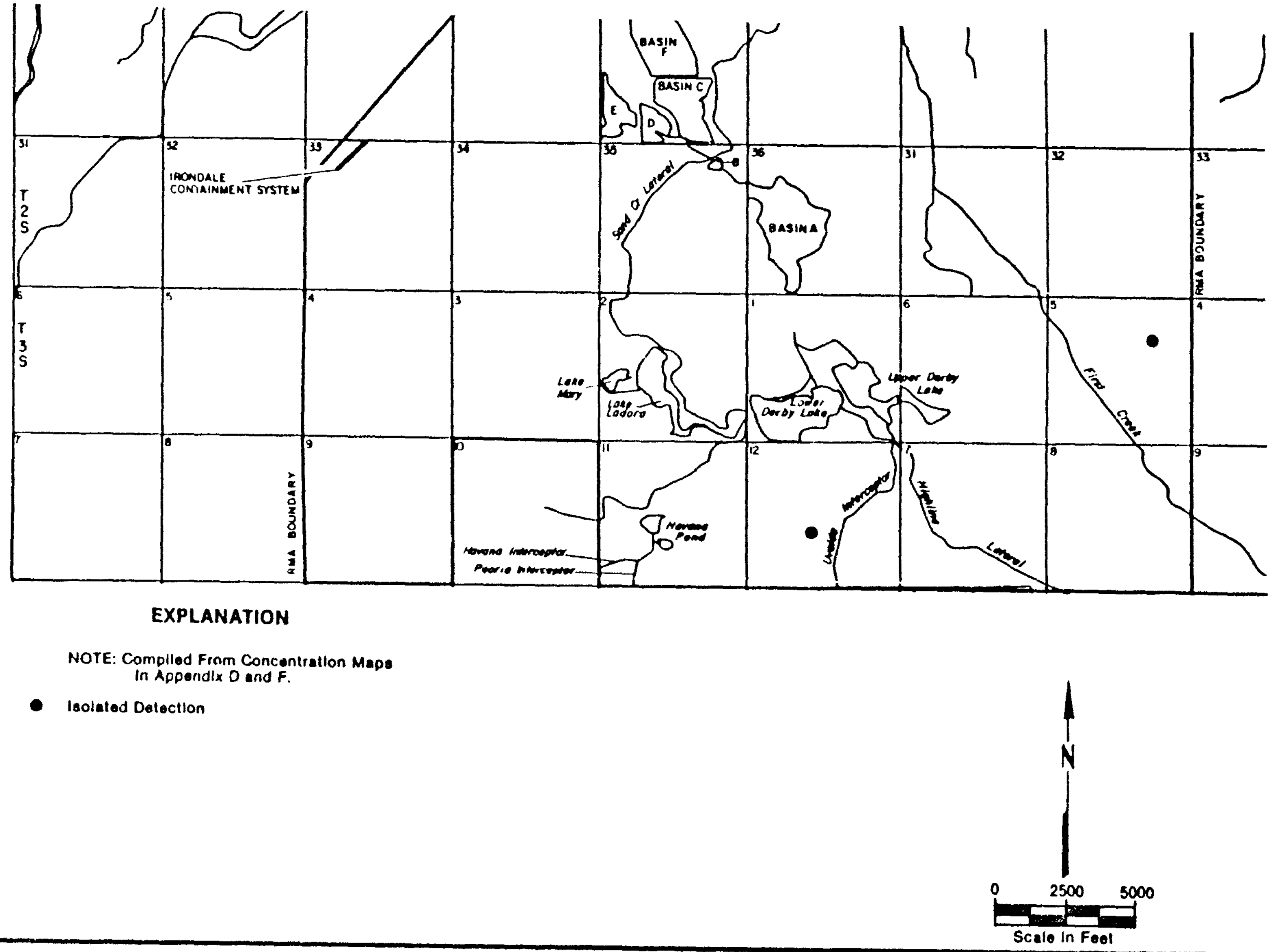
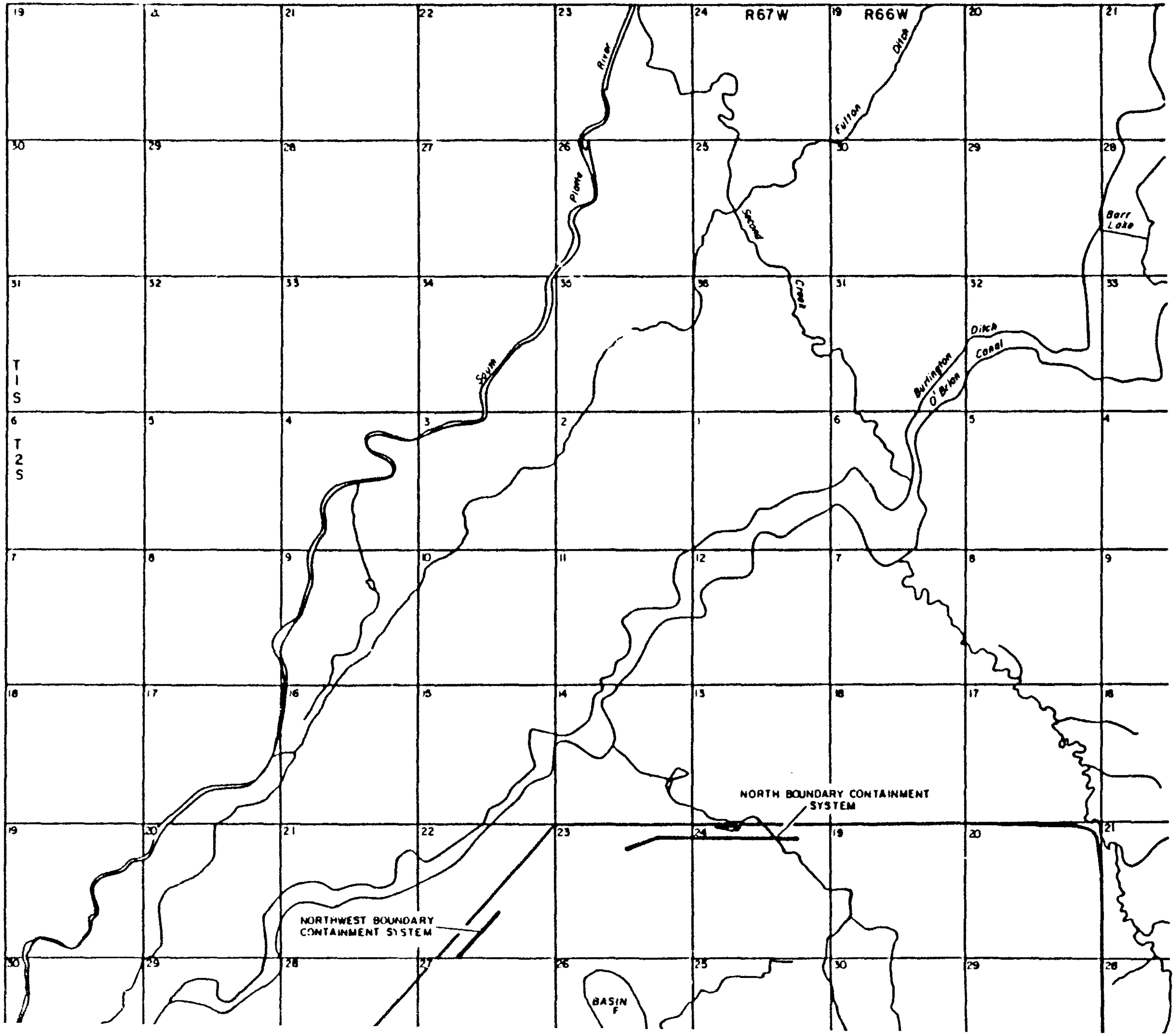


Figure 3.11
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONE B

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T1S
T2S
Fulton Ditch
Barr Lake
Second Creek
South Platte River
Burlington Ditch
O'Brian Canal
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F

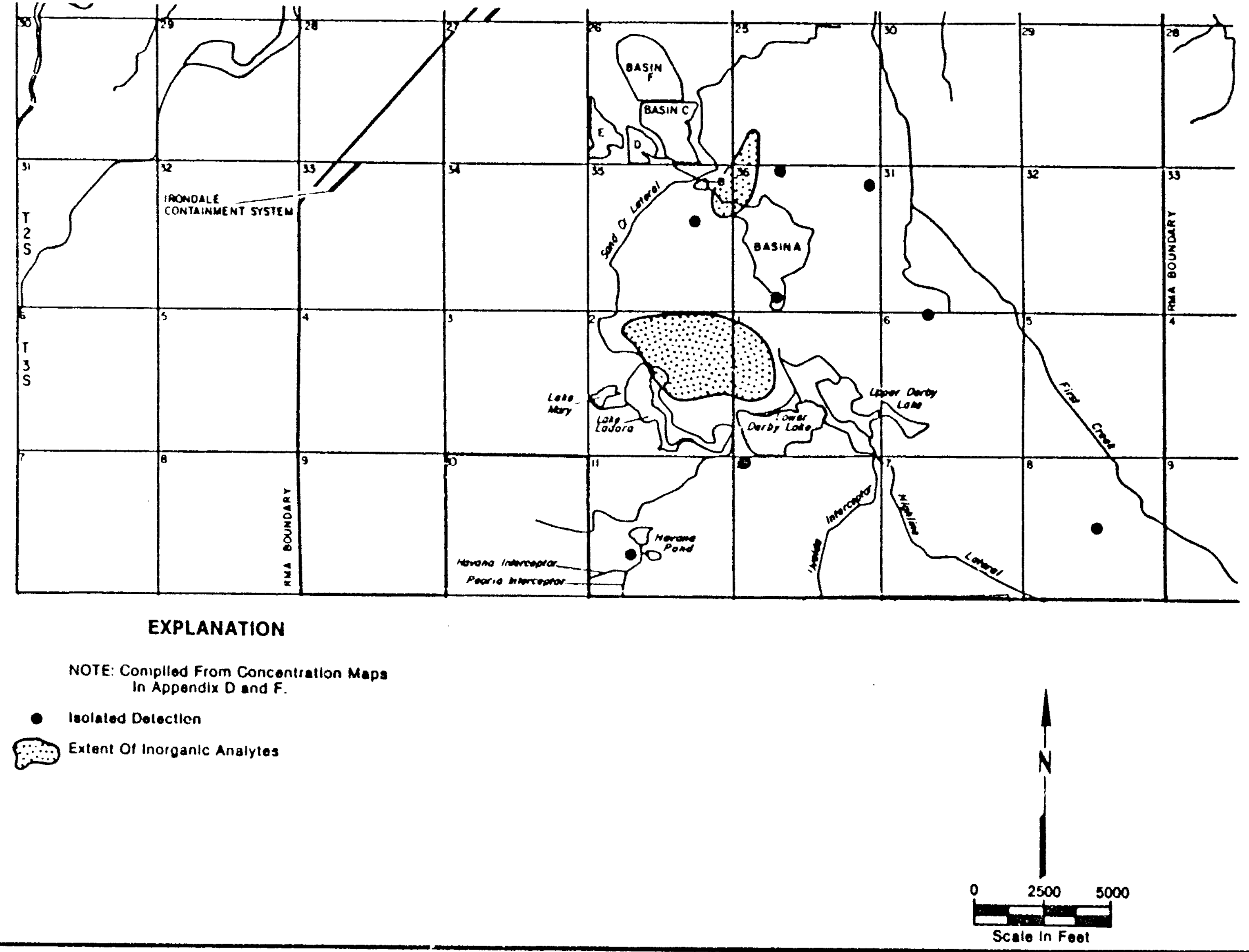
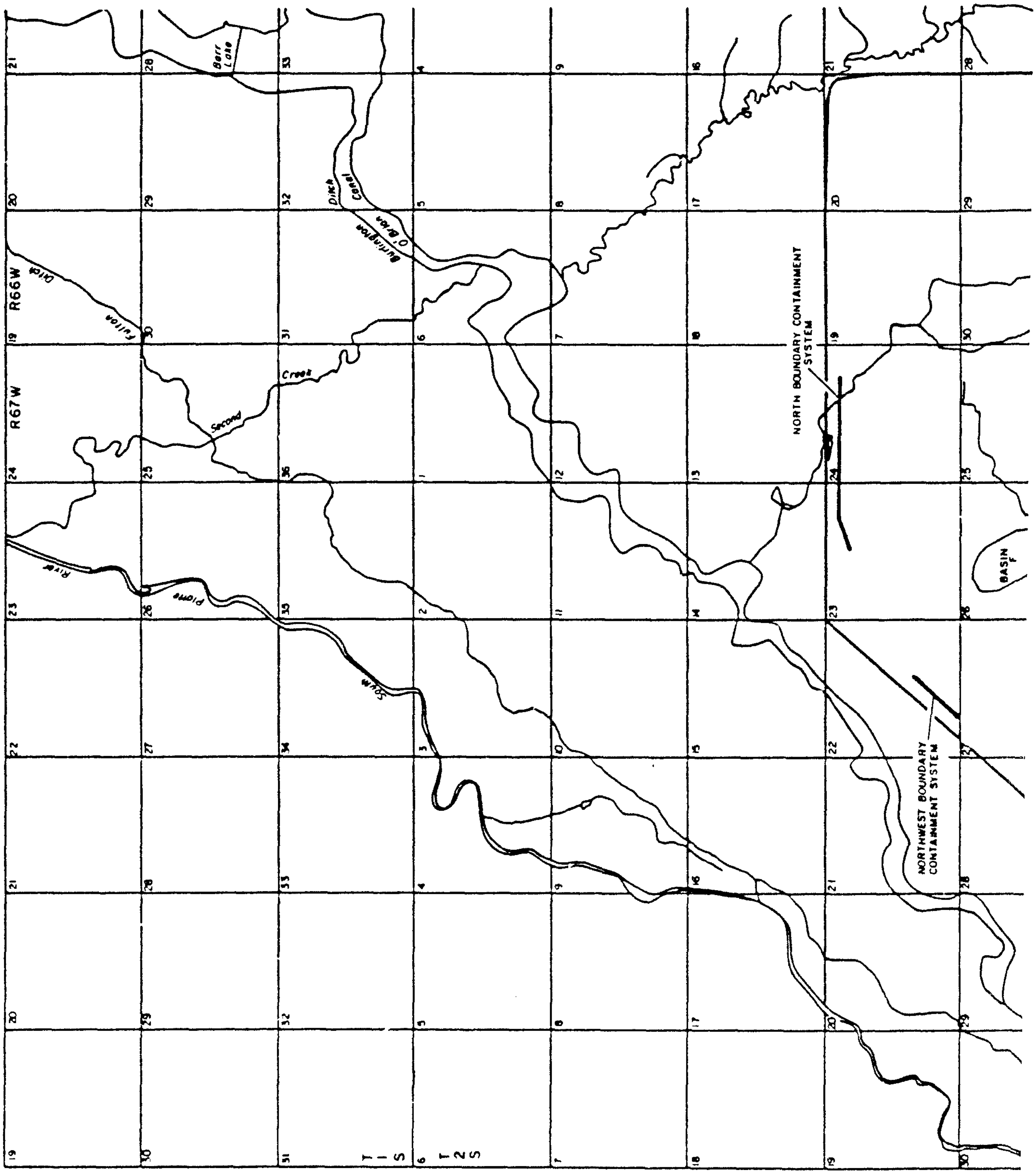


Figure 3.12
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONE A

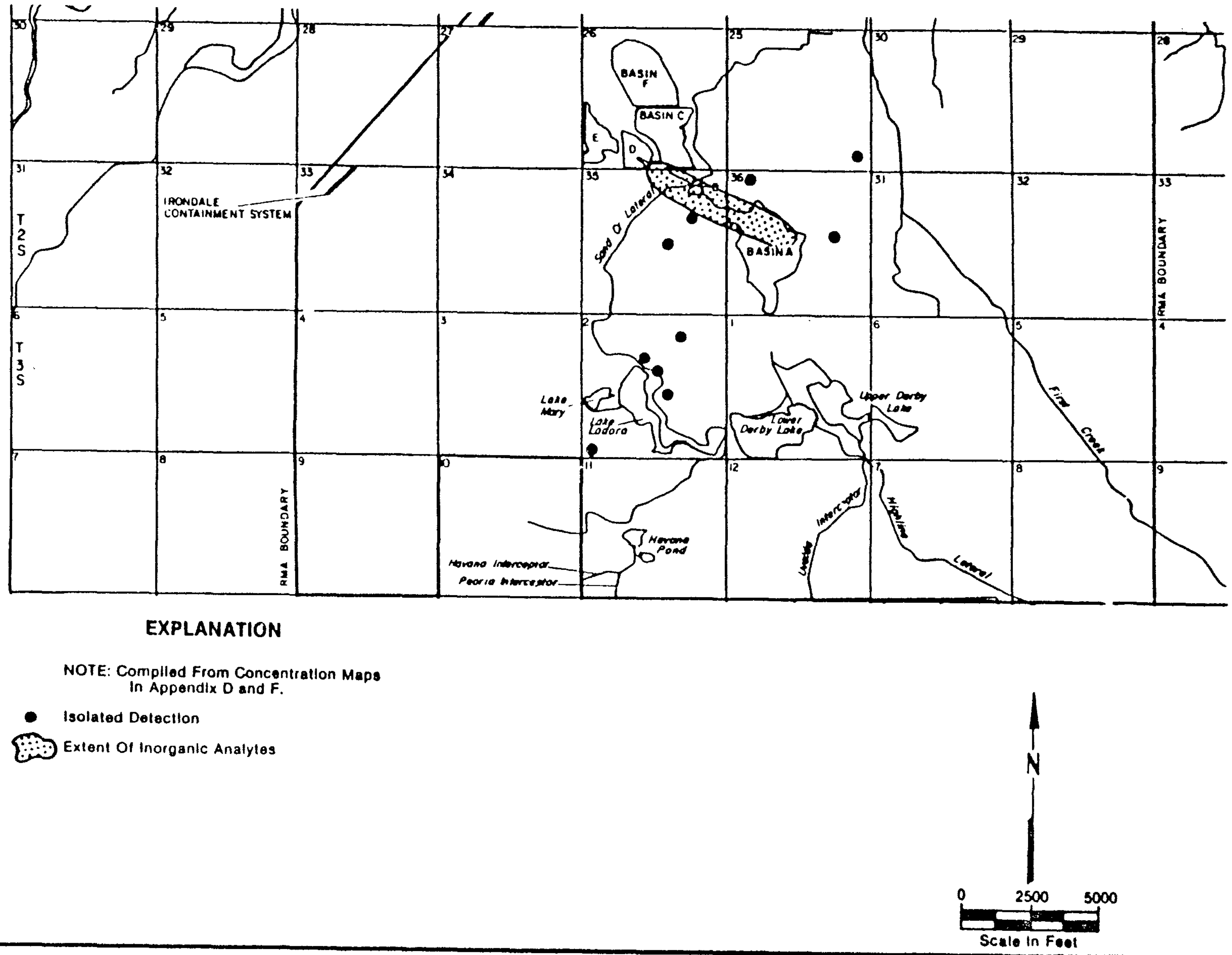
SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland



R66W
R67W
T 1 S
T 2 S
Barr Lake
O'Brian Canal
Burlington Ditch
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F



EXPLANATION

NOTE: Compiled From Concentration Maps
In Appendix D and F.

● Isolated Detection

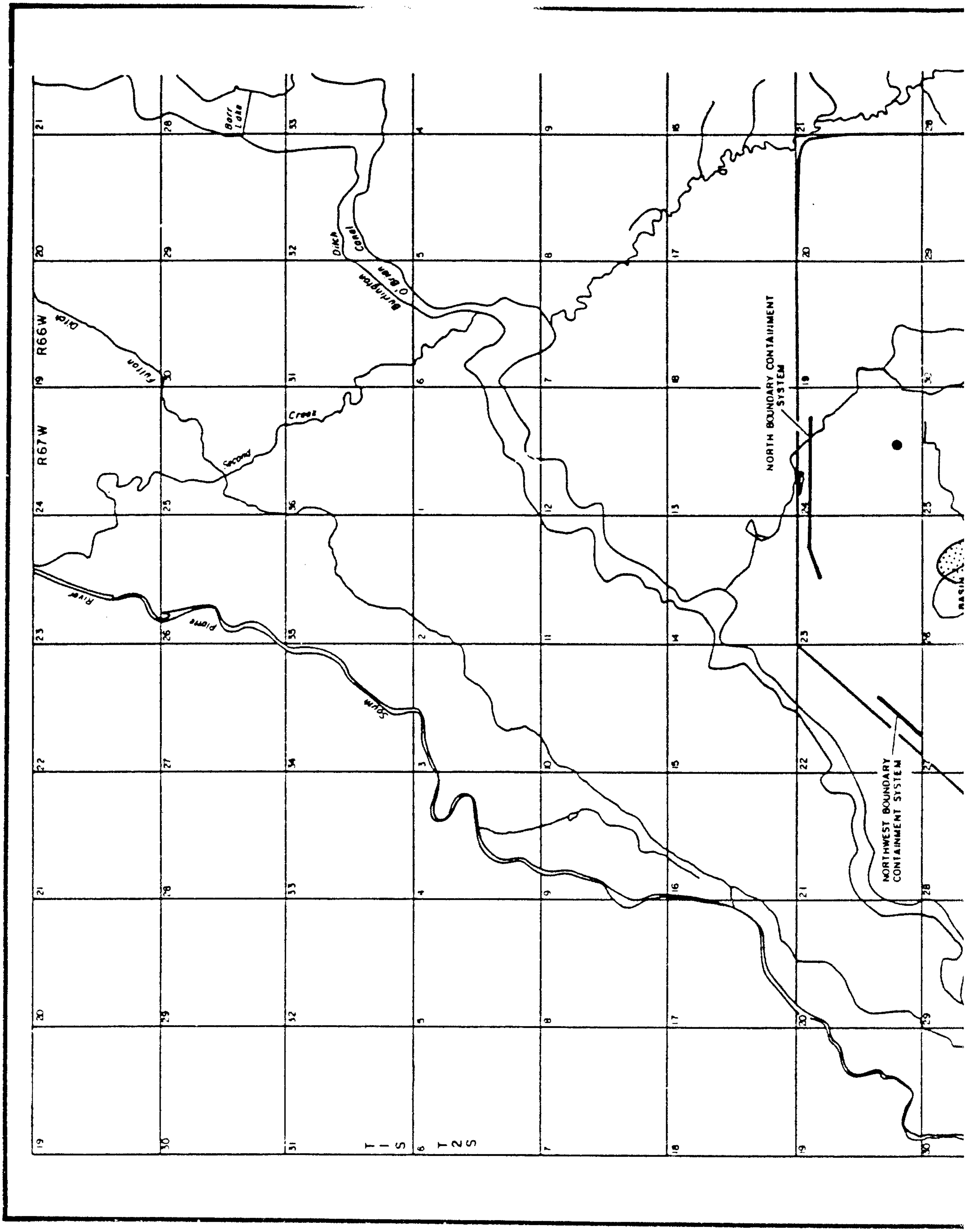
▨ Extent Of Inorganic Analytes

Figure 3.13
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONE 1U

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland



Barr Lake
Dike Canal
Burlington O'Brien Canal
Fulton Ditch
R66W
R67W
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN
T1S
T2S

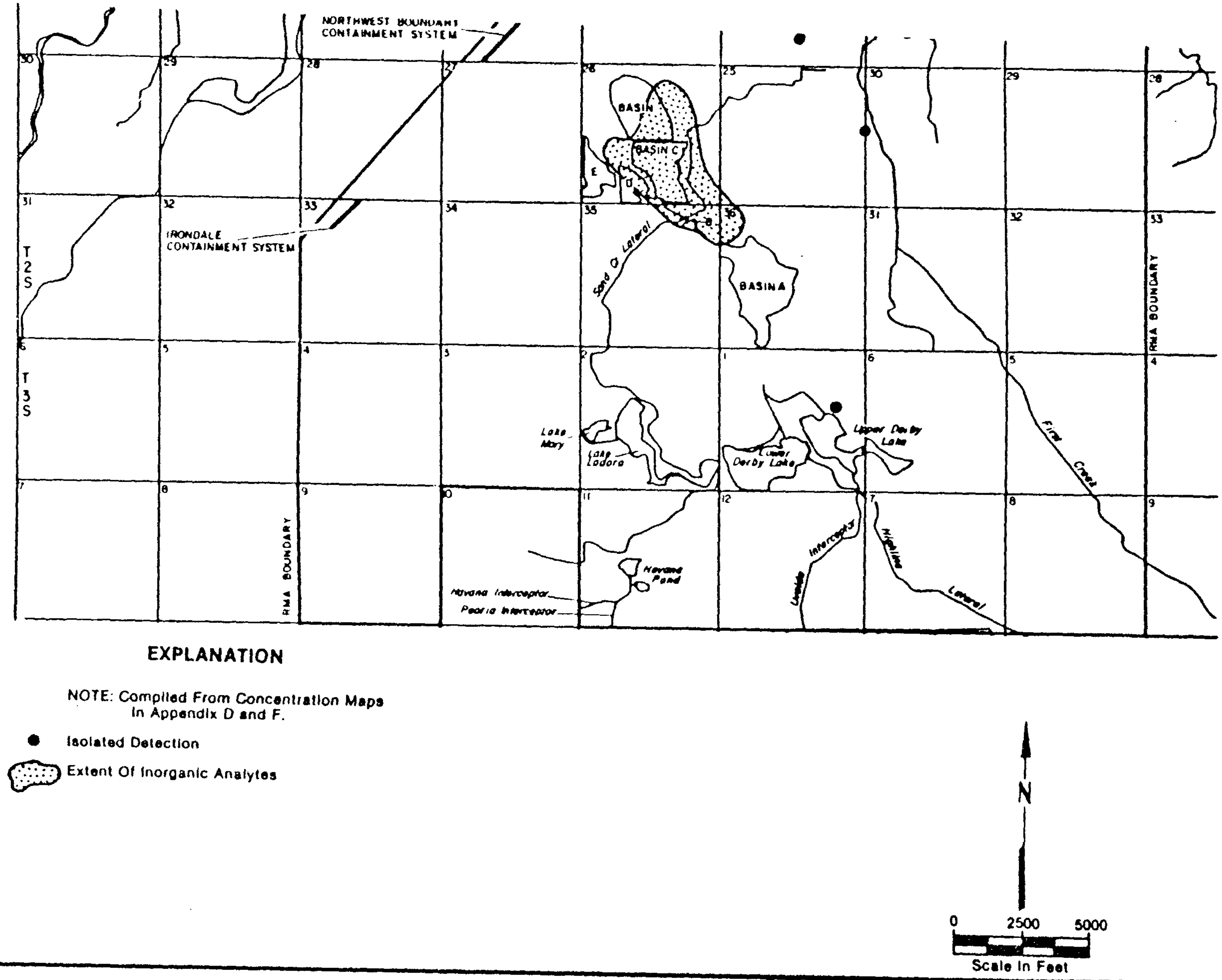
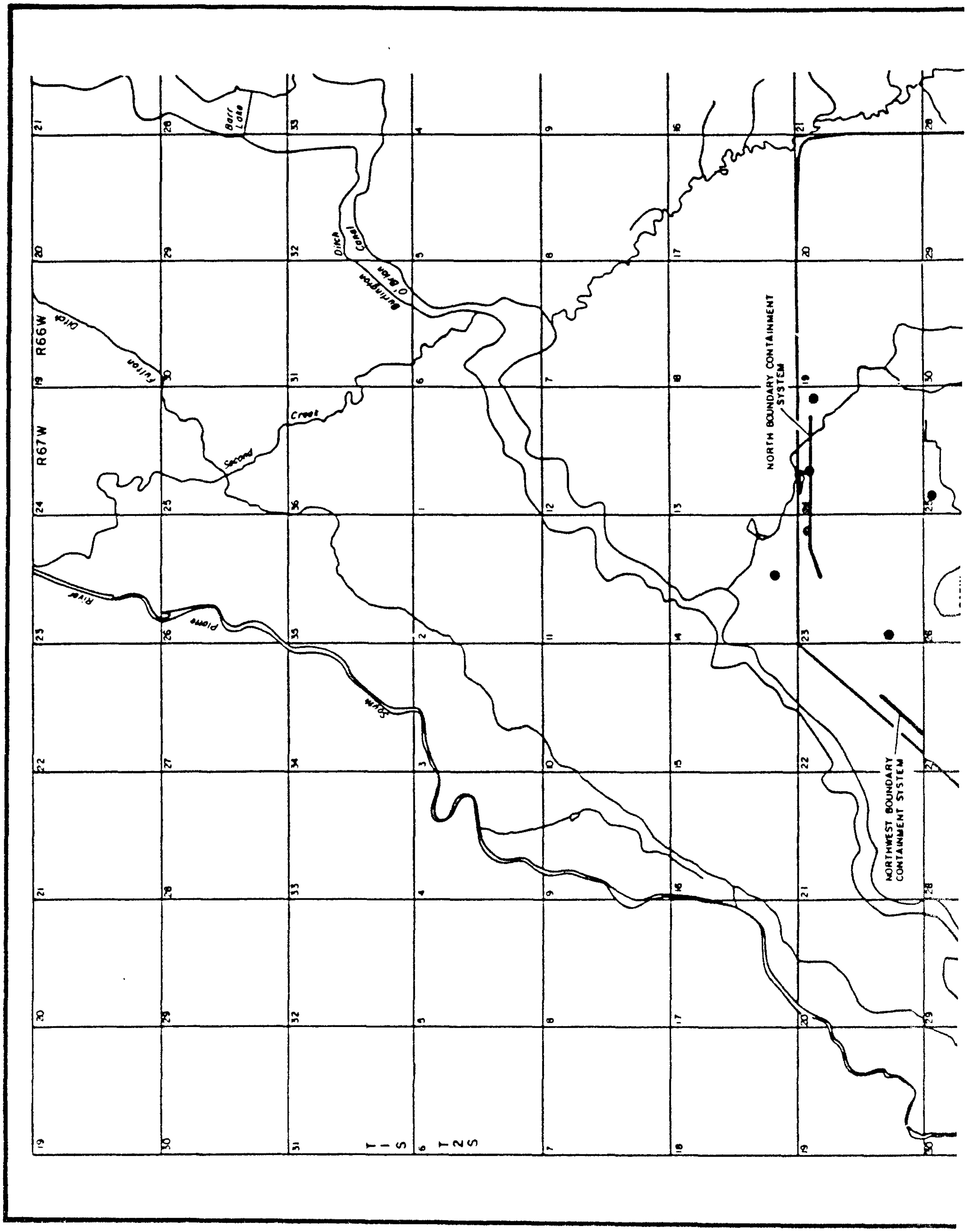


Figure 3.14
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONE 1

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R66W
R67W
T 1 S
T 2 S
Barr Lake
Fulton Ditch
Second Creek
Burlington O'Brian Canal
Dike
Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM

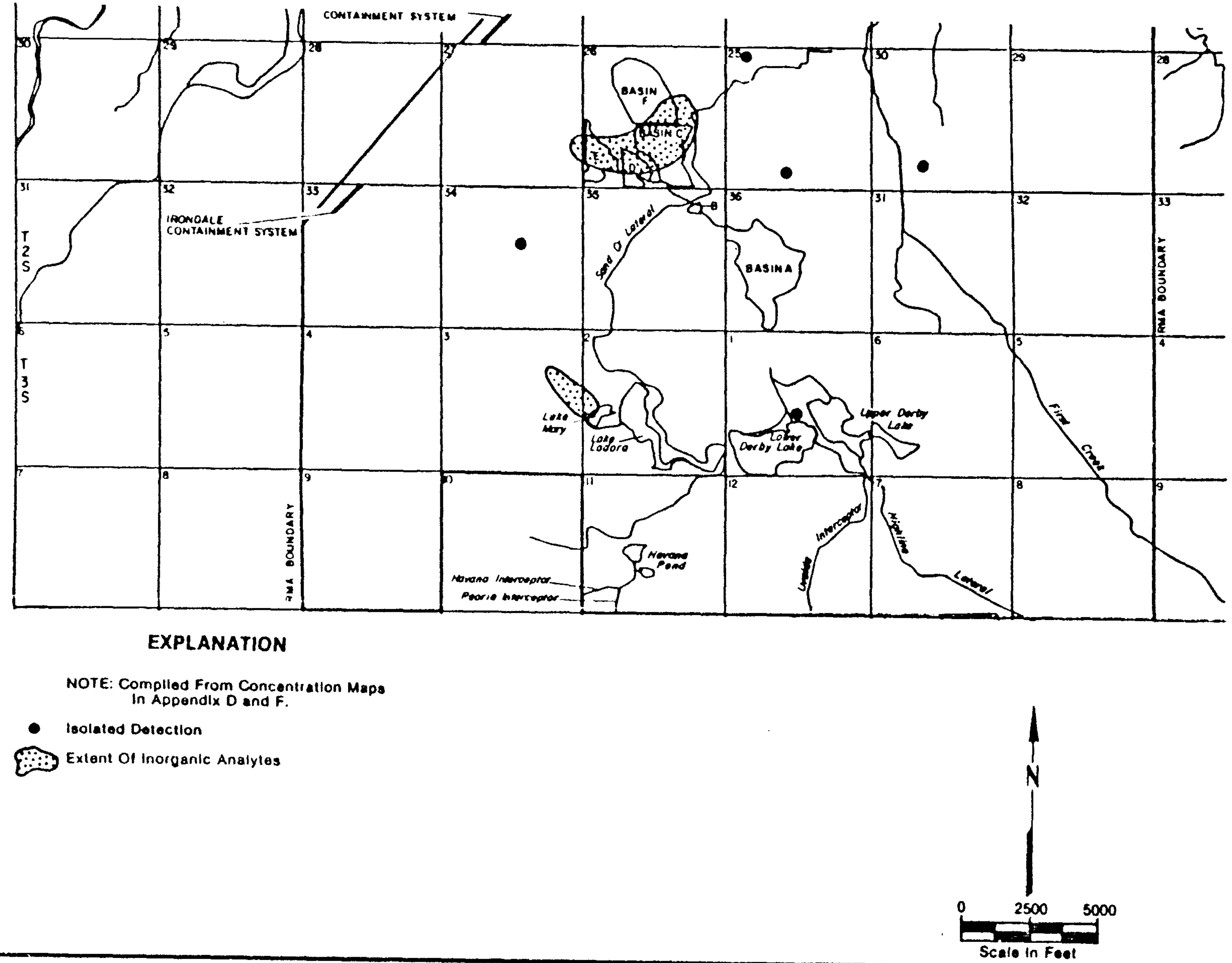
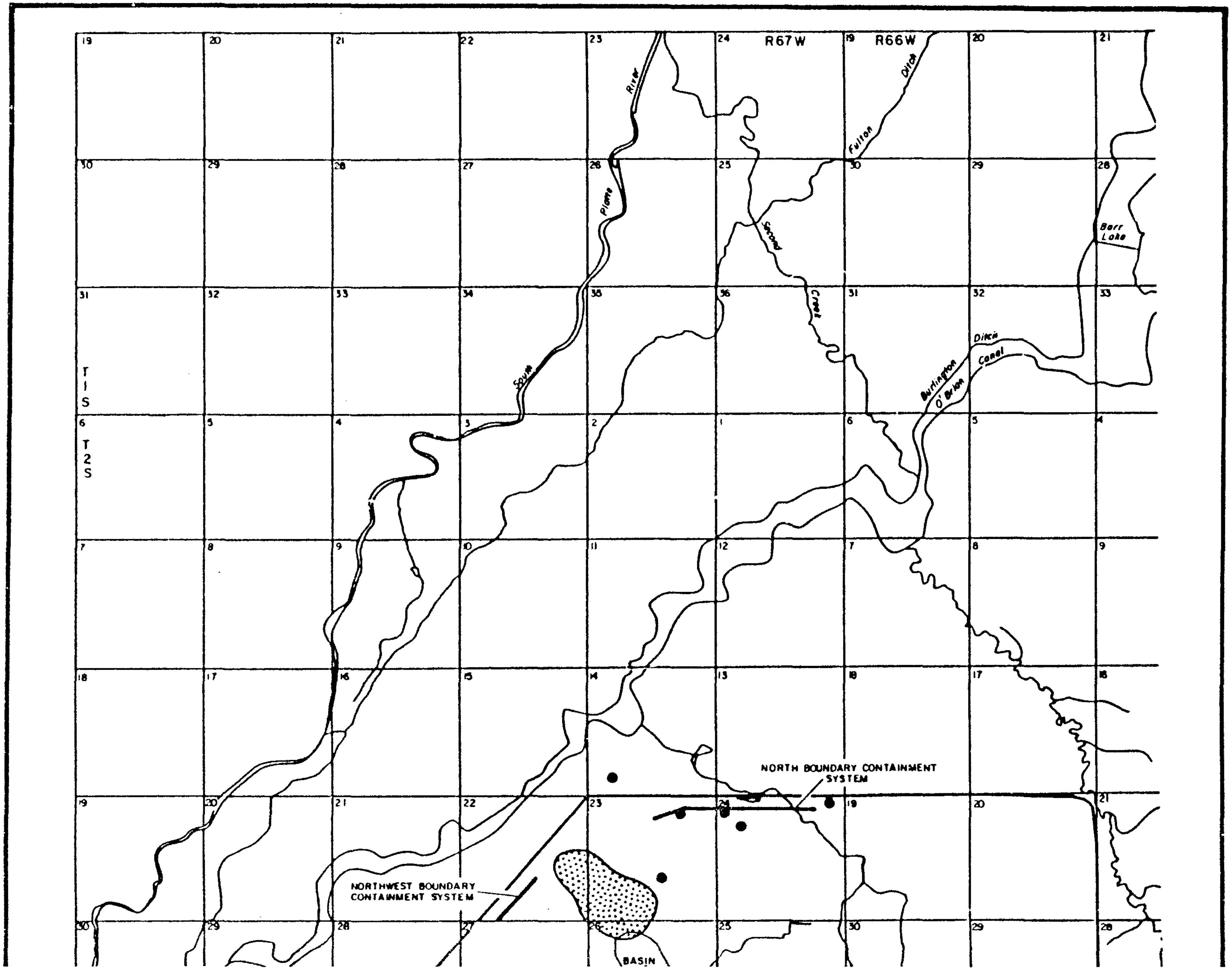


Figure 3.15
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONE 2

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T 1 S
T 2 S
South Platte River
Second Creek
Fulton Ditch
Burlington Ditch
O'Brien Canal
Barr Lake
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN

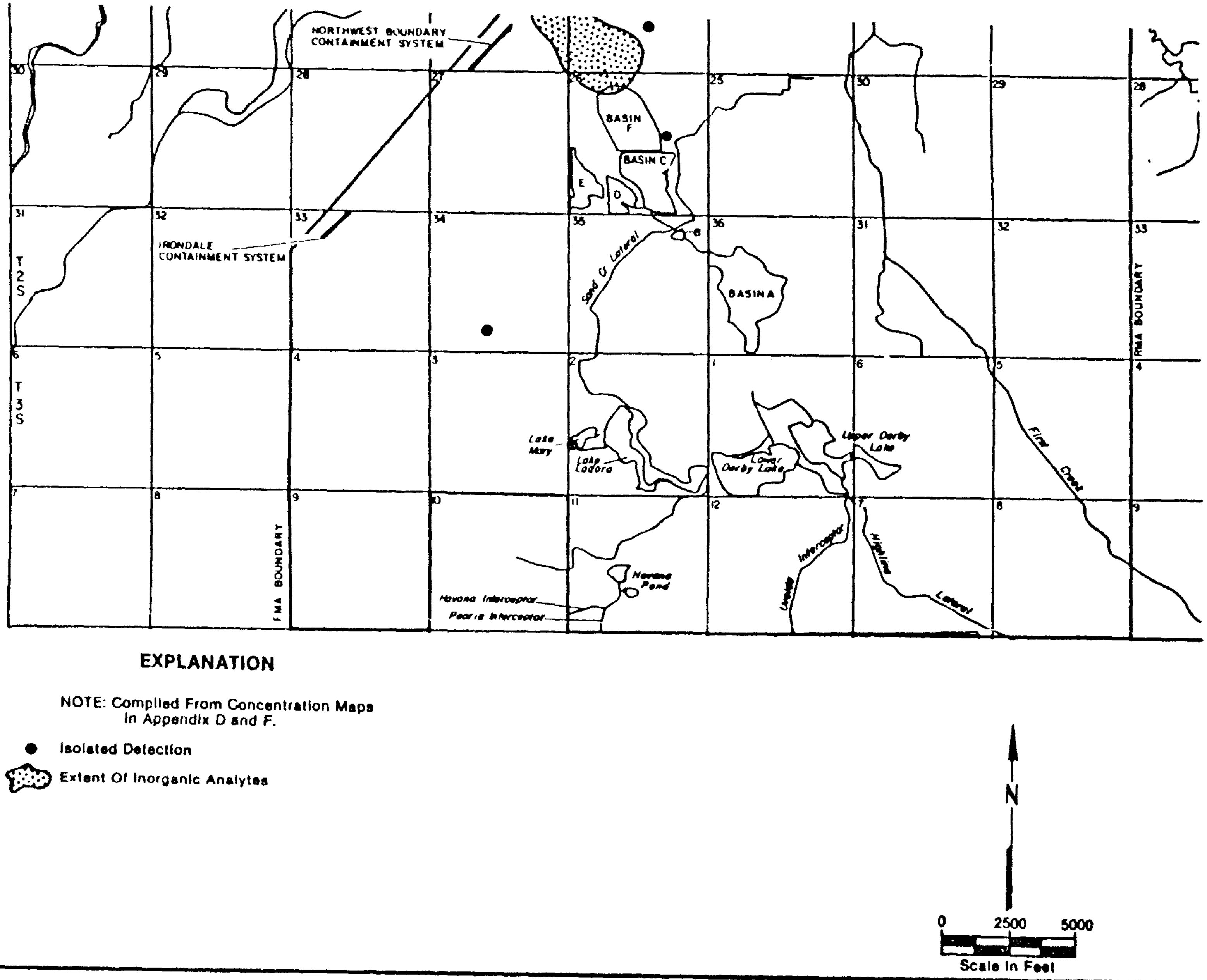
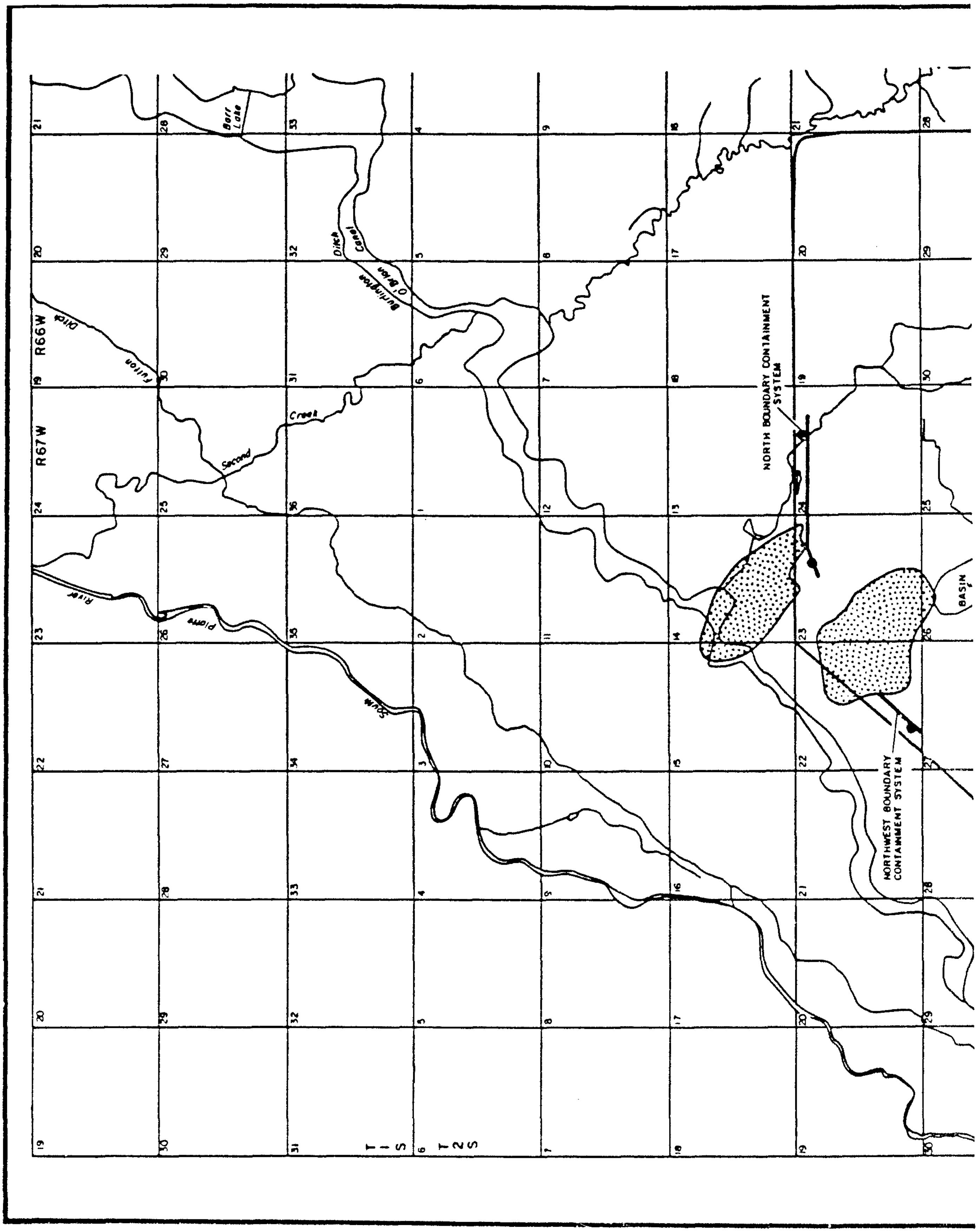


Figure 3.16
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONE 3

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R66W
R67W
T1S
T2S
Barr Lake
Burlington Ditch
O'Brian Canal
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F

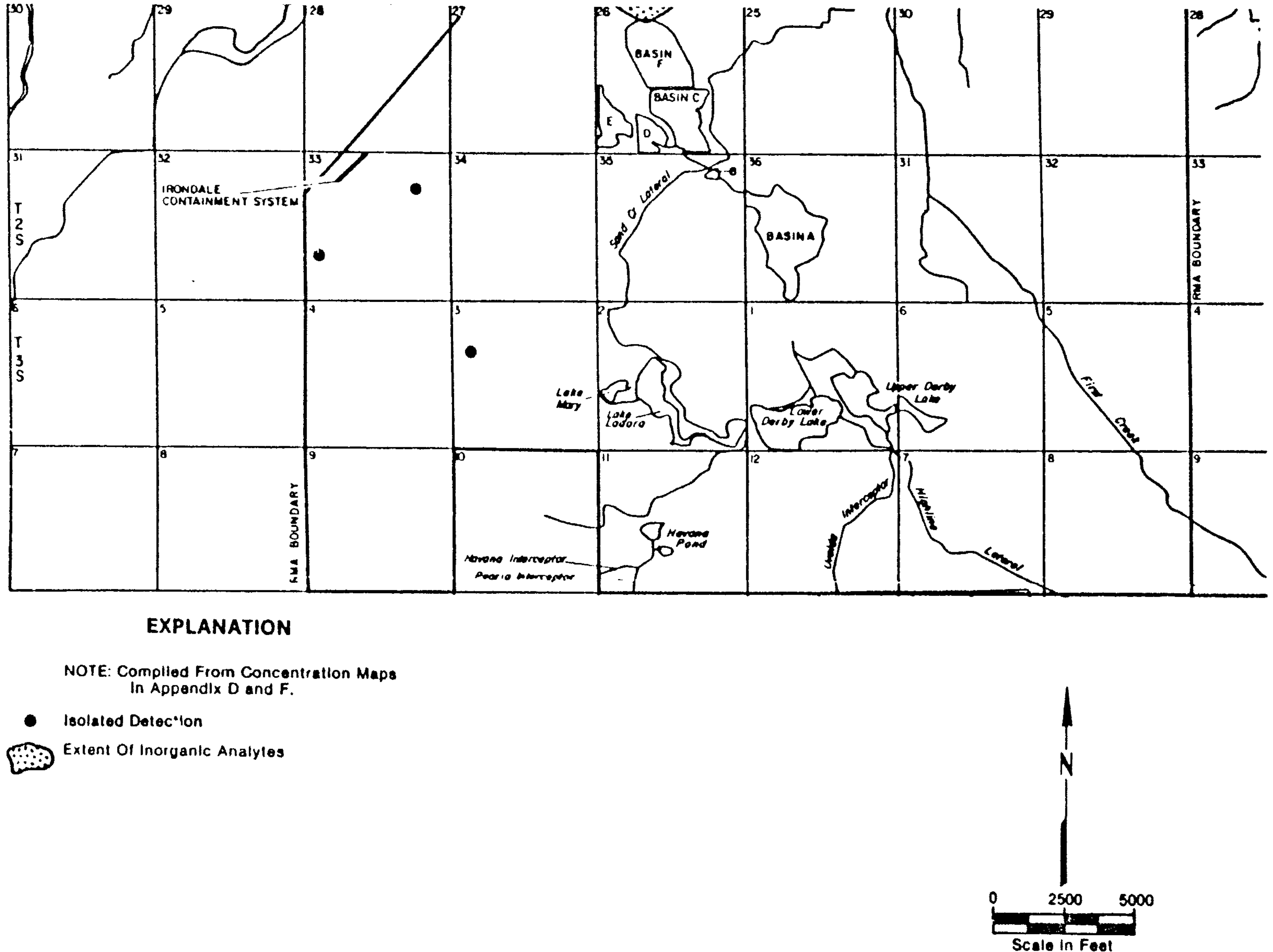
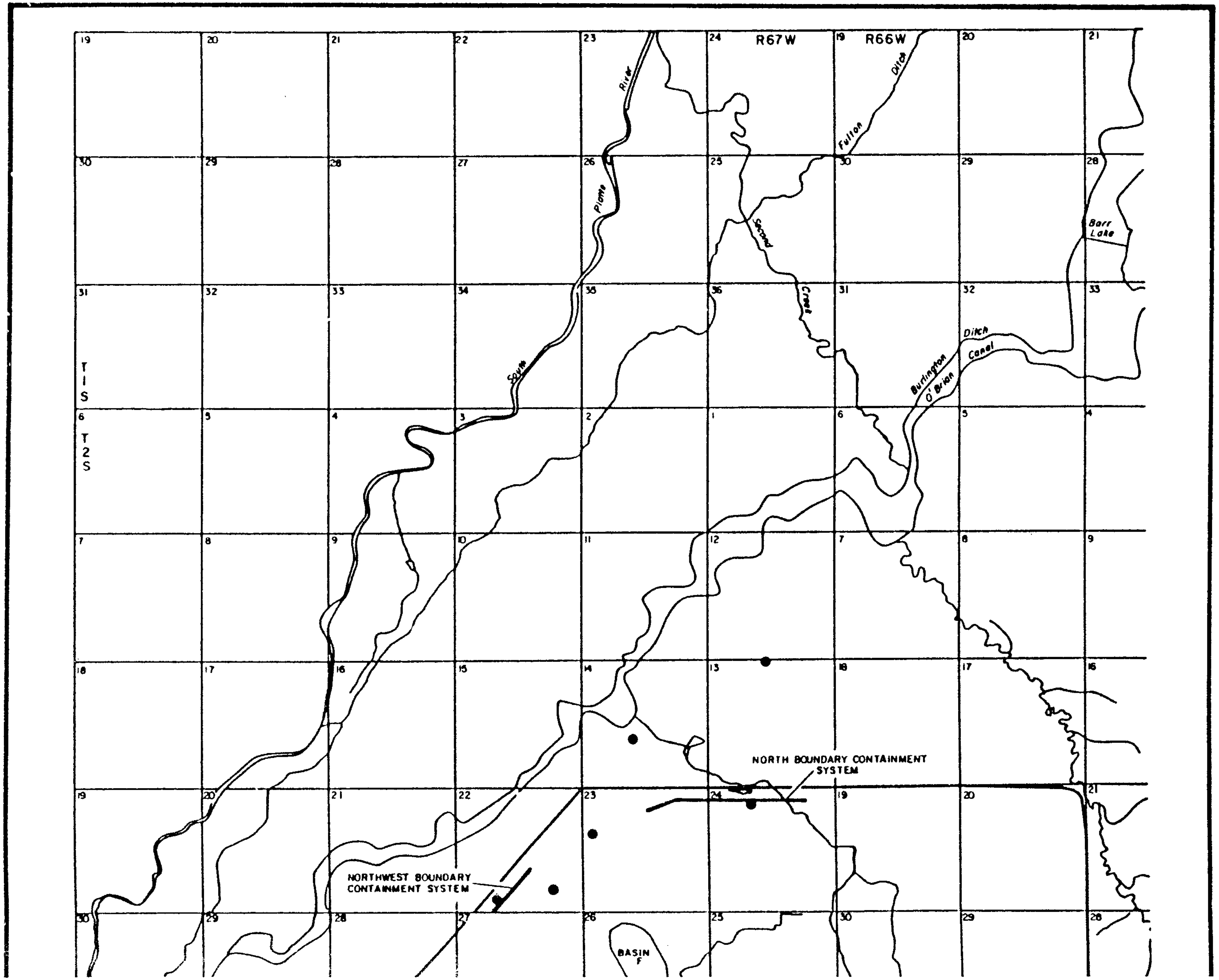


Figure 3.17
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONE 4

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T 1 S
T 2 S
South Platte River
Fulton Ditch
Second Creek
Barr Lake
Burlington Ditch
O'Brian Canal
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F
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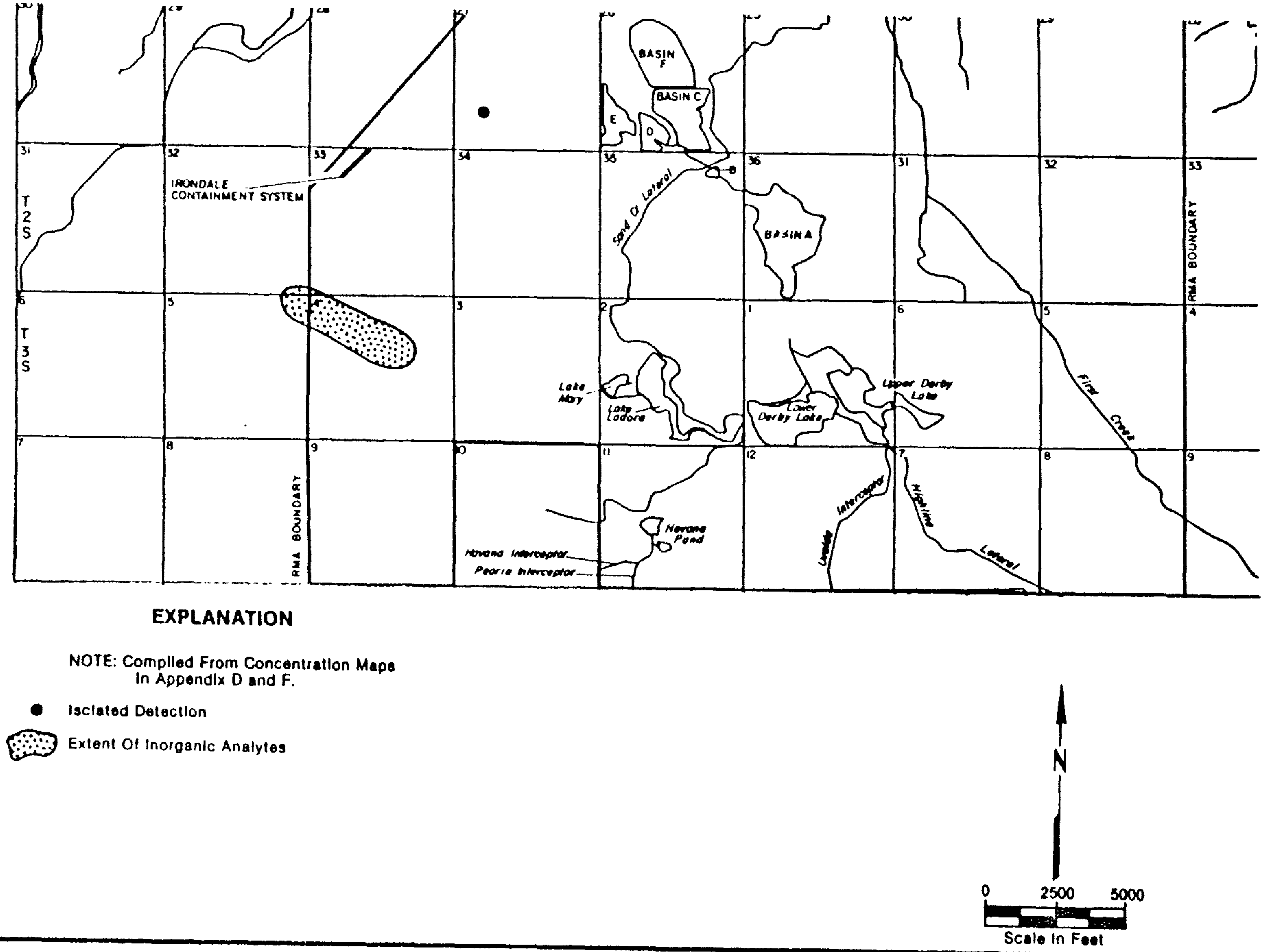


EXPLANATION

NOTE: Compiled From Concentration Maps
In Appendix D and F.

● Isolated Detection

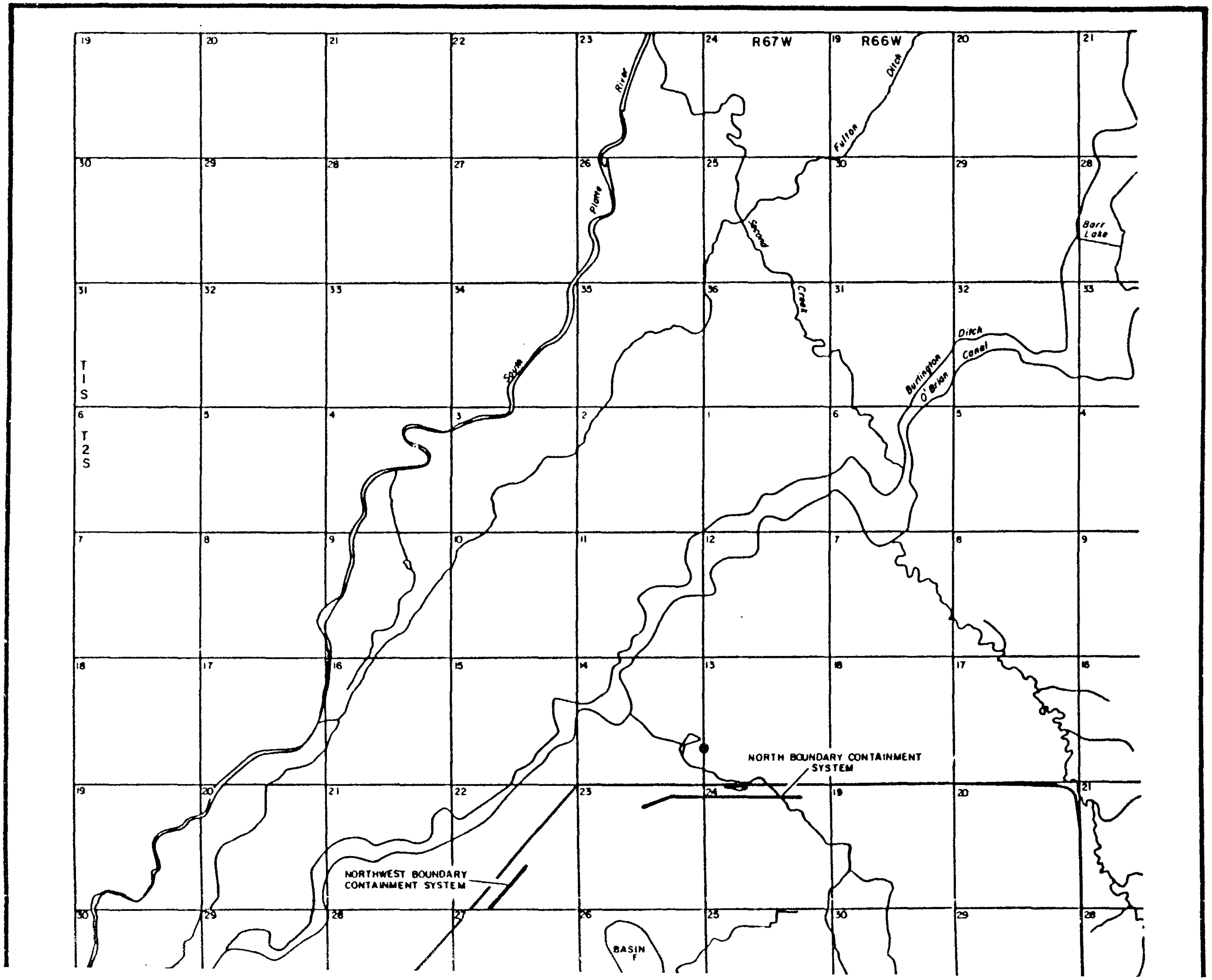
▨ Extent Of Inorganic Analytes

Figure 3.18
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONE 5

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland

R67W
R66W
T1S
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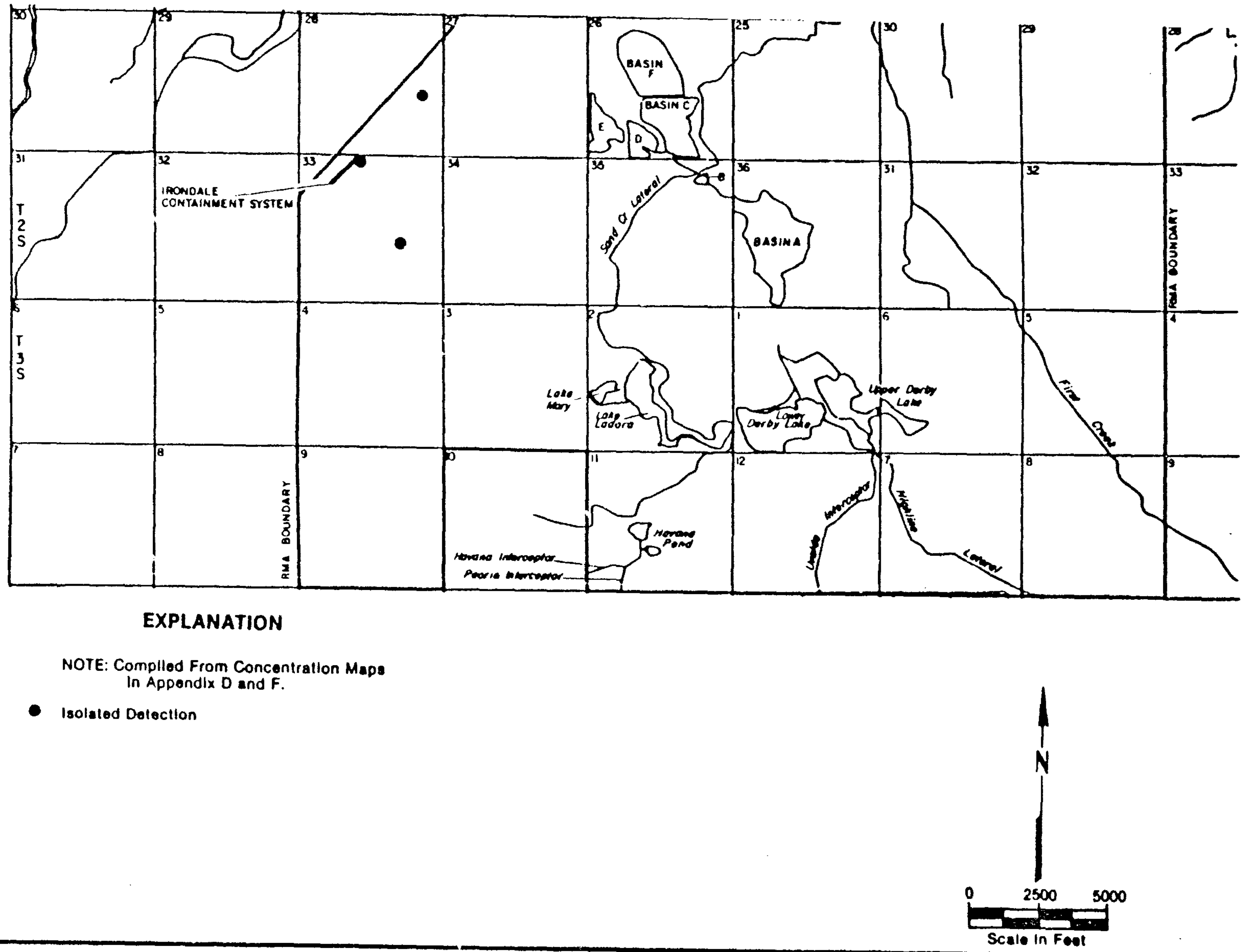
South Platte River
Fulton Ditch
Second Creek
Barr Lake
Burlington Ditch
O'Brian Canal
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F



EXPLANATION

NOTE: Compiled From Concentration Maps
In Appendix D and F.

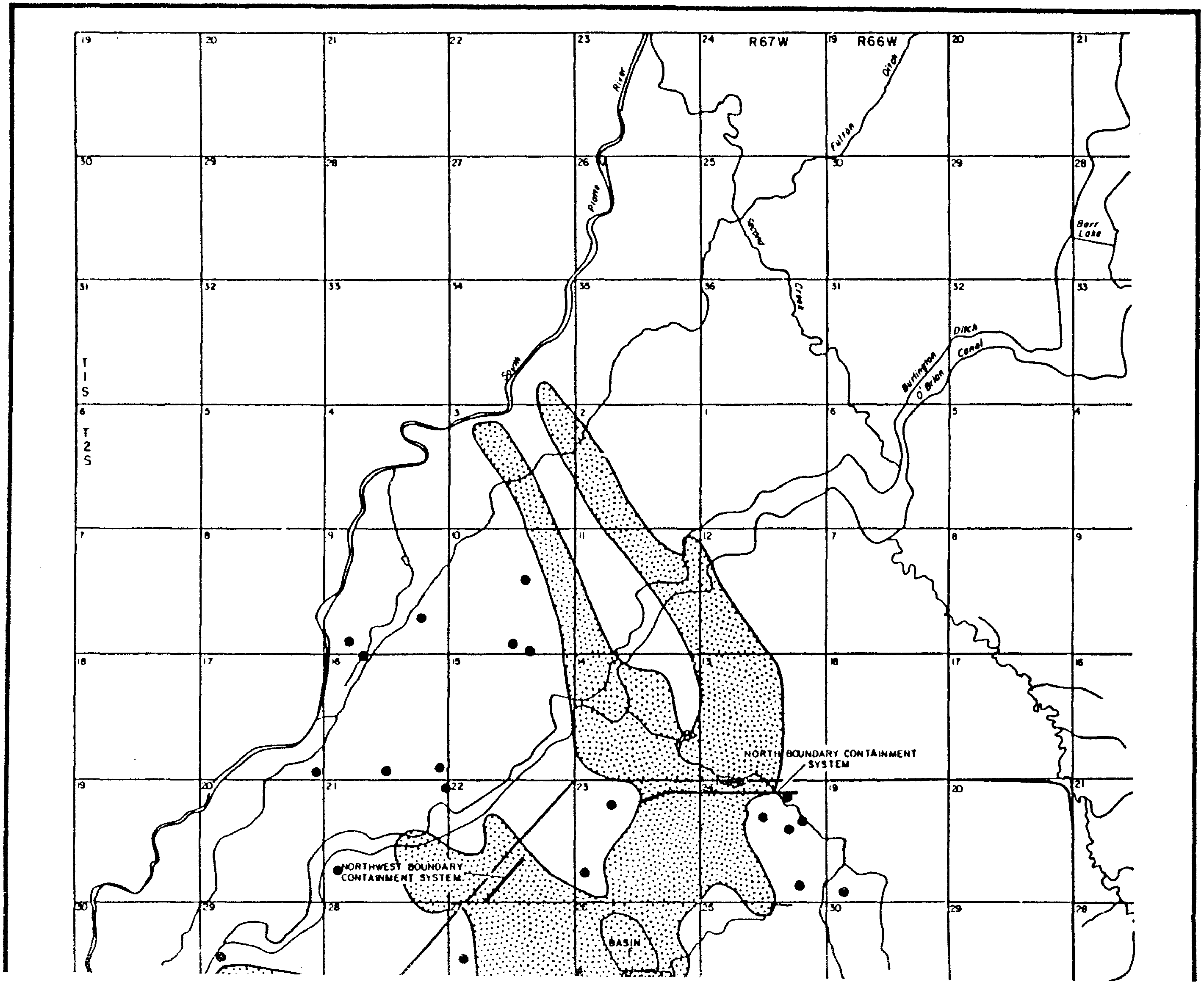
● Isolated Detection

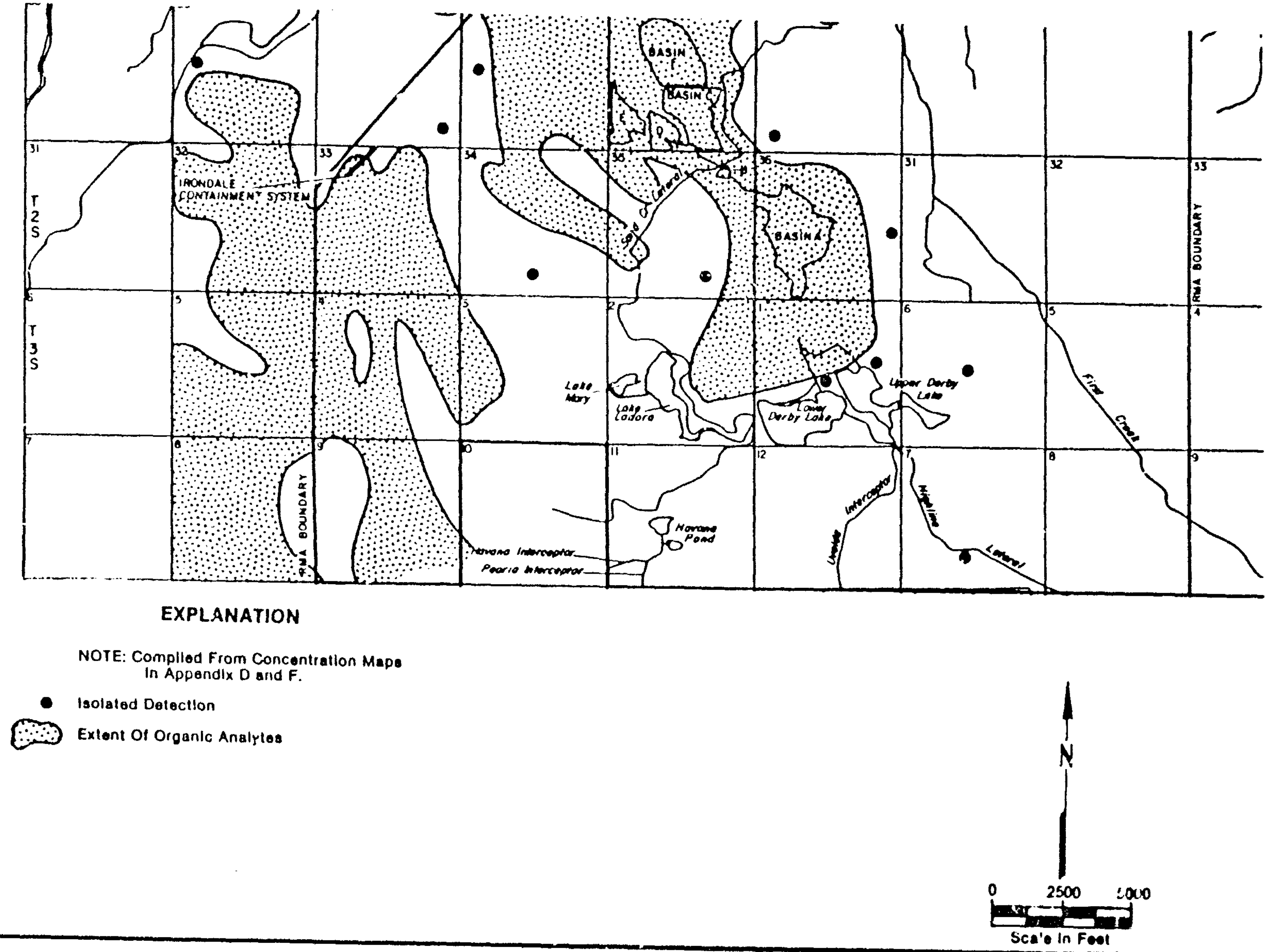
Figure 3.19
AREAL EXTENT OF INORGANIC ANALYTES
DENVER FORMATION ZONES 6 AND 7

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T 1 S
T 2 S
South Platte River
Fulton Ditch
Second Creek
Barr Lake
Burlington Ditch
O'Brian Canal
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F



EXPLANATION

NOTE: Compiled From Concentration Maps
In Appendix D and F.

● Isolated Detection

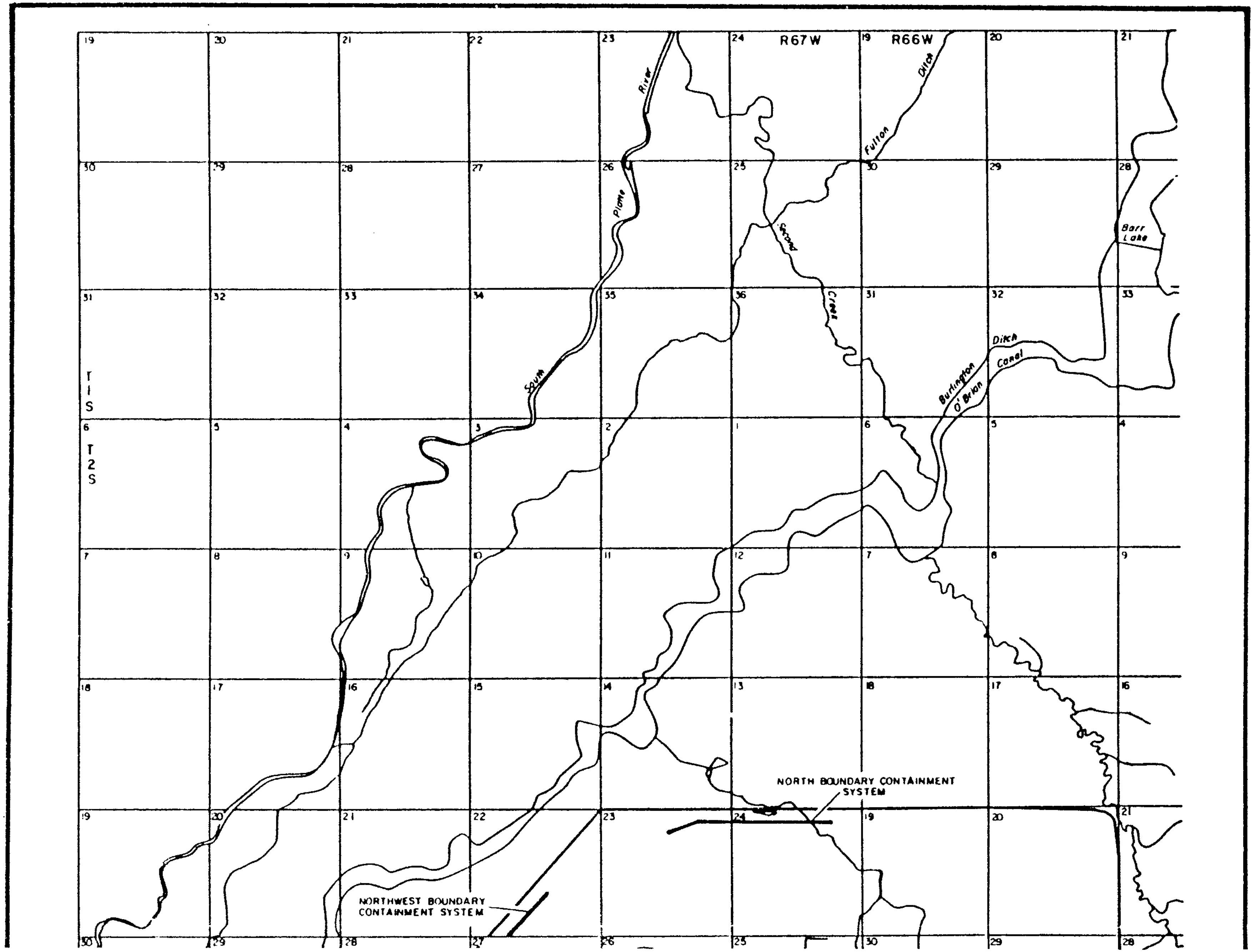
▨ Extent Of Organic Analytes

Figure 3.20
AREAL EXTENT OF ORGANIC ANALYTES IN THE UNCONFINED FLOW SYSTEM

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland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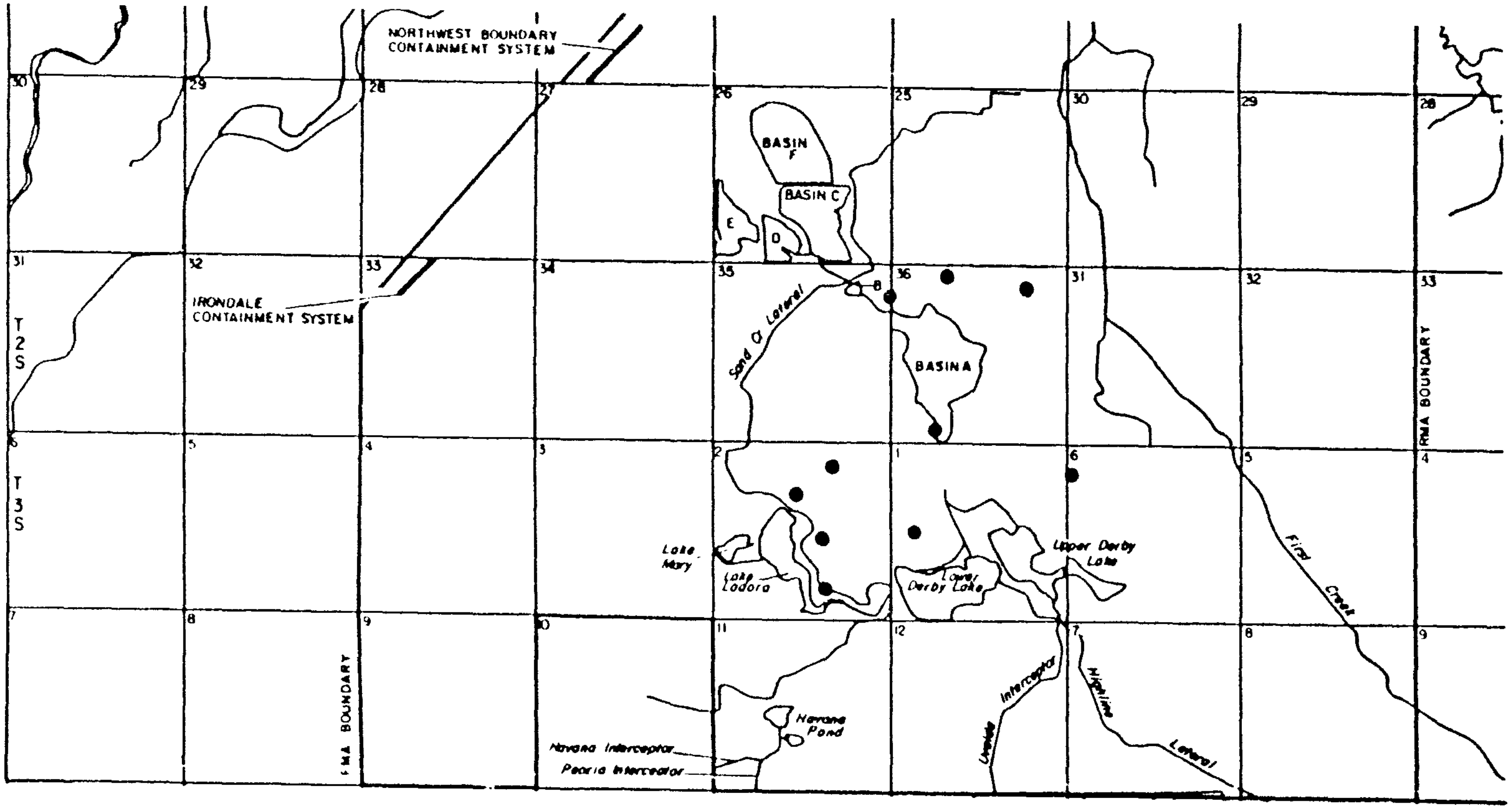
R66W
T1S
T2S
South Platte River
Fulton Ditch
Second Creek
Barr Lake
Burlington Ditch
O'Brian Canal
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM



EXPLANATION

NOTE: Compiled From Concentration Maps
In Appendix D and F.

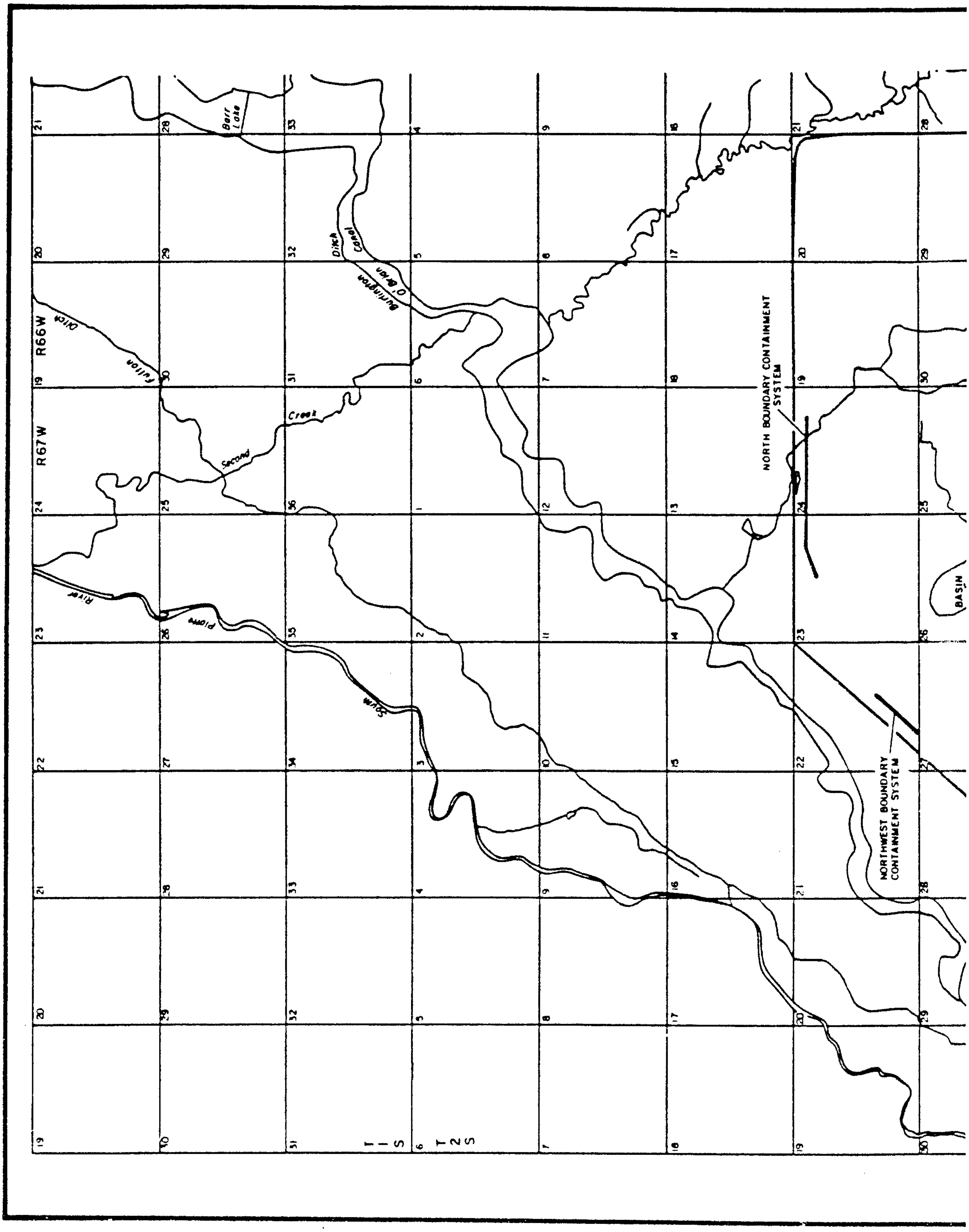
● Isolated Detection

Figure 3.21
AREAL EXTENT OF ORGANIC ANALYTES
DENVER FORMATION ZONE A

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R66W
R67W
T1S
T2S
Barr Lake
Burlington Ditch
O'Brian Canal
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN

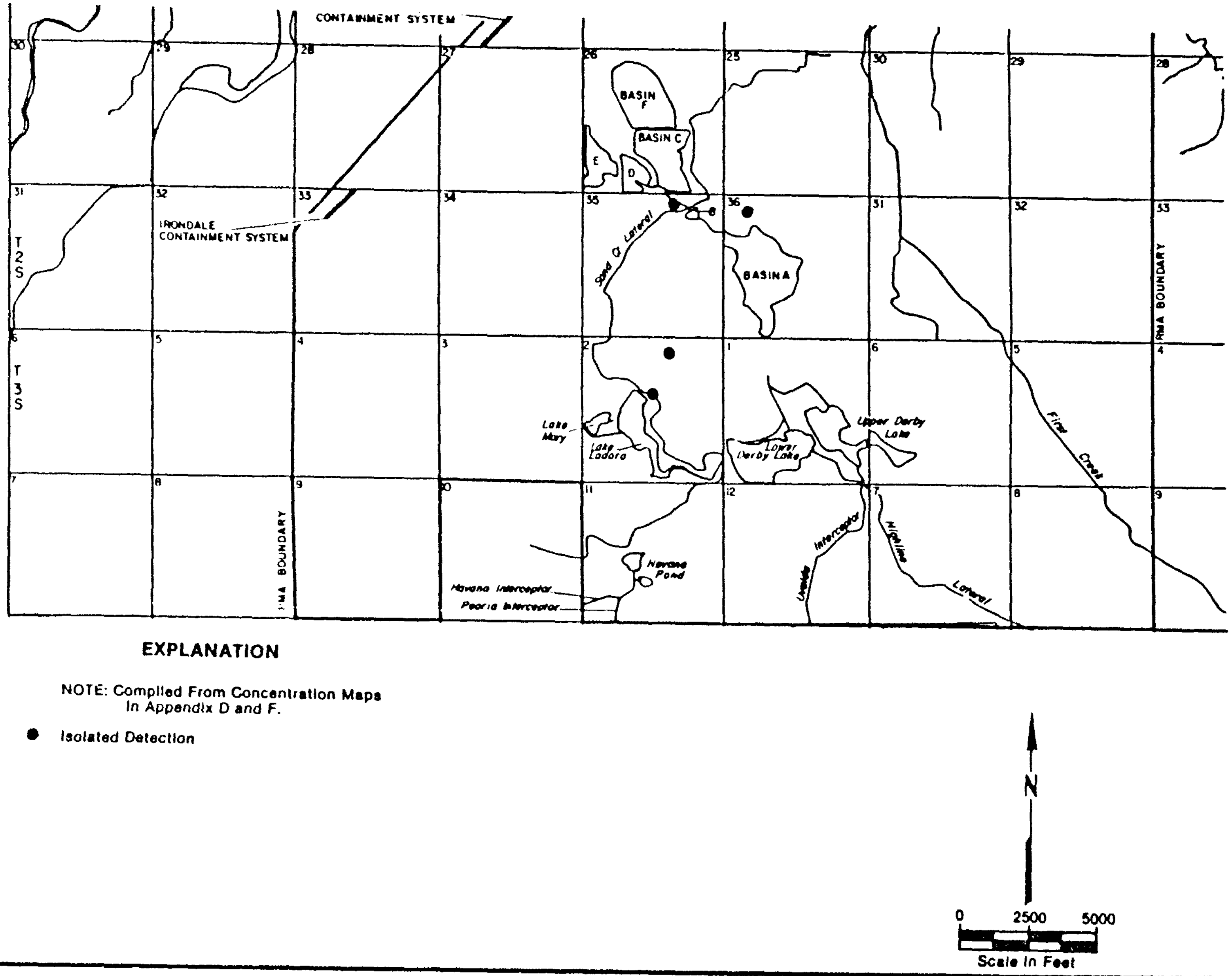
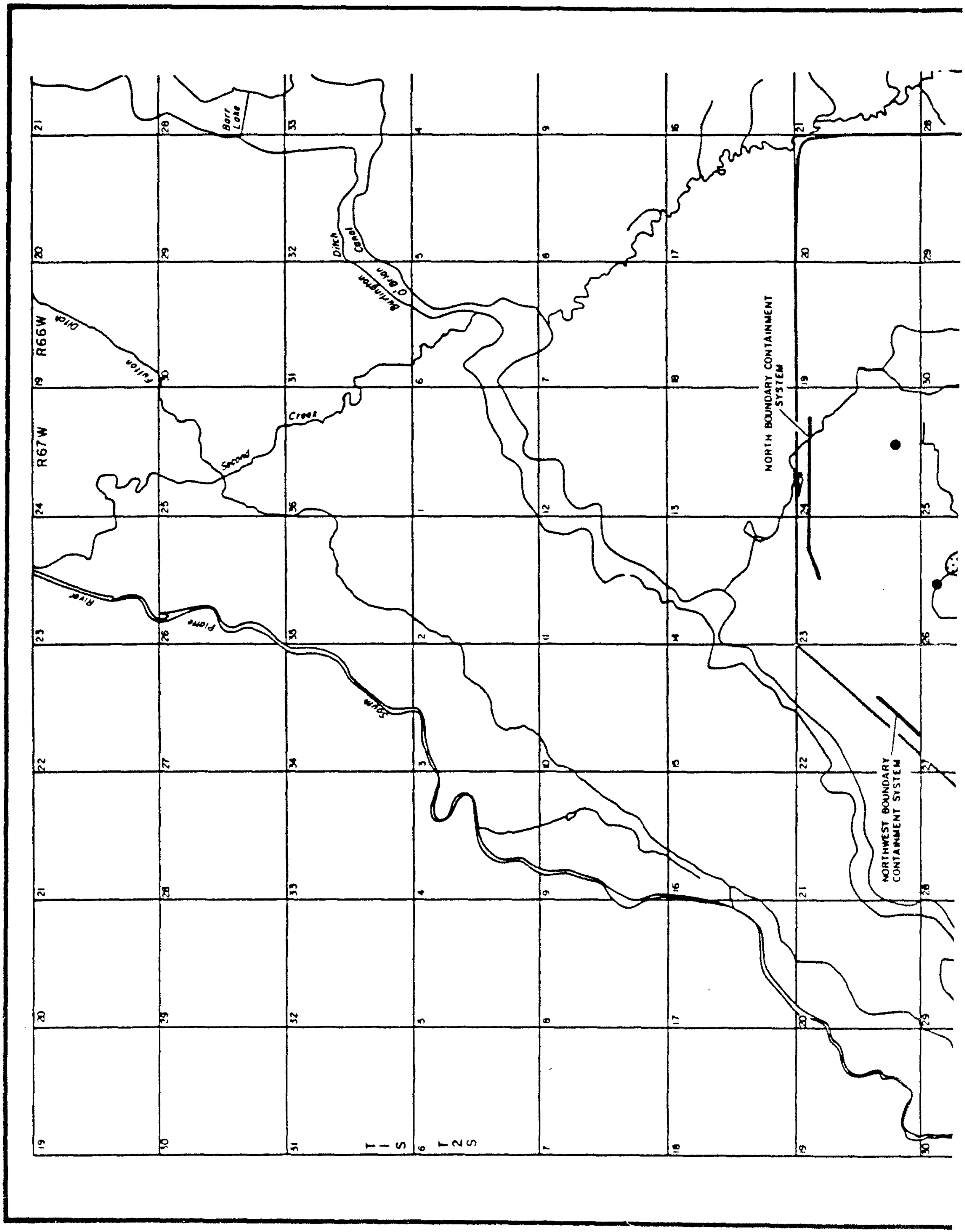


Figure 3.22
AREAL EXTENT OF ORGANIC ANALYTES
DENVER FORMATION ZONE 1U

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R66W
R67W
T 1 S
T 2 S
Barr Lake
Burlington Ditch
O'Brian Canal
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM

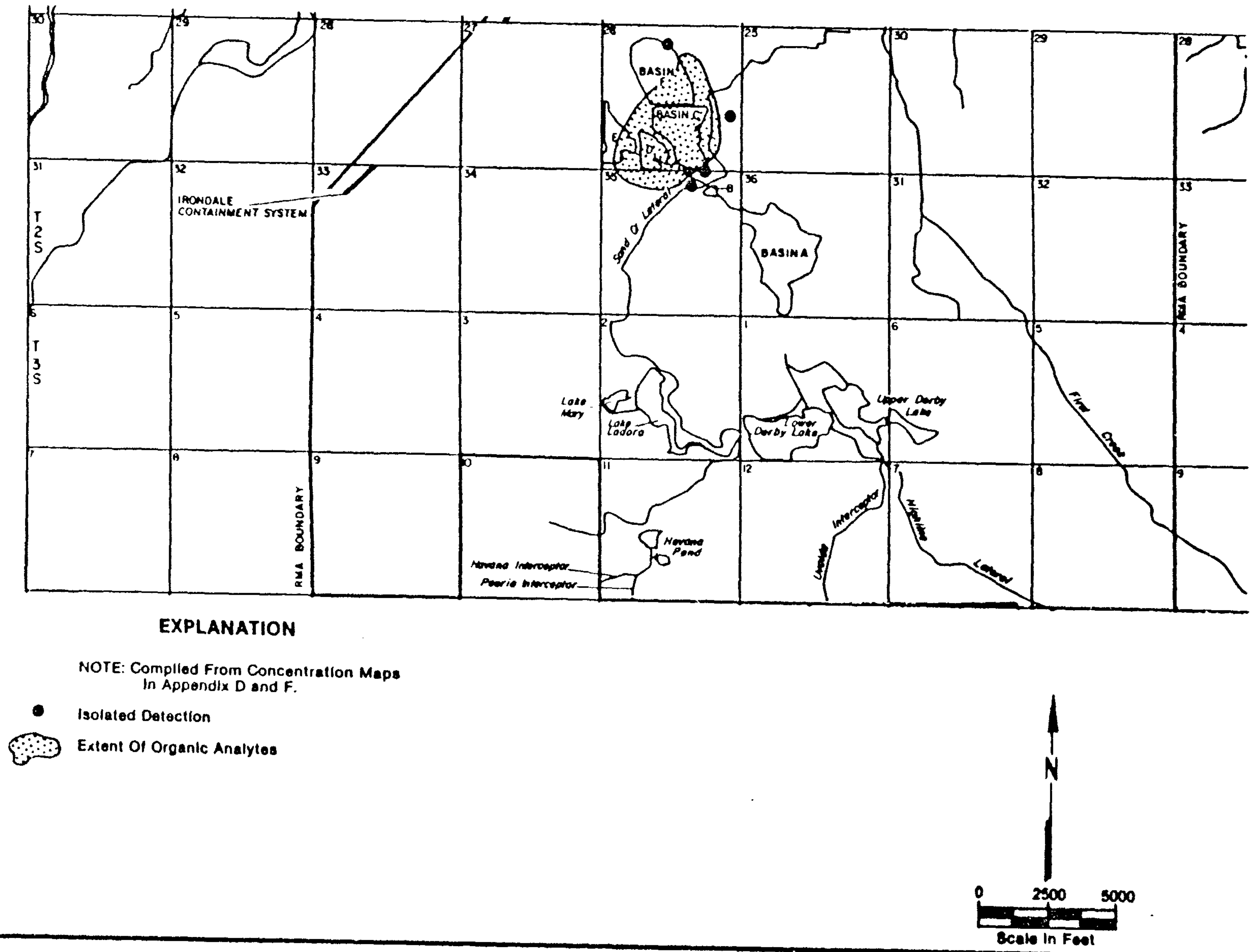
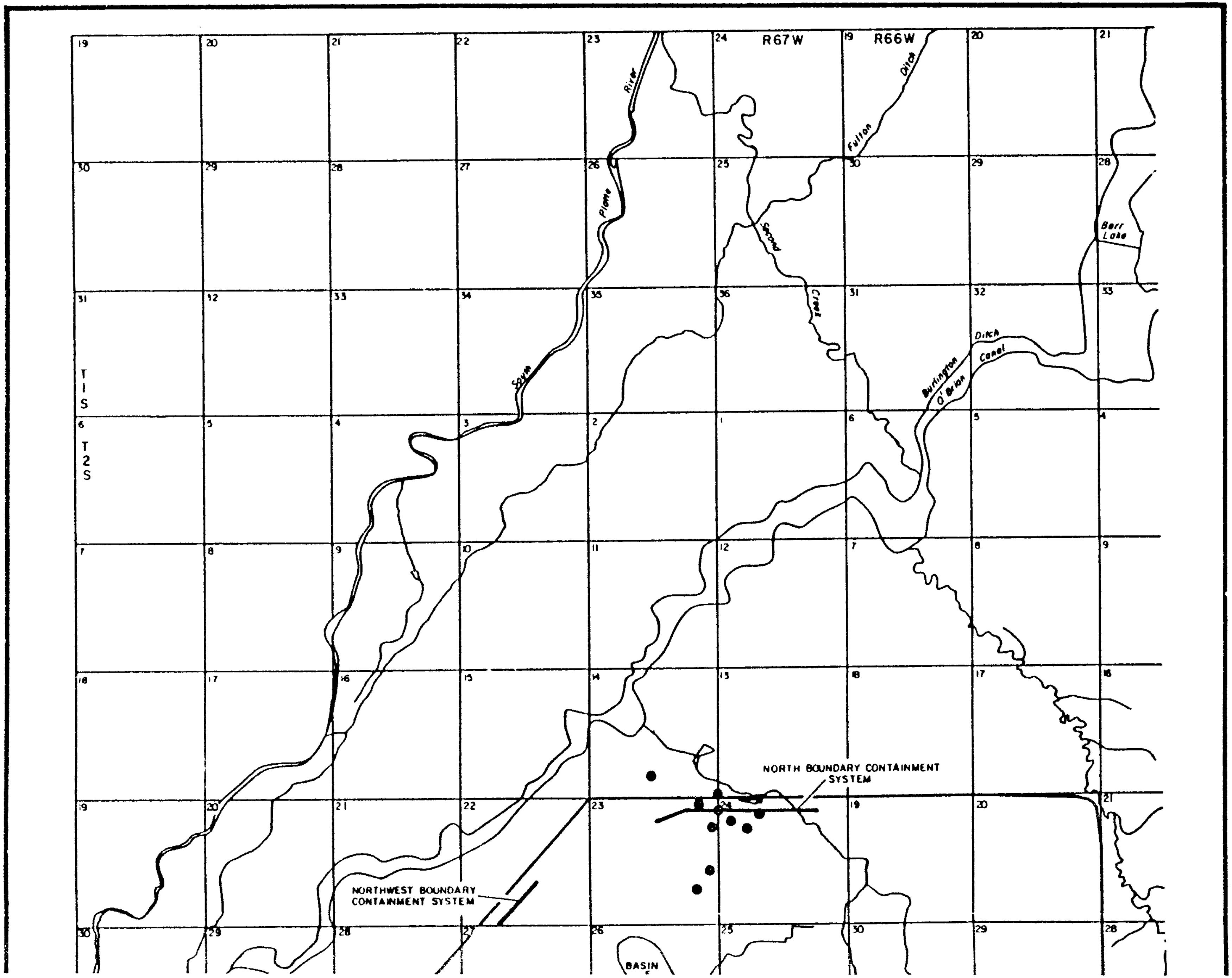


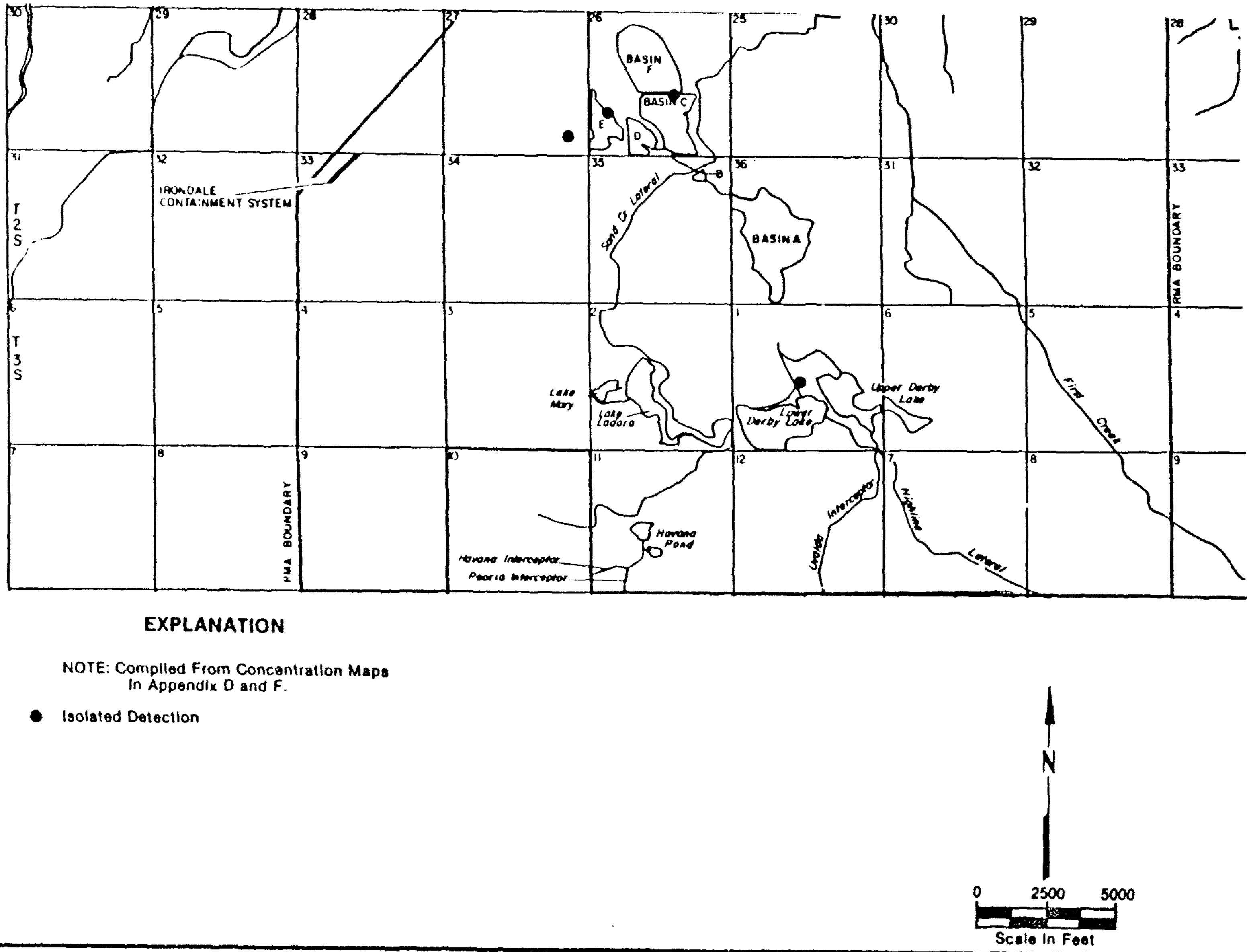
Figure 3.23
AREAL EXTENT OF ORGANIC ANALYTES
DENVER FORMATION ZONE 1

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T 1 S
T 2 S
Fulton Ditch
Second Creek
South Platte River
Barr Lake
Burlington Ditch
O'Brian Canal
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN



EXPLANATION

NOTE: Compiled From Concentration Maps
In Appendix D and F.

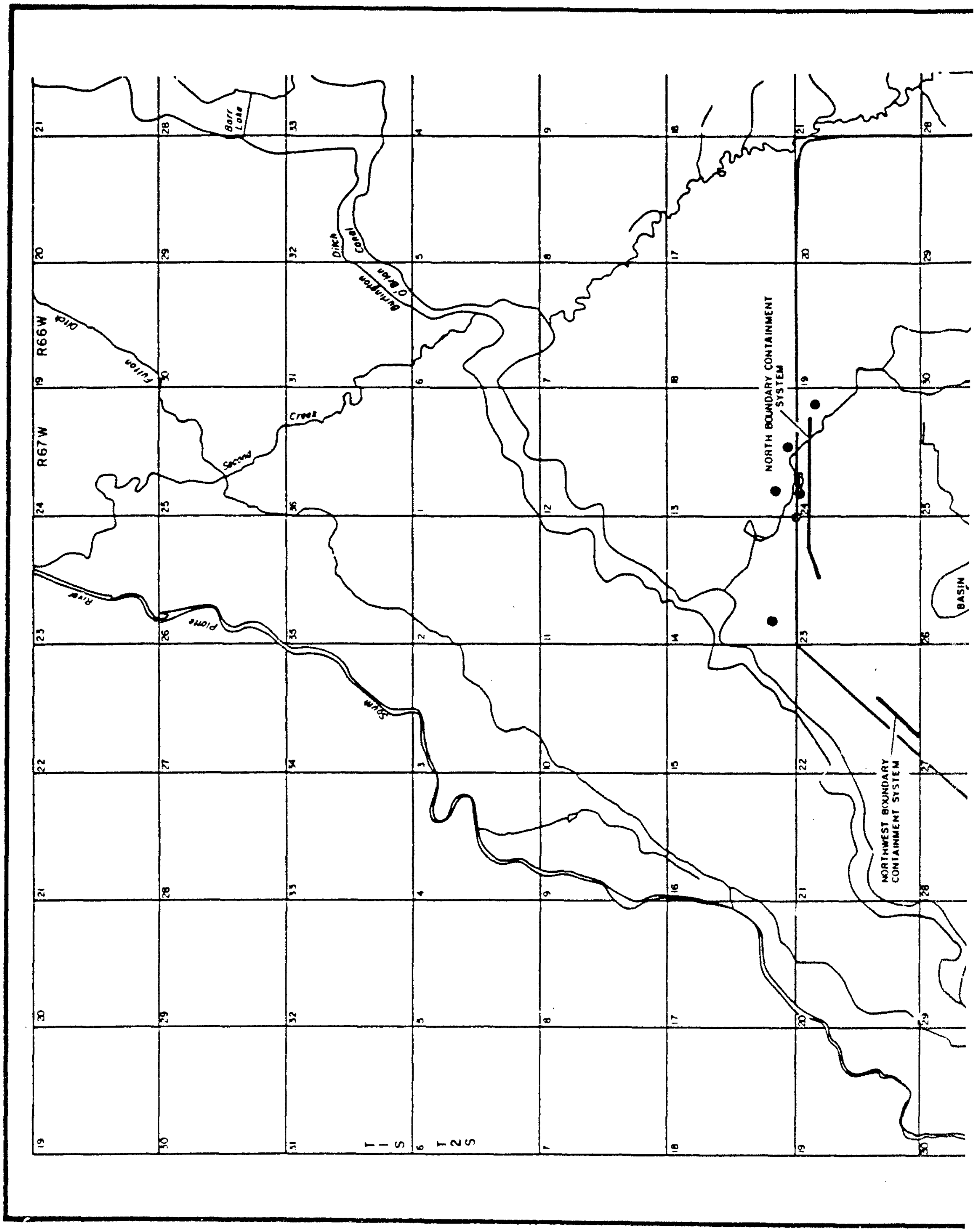
● Isolated Detection

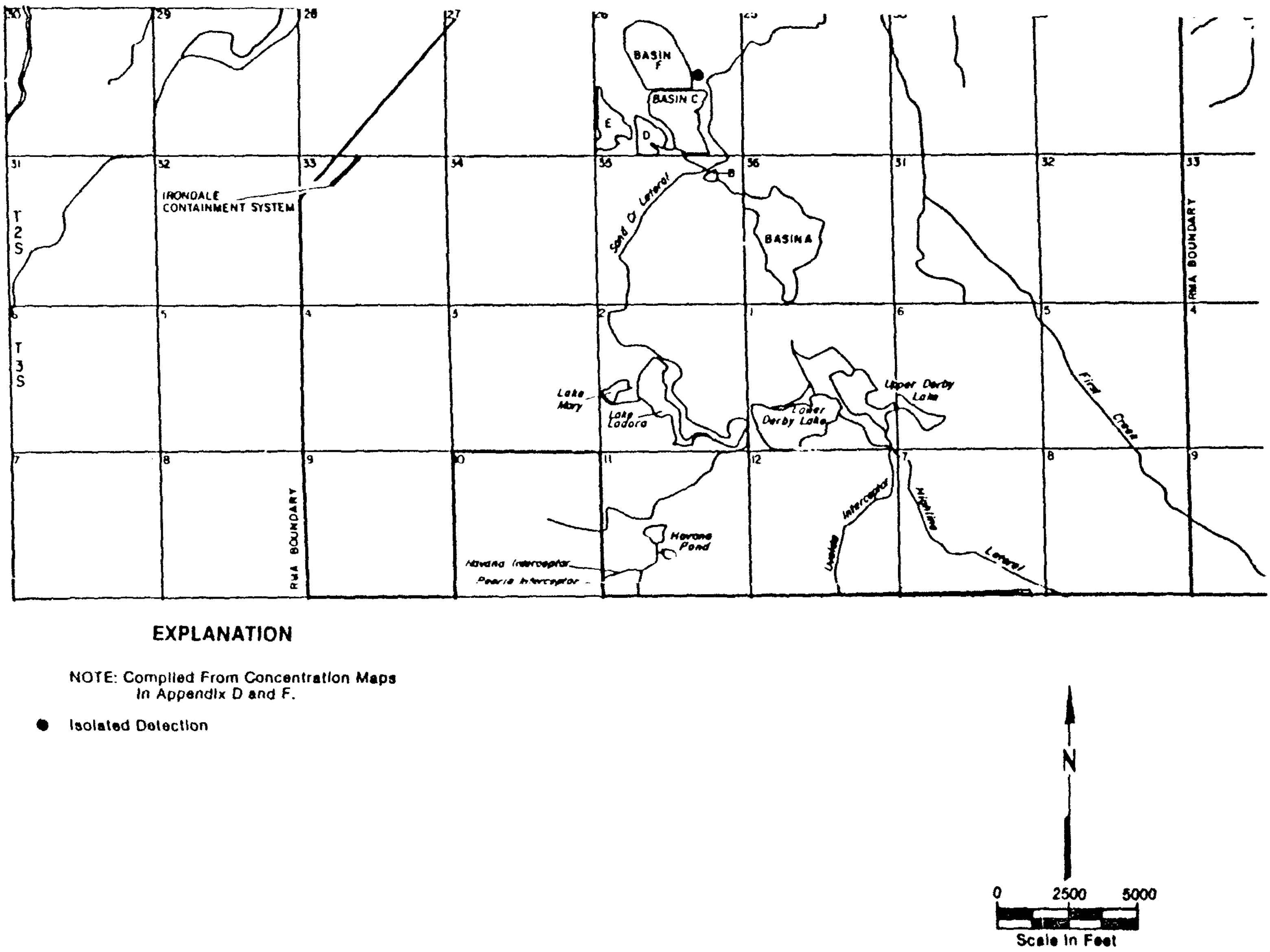
Figure 3.24
AREAL EXTENT OF ORGANIC ANALYTES
DENVER FORMATION ZONE 2

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R66W
R67W
T 1 S
T 2 S
Barr Lake
Burlington O'Brian Ditch Canal
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN



EXPLANATION

NOTE: Compiled From Concentration Maps In Appendix D and F.

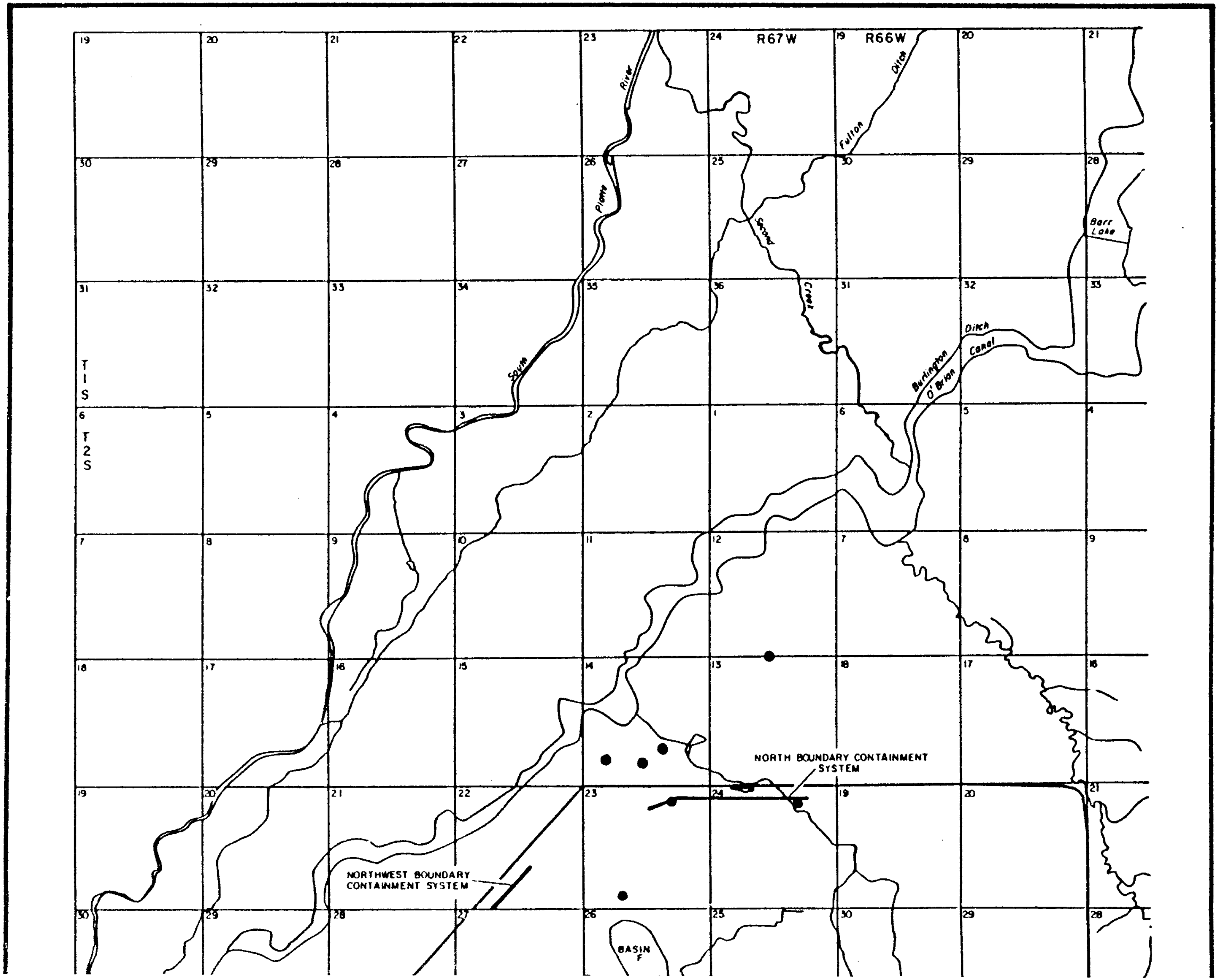
● Isolated Detection

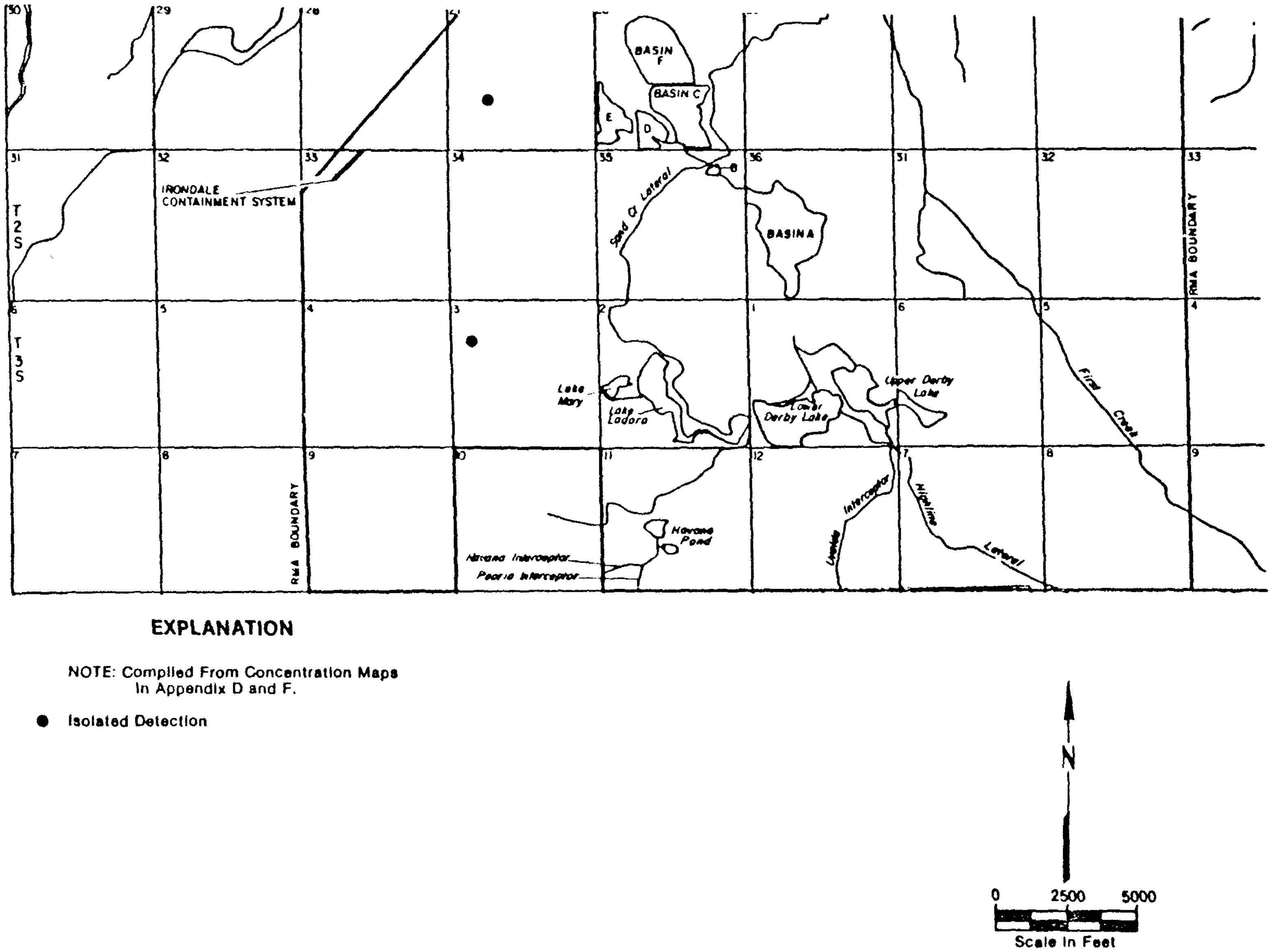
Figure 3.25
AREAL EXTENT OF ORGANIC ANALYTES
DENVER FORMATION ZONE 3

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R67W
R66W
T1S
T2S
South Platte River
Fulton Ditch
Second Creek
Barr Lake
Burlington Ditch
O'Brian Canal
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F



EXPLANATION

NOTE: Compiled From Concentration Maps
In Appendix D and F.

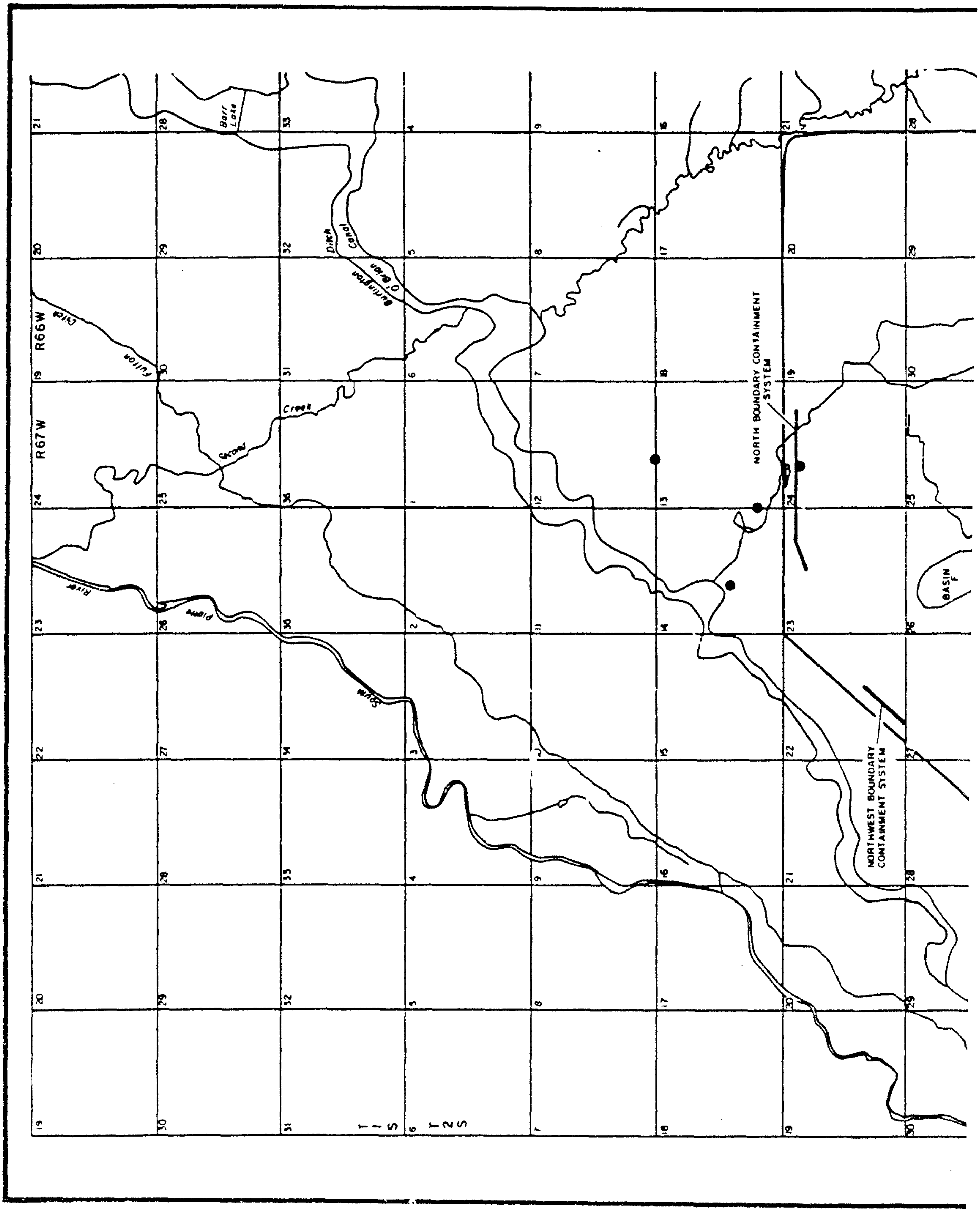
● Isolated Detection

Figure 3.26
AREAL EXTENT OF ORGANIC ANALYTES
DENVER FORMATION ZONE 4

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland


R66W
R67W
T1S
T2S
Barr Lake
Burlington O'Brian Canal
Ditch
Fulton Ditch
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
BASIN F

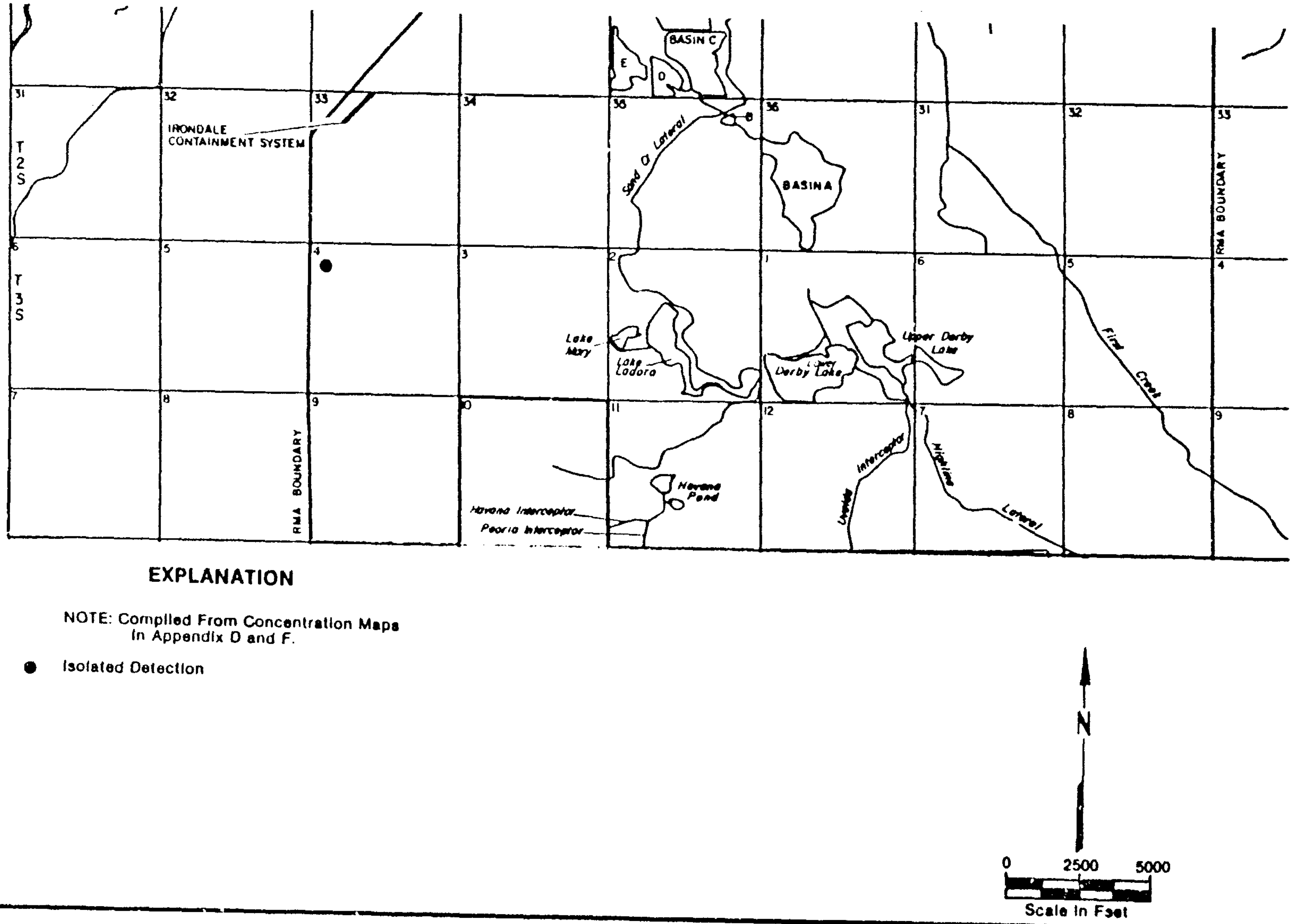


Figure 3.27
AREAL EXTENT OF ORGANIC ANALYTES
DENVER FORMATION ZONES 5 AND 6

SOURCE: R. L. Stollar & Associates Inc., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland

4.0 CONTAMINATION ASSESSMENT

The objectives of the Water Remediation Investigation contamination assessment at RMA are:

- To identify sources of groundwater and surface water contaminants;
- To describe mechanisms whereby contaminants may be introduced to water;and
- To develop conceptual models for migration and alteration of contaminants in water.

In combination with hydrogeologic and water quality data available for RMA, this assessment provides sufficient hydrologic information to begin evaluating the feasibility of remedial action alternatives for contaminated water.

4.1 Hydrologic Mechanisms for Contamination of Surface Water

Surface water features at RMA include lakes, ponds, basins, canals, ditches, and natural depressions. Several of these features,such as First Creek, ponds within Basin A, the sewage treatment plant tributary to First Creek, and Sand Creek Lateral,are potential contaminant pathways or are areas where surface water contaminants have been detected.

The rates at which contaminants can migrate in surface water are far greater than in groundwater. It is important to consider surface water flow when evaluating groundwater contaminant migration rates. For example, the Sand Creek Lateral was used to deliver South Plants waste to the basins in Section 26. These basins are located one mile north of South Plants; therefore, calculations of migration rates from South Plants must consider that contaminants were introduced to the groundwater in two or more locations during the same general time period.

Contaminants may enter the surface water by flushing and dissolving contaminants from surrounding soil, eroding and transporting contaminated soils and materials, direct discharge of contaminants or contaminated water, or by the discharge of contaminated groundwater to the surface water. The erosion of contaminants into ditches, canals, ponds, and lakes is a major mechanism of contaminant migration during thunderstorms and snow melt. Thunderstorms can be very localized, resulting in contaminant migration in some portions of RMA and not in others on the same day. Because large fluctuations in temperature are common at RMA, conditions for snow melt may occur from October to April. Snow melt provides a widespread distribution of runoff throughout RMA. If temperatures remain near freezing and melting is slow, the potential for erosion of contaminated soils that are not in ditches or canals is low.

A wide range of contaminants have been detected in the surface water at RMA. These contaminants are carried either in solution by surface water; carried by surface water as bed load in streams, canals, and ditches; or migrate as suspended load in the water.

Several processes decrease the relative concentrations of contaminants in surface water. Contaminant concentrations in a ditch or canal may be diluted by the influx of relatively clean water from an entering tributary. Concentrations also may be reduced due to volatization, degradation, or sorption of contaminants onto channel sediments. The addition of rain water and snow melt may also dilute contaminant concentrations.

Contaminant concentrations may increase during storm events as contaminated soils or materials are introduced to surface water. Where surface water collects in ponds or depressions for several days following a storm, evaporation may increase contaminant concentrations. An increase in contaminant levels has also been recognized in an off-post reach of First Creek near the north boundary of RMA when stream flow is low. Groundwater discharges into First Creek in this area. When flow rates are high, contaminants are diluted, the relative hydraulic heads between the creek and groundwater are reversed, and First Creek loses fresh water to the groundwater. Infiltration of surface water downward to the groundwater locally affects groundwater flow directions and rates and changes contaminant levels in the groundwater.

4.2 Hydrologic Mechanisms for the Introduction of Contaminants to Groundwater

There are four mechanisms by which contaminants migrate from a source to the groundwater system at RMA. The four mechanisms are: migration in the unsaturated zone, direct migration from sources beneath or at the water table, introduction along improperly constructed well bores, and hydraulic interchange of surface water and groundwater. Water level fluctuations can cause changes in the relative magnitudes of each mechanism.

Migration in the Unsaturated Zone

Water moving downward through the unsaturated zone will mobilize chemicals in the soil. In areas where the rate of water infiltration exceeds the rate of evaporation, the percolating water and any dissolved chemicals will reach the water table. In addition to dissolution of chemicals in the unsaturated zone, a substantial liquid contaminant spill could reach the water table by percolation. Direct percolation of contaminants also could occur from basins, sewers, and ditches as well as leakage from tanks, sumps, and pits.

Long-term evaporation at RMA exceeds precipitation. For this reason, contaminant migration through the unsaturated zone is likely only during periods of greater than average precipitation, during snowmelt, or where water accumulates at land surface. Regional groundwater budgets have been used to estimate effective distributed rates of recharge (HLA, 1989). Values typically range from 0.06 to 0.13 ft/yr.

Soils data presented in Study Area Reports indicate that a large mass of contaminants is present in the unsaturated zone. Strongly sorbed chemicals tend to occur in large concentrations in shallow soils beneath disposal basins but generally are not detected at depths greater than 5 ft. Weakly sorbed chemicals generally are not detected except beneath chemical sewers. Concentrations beneath the chemical sewers tend to be approximately uniform from the sewers to the water table.

To demonstrate the possible importance of contaminant migration in the unsaturated zone, a series of worst-case scenarios was evaluated. Although long-term average rates of flow probably are small, unusually rainy periods or periods of ponding may substantially increase flow rates. Data were not available to evaluate actual contaminant migration during unusual conditions such as extreme thunderstorms or ponding. Consequently the following worst-case scenarios were assumed: infiltration equal to 5 inches of rainfall during 24 hours; infiltration equal to the maximum amount of precipitation measured at Stapleton International Airport during a 30 day period (approximately 8 inches); and a period of surface water ponding.

Contaminant migration of dieldrin was evaluated for each infiltration scenario. Dieldrin strongly sorbs to soils and concentrates in shallow horizons. For purposes of the analysis, dieldrin concentration of 100 ug/g dry weight was assumed in the top 5 ft of soil. The concentration of dieldrin at greater depths was assumed to be zero. These assumptions are consistent with a typical distribution of organochlorine pesticides beneath basins in the North Central Study Area.

Dieldrin migration was evaluated under conditions of steady-state unsaturated flow. The effect of assuming steady-state flow is to overestimate dieldrin mass migration to the water table, and is consistent with the approach of evaluating worst-case scenarios. Linear sorption with a distribution coefficient (K_d) of 271 g/cm^3 is considered. An analytical solution for contaminant migration under the above assumptions, presented by Parker and van Genuchten (1984), is used in the subsequent evaluations. A dispersivity value of 1 ft and bulk density of 1.8 g/cm^3 were assumed.

Infiltration during a large 24 hour storm was assumed to total 5 inches. Although this rate of infiltration is large (0.208 inches/hr), it is less than infiltration capacity reported for many soils at RMA. Soils beneath Basin A probably have infiltration capacity substantially less than 0.2 inches/hr.

Based on a sorbed concentration of 100 ug/g in the top 5 ft of soil and a K_d of 27 cm^3/g, the equilibrium concentration of dieldrin in water percolating through the 5 ft horizon would be 3,700 ug/l. However, this concentration is unrealistic because the maximum solubility of dieldrin is 84 ug/l (Table 4.2). Subsequent worst-case analysis uses a value of 84 ug/l for concentration of dieldrin in water percolating through the 5 ft horizon. The estimated concentration of dieldrin at the 10 ft horizon after 24 hours would be well below detection limits. Consequently a large 24 hour storm probably would not result in contamination of groundwater by dieldrin unless the water table is near land surface and surface soils are contaminated.

The largest amount of precipitation recorded at Stapleton International Airport during a 30 day period was approximately 8 inches. For the purposes of evaluating a worst-case scenario, it was assumed that all precipitation resulted in infiltration. As with the previous scenario, the equilibrium concentration of dieldrin in water percolating through the 5 ft horizon was estimated as 84 ug/l. At the 10 ft horizon, the concentration of dieldrin in water was estimated to be well below detection limits throughout the 30 day period. Consequently a month of unusually high precipitation probably would not result in contamination of groundwater by dieldrin unless the water table is near land surface and surface soils are contaminated.

The preceding scenarios do not include effects of runoff and ponding. In areas where surface water ponds, infiltration rates would increase to equal the infiltration capacity of surface soil. Infiltration capacities of soils at RMA vary greatly but generally are large. For purposes of evaluating worst-case scenarios, an infiltration capacity of 0.5 inch/hr was assumed. As with previous scenarios, the equilibrium concentration of dieldrin in water percolating through the 5 ft horizon was estimated at 84 ug/l.

The concentration of dieldrin in water at a depth of 10 ft would be below detection limits after 30 days of ponding but would increase to approximately 0.23 ug/l after 45 days. The concentration of dieldrin in water at a depth of 15 ft would be below detection limits after 45 days. Although the worst-case analysis of ponding is based on numerous assumptions, it demonstrates that contaminant migration may occur through the unsaturated zone during extended periods of ponding.

Volatile and semivolatile organic contaminants usually are noted beneath chemical sewers. Concentrations of sorbed contaminants, documented in Study Area Reports, frequently are in excess of 100 ug/g. Concentrations of this magnitude often can be traced from the chemical sewers to the water table. In areas where ponding occurs, the water table is near land surface, or sewers continue to lose water to the vadose zone, rates of recharge would be enhanced substantially over average rates.

As an example of the possible importance of contaminant migration in the vicinity of chemical sewers, equilibrium concentrations of benzene were estimated. Assuming a sorbed concentration of 100 ug/g dry weight and a distribution coefficient (K_d) of 0.16 cm^3/g, the equilibrium concentration of benzene in soil water would be approximately 625,000 ug/l. Assumed values of sorbed concentration and K_d compare favorably with information provided in the South Plants Study Area Report. If the rate of percolation were enhanced by ponding or other means, contaminant migration in the vadose zone beneath chemical sewers would be significant.

Direct Migration

Contaminant sources located below the water table are in direct hydraulic connection with the groundwater system and will migrate with groundwater. Examples of sources for direct migration of contaminants are underground storage tanks, transfer pipelines, sewers, sumps, basins, ditches, disposal pits, and building structures.

Introduction along Improperly Constructed Wells

Migration may occur from a source through well bores or well clusters that are not properly closed or sealed. Interaquifer contamination along well bores can occur if wells are open to several aquifers of differing hydraulic head. Contaminants in the aquifer with greatest head will move through the well bore to other aquifers.

Hydraulic Interchange of Surface Water and Groundwater

Migration of contaminated surface water in streams, canals, lakes, and basins will occur if the head of the surface water feature is greater than the water table. Migration will occur by saturated flow if the water table rises above the bottom of the surface water feature. If the water table is below the bottom of the surface water feature, migration will occur through the unsaturated zone.

4.3 Hydrologic Model of Groundwater Flow and Contaminant Migration

Groundwater is the primary concern of this contamination assessment because it has been the principal medium for off-post transport of contaminants. In Section 2.0, two major groundwater flow systems are described. The first is the Unconfined Flow System, which comprises the saturated alluvium and upper Denver Formation, where alluvium is unsaturated. The Unconfined Flow System is conceptualized to be laterally continuous across the RMA study area. The second system, underlying the Unconfined Flow System, is the Denver aquifer, which contains groundwater flowing through confined sandstone and lignitic strata that are interbedded with shales and claystones of relatively low hydraulic conductivity.

The greatest mass of contaminants within the RMA study area is contained within the Unconfined Flow System. The Unconfined Flow System is in direct contact with several chemical source areas and is responsible for the transport of the majority of the contaminants both within and adjacent to the RMA. Due to the large mass of contaminants present, the Unconfined Flow System has a high priority in site remediation.

4.3.1 Conceptual Model of Groundwater Flow

A conceptual model of groundwater flow at RMA has been developed and includes lateral flow within the Unconfined Flow System and vertical interchange of water between the Unconfined Flow System and the Denver aquifer, as well as lateral and vertical flow within the Denver. A complete description of the conceptual model is presented in Sections 2.4 through 2.6; supporting information is provided in Appendix F, Section 2.0. Only those components of the conceptual model that are relevant to contaminant migration are summarized in this section.

Unconfined Flow System

The Unconfined Flow System is composed of saturated alluvium, some areas of weathered Denver Formation directly below saturated alluvium, and shallow weathered Denver Formation in areas of unsaturated alluvium. Although the Unconfined Flow System is areally continuous, there is a substantial difference between hydraulic conductivity of alluvium and Denver Formation. This difference greatly affects groundwater flow velocity and directions of contaminant transport.

The Unconfined Flow System has been divided into seven hydrogeologic units on the basis of similarities in lithology and aquifer test results. Although there is substantial variation within each unit, hydraulic conductivity of unconfined Denver Formation is one to two orders of magnitude less than the eolian unit and two to three orders of magnitude less than other units. Figure 2.3 shows the areal distribution for each hydrogeologic unit and representative hydraulic conductivity estimates for each unit.

Because the unconfined Denver Formation is significantly less permeable than unconsolidated materials, the Denver will tend to act as a partial barrier to lateral flow in areas of unsaturated alluvium. However, groundwater flow laterally into the unconfined Denver Formation is possible locally where the Denver Formation consists of sandstone or fractured rock. Within alluvial materials, larger hydraulic conductivity and greater saturated thickness tend to occur within paleochannel deposits.

The nature of flow in shallow parts of the Denver Formation is substantially more complex than the nature of flow in alluvial and eolian deposits. Transmissive rock of the Denver Formation is discontinuous and extremely heterogeneous. Consequently, there is a greater degree of uncertainty when characterizing flow in the Denver Formation than occurs when characterizing flow in alluvial and eolian deposits.

Horizontal hydraulic gradients within the Unconfined Flow System were assessed using the Third Quarter FY87 Water-Table Map (Figure 2.4). Spatial variations in gradient are dependent largely on topography, saturated thickness, bedrock surface configuration, and hydraulic conductivity. Streamlines indicating groundwater flow directions have been drawn perpendicular to the water table contours in selected areas (Figure 4.1).

Sources of water to the Unconfined Flow System include seepage from surface water bodies, recharge from irrigation and precipitation, groundwater inflow along southern and eastern study area boundaries, and flow from subcropping units of the confined Denver aquifer. Discharge from the Unconfined Flow System occurs as lateral flow northwest toward the South Platte River, seepage to three lakes, pumpage by wells, and vertical flow into the confined Denver aquifer. Methods for initially estimating surface water seepage, recharge of irrigation and precipitation, and pumpage are described in Appendix F, Section 2.4.3. Estimates of steady state recharge and discharge presented in Table 4.1 are obtained from results of the regional flow model of RMA (HLA, 1989). A summary of the model is provided in Section 4.3.2.

Denver Aquifer

The Denver aquifer consists of interconnected beds of permeable sandstone and lignitic material and relatively impermeable claystone. In parts of the Denver Formation close to the bedrock-alluvial contact, secondary permeability may exist within the claystone, and hydraulic interchange between the Unconfined Flow System and Denver aquifer may be enhanced.

Flow in the Denver aquifer is substantially more complex than flow in the Unconfined Flow System. Transmissive rock in the Denver aquifer is discontinuous and heterogeneous. The distribution of hydraulic head in the Denver aquifer indicates the presence of a complex three-dimensional flow system. Consequently, understanding of flow in the Denver aquifer is less certain than understanding of flow in the Unconfined Flow System.

The Denver aquifer has been differentiated into stratigraphic units on the basis of lithologic description (Appendix F, Subsection 2.2.3). Sequences containing a large proportion of sandstone and lignitic strata have been interpreted as units with relatively high hydraulic conductivity. Sequences composed primarily of claystone, clayshale, and volcaniclastics have been interpreted as units with low hydraulic conductivity. Individual sandstones are highly lenticular and do not extend over significant distances. However, stratigraphic zones can commonly be correlated at the scale of the study area (Plates 1 and 2). Lignitic units tend to have greater lateral continuity than sandstones.

Hydraulic conductivity varies spatially and reflects variations in lithology. Horizontal hydraulic conductivity of the shale and claystone matrix is low; it is probably 10^{-2} to 10^{-4} ft/day. In contrast, horizontal hydraulic conductivity for sandstone in the Denver aquifer has been estimated by slug-test analyses to range from 0.03 to 3 ft/day. Values

Table 4.1 Model Estimated Recharge and Discharge for the Unconfined Flow System

Component	Estimated Value (ac-ft/yr)
RECHARGE TO GROUNDWATER UFS	
Precipitation (includes developed areas)	2,170
Irrigation	6,550
Subcropping Denver Fm	800
Stream and Canal Seepage	18,240
Lake and Pond Seepage	1,600
Other Surface Water Features	120
Groundwater Flow into the area	6,460
Total Recharge:	35,940
DISCHARGE FROM GROUNDWATER UFS	
Lakes and ponds (includes gravel pits)	2,010
Irrigation Wells	1,490
South Adams County Wells	3,540
Groundwater Flow to the South Platte River	28,380
Groundwater Flow to Other Streams	520
Total Discharge:	35,940

Note: Estimates apply to the area bound by Sand Creek, South Platte River, Second Creek and Highline Canal.

less than 0.3 ft/day are typical of silty sandstone. Values from pumping tests range from 1.1 to 7.7 ft/day. Estimates of hydraulic conductivity for fractured lignitic beds are not available. Fractures can substantially increase hydraulic conductivity. Several orders-of-magnitude increase are possible if fractures are highly interconnected. Flow-model analyses indicate that the horizontal hydraulic conductivity of lignitic beds may be an order of magnitude greater than the hydraulic conductivity of sandstone.

Vertical head gradients in the Denver aquifer generally indicate downward potential for flow, and horizontal gradients generally indicate horizontal potential for flow from southeast toward northwest. Based on these observations, a conceptual model of regional flow has been developed in which water moves downward from the Unconfined Flow System through strata with relatively low hydraulic conductivity into predominantly sandstone and lignite units of the Denver aquifer. The rate of vertical movement per unit area may be small. Water in sandstone and lignite units generally moves vertically downward and laterally toward the northwest, and may return to the Unconfined Flow System where the units subcrop.

Local gradients vary substantially from overall regional trends. As a result, localized flow paths are common in the Denver aquifer. Localized recharge and discharge occurs in areas where sandstone or other permeable material of the Denver aquifer is in contact with the Unconfined Flow System and the elevation of the bedrock surface varies appreciably in a short distance. Longer flow paths may occur in areas where vertical hydraulic conductivity is sufficiently large to permit deeper circulation of water.

4.3.2 Numerical Models of Groundwater Flow

Numerical models of groundwater flow in the vicinity of RMA have been developed to evaluate components of the conceptual model and to refine estimates of hydraulic conductivity and other aquifer characteristics. Separate models of flow in the Unconfined Flow System and Denver aquifer have been developed. A detailed description of the numerical models, including theory, input data, calibration procedure, and results is given in HLA (1989). Only results and conclusions are presented in this report.

Unconfined Flow System

The numerical model represents steady-state conditions in the Unconfined Flow System corresponding to time-averaged conditions from 1981 through 1987. Consequently, the model may not be appropriate for simulation of historical conditions where substantial water level fluctuations saturated alluvial deposits that currently are unsaturated. Water level fluctuations that affect hydraulic relations between the Unconfined Flow System and the confined Denver aquifer cannot be simulated with the existing model. The model also does not simulate hydraulic interchange between the Unconfined Flow System and the Denver aquifer. Leakage between the two units is treated as a specified flux boundary.

Initial simulations of flow in the Unconfined Flow System were based on estimates of hydraulic conductivity, hydrogeologic unit boundaries, and recharge and discharge presented previously in Section 2.0 of this report. Model calibration consisted of adjusting hydraulic parameters, primarily hydraulic conductivity, until simulated hydraulic head adequately reproduced measured water levels. With few exceptions, model calibration was achieved without major modifications to initial estimates. Calibration results indicate that the model is sufficiently reliable for purposes of the Remedial Investigation. Differences between calculated and measured heads generally were less than 10 ft. However, differences between 10 and 20 ft occurred in the vicinity of the Basin A Neck. Additional refinement in parameter estimates may be needed to meet objectives of the Feasibility Studies.

Model results are consistent with the concept that paleochannels and terrace deposits generally convey higher volumes of water than interfluvial zones. The axes of most paleochannels trend from southeast to northwest and are consistent with the general direction of groundwater movement. Material in the paleochannels and terrace deposits near the South Platte River are characterized by higher hydraulic conductivity than exists in Unconfined Flow System materials southeast of the river terraces. As a result, hydraulic gradients in the river terraces are less steep than in other areas.

Efforts to simulate flow in the Unconfined Flow System were unsuccessful unless recharge from subcropping sandstone in the Denver Formation was specified. Sensitivity analyses with the numerical model of the Unconfined Flow System show that the overall effect of hydraulic interchange between the Unconfined Flow System and the Denver aquifer is small. However the model was sensitive to hydraulic interchange in areas of relatively small lateral flow. These areas generally are located in the vicinity of South Plants and Basins A through F. These areas are important because they contain the majority of contaminant source areas.

Hydraulic conductivity estimates in the Basin A Neck and areas immediately downgradient obtained during model calibration are smaller than values indicated in this report (Figure 2.3). If the model estimates are reliable, flow to the Northwest Boundary Containment System from Basin A Neck are less than originally inferred. The comparison between simulated and measured hydraulic head is least favorable in the vicinity of Basin A Neck. Aquifer tests were conducted in the Basin A Neck by MKE during 1988. Test data have not been published and consequently reliability of the test analysis can not be evaluated. Estimates of hydraulic conductivity obtained from these tests varied from 10 ft/day to 106 ft/day.

The numerical model indicates that flow to the northwestern boundary of RMA from the Basin A Neck area probably is lower today than in past years. Flow is currently estimated to be 0.15 cfs and reflects a period when Basins A through E were not used for waste storage. Robson (1977) estimated flow of 0.77 cfs for this area from 1952 to 1975. Waste fluids from RMA were released to Basins A through E during part of this earlier period.

The regional model of the Unconfined Flow System is a nonunique representation of the groundwater flow system at RMA. The areas of largest parameter uncertainty are mostly south and east of RMA, where few wells exist and hydrogeologic data are limited. Considerable uncertainty also exists in areas of low flow near South Plants and Basins A through F. Uncertainty in these areas may be due to uncertain estimates of recharge from the basins, and the wide range of estimates available to describe hydraulic interchange between the Unconfined Flow System and the Denver aquifer.

Denver Aquifer

A cross-section numerical model was developed to gain a better understanding of the mechanisms of flow within the Denver aquifer, rather than refining hydraulic parameter values at particular locations. This included evaluating the conceptualization of layered hydrogeologic units, the degree of confinement provided by clayshale strata of the Denver

Formation, and whether alternative conceptualizations of the hydrogeologic system were possible.

The cross-sectional flow model was constructed approximately along flow paths in the Denver aquifer from Upper Derby Lake to the Basin A Neck. The modeled flow region extended from the alluvium-bedrock contact to a depth of about 150 ft. The Unconfined Flow System was not specifically modeled in this study, but provided upper prescribed head boundary conditions to the modeled area. A variety of layered heterogeneous flow systems were hypothesized and steady-state flow through each system was simulated. As an alternative, the flow region was also modeled as a single homogeneous anisotropic material to evaluate whether this conceptualization might also be representative of the Denver aquifer.

Model analyses were performed by varying the hydraulic conductivity of materials and observing the effects of such changes on the distribution of hydraulic head within the flow system. The purpose was to define plausible ranges of hydraulic conductivity values and the ratios of hydraulic conductivity between different materials. Distributions of hydraulic head predicted by the model were compared with point measurements of hydraulic head from piezometers to evaluate the reliability of the input parameter values and the modeled geometries of hydrogeologic units. The findings in this cross-sectional model may not be applicable to other areas of RMA.

Results of the cross-sectional numerical model are summarized below:

- A conceptual model based on layered material of differing hydraulic conductivity is more representative than a model that considers a single homogeneous anisotropic material. However, layers of uniform hydraulic conductivity are not necessarily continuous across RMA.

- Shale and claystone layers may have vertical hydraulic conductivity approximately four to five orders of magnitude less than horizontal hydraulic conductivity. This indicates that, where continuous, shale and claystone provide a high degree of confinement within the Denver aquifer.

- Lignitic layers appear to have the highest hydraulic conductivity within the Denver aquifer. Horizontal hydraulic conductivity of lignite may be on the order of 10 to 20 ft/day (4 x 10^{-3} to 7 x 10^{-3} cm/sec).

4.3.3 Conceptual Model of Contaminant Migration

Changes in contaminant concentrations in groundwater at RMA are due to advective transport, hydrodynamic dispersion, dilution, and chemical or physical reactions. Advection, dispersion, and dilution are related to groundwater flow and are discussed in this section of the report. Changes in contaminant concentration due to chemical or physical reactions are discussed in Section 4.4.

Contaminant migration due to the movement of water is described by advection and hydrodynamic dispersion. Advection is migration at the average rate of water molecules and is described by the average linear velocity of the groundwater. The average linear velocity is estimated as the product of hydraulic conductivity and hydraulic gradient divided by effective porosity. Hydrodynamic dispersion describes deviations from the average rate of migration. Hydrodynamic dispersion may be viewed as the result of tortuosity or small-scale variations in hydraulic conductivity along a flow path. In isotropic homogeneous material, hydrodynamic dispersion can be quantified by a dispersivity tensor with principal axes aligned parallel and perpendicular to the direction of flow. Models to describe hydrodynamic dispersion coefficients in anisotropic or heterogeneous material are more complex.

Changes in contaminant concentration due to dilution occur when water having a certain concentration of contaminant mixes with water having a different concentration. Qualitatively, areas of dilution are indicated by maps showing converging flow paths. Quantitatively, areas of dilution are indicated by mass balance calculations using flow models or flow net analyses.

Unconfined Flow System

Rates of migration due to advection depend on hydraulic conductivity, hydraulic gradient, and effective porosity. Values of these parameters generally are site-specific. Descriptions of migration due to advection along selected flow paths are presented later in this report (Section 4.6). Descriptions of hydraulic conductivity and hydraulic gradients were presented previously. Effective porosity of alluvial material and subcropping sandstone of the Unconfined Flow System is not well known. Numerical models of contaminant migration in alluvial material at RMA have been developed successfully using effective porosity estimates of approximately 0.4 (Konikow, 1977; Robson, 1981). Estimates of effective porosity in coarse grained strata typically vary from 0.1 to 0.4. Effective porosity estimates in weathered or fractured clayshale may be less than 0.05.

Regional estimates of migration due to hydrodynamic dispersion have been made as part of numerical modeling studies. Hydrodynamic dispersion in alluvial material of the Unconfined Flow System appears to be similar to dispersion in isotropic homogeneous media. Regional estimates of dispersivity in the direction of flow are approximately 100 ft while dispersivity transverse to the direction of flow is approximately 30 ft (Konikow 1977; Robson, 1981). These estimates were obtained during transport model calibration at a scale of several miles.

Changes in solute concentration due to dilution are important in the vicinity of the South Platte River and associated alluvial terraces. Contaminated water migrating toward this area from RMA is diluted substantially by relatively uncontaminated water moving in terrace gravel parallel to the South Platte River. Much of the dilution occurs beyond the boundaries of RMA.

Dilution may have been an important mechanism for modifying contaminant concentrations beneath and north of Basin F. Relatively uncontaminated water diverted to Basin C in the past probably increased the rate of advective transport beneath Basin F toward the northern boundary of RMA. Enhanced recharge beneath Basin C caused water levels to rise and temporarily increased contaminant concentration by flushing contaminants that had accumulated previously above the water table. Following flushing of contaminants, enhanced recharge may have decreased contaminant concentrations by dilution in the vicinity of Basin C.

Denver Aquifer

Contamination of the Denver aquifer probably occurred by intergranular flow in areas where sandstone channels provided direct hydraulic connection with the Unconfined Flow System. For example, contamination of sandstone zone 1 in the Denver aquifer beneath

Basin C probably occurred by intergranular flow. The rate of migration probably was enhanced by rising water levels in the Unconfined Flow System during periods when Basin C contained water. Contamination of the Denver aquifer also can occur by molecular diffusion from areas of high concentration to areas of low concentration. However rates of contamination by this mechanism probably are negligible compared to rates of intergranular flow.

These mechanisms of vertical migration only are effective in explaining local areas of contamination within the upper most permeable zones of the Denver aquifer. Within RMA, contamination has been observed in deeper sandstone zones, as well as in sandstone zones separated from the Unconfined Flow System by shale or claystone. Calculated rates of migration by intergranular flow are not sufficiently large to explain contamination in these intervals.

Contamination of deeper sandstone zones of the Denver aquifer may have occurred by vertical migration through fractured shale and claystone. Interconnected fractures are likely to form clusters rather than being distributed uniformly throughout RMA. Fracture density appears to decrease with increasing depth, indicating that migration through fractures may be more common at shallow depths than in deeper parts of the Denver aquifer. Contaminant migration through fracture clusters would result in irregular patterns of contamination in the Denver aquifer. Contamination would not occur uniformly beneath areas of the Unconfined Flow System known to be contaminated. Instead, areas of contamination in the Denver aquifer would reflect the areal distribution of fracture clusters. Vertical migration through fractured shale and claystone also may result in contamination of several stratigraphic intervals of sandstone that are separated vertically by shale and claystone.

Other possible mechanisms for vertical contaminant migration at RMA include flow through vertically interconnected sandstone channels, and leakage along poorly sealed boreholes. Patterns of contamination due to migration along vertically interconnected sandstone channels would be similar to patterns due to migration along fracture clusters. Contamination due to poorly sealed boreholes would exhibit approximately random patterns unrelated to geologic characteristics.

As in the Unconfined Flow System, rates of contaminant migration due to advection in the Denver aquifer are site-specific and are described for selected pathways in Section 4.6 of this report. Effective porosity and hydraulic conductivity of the Denver aquifer probably depend on the interconnected nature of individual sandstone lenses and other permeable strata. When contaminant migration occurs over substantial distances within several highly interconnected sandstone lenses, the values of these hydraulic properties probably approach the values for individual sandstone channels. When contaminant migration occurs in areas where sandstone lenses or networks of fractures are not highly interconnected, values of hydraulic conductivity and effective porosity probably are substantially less. Because connectivity of permeable sandstone and fractures in the Denver aquifer is less in the vertical direction than in horizontal directions, it is possible that hydraulic conductivity and effective porosity also are directionally dependent.

Because individual contaminant plumes in the Denver aquifer have not migrated over a large area, hydrodynamic dispersion characteristics are not well understood. Limitations in the understanding of advective transport in the Denver aquifer have also contributed to difficulties in describing dispersion. The anisotropic and heterogeneous nature of the Denver aquifer indicates that dispersion characteristics of the Denver aquifer probably are more complex than dispersion characteristics of the Unconfined Flow System.

Effects of dilution on contaminant concentration in the Denver aquifer would be most noticeable as contaminated water moves vertically. Water in the Denver aquifer moving horizontally along regional flow paths would dilute the contaminated water moving vertically.

4.4 Chemical Properties and Hydrochemical Processes Affecting Contaminant Migration

The purpose of this section is to describe physical and chemical properties and hydrochemical processes that affect contaminant migration at RMA. In addition to the effects of dilution described above, the predominant processes affecting changes in contaminant concentration are chemical and biological degradation, sorption, and volatilization.

Highly soluble target analytes are generally more mobile, are transported more readily in groundwater and surface water environments, and tend to be less persistent in soil environments. Such highly soluble compounds also tend to be retained by soil matter less readily and tend to be more amenable to biodegradation.

Some organic compounds can volatilize from soil or water. The rate of volatilization is compound-specific. Factors that control volatilization of organic compounds include solubility, molecular weight, vapor pressure, and temperature.

Compound partitioning between soil and water, between soil and air, and between water and air also affects the mobility of that compound. Partitioning between air and other media is influenced by properties affecting volatilization described above. Partitioning of target compounds between soil and water is discussed in Section 4.4.2.

Several chemical processes contribute to the overall process of chemical transformation. The primary components of chemical transformation are hydrolysis and photolysis. During hydrolysis, an organic compound reacts with water forming a hydroxyl group. With alteration in the chemical structure of the compound, the physical properties of the compound (i.e,. solubility, volatility) and compound toxicity also change.

Photochemical processes include both direct photolysis in which the compound absorbs solar radiation and is transformed, and sensitized photolysis in which the energy that transforms an organic compound is derived from another species in solution. At RMA, photolysis reactions may occur in surface water and surface soils.

Biodegradation is an additional mechanism by which RMA target compounds may be lost or transformed from soils and waters. Although very little is known of rates of biodegradation, a sufficient amount of historical data from RMA may be helpful in evaluating the possible utility of biodegradation processes in remediating present site conditions. Rates of biodegradation are dependent upon microbial tolerance to specific compounds and groups of compounds as food sources. Therefore, rates of biodegradation are dependent upon molecular characters and physiochemical properties.

4.4.1 Physical and Chemical Properties

To a great extent, the physical and chemical properties of target analytes are responsible for their rates of migration and degree of attenuation. The most important of the physical and chemical properties are physical state, specific gravity, solubility, vapor pressure, Henry's Law Constant (Hc), octonol/water partition coefficient (K_{ow}), and the soil-water distribution coefficient (K_d). These basic properties of the RMA target analytes are presented in Table 4.2. Appendix E includes a discussion of these properties, including appropriate references for values in Table 4.2. The discussion given in Appendix E is summarized in this section of the report.

The physical state of a compound (solid, liquid, or vapor) may influence its occurrence within a given system. Contaminants in RMA groundwater generally occur in a dissolved state. However, free organic phase liquids may be present in the saturated zone near South Plants, as indicated by very high aromatic concentrations in groundwater and historic spills of benzene. The potential presence of such organic contamination would not alter regional contaminant transport mechanisms but would act as a subsurface contaminant source.

Specific gravity of a dissolved contaminant (Table 4.2) may affect the distribution of a dissolved contaminant. Lighter solutions may be distributed in the upper part of an aquifer and heavier solutions may sink to the bottom of the aquifer. Migration of dense brines is dependent on specific gravity as well as concentration and solubility.

Aqueous solubility controls the maximum contaminant concentration that may occur in solution as well as the concentration released from a source area. Factors that increase solubility include increased temperature, decreased dissolved solids, decreased pH, and increased dissolved organic matter. Table 4.2 lists solubilities of select contaminants found in RMA waters. Aromatics and volatile halogenated organics are highly soluble while pesticides are less soluble. Solubilities of chloride and fluoride are high. Solubilities of other inorganic compounds such as arsenic are dependent on the oxidation and pH conditions of the system, and must be evaluated on a site-specific basis.

Vapor pressure is the pressure at a given temperature of a vapor in equilibrium with its liquid phase. Values given in Table 4.2 are for temperatures between 20° and 25° C. The Henry's Law Constant (Hc) for a specific contaminant relates the equilibrium concentration of the contaminant in liquid phase to the equilibrium concentration in vapor phase. The constant is used to predict the loss of volatile components from groundwater. As shown in Table 4.2, Hc varies for contaminants in RMA groundwater. Compounds with $Hc<10^{-7}$ atmospheres-cubic meter per mole (atm-m^3/mole) are not volatile and include dieldrin. Semivolatile compounds exhibit Hc from 10^{-7} to 10^{-3} atm -m^3/mole, and include the

Table 4.2 Physiochemical Properties of Select RMA Contaminants
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Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (Hc) (atm-m^3/mol)	Log Octonal-Water Partition Coefficient	Distribution Coefficient	Retardation Factor[1]	Environment Fate[2]
Aldrin	1.6	.021	6.6×10^{-6}	1.6×10^{-5}	5.3-7.4	220	1361	Long lived in soil and water. Decomposes to dieldrin in soil (half life = 4-5 years). Highly resistant to biodegradation.
Benzene	0.88(20°C)	1,700	95(20°C)	5.6×10^{-3}	2.0-2.1	0.16	2.0	Soil half life = approximately 1 montl Somewhat resistant to biodegradation.
Benzothiazole	1.2	572	.05	1.64×10^{-5}	1.45-1.67	0.32	3.0	Highly resistant to biodegradation.
Carbon Tetrachloride	1.6(20°C)	810	90(20°C)	2.4×10^{-2}	2.64-2.83	0.73	5.5	Resistant to microbial degradation. Does not hydrolyze.
Chlordane	1.6(16°C)	.13	1×10^{-5}(25°C)	9.6×10^{-5}	2.78-5.48	530	3278	Epoxidized to chlordene epoxide by soil bacteria. Slow reaction, resistant to decomposition, bioaccumulates.
Chlorobenzene	1.11(20°C)	450	11.7	3.72×10^{-3}	2.84-2.98	1.34	9.3	Slowly microbially degraded. Resistant to biodegradation.
Chloroform	1.48(20°C)	8,300	151	2.87×10^{-3}	1.90-1.97	0.47	3.9	Stable in the environment. Highly resistant to biodegradation.
Chlorophenylmethyl sulfide	1.2	16	.05	6.4×10^{-4}	3.2	4.25	27	Soil half life = less than 6 months, oxidizes to analogous sulfoxide and sulfone.
Chlorophenylmethyl sulfoxide	-	1,100	7.8×10^{-2}	1.5×10^{-5}	1.2	0.20	2.2	Soil half life =<6 months, oxidizes to analogous sulfone.

Table 4.2 Physiochemical Properties of Select RMA Contaminants
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Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (Hc) (atm-m^3/mol)	Log Octonal-Water Partition Coefficient	Distribution Coefficient	Retard-ation Factor[1]	Environment Fate[2]
Chlorophenylmethyl sulfone	-	910	3×10^{-3}	8.0×10^{-6}	1.3	0.24	2.5	Degraded by micro organisms. Stable in solution.
Dibromochloropropane	2.09(14°C)	11,000	1.0(21°C)	3.11×10^{-4}	2.29-2.43	0.97	7.0	Stable in neutral and basic media. Reacts with dilute inorganic bases. Hydrolyzed under basic conditions to 2-bromoallylic acid. Light can cause free radical elimination to form chlor and bromo olefins.
1,1-Dichloroethane	1.18(20°C)	5,500(20°C)	180(20°C)	4.31×10^{-3}	1.79	0.30	2.9	Can react with oxidizing materials.
1,2-Dichloroethane	1.25(20°C)	8,600(20°C)	64(20°C)	9.8×10^{-4}	1.45-1.79	0.061	1.4	Not Documented.[3]
1,1-Dichloroethylene	1.22(20°C)	2,200(20°C)	600(20°C)	3.4×10^{-2}	1.84	0.40	3.5	Gradually decomposed by air, light ar moisture to form HCl. Somewhat persistent.
1,2-Dichloroethylene	1.26(20°C)	6,300(20°C)	265(20°C)	7.6×10^{-3}	1.48-1.53	0.16	2.0	Gradually decomposes by air, light an moisture to form HCl. Somewhat persistent.
Dicyclopentadiene	0.98	19.4	1.7(20°C)	1.9×10^{-2}	3.14	3.80	24	-

Table 4.2 Physiochemical Properties of Select RMA Contaminants
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Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (Hc) (atm-m^3/mol)	Log Octonal-Water Partition Coefficient	Distribution Coefficient	Retardation Factor[1]	Environment Fate[2]
Dieldrin	1.75	.084	$1.78x10^{-7}$	$4.6x10^{-7}$	3.5-6.2	27.0	168	Decomposition product of Aldrin. Very persistent in soils. Half life = 7 years. Stable to normal temperatures and to light. Hydrolosis is slow, moderate bioaccumulation.
Diisopropylmethyl phosphonate	0.98	720	0.28(25°C)	$1.9x10^{-4}$	1.73-1.82	0.46	3.8	Half life is approximately 530 years.
Dithiane	-	3,000	0.80	-	0.77	0.087	1.5	Not documented.[3]
Dimethyldisulfide	1.1	360	15	$5.1x10^{-3}$	1.8	0.47	3.9	Microbial degradation, probably rapidly degraded.
Dimethylmethyl phosphonate	1.14	$8x10^5$	.73(25°C)	-	-1.88	0.00038	1.0	Not Listed.
Endrin	1.7(25°C)	.082	$2.0x10^{-7}$(25°C)	$1.4x10^{-6}$	3.5-5.6	28.0	174	Half life in soils 4 to 8 years. Rapidly transformed by sunlight to form a ketone.
Ethylbenzene	0.87(20°C)	150(20°C)	7(25.9°C)	$6.4x10^{-3}$	3.1-3.2	2.15	14	Half life less than 1 month. Somewhat resistant to biodegradation.
Isodrin	1.6	.17	$1.0x10^{-4}$	$33x10^{-4}$	4.4-6.5	145	898	Half life in soil approximately 6 year Byproduct in an aerobic environment endrin. Photodrin is a probable byproduct of photolysis in the environment.

Table 4.2 Physiochemical Properties of Select RMA Contaminants
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Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (Hc) (atm-m^3/mol)	Log Octonal-Water Partition Coefficient	Distribution Coefficient	Retard-ation Factor[1]	Environment Fate[2]
Methylene Chloride	1.33(20°C)	18,000(20°C)	362(20°C)	2.03×10^{-3}	1.25-1.30	0.061	1.4	Not Documented.[3]
Methylisobutyl ketone	0.798(20°C)	19,000	16(20°C)	1.1×10^{-4}	1.25	0.015	1.1	Rapidly degraded by soil micro-organisms. Half life <1month.
Oxathiane	1.1	20,000	5.1	-	-0.16	0.019	1.1	Not Documented.[3]
Dichlorodiphenylethane (DDE)	1.6	.08	6.5×10^{-6}(20°C)	6.8×10^{-5}	4.86-7.1	350	2165	First decomposition product of DDT soils. Resistant to biodegradation.
Dichlorodiphenyl-trichloroethane (DDT)	1.56	.002	5.5×10^{-6}(25°C)	5.1×10^{-4}	3.98-7.48	1150	7112	Persistent in soil.
Tetrachloroethylene	1.63	2.52(20°C)	18(20°C)	2.6×10^{-2}	2.53-2.60	1.38	10	Stable in the environment.
Toluene	0.87(20°C)	520	28(20°C)	6.4×10^{-3}	2.6-2.7	1.64	11	Somewhat resistant to biodegradation.
1,1,1-Trichloroethane	1.34(20°C)	2,500(20°C)	123(20°C)	0.0144	2.47-2.50	0.80	5.0	Resistant to biodegradation.
1,1,2-Trichloroethane	1.44(20°C)	4,500(20°C)	30(20°C)	1.17×10^{-3}	2.47	0.65	-	Highly resistant to microbiological degradation.
Trichloroethylene	1.46(20°C)	950	58(20°C)	9.1×10^{-3}	2.29-3.30	1.65	11	Evidence of bioaccumulation. Stable in environment. Degrades to vinyl chloride under anaerobic conditions and proper microbes.

Table 4.2 Physiochemical Properties of Select RMA Contaminants
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Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (Hc) (atm-m^3/mol)	Log Octonal-Water Partition Coefficient	Distribution Coefficient	Retardation Factor[1]	Environment Fate[2]
Meta-xylene	0.86	130(25°C)	10(25°C)	$5.6x10^{-4}$	3.2	4.00	26	Somewhat resistant to biodegradation.
Ortho- & Para-xylenes[4]	0.86	180(25°C)	10(25°C)	$5.6x10^{-4}$	2.8-3.1	4.00	26	Somewhat resistant to biodegradation.

1 Based on 30% porosity, density = 2.7 g/cm^3
2 From the Chemical Index, Ebasco, 1988
3 Other than parameters listed on table
4 Average from ortho-xylene and para-xylene values

organochlorine pesticides other than dieldrin, DBCP, diisopropylmethyl phosphonate, and some of the halogenated hydrocarbons and aromatics. Volatile compounds exhibit $Hc>10^{-3}$ atm-m^3/mole, and include many halogenated organics and halogenated aromatics (ESE, 1988f/RIC88344R01).

Distribution coefficients (K_d) for RMA (Table 4.2) contaminants describe the ratio of contaminant concentration adsorbed by aquifer material to contaminant concentration in the liquid phase. Values of K_d were derived from the Task 35 Toxicity Assessment Report (Ebasco, 1987/RIC87197R05). In addition, Task 23 (ESE, 1988f/RIC88344R01) measured site-specific values of K_d for key RMA contaminants. The measurements consisted of comparing contaminant mass in drill cores with contaminant concentration of water samples obtained from the cored wells. This program concluded that, for organic contaminants, partitioning was primarily controlled by the concentration of organic matter in the aquifer material, and that measured values, when available, generally fell within the range of K_d values present in the literature. However, the range of K_d values present in the literature for key RMA contaminants varies over two to four orders of magnitude.

Laboratory and field experiments designed to measure the retardation factor of trichloroethylene have been conducted in the Unconfined Flow System in the western tier (Douglas M. Mackay, UCLA School of Public Health, written communication, 1988). Laboratory experiments consisted of column studies to estimate hydraulic conductivity and distribution coefficients as functions of depth. The field experiment consisted of a two-well recirculating test with several additional monitoring wells. Results of laboratory experiments indicated that spatial variability of aquifer properties is substantial. This suggests that field tests should be as large in scale as feasible. Results of the field experiment indicated that the retardation factor for trichloroethylene varied spatially between 1.0 and 1.8. This value is approximately an order of magnitude less than the value reported in Table 4.2 and is similar to values reported for trichloroethylene at locations other than RMA.

Using a porosity of 30 percent and a bulk density of 2.7, retardation factors of the different constituents for migration within the alluvium have been calculated (Table 4.2). Given the uncertainty of K_d values, these values must be used only in a relative sense. Compounds with lower retardation factors are likely to migrate more quickly than compounds with higher retardation factors. Additional discussion of Kd is given in Appendix E.

Organochlorine Pesticides

This group of compounds is generally persistent in soil environments and exists in waters at relatively low concentrations. Distribution in the environment is a result of relatively low aqueous solubilities, a high affinity for soil organic matter, and low volatility. Therefore organochlorine pesticides which that been disposed as solid wastes in unsaturated zone soils or in waste waters would strongly partition to organic matter in unsaturated zone soils and would only be leached from these soils at very low rates. Once mobilized, there is a tendency to remove these compounds from groundwater onto soil organic matter

Pesticides can be classified into three groups based on their half lives: non persistent ($t_{0.5}$<20 days); moderately persistent (20 days< $t_{0.5}$<100 days); and persistent ($t_{0.5}$>100 days). Based on these criteria, aldrin, endrin, and dieldrin must be considered persistent because their field measured half lives range from 130 to 460 days for endrin, to 1,240 days for aldrin and dieldrin (Rao and Davidson, 1982). Persistence under laboratory conditions typically is less than persistence under field conditions. This suggests that caution is needed when using laboratory data to estimate time required for degradation of chlorinated pesticides in RMA groundwater.

At RMA, dieldrin has migrated greater distances than would be expected for a strongly sorbed compound. The retardation factor for dieldrin listed in Table 4.2 is 168, indicating strong adsorption. The discrepancy between expected behavior and observed data suggests that a more detailed interpretation of the available data (from the perspective of both variable seepage velocities and non linear distribution coefficients) is necessary to accurately predict the subsurface transport of the organochlorine pesticides. It is also important to note that aquifer material in the region, especially coarse grained alluvial material, generally is low in organic matter. This will reduce the sorptive capacity to the point that sorption may be dominated by inorganic surfaces such as clays or amorphous ferric hydroxide, rather than by organic material (Olsen and Davis, 1989).

DBCP

This compound has a relatively high aqueous solubility, 1,230 mg/l, moderate volatility and a moderate affinity for organic matter in soil. Therefore DBCP would be solubilized at moderate rates and also lost from near-surface soils by volatilization. Once flushed from shallow soils, DBCP will be moderately retained by soil organic matter and transported at moderate rates by groundwater.

Based on the retardation factor (7.0), DBCP would be anticipated to travel a much shorter distance over the last 30 years, the length of the observed plume emanating from Basin F through the NBCS, and from Basin A to the Northwest Boundary Containment System (NWBCS). This interpretation provides further evidence that simple linear models based on distribution coefficients given in Table 4.2 should be used with caution to estimate transport of contaminants in RMA groundwater.

Degradation of DBCP is highly dependant on the temperature, pH and spatial distribution of the microflora. Under conditions typical of the Unconfined Flow System at RMA, the half life may be approximately 140 years (Burlinson et al., 1982). Because microbial degradation rates are highly dependent on site-specific environmental conditions this estimate of DBCP half life is highly uncertain.

Dicyclopentadiene

Dicyclopentadiene has a moderate aqueous solubility of 20 mg/l, and moderate to high vapor pressure with a high affinity for solid organic matter. Therefore dicyclopentadiene is readily volatilized from shallow soils and surface waters. Dicyclopentadiene is also volatilized from groundwater but at lower rates due to lower temperatures encountered in this media. Transport of dicyclopentadiene in aqueous media is slower than transport of many organic compounds at RMA because dicyclopentadiene sorbs readily to organic matter.

The configuration of the dicyclopentadiene plumes are described in Section 4.2.10. Attenuation of dicyclopentadiene in the Unconfined Flow System, relative to other constituents, conforms to the higher retardation factor (24 ml/g) of the compound.

Diisopropylmethyl phosphonate

Diisopropylmethyl phosphonate has a high aqueous solubility, 1,500 mg/l, a relatively low vapor pressure, and low affinity for solid organic matter. Therefore, diisopropylmethyl phosphonate is readily solubilized to surface water and groundwater, and once solubilized is transported at relatively high rates due to low affinity for aquifer materials.

The rapid transport of diisopropylmethyl phosphonate is a function of the low distribution coefficient (0.46) and is further reflected in the extensive bifurcation of the plume toward the South Platte River. The extended half life of the compound (530 yr.) in conjunction with the low retardation factor suggests that, without treatment, this compound will be mobile and persistent in the Unconfined Flow System for thousands of years.

Organosulfur Compounds

This group of compounds has solubilities ranging from 16 mg/l to approximately 1,000 mg/l, relatively low vapor pressures, and a low affinity for soil organic matter. However, chlorophenylmethyl sulfide has a moderately high affinity for organic matter. Therefore, organosulfur compounds will not be readily volatilized but will be dissolved and transported in surface waters and groundwaters at relatively rapid rates.

The transport of organosulfur compounds in groundwater at RMA appears unrelated to their distribution coefficients as detailed in Table 4-2. For example, chlorophenylmethyl sulfide and chlorophenylmethyl sulfoxide have migrated approximately the same distance north of the Northern Boundary Containment System (NBCS), although the calculated retardation factors are 27 and 2.2 respectively. This discrepancy may be due to chemical transformations within the aquifer. For example, while chlorophenylmethyl sulfide is usually oxidized to chlorophenylmethyl sulfoxide in an aerobic soil environment, chlorophenylmethyl sulfoxide may be reduced to chlorophenylmethyl sulfide in anoxic groundwater. This mechanism may partly explain the apparent discrepancy between the theoretical and the observed distances over which these compounds have traveled.

Dithiane/Oxathiane

Both of these compounds, resulting from the degradation of mustard, have high aqueous solubilities, moderate to low vapor pressures, and a low affinity for organic matter. Therefore, these compounds would readily mobilize to surface waters and groundwaters and be transported with low attenuation rates. The extreme mobility of dithiane is reflected in the low retardation factor (R=1.5) and by the extensive migration of the compound in the Unconfined Flow System along First Creek to the Burlington Ditch.

Volatile Halogenated Organics

All of these compounds have high aqueous solubilities, high vapor pressures, and moderate to high affinities for organic matter. Therefore these chlorinated "solvent" compounds are readily mobilized from shallow soils by vaporization and infiltration. Once in a dissolved state in surface waters and groundwaters these compounds are transported at moderate rates with moderate rates of attenuation and high rates of vaporization. Volatile halogenated organics typically undergo a variety of dehydrohalogenation and hydrogenolysis reactions. A detailed discussion of these reactions at RMA is provided in Section 4.2.2.

Volatile Aromatic Organics

This group of compounds is characterized by moderate to high aqueous solubilities, 100 to 2,000 mg/l, moderate vapor pressures, and a variable affinity for organic matter. Solubilities generally are lower than for volatile halogenated organic compounds but still high enough to result in significant losses from shallow soils due to vaporization and dissolution during infiltration. A detailed discussion of degradation mechanisms for volatile aromatic organics is provided in Section 4.2.2.

Arsenic

This element is relatively volatile in comparison to other metals, but still would vaporize from near-surface soils only at very low rates. Arsenic solubility is dependent upon Eh-pH conditions in soil-water systems but in general is more mobile than other metals due to the formation of oxyanion complexes.

As described in Appendix F, Section 4.2, arsenic has been found to follow the Basin F pathway (Figure 4.2-21). The major source of anthropogenic arsenic at RMA is probably a result of the decomposition products of lewisite ($C_2H_2AsCl_3$). Arsenic probably occurs either as a methylated complex (e.g., monomethylarsonic acid) or as a neutral inorganic pentavalent aqueous complex. Either of these forms have less affinity for sorption than the inorganic anionic forms.

Mercury

This element has high volatility relative to other metals and complexes strongly with both inorganic and organic species to form mobile complexes. Therefore, with respect to other metals, mercury is considered mobile in the environment. Depending on the oxidation state, mercury may be less mobile than other compounds in the environment. Mercury has been introduced to the environment at RMA in element form and as mercuric compounds.

Mercury is probably present as the soluble species $HgCl_2^o$ and $Hg(OH)_2^o$ in RMA groundwater. In areas where thiols, phenols, and amines are present, mercury may occur as CH_3HgS^-. Mercury is also readily methylated by bacterially mediated reactions to form $Hg(CH_3)_2$. Therefore mercury is likely to remain in solution.

Metals

The group of ICP metals (copper, lead, zinc, chromium, cadmium) examined during the RMA Remedial Investigation are in general relatively immobile in soil environments because these metals are not volatilized and are not readily soluble at neutral to basic pH values. Solubility is dependent upon specific Eh/pH conditions of the soil/water system, but at RMA these metals are strongly retained in unsaturated zone soils.

The relative immobility of copper, lead, zinc, and cadmium can be attributed to the sorptive capacities of the cations or their positively charged complexes. The neutral pH conditions typical of RMA groundwater are greater than those pH levels at which the sorption envelopes retain metals in solution. Therefore, metal solubility is controlled by inorganic sorption processes and is reflected in the generally low concentrations of these metals in the groundwater. Chromium concentrations in groundwater are low. There does not appear to be an anthropogenic source of this metalloid at RMA.

4.4.2 Attenuation of Target Analytes

During the process of contaminant transport, a number of physical and chemical processes occur that result in a reduction of the measured concentration of a target analyte. The processes that most strongly affect reductions in contaminant concentrations include degradation (hydrolysis, photolysis, and biodegradation), sorption, and volatilization. Each of these processes is discussed in more detail below.

Sorption

Partitioning between coexisting aqueous and solid phases is a critical factor in determining the extent to which a contaminant will be transported in groundwater. Contaminants that are strongly adsorbed, have a strong affinity for organic matter and fine grained mineral and clay surfaces. Under normal conditions, strongly sorbed contaminants will not migrate significantly from the place where they are introduced. For strongly adsorbing chemicals, erosion and surface runoff of contaminated soil particles may provide a significant migration pathway. Chemicals that are weakly adsorbed, having an affinity for the dissolved aqueous phase, will be readily leached from contaminated soil and move with groundwater. Many contaminants of concern are moderately adsorbed and exist in both solid and aqueous phase. The degree to which a compound is adsorbed to naturally occurring organic carbon is directly related to the magnitude of the octanol-water partition coefficient (K_{ow}) for the compound and the organic carbon content of the solid phase. The relations among adsorption, partition coefficients, and organic carbon are described in greater detail in Appendix E.

Volatilization

Volatilization is the process by which a compound evaporates from either a liquid or solid phase to the gas phase. Loss of contaminants by volatilization can be substantial in soil and can decrease contaminant mass available for migration with water. The degree to which a compound will be volatilized depends on physical and chemical characteristics, such as vapor pressure and Henry's Law Constant, as well as properties of the soil or water phase.

Volatilization from groundwater appears to be an insignificant mechanism for contaminant distribution at RMA. This conclusion is based on the lack of volatile constituents in the soil profile overlying groundwater contamination in areas where there is no evidence of surface contamination. For example, the soil profiles overlying the groundwater plume between Basin F and the North Boundary Containment System do not contain volatile halogenated organics. Halogenated aliphatic compounds are not found overlying the trichloroethylene plume in the western tier.

Transformation and Degradation

Transformation and degradation processes determine if a chemical will persist in the environment. Transformation and degradation of contaminants generally result in reaction products that are less hazardous. However, some transformations and degradations can yield products with increased toxicity, persistence, or mobility. Specific examples where degradation results in hazardous compounds are identified in Table 4.2. Rates at which these processes occur depend on individual chemical, soil, and environmental characteristics. In general, the processes occur at faster rates in the surface environment than in the subsurface. Many chemicals tend to degrade more slowly when buried than when exposed at the soil surface. However, most volatile halogenated organics tend to degrade more rapidly under anaerobic conditions.

Key transformation processes are biotransformation, hydrolysis, photolysis, and oxidation-reduction. During hydrolysis, an organic compound reacts with water, resulting in the addition of a hydroxyl group to the molecule and elimination of another functional group. Transformation by photolysis can occur by absorption of solar radiation or by deriving energy from another species in solution. Inorganic oxidation and reduction results in the loss of electrons by one chemical and the gain of electrons by another. Organic oxidation reactions generally result in a gain of oxygen and loss of hydrogen, while the reverse generally is true for organic reduction. Oxidation and reduction often are biologically mediated. Biotransformation occurs as a result of metabolic activity of microorganisms that use enzymes to catalyze chemical reactions. Additional description of transformation and degradation process is provided in Appendix E.

Degradation of Volatile Aromatic Organics

The concentration of volatile aromatic organics in groundwater is mitigated to some degree by oxidation during unsaturated flow to the water table. For example, in the soil profile overlying the groundwater, benzene, toluene, and xylene degrade by dioxygenase-catalyzed reactions in the aerobic unsaturated environment to form catechol. Further degradation results in generation of an aliphatic moiety with a carboxylic acid functional group (Rochkind and Blackburn, 1986).

The presence of electrophilic functional groups (e.g., CH_3, OH) on the benzene skeleton enhance the reactivity of the aromatic ring, while the presence of halogen substituents (e.g., Cl) deactivates the aromatic ring from electrophilic attack (Dragun, 1988). This suggests that chlorobenzene should be the most inert of the aromatic volatile compounds during percolation of the analytes through the unsaturated zone, followed by benzene, ethylbenzene, xylene, and toluene.

Degradation in an aqueous medium has not been extensively studied. Under anerobic conditions, the degradation pathway probably involves the bacterially mediated reduction of the carbon ring to form a cyclic hydrocarbon that can then be degraded anaerobically (Hutzinger, 1980). Generally, degradation of aromatic rings occurs more slowly in an anoxic environment than in the presence of air (Bouwer and McCarty, 1984). However, the experiments of Zoeteman and others (1981) and Barker and Patrick (1985) both indicate that the half life of the volatile aromatic compounds is approximately one month in groundwater.

In the Unconfined Flow System at RMA, the transport distance away from the source increases in the order chlorobenzene> benzene> ethylbenzene = xylene> toluene. This pattern agrees at least qualitatively with the mechanistic interpretation of the degradation process and suggests that the extent of travel in the groundwater may be directly related to the affinity of a constituent to biodegradation.

Transformation of Volatile Halogenated Organics

Solvent chemistry in groundwater at RMA appears to be controlled primarily by dehydrohalogenation and hydrogenolysis reactions. Although some evidence exists supporting the abiotic (nonbiologically mediated) nature of the principal solvent transforming reactions, most investigators recognize the significant role of microorganisms in mediating dehydrohalogenation and hydrogenolysis reactions under the anaerobic conditions typical of most aquifers. The known transformation reactions of the chlorinated aliphatic solvents are summarized in Figure 4.2. Table 4.3 presents a specific listing of the abiotic and biotic degradation rates of these compounds.

Dehydrohalogenation is an elimination reaction that results in the creation of an ethene from a saturated halogenated compound. This occurs by removal of a halogen from one carbon together with concomitant removal of a hydrogen ion from an adjacent carbon. An example of this reaction is the dechlorination of trichloroethane to generate dichloroethylene. The reaction rates are dependant upon the degree of chlorination; increased halogenation tending to increase the rate of dehydrohalogenation.

Table 4.3 First Order Biodegradation Constants and Half Lives for Environmental Processes Controlling Solvent Transformations[a]

Compound	Abiotic Hydrolysis or Dehydrohalogenation (months)	Volatilization (minutes)	Biodegradation Half Life (days)	Reaction Rate (day^{-1})
PCE	8.8	30	230^b 34^h	$3x10^{-3}$
TCE	10.7	20	230^b 33^c 43^h	$3x10^{-3}$
trans 1,2-DCE	--	24	$132-147^d$ 53^h	$4.7x10^{-3}$
cis 1,2-DCE	--	--	$88-339^d$ $>60^h$	$2x10^{-3}$
1,1-DCE	12	27	$81-173^d$	$4x10^{-3}$
Vinyl Chloride	<120	26	$>60^h$	
1,1,2,2-PCA	3.3^g, 10^i	55		
1,1,1,2-PCA	384^i			
1,1,2-TCA	170^i	35	24^h	
1,1,1-TCA	6 3.5 yr^e -> Acetic acid	25	17 yr -> 1,1-DCE^f 230^b	$3x10^{-3}$ 16^h
1,2-DCA	50^i	28	$>60^h$	
1,1-DCA	--	30	$>60^h$	
Chloroethane	1.3	25	10^h	

a U.S. EPA (1979)
b Roberts et al (1982)
c Barrio-Lage et al (1987)
d Barrio-Lage et al (1986)
e Vogel & McCarty (1987b)
f Vogel & McCarty (1987a)
g Cooper et al (1987)
h Wood et al (1985)
i Mabey et al (1983)

All references apply to laboratory studies except b

Vogel and McCarty (1987a) demonstrated that trichloroethylene can undergo abiotic dehydrohalogenation to form 1,1-dicloroethylene and 1,2-dichloroethylene. Further, they identified a reaction rate of 0.04 yr^{-1} at 20°C. This is rapid enough that both parent and daughter would be expected to occur in groundwater contaminated with trichloroethane. It is likely that biotic transformations would proceed even more rapidly.

In the western tier, there appears to be two distinct 1,1,1-trichloroethane plumes, one emanating from Stapleton International Airport and one from an off-post location to the southwest of RMA. As would be expected based on mechanistic predictions, a distinct plume of both 1,1-dichloroethylene and trans-1,2-dichloroethylene is associated with each of the 1,1,1-trichloroethane plumes.

Hydrogenolysis involves the transfer of electrons to an unsaturated aliphatic compound with the simultaneous addition of a proton and the loss of a halogen as a leaving group. This results in the generation of a less halogenated compound, for example, the formation of dichloroethylene from trichloroethylene or 1,1-dichloroethane from 1,1,1-trichloroethane.

Accumulated evidence suggests that hydrogenolysis is an important reaction in aquifers. Vogel and McCarty (1987b) demonstrated that the mechanism is responsible for the stoichiometric bioconversion of 1,1-trichloroethane to 1,1-dichloroethane and chloroethane under methanogenic conditions. They also verified that 1,1-dichloroethylene could be transformed to vinyl chloride by the same process.

At RMA, tetrachloroethylene and trichloroethylene appear to be present as parent products both in the western tier and emanating from the South Plants and Basin F areas. The presence of dichloroethylene within the trichloroethylene plume is indicative of the degradation. Eventually the halogenated compounds degrade to vinyl chloride prior to mineralization. Vinyl chloride has not been routinely analyzed at RMA, so it is not possible to estimate the degree of completion of this reaction. However, it is possible that vinyl chloride is present in the groundwater because several investigators have demonstrated that the vinyl chloride precursors have a half life of between three months and one year (e.g., Wood et al., 1985; Barrio-Lage et al., 1986).

Oxidation reactions involving chlorinated compounds have not been extensively researched because the available evidence suggests that organic degradation of these solutes occurs principally under anoxic conditions. However, Nelson and others (1986) found that the bacterial isolate G4 was capable of completely mineralizing trichloroethylene in an aerobic environment but failed to generate the usual trichloroethylene daughter products, suggesting that the aerobic pathway proceeds via a different set of intermediate compounds. This observation is pertinent to the interpretation of groundwater chemistry at RMA because at least two chlorinated daughter products (1,1-dichloroethylene and trans 1,2-dichloroethylene) are present in the groundwater, supporting the hypothesis that degradation of solvents proceeds under anaerobic conditions, probably by a microbially mediated pathway.

Transformation of hydrazine to NDMA

Hydrazine (N_2H_4) is extremely unstable in the atmosphere, rapidly degrading to molecular nitrogen and water in the presence of oxygen and ultraviolet light. In the presence of water, hydrazine decomposes to hydrazine hydride and thence to ammonia, nitrate, and nitrite, a conversion requiring only one or two days. Evidence of hydrazine in the groundwater would be reflected in elevated levels of total nitrogen. However, this does not appear to be the case at RMA, suggesting that hydrazine probably degraded near the surface in the presence of oxygen and did not impact groundwater at the facility.

Transformation of aldrin to dieldrin

The transformation from aldrin to dieldrin in the groundwater is not supported by the available groundwater data at RMA. There were only two isolated, nonrepeated occurrences of aldrin in RMA groundwater, one in the Basin A Neck area and one to the west of Basin E, both of which were downgradient from elevated dieldrin concentrations.

Transformation of DIMP to IMPA

Diisopropylmethyl phosphate is distributed extensively in the Unconfined Flow System. However, there were no occurrences of isopropylmethyl phosphonate in the nontarget analyte list and no evidence to indicate transformation of diisopropylmethyl phosphonate to isopropylmethyl phosphonate in the groundwater.

4.5 Contaminant Source Areas and Pathways

Previous investigations at RMA have documented sources of water contamination. The interpretive work performed in support of Section 4.0 of this report confirms five major source areas that contribute to water contamination at RMA. These areas are the South Plants manufacturing complex, the Basin A, the Basin F, North Plants manufacturing complex and the western tier sites, and chemical sewers (Figure 4.3). In addition to major source areas, suspected source areas were identified when the source of contamination was masked by the presence of a major source area along the contaminant pathway. Suspected source areas included the western tier warehouse area, Sand Creek Lateral, and Basins B, C, D, and E.

Primary groundwater pathways away from each source area noted above are flow paths that exhibit pervasive and historically frequent occurrences of one or more RMA contaminants (Figure 3.1). Surface water pathways include ponds, ditches, canals, and natural drainages where contaminants have been detected or where the migration of contaminants with surface water is probable. The sewer systems and process water systems at RMA have also contributed to contaminant migration. Surface water, groundwater, and sewer or process water pathways for each major source area are described below.

4.5.1 South Plants Source Area and Pathways

The South Plants manufacturing complex was constructed in 1942 with various structures and facilities added at later dates. Sewers within South Plants were constructed in 1942 and were upgraded and expanded through time. Various chemical and incendiary munitions were manufactured at this complex. Chemicals manufactured during 1943 included mustard, lewisite, acetylene, arsenic trichloride, sulfur monochloride and dichloride, thionyl trichloride, chlorine, and caustic. In addition, various incendiary weapons were manufactured at the complex during this time frame. Between 1943 and 1948, distilled mustard operations took place. These operations included mustard distillation and shell/ton container filling. Army operations at South Plants during the 1950s, 1960s and 1970s included the manufacture and filling of incendiary weapons. In addition, various demilitarization activities were undertaken. Continuous Army operations in the South Plants area included clothing impregnation and analytical laboratory activities.

Various facilities within the South Plants manufacturing complex were leased to private industry for the manufacture of chemicals from 1946 to 1982. Manufactured chemicals included chlorinated insecticides, organophosphate insecticides, carbamate insecticides, herbicides, and soil fumigants. Additional information on the specific time that these chemicals were manufactured can be found in the South Plants Study Area Report and the Remedial Investigation Contamination Assessment Reports pertaining to South Plants.

Many of the compounds on the target list have been detected in South Plants; however, the most commonly occurring contaminants in soils are organochlorine pesticides, arsenic, mercury, volatile halogenated organics, volatile aromatics, and volatile hydrocarbons. Although relatively low levels of contaminants are present throughout most of the South Plants, the most concentrated areas of contamination are the central processing area and south tank farm located in the north-central and southeastern portions of the complex respectively. Organochlorine pesticides, arsenic, mercury, volatile halogenated organics, volatile aromatic organics, and DBCP are common in the soils in the central processing area. Benzene and other volatile aromatic organics and volatile hydrocarbons are common in the area of the south tank farm.

Several analyte groups, including organochlorine pesticides, organosulfur compounds, volatile hydrocarbons, volatile aromatic organics, and volatile halogenated organics, have been detected in surface water collected from ditches that exit the South Plants. Historically, discharges from pipelines and the direct flow of chemicals to ditches during spill events was likely. Under current conditions, runoff may erode contaminated soils and transport and deposit them in downstream areas. Contaminants may also be dissolved by surface water and later deposited elsewhere. Contaminated surface water and potentially contaminated sediments are transported from South Plants north into Basin A, southeast into Lower Derby Lake, and west into Sand Creek Lateral. Contaminated soils and surface water are present in Basin A and are described later. Water in the Lower Lakes is not considered to be contaminated; however, pesticides and mercury have been detected in the lake bottom sediments. Sand Creek Lateral flows north toward Section 26 and is a suspected source of groundwater contamination in Section 35.

Numerous contaminants have been detected in groundwater beneath South Plants, including organochlorine pesticides, organosulfur compounds, volatile halogenated organics, volatile aromatic organics, and other organic compounds such as dicyclopentadiene, diisopropylmethyl phosphonate, acetone, bicycloheptadiene, and methylisobutyl ketone. The depth to groundwater varies from approximately 5 to 10 feet in the central portion to 35 feet in the northwest and south portions of the area.

A variety of activities have resulted in the deterioration of groundwater quality in the area. The primary site-specific mechanisms by which contaminants may have been introduced into the groundwater at South Plants are summarized in Table 4.4.

Throughout most of RMA, plumes flow away from their given source areas in a single direction. However, groundwater and contaminants flow away from the central portion of the South Plants in several directions (Figure 3.1). Four preferential flow paths for contaminant migration that radiate away from the mound have been identified in the South Plants Study Area Report as the north, southeast, south, and west-southwest flow paths. The north flow path is the widest and contains the most analytes. The southeast flow path contains fewer analytes than the north flow path, and is commonly distinguished by two areas of higher concentration connected by an area of lower concentration. The northwest flow path is less well defined and has fewer contaminants than the north or southeast flow paths. The south flow path contains continuous plumes of volatile halogenated organics and volatile aromatic organics (Appendix F, Figures 4.2-9 and 4.2-14). This flow path continues through the south tank farm area and extends southwestward toward Lake Ladora. The west-southwest flow path contains only carbon tetrachloride and chloroform (Appendix F, Figure 4.2-15). Maximum concentrations are much lower within this flow path than along other South Plants flow paths. Additionally, a plume of diisopropylmethyl phosphonate and dicyclopentadiene extends southwest from the steam/chlorine plant.

4.5.2 Basin A Source Area and Pathways

Basin A, an unlined basin, was used beginning in 1943 for the disposal of contaminated wastes from South Plants. Beginning in 1953 wastes from North Plants were also disposed in the basin. A lined disposal basin, Basin F, was constructed in 1956 to replace Basin A. The ponded liquid wastes contained in Basin A were transferred to Basin F

Table 4.4 Mechanisms for the Introduction of Contaminants to Groundwater

Condition	South Plants	Basin A	Basin F/ Other Basins	North Plants	Western Tier	Sand Creek Lateral
Accidental Release associated with Building Operation, includes spills, leaking pipelines, sumps and defective equipment	X			X		
Building basement intersecting the groundwater resulting in entry of contaminated groundwater and/or mixing of spills with groundwater	X					
Spills associated with tank or tank car filling operations	X	X		X	X	
Underground storage tank leaks or groundwater intersection with the tank	X			X	X	
Leaking sewer lines or intersection of sewer with groundwater	X	X	X	X		X
Disposal pits, lime basins, or decontamination basin remobilization of a contaminant via surface water or groundwater, or both	X	X				
Historic and seasonal water table variations	X	X	X			
Ditches either transport contaminated runoff or intersect the groundwater	X	X	X	X	X	X
Vertical migration of contaminants via an improperly constructed or abandoned well or conducive geologic conditions, i.e. highly fractured bedrock or material with a large hydraulic conductivity in contact with a paleochannel	X	X	X			
Open storage yards improper decontamination of equipment	X	X		X		

between December 1956 and September 1957. With the exception of the period May 1 to June 2, 1957, Basin A was not used for liquid waste disposal after December 1956. The Army continued to drain accumulated surface runoff in Basin A to Basin F until the summer of 1960.

A large variety of contaminants at elevated concentrations have been detected in Basin A soils. The most commonly occurring compounds include organochlorine pesticides (primarily dieldrin), mercury, arsenic, and diisopropylmethyl phosphonate.

Surface runoff from the northern portion of South Plants and surrounding areas collects within topographic depressions contained within Basin A. Numerous contaminants, including volatile halogenated organics, volatile aromatic organics, volatile hydrocarbons, organochlorine pesticides, organosulfur compounds, DBCP, and arsenic, have been detected in Basin A surface water. Surface water can discharge from Basin A to Basin B via a northwest trending ditch. A ditch located west of the basin also carries surface water from South Plants along the western margin of Basin A and eventually discharges to Section 34. This ditch has been breached in some areas and surface flow can overflow and collect in Basin A. More target analytes have been detected in this ditch than in the central pool of Basin A but generally at lower concentrations.

Groundwater contaminants that occur in the greatest concentrations in the vicinity of Basin A include dithiane/oxathiane, benzene, chlorobenzene, chloroform, diisopropylmethyl phosphonate, fluoride, and chloride. Other target analytes have also been detected, but at lower concentrations. The highest concentrations of most contaminants are located in the southwestern corner of Section 36. The source of contaminants probably was nearby disposal pits and/or leaky sewer lines. Compounds such as benzothiazole, dicyclopentadiene, diisopropylmethyl phosphonate, arsenic, fluoride, and chloride are most concentrated in the northern portion of Basin A. Groundwater is generally within a few feet of the surface and may locally recharge the surface ponds within Basin A.

The primary pathway from the Basin A source area is the Basin A pathway. This pathway originates in the southern portion of Section 36 and continues through a northwest trending paleochannel known as Basin A Neck. Most of the contaminants detected in the Basin A source area have also been detected in the Basin A Neck pathway. Contaminants have also been detected in unconfined portions of the Denver Formation beneath unsaturated alluvium along the northern margin of Basin A. In addition, zone A of the Denver Formation subcrops on either side of the Basin A Neck paleochannel and intersects with alluvial materials. These conditions indicate that lateral migration of contaminants northward through the Denver Formation may be occurring.

4.5.3 Basin F Source Area and Pathways

Basin F, a 92.7 acre disposal pond equipped with a catalytically blown asphalt liner and 12 inch protective earthen blanket, was built by the Army between July and December 1956. Basin F had a capacity of 240,000,000 gallons and was built to contain contaminated waste from Army and lessee (principally Shell) chemical operations. The basin was constructed on the site of a large natural depression. Eight and 10 inch underground gravity flow vitrified clay sewer laterals were installed, linking Basin F to chemical sewer lines from the chlorine plant, the Shell manufacturing area in the South Plants, and the North Plants complex. By December 1956, final work on dikes and connecting sewer laterals was complete, and all contaminated liquid waste was being discharged to Basin F. Basin F was used continuously between 1956 and 1981 for the solar evaporation of contaminated aqueous wastes.

Nearly 100 hazardous chemicals are known to have been present in liquid waste discharged to Basin F. In very limited areas of Basin F, organochlorine pesticides, DBCP, dicyclopentadiene, volatile halogenated organics, and volatile aromatic compounds were detected in soils at depths of 20 ft or greater. Data from a single soil boring in the eastern side of the basin where the liner appeared to be deteriorated indicate that there is a relatively uniform vertical distribution of organic compounds. This suggests that downward fluid migration has occurred over a long time period, and that maximum soil retention of these compounds has been attained in the soil column down to the water table in these limited areas.

Surface water was diverted around Basin F and inlets were blocked so that direct precipitation was the only source of inflow to the basin. No surface outflows of surface water or contaminated wastes occurred at the basin.

Many compounds have been detected in groundwater in the Basin F area. Downgradient wells immediately northeast of Basin F have greater frequency and concentrations of contaminants, notably DBCP, diisopropylmethyl phosphonate, dithiane, chlorophenylmethyl sulfone, and volatile aromatic compounds, than in other adjacent wells. Contaminant occurrences and concentrations upgradient of Basin F are variable. Wells south of Basin F in the vicinity of Basin C generally contain numerous contaminants, whereas wells to the southeast generally contain fewer contaminants at lower concentrations. Depth to groundwater below land surface ranges from approximately 35 to 45 ft.

The primary mechanisms by which contaminants were introduced into the groundwater at Basin F are summarized in Table 4.4. Data from a single boring have been used to infer leakage of Basin F fluids through damaged portions of the liner. Downward infiltration of contaminants through the vadose zone from chemical and sanitary sewers also is an important mechanism in the Basin F area. Surface facilities associated with the deep well pretreatment complex are important points of downward infiltration.

The Basin F contaminant pathway which from Basin F to the North Boundary Containment System. Diisopropylmethyl phosphonate, oxathiane/dithiane, organosulfur compounds, dicyclopentadiene, benzene, tetrachloroethylene, trichloroethylene, fluoride, chloride, and arsenic all exclusively follow the primary Basin F pathway. DBCP and endrin follow a second Basin F pathway located east of and parallel to the first Basin F pathway. Other compounds such as dieldrin and chloroform occur in both pathways. Many volatile halogenated organics and volatile aromatic organics occur in the Basin F east pathway, which originates south of Basin F. Dieldrin, diisopropylmethyl phosphonate, arsenic, chloride, and fluoride occur in the Basin F west and northwest pathways that trend from Basin F to the northwest boundary of RMA.

4.5.4 North Plants Source Area and Pathway

The North Plants manufacturing complex was in operation between 1953 and 1969. Operations in this facility included the manufacture of the nerve gas GB (Sarin) and associated munition filling. Compounds used in the manufacture of GB include methylphosphonic dichloride (dichlor), hydrofluoric acid, isopropyl alcohol, and tributyl amine. In addition to the above operations various demilitarization of various items occurred between 1965 and 1984. These demilitarization operations included munitions filled with GB, phosgene, and other agent-containing munitions. Solvents used at the facility include carbon tetrachloride and 1,1,1-trichloroethane.

Fewer and generally lower concentrations of compounds were detected in North Plants than in the South Plants, Basin A, and Basin F source areas. The most notable compounds in the North Plants soils are volatile halogenated organics, arsenic, mercury, dimethylmethyl phosphonate, chloroacetic, and dieldrin.

Ditches that carry surface water from the North Plants to First Creek are normally dry. However, contaminant migration along these ditches could occur during storm events for short time periods. Depth to groundwater in the North Plants area is approximately 25 feet.

Diisopropylmethyl phosphonate is the primary contaminant observed in the North Plants area. However, low levels of volatile halogenated organics, namely chloroform, as well as mercury and fluoride, have also been detected. The primary mechanisms by which contaminants were introduced into the groundwater at North Plants are summarized in Table 4.4.

The North Plants pathway originates in North Plants and trends toward the north boundary of RMA. The primary contaminant detected in this pathway is diisopropylmethyl phosphonate. Several wells have recently been installed in this pathway to better characterize the nature and extent of contamination in this area.

4.5.5 Western Tier Source Areas and Pathways

Two building complexes, the rail classification yard and the western tier motor pool area are source areas in the western tier.

The rail classification yard was used to store a variety of tank cars that contained various chemicals. This area has been identified as the source of DBCP contamination detected in the off-post community of Irondale in 1980. The Irondale Containment System was constructed to control off-post migration of this contaminant.

The western tier motor pool area was constructed in 1942. The area was used for support operations. Located within the motor pool is an area where solvents were used for degreasing operations.

Volatile organic compounds, mainly solvent-related, and pesticides have been detected at several locations within the railyard and motor pool areas. Other sites located west or north of the motor pool also contain isolated contaminants but do not appear to be sources of groundwater contamination. In general, the amounts of contamination in the western tier are much lower than other source areas such as South Plants or Basin A.

The potential for the migration of contaminants in surface water is limited. Most surface water collects in short ditches or closed depressions where much is lost to evaporation. However, it is likely that surface contaminants are carried to and accumulate in topographic low areas. Some surface water will infiltrate the vadose zone and discharge soluble contaminants to the Unconfined Flow System.

The main contaminants in the western tier groundwater are volatile halogenated organics, volatile aromatics, and DBCP. Depth to groundwater in the source areas of the western tier is approximately 60 feet. Therefore, direct discharges of contaminants to the groundwater are not possible. The primary site-specific mechanisms by which contaminants were introduced into the groundwater in the western tier are summarized in Table 4.4.

Three general groundwater migration pathways have been identified as the off-post western tier, western tier, and motor pool and railyard pathways. Volatile halogenated organic plumes consisting mainly of trichloroethylene and DBCP are present in these Unconfined Flow System flow paths. The off-post western tier plume flows from an off-post source, located southwest of RMA, north to the South Adams County Water and Sanitation District water supply wells. The western tier plume flows north from an off-post source located south of RMA. A third trichloroethylene plume flows from the motor pool area towards the Irondale Containment System. These plumes are best defined by concentrations of trichloroethylene, but other volatile halogenated and aromatic organics have been detected across the area in broader and less distinct trends. A DBCP plume originates in the railyard in Section 3, and follows a pathway that is parallel to and east of the trichloroethylene plume that originates in the nearby motor pool. This DBCP plume is migrating toward the Irondale Containment System.

4.5.6 Chemical Sewer

The chemical sewer is a gravity system that collected chemical wastes from manufacturing activities at RMA and transported them initially to Basin A and later to Basin F. The first chemical sewer was installed in the South Plants manufacturing complex in 1942. It originally consisted of three separate waste systems; the toxic waste system, the nontoxic contaminated waste system, and the caustic waste system. These systems were consolidated in 1956 and all chemical wastes were then routed to Basin F.

The North Plants chemical sewer was built by the Army in 1952 during initial construction of the North Plants complex. This system included a collection system leading to the contaminated waste sump (Building 1727) and force lines connecting the sump with laterals leading intially to Basin A and after 1956 to Basin F.

The South Plants and North Plants chemical sewers were linked in 1956 when an interceptor line was constructed. This line originated in South Plants and headed north to collect wastes from North Plants before emptying into Basin F. The chemical sewer interceptor line was removed by the Army in 1982, and the collection systems in both North and South Plants were abandoned in place.

The chemical sewer in South Plants was constructed of vitrified clay pipe with brick manholes. Chemicals transported by the chemical sewer may have caused deterioration of this system, resulting in leakage. Where the water table is high, as occurs in part of the South Plants area, segments of the sewer would have been in direct contact with groundwater and any leaks in the system would have become direct sources of these chemicals to the groundwater.

The chemical sewer collection system in North Plants was constructed of cast iron and is assumed not to have deteriorated nearly as much as the South Plants system. The portion of the line downstream of the sump (Building 1727) was constructed of vitrified clay pipe. This was investigated in the Remedial Investigation and no significant contamination was identified (Ebasco, 1988b).

4.5.7 Other Source Areas and Pathways

In addition to the five major source areas described previously, other areas have been identified as suspected source areas. These source areas have been identified by historical information describing the presence of the chemical in the area and/or a contaminant plume present either at the site or downgradient of the site. Areas fall under this category include the Sand Creek Lateral and Basins B, C, D, and E.

Sand Creek Lateral

Sand Creek Lateral was present in the 1940s prior to the construction of RMA. The canal was used for irrigation. During the 1940s and early 1950s, the canal was used intermittently to transport chemical waste from the South Plants area to disposal basins located to the north. Because the overall gradient of the lateral is low, much of the water did not reach the basins but would pond and either infiltrate or evaporate.

The central north, central south, and the Basin A Neck pathways extend from the Sand Creek Lateral toward the northwest boundary of RMA. Dieldrin and chloroform have been detected along the central north and central south pathways. Numerous contaminants have been detected in the Basin A Neck pathway, which is described in the Basin A source area discussion above.

Basins B, C, D, and E

Overflow from Basin A in the early 1950s entered Basin B. Overflow discharge from Basin B to Basins D and E occurred prior to 1953.

Basin C held fresh water during 1957 and 1958, again in 1966 and 1967 and, for a third time during the consecutive years beginning in 1969 and ending in 1974. Liquid wastes were transferred from Basin F to Basin C on one occasion only in the spring of 1957, and were retained in Basin C for a period of approximately 30 days while the liner in Basin F was repaired. The liner was damaged due to wind induced wave action.

Basins D and E received liquid wastes discharged via the Sand Creek Lateral (1942-1953), liquid waste overflows from Basins B and A (1946-1953) and overflows from Basin C (1953-1956). Despite the modifications to the Basin A dam in 195' and again in 1952, liquid waste overflows from Basin A continued. Overflow discharges from Basin A flowed to Basin B and ultimately to Basins D and E.

The continuation of the Basin A Neck pathway is the primary pathway away from the Basins Area. In addition, some migration may presently be migrating, or may have historically migrated, from Basin C northward along the Basin F east pathway.

Other Pathways

The northern off-post and First Creek off-post pathways originate at the North Boundary Containment System and extend off-post to the north and northwest, respectively. Contaminants that are commonly detected include chloroform, dicyclopentadiene, DBCP, diisopropylmethyl phosphonate, tetrachloroethylene, organosulfur compounds, and dieldrin.

The Quincy Street pathway extends from the Northwest Boundary Containment System towards the northwest. Dieldrin, chlorobenzene, and chloroform plumes extend off-post along this pathway.

4.6 Contaminant Migration and Alteration Along Major Groundwater Pathways

The purpose of this section of the report is to describe hydraulic characteristics, rates of contaminant migration, and mechanisms for alteration of contaminants along major groundwater pathways. Based on the description of hydraulic characteristics and the potentiometric surface configuration for the Third Quarter of FY87, rates of advective transport and apparent times of migration are estimated for each pathway. Where possible, results of these estimates are compared to maps showing the distribution of contaminants and reasons for any differences are noted. An evaluation of adsorption-desorption is made by comparing contaminant distribution maps for consistency with partition coefficients (K_d). Possible reasons for any inconsistencies are noted.

Major pathways were identified previously in Section 4.5. Although the emphasis of pathway identification and discussion is placed on flow in the Unconfined Flow System, flow in the Denver aquifer will be discussed in areas where substantial migration has been noted. Major pathways discussed in this section of the report are South Plants, Basin A-Basin A Neck, central, Basin F, and western tier. Discussions of off-post contamination are included in the Off-Post Operable Unit Remedial Investigation and Chemical Applicable or Relevant and Appropriate Requirements, Draft Final Report (ESE, 1989b/RIC89024R01).

4.6.1 South Plants Pathways

Contaminant migration from the South Plants area occurs along several pathways identified in Section 4.5. Pathways radiate from the centrally located water table mound beneath South Plants. Although several pathways originating at South Plants have been identified, migration along only two of these pathways will be described in this section of the report. One pathway is associated with contaminant migration north from South Plants toward Basin A; the second pathway is associated with migration south-southwest toward Lake Ladora.

Water in the north pathway flows primarily through eolian and alluvial deposits of the Unconfined Flow System. However, flow is through unconfined Denver Formation in the central part of the water table mound. Saturated thickness is less than 10 ft beneath South Plants but increases to 30 ft near Basin A (Plate 2). Estimates of hydraulic conductivity obtained from long-term pumping tests in alluvial material near South Plants and Basin A are approximately 14 ft/day in alluvial material and 3 ft/d in the unconfined Denver Formation (Appendix F, Section 2.0).

Average linear velocity and groundwater travel time along the north pathway have been estimated for a range of hydraulic conductivity estimates and various assumed values of effective porosity. Hydraulic gradient was obtained from Figure 2.4. The range of hydraulic conductivity estimates used was 10 to 100 ft/day for alluvium and 0.5 to 10 ft/day for unconfined Denver Formation. Average linear velocity in alluvium ranged from 0.3 ft/day to 9 ft/day, assuming effective porosity values from 0.1 to 0.3. Average linear velocity in unconfined Denver Formation ranged from 0.013 to 1.5 ft/day, assuming effective porosity values between 0.05 and 0.30. Groundwater travel time from the center of the water table mound to the center of Basin A ranged from 1.6 years to 115 years. The vast majority of the travel time would pass while contaminants were in the Denver Formation. Travel time within saturated alluvium was substantially less than in the Denver Formation. Estimated travel time in alluvium along this flow path ranged from approximately one to 14 years. These estimates could not be readily compared with maps showing contaminant distribution because possible contamination from source areas in Section 35 and 36 masks evidence of migration from South Plants.

Water in the south-southwest pathway flows through both alluvium and Denver Formation. Consisting primarily of claystone and volcaniclastic sediments, the Denver Formation is weathered and fractured near South Plants. Saturated thickness is generally 10 to 20 ft along the pathway. Hydraulic conductivity estimated from a long-term pumping test of the Denver Formation is approximately 3.5 ft/day (Figure 2.3). Volatile aromatic contaminants including benzene occur along the pathway.

Average linear velocity and groundwater travel time along the south-southwest pathway were estimated using hydraulic gradients extrapolated from Figure 2.4. Hydraulic conductivity and effective porosity were varied within the ranges used along the north pathway. Average linear velocity in alluvium ranged from 0.017 ft/day to 2.1 ft/day. Estimated groundwater travel time in the Denver Formation ranged from 2.3 to 140 years. Groundwater travel time from the center of the water table mound to Ladora Lake ranged from 2.8 to 249 years. Uncertainty regarding the location and time of initial contamination along this pathway precludes meaningful comparisons between observed and calculated contaminant migration. However the calculations indicate that travel time in the saturated alluvium is substantially less than in the Denver Formation.

Water levels in the Unconfined Flow System along the southwest pathway are near the base of alluvial deposits, and small increases in water levels would cause the alluvial deposits to become saturated. Water level changes as large as 7 ft have been measured beneath South Plants in the past five years. If alluvial deposits became saturated, average linear velocity along this pathway probably would increase substantially and groundwater travel time would decrease.

4.6.2 Basin A-Basin A Neck Pathways

Contaminant migration from source areas beneath Basin A and other source areas that are hydraulically upgradient occurs primarily in alluvial deposits from Basin A through the Basin A Neck. The bedrock composition directly underlying the alluvial deposits consists of poorly cemented subcropping sandstone and siltstone lenses that provide direct hydraulic connection between the alluvium and Denver Formation.

Water in the Basin A-Basin A Neck occurs primarily in areas of saturated alluvium and underlying unconfined parts of the Denver Formation. Saturated thickness of the Unconfined Flow System in this area typically is less than 20 ft. Hydraulic conductivity is not accurately known. Estimates from three multiple well aquifer tests along the pathway ranged from 10 ft/day to 106 ft/day.

Average linear velocity and groundwater travel time along the Basin A-Basin A Neck pathway have been calculated for a range of hydraulic conductivity estimates between 10 and 100 ft/day and various assumed values of effective porosity. Hydraulic gradient was extrapolated from Figure 2.4. For effective porosity values from 0.1 to 0.4 average linear velocity ranged from 0.4 ft/day to 11.7 ft/day. Corresponding travel times from the center of Basin A to the downgradient end of Basin D ranged from 1.5 to 44.5 years.

Basin A was used for waste disposal primarily from 1943 to 1956. Based on the assumption that dithiane and oxathiane, by-products in the manufacture of mustard gas, were introduced to Basin A, it is reasonable to compare calculated travel time with contaminant distribution maps. Dithiane and oxathiane are relatively nonsorbing organosulfur compounds. The contaminant distribution map for dithiane and oxathiane (Appendix F, Figure 4.2-5) indicates that the contaminants have migrated to the area beneath Basin E. Assuming that Basins D and E were not major sources of these contaminants, a travel time of 44 years and contaminant migration rate of 1.1 ft/day approximately matches the observed distance of migration. Assuming a value of 0.20 for effective porosity, the observed distance of migration was most closely matched by using a hydraulic conductivity estimate of 29 ft/day.

Secondary pathways for contaminant migration through subcropping sandstone and siltstone lenses of the Denver Formation can be formed under appropriate hydrologic conditions. Two secondary pathways have been identified in the Basin A-Basin A Neck area. Although lateral migration along these pathways may occur through upper parts of the Denver Formation, small increases in water levels from present day conditions could cause groundwater flow and contaminant migration through alluvium. The water table elevation as of Third Quarter FY87 is at or just below the bedrock contact in the area north of the Basin A Neck.

Figures 3.13 through 3.17 identify areas of continuous contamination by inorganic compounds, primarily fluoride and chloride, in the upper sandstone stratigraphic units of the Denver aquifer. The areas of contamination generally occur in the sandstone unit that subcrops beneath the Unconfined Flow System or the immediately underlying unit. The area of contamination extends from Basin A, through the Basin A Neck, beneath Basins C and F, and toward the northwest. The orientation of this contaminated area coincides with the direction of flow inferred from potentiometric surface maps of the Denver aquifer (Appendix F, Figures 2.4-5 through 2.4-10). Contamination may be the result of migration along relatively short flow paths originating locally in contaminated water of the Unconfined Flow System. Because migration mechanisms in the Denver aquifer are complex, average linear velocity and travel time are not calculated.

4.6.3 Central Pathways

Based on contaminant distribution in Sections 27 and 34, several pathways, collectively called the central pathways, have been identified. A major pathway extends from beneath Basin D to the Northwest Boundary Containment System and is a continuation of the Basin A-Basin A Neck pathway. Other pathways originate near the Sand Creek Lateral or Basin F and have been traced toward the Northwest Boundary Containment System. Contaminants along the central pathways occur primarily in alluvial deposits of the Unconfined Flow System.

Hydraulic characteristics of the Unconfined Flow System along the central pathways are similar to hydraulic characteristics within the Basin A Neck. Saturated thickness typically is 10 ft or less; however, a north-trending channel with a saturated thickness of 20 ft is located in the western part of Section 27. Hydraulic conductivity estimates from aquifer tests near the Northwest Boundary Containment System indicate that a value of approximately 1,600 ft/day is typical for the north-trending channel in Section 27 (Figure 2.3). Hydraulic gradients in areas east of this channel indicate that hydraulic conductivity is similar to the estimate in the Basin A Neck.

Average linear velocity and groundwater travel time along the central pathway from Basin D to the Northwest Boundary Containment System have been calculated for a range of hydraulic conductivity estimates and various assumed values of effective porosity. Hydraulic gradients were obtained from Figure 2.4. A range of 10 to 100 ft/day was used for hydraulic conductivity in the eastern part of Section 27, where gradients are relatively steep. This range was obtained from multiple well aquifer tests in the Basin A Neck. A range of 1,000 to 1,600 ft/day was used for hydraulic conductivity in the area of relatively flat gradient in the western part of Section 27 (Figure 2.3). For assumed values of effective porosity from 0.1 to 0.3, average linear velocity ranged from 0.33 ft/day to 10.0 ft/day in the area of steep gradient, and 13 ft/day to 64 ft/day in the area of flat gradient. Corresponding travel times from the downgradient end of Basin D to the Northwest Boundary Containment System range from 0.2 years to 41 years.

Calculated linear velocity compared well with apparent velocities of contaminants that are slightly sorbing. Diisopropylmethyl phosphonate is associated with manufacturing of the nerve gas agent GB, and was disposed in Basin A from 1953 through 1956. During 1957 wastes containing diisopropylmethyl phosphonate were stored in Basin F. However, Basin F waste was pumped into Basin C in 1957 for a period of approximately 30 days while repairs were made to the Basin F liner. Figure 3.7 shows diisopropylmethyl phosphonate plumes along two central pathways. This pattern, along with the late 1950s configuration of the water table (Smith et al., 1963/RIC84324R02), indicates that the source of these plumes probably was Basin C. Based on present-day hydraulic gradients, a travel time of 29 years, contaminant migration rate of 1.2 ft/day, and an assumed effective porosity of 0.2, calculated groundwater travel distance was matched with the observed distance of migration. The best match was obtained by using a hydraulic conductivity estimate of 15 to 20 ft/day for the area of steep gradient. The match was not sensitive to the value of hydraulic conductivity used in the area of flat gradient. Using hydraulic gradients measured in the late 1950s, a reasonable match was obtained with an estimated hydraulic conductivity of 10 to 15 ft/day.

4.6.4 Basin F Pathway

Contaminant migration from Basin C and Basin F occurs in alluvial material and weathered bedrock of the Unconfined Flow System. The Basin F pathway extends north to the North Boundary Containment System. Saturated thickness of the Unconfined Flow System along the pathway is typically less than 10 ft. The median value of hydraulic conductivity obtained from aquifer tests near the pathway is approximately 230 ft/day. Hydraulic conductivity estimates from aquifer tests near Basin F range from 1 ft/day to

900 ft/day (Figure 2.3). The value of 1 ft/day is substantially less than other values and was not used in the subsequent analysis.

Average linear velocity and groundwater travel time along the Basin F pathway have been calculated for a range of hydraulic conductivity estimates between 30 and 900 ft/day and various assumed values of effective porosity. Hydraulic gradient, obtained from Figure 2.4, reflects conditions during 1987. Assuming effective porosity values between 0.1 and 0.3, average linear velocity ranged from 0.17 ft/day to 15.6 ft/day. Travel time from the northeast corner of Basin F to the North Boundary Containment System ranged from 1.1 years to 99 years.

Hydraulic gradients in recent years are substantially less than gradients from 1957 to 1971. Basin C was used as an artificial recharge basin during part of this period. Hydraulic gradients from Basin C to the northern boundary of RMA from 1957 to 1971 were approximately three to five times greater than present-day gradients. Average linear velocity during periods when Basin C stored water was three to five times larger than present-day velocity. Travel time from Basin F to the northern boundary of RMA probably was three to five times shorter.

Concentrations of fluoride in excess of 10,000 ug/l have been observed in wells north of Basin F. Hydraulic gradients in this area are flat, and the water table is near the bedrock contact. Migration in areas where the water table is in the Denver Formation would be slow because of the small gradient and hydraulic conductivity. In areas where migration occurs in alluvium, hydraulic conductivity would be greater. However, the flat gradients would strongly influence migration rate. Gradients in the area average 0.0002 ft/ft but are an order of magnitude lower in local areas. The lower gradients tend to occur in more permeable alluvium.

Assuming an effective porosity of 0.2, travel time to the North Boundary Contaminant System has been estimated. The estimate was based on a hydraulic conductivity of 730 ft/day and a hydraulic gradient of 0.0002 ft/ft. Time for the northeast arm of the fluoride plume to arrive at the containment system with concentrations in excess of 5,000 ug/l was approximately 36 years. The projected flow path of the plume was primarily in saturated alluvium.

Near the RMA north boundary, groundwater flows primarily through coarse basal sediments of the alluvium, with substantially less flow through upper alluvial layers of relatively fine grained eolian deposits and the fractured or weathered materials of the upper Denver Formation. Flow direction near the North Boundary Containment System is to the north. Flow through the alluvium downgradient of the north boundary area generally took place along two distinct flow paths. These flow paths were primary factors that determined how contaminants migrated to off-post areas before the North Boundary Containment System was installed.

Changes in flow patterns as a result of the North Boundary Containment System have been noted within about 500 ft of the system. Water in the Unconfined Flow System has mounded on the upgradient side of the soil-bentonite barrier, and the upgradient water table is up to 9 ft higher than on the downgradient side of the barrier. This condition has apparently resulted in contaminant migration beneath the pilot portion of the system. Many of the large head differences across the barrier have been attributed to inadequate North Boundary Containment System recharge capabilities downgradient of the pilot portion of the system. This situation has been addressed through installation of recharge trenches, and the hydraulic gradient has now been reversed across part of the North Boundary Containment System.

Near the North Boundary Containment System, the Denver Formation consists of a 250 to 300 ft thick series of carbonaceous clayshales, claystones, and siltstones. These fine grained sediments are interbedded with weakly lithified, more permeable, lenticular sandstone units. Where sandstones are uncemented, they act as the dominant pathway for lateral groundwater flow through the Denver Formation. However, in the upper Denver Formation, the low permeability strata may be heavily weathered and fractured and have hydraulic conductivity similar to that of sandstone units. The average thickness of sandstone units near the North Boundary Containment System averages from about 10 ft for crevasse-splay type deposits to over 20 ft for channel type deposits. The regional groundwater flow direction through the Denver aquifer is to the northwest. However, changes in the water table configuration caused by the North Boundary Containment System have created more of a northward direction in the uppermost units beneath the system. Estimates of hydraulic conductivity of the Denver aquifer vary significantly near the North Boundary Containment System and range from about .007 ft/day to 1.6 ft/day.

Average linear velocity within the most permeable zones of the Denver Formation was estimated at less than 0.03 ft/day.

The more strongly sorbed compounds in the Basin F pathway tend to occur over less extensive areas and tend to migrate over shorter distances than weakly sorbed compounds. Organochlorine pesticides are exceptions to these generalizations. Although strongly sorbing, these compounds have migrated substantial distances. The explanation for this anomalous behavior is not well established. Organochlorine pesticides were introduced to the groundwater system principally in solution with benzene, chloroform, or other organic solvents. Distribution coefficients for sorption presented in this report were obtained for single contaminants in solution with water. Distribution coefficients for sorption in a system of pesticides, organic solvent and water are likely to be substantially different.

Quantitative estimates of the distance of contaminant migration based on retardation factors given in Table 4.2 generally do not conform with observed migration distances. For example, the distance of migration by trichloroethylene predicted on the basis of the retardation factor in Table 4.2 is approximately 15 percent of the observed migration distance indicated in Appendix F, Figure 4.2-16. A retardation factor of 1.6 more closely matches the observed migration distance. A range of values between 1.0 and 1.8 was obtained for trichloroethylene during a two-well recirculating test in the western tier (Mackay, 1988, written communication).

4.6.5 Western Tier Pathways

Two major pathways for contaminant migration have been identified in the western tier. Water along these pathways occurs in alluvial sand and gravel. Saturated thickness varies from 10 to 70 ft. Hydraulic conductivity estimates obtained from long-term aquifer tests range from 400 ft/day to 1,500 ft/day. Hydraulic gradients typically are 0.005 ft/ft or less. Contaminants along both pathways flow toward the Irondale Containment System.

Assuming effective porosity values between 0.1 and 0.3 and a range of hydraulic conductivity estimates between 400 ft/day and 1,500 ft/day, average linear velocity along the railyard and motor pool pathway was estimated to range from 3.0 ft/day to 60 ft/day. Travel time from the motor pool to the Irondale Containment System was between 0.44 and 8.6 years. These estimates were obtained using hydraulic gradients extrapolated from

Figure 2.4. Based on a retardation factor of 1.8 (Mackay, 1988, written communication), travel time for trichloroethylene is between 0.79 and 15.5 years.

Average linear velocity and groundwater travel time along the western tier pathway has been calculated on the basis of hydraulic gradients indicated in Figure 2.4 and hydraulic conductivity estimates between 400 and 1,500 ft/day. For values of effective porosity between 0.1 and 0.3, average linear velocity was between 3.0 ft/day and 60 ft/day. Travel time from the southern boundary of RMA to the Irondale Containment System was between 3.5 years and 6.8 years. The widespread distribution of contaminants along this pathway have precluded meaningful comparisons between calculated values and measured rates of migration. Average linear velocity along the off-post western tier pathway and the western tier pathway are similar.

4.7 Vertical Contaminant Migration

Contamination of the Denver aquifer primarily has been the result of downward migration of contaminants in groundwater from the overlying Unconfined Flow System. The most extensive contamination of the Denver aquifer is located in areas where sandstone or fractures probably provide hydraulic connection with contaminated groundwater in the Unconfined Flow System and hydraulic gradients indicate potential for downward migration. Rates of lateral flow in the Denver aquifer are generally not sufficiently high to interpret the distribution of contaminants on the basis of lateral migration.

In some cases, the depth of contamination is determined by the depth of interconnected sandstone zones in the Denver aquifer. Where sandstone zones are separated by claystone or other material of low hydraulic conductivity, vertical migration into the lower sandstone is sporadic. Some wells that obtain water from the lower sandstone will be contaminated, while other wells completed in the lower sandstone show no evidence of contamination. In cases where sporadic contamination of a sandstone zone occurs, migration probably occurs through localized clusters of fractures.

Vertical contaminant migration has been most extensive in three areas of RMA. These areas are located near South Plants, Basins C and F, and the North Boundary Containment System. Mechanisms and hydrogeologic conditions in each area are different. Therefore, the areas will be discussed separately.

In addition to these three areas, contaminants have been detected in isolated wells of the Denver aquifer in many parts of RMA. Distribution of these isolated detections was discussed in Section 3.2.11. Because the detections are isolated, a detailed assessment of vertical contaminant migration is not possible. However, likely explanations for isolated points of contamination in the Denver aquifer are vertical migration through localized clusters of fractures, migration along well bores that were not constructed in a manner to prevent vertical intraborehole flow, contamination while drilling, and water quality sampling or laboratory error.

4.7.1 South Plants

A limited number of contaminants have been detected in the Denver aquifer beneath South Plants. The distribution of contaminants is sporadic. The most frequently detected contaminant was chloroform. Other organic contaminants were detected infrequently. This is a sharp contrast to the larger number of contaminants detected in the Unconfined Flow System beneath South Plants. Sandstone zone A is the most extensively contaminated zone of the Denver aquifer. Although a limited number of wells have been completed in sandstone zones above and below zone A, some show contamination and others do not. The irregular distribution of contaminants in the Denver aquifer indicates that the mechanism for vertical migration is probably very localized.

Sandstone zones beneath South Plants are separated from the Unconfined Flow System by volcaniclastic material with low matrix hydraulic conductivity. Rates of vertical flow through the matrix are not sufficiently large to explain the extent of vertical contamination. Matrix hydraulic conductivity estimated from cores as part of Task 26 is less than 10^{-6} ft/day (Chen and Associates, 1987, written communication). Assuming a range of matrix hydraulic conductivity from 10^{-4} to 10^{-6} ft/day, an effective porosity of 0.10, and a unit vertical head gradient, the average linear velocity would range from approximately 0.4 ft/yr to 0.004 ft/yr. Actual average linear velocity through the matrix is probably less. On the basis of this velocity, vertical migration would not have extended more than 20 ft into the Denver aquifer from 1947 to present.

Contamination of the Denver aquifer beneath South Plants may have occurred by vertical migration through interconnected clusters of fractures. Cores obtained during well installation at South Plants frequently indicate the presence of fractures in the zone of volcaniclastic material. Fractures typically are subvertical, with oxidized material coating the fracture surfaces. Although core data below the first lignitic bed (approximately 50 ft below surface) are limited to a single well in the central part of South Plants, fractures are less common. The evidence of fractures, in combination with the irregular distribution of contamination in the Denver aquifer, indicates that migration along fractures may have occurred.

4.7.2 Basins C and F

A large number of contaminants have been detected in the Denver aquifer near Basins C and F; however, contamination generally is restricted to sandstone zones 1 and 2. The list of contaminants detected in several wells includes chlorobenzene, chloroform, diisopropylmethyl phosphonate, oxathiane, and dithiane. Most wells screened in sandstone zone 1 near Basins C and F indicate elevated levels of contaminants. However, the percentage of wells with detectable concentrations of contaminants decreases in sandstone zone 2.

Sandstone zone 1 near Basin C is in direct hydraulic connection with the overlying Unconfined Flow System. This provides a direct pathway for vertical migration. Present-day hydraulic gradients indicate a potential for downward flow. During periods when Basin C contained water, the water table in the Unconfined Flow System rose substantially and the potential for downward flow was enhanced.

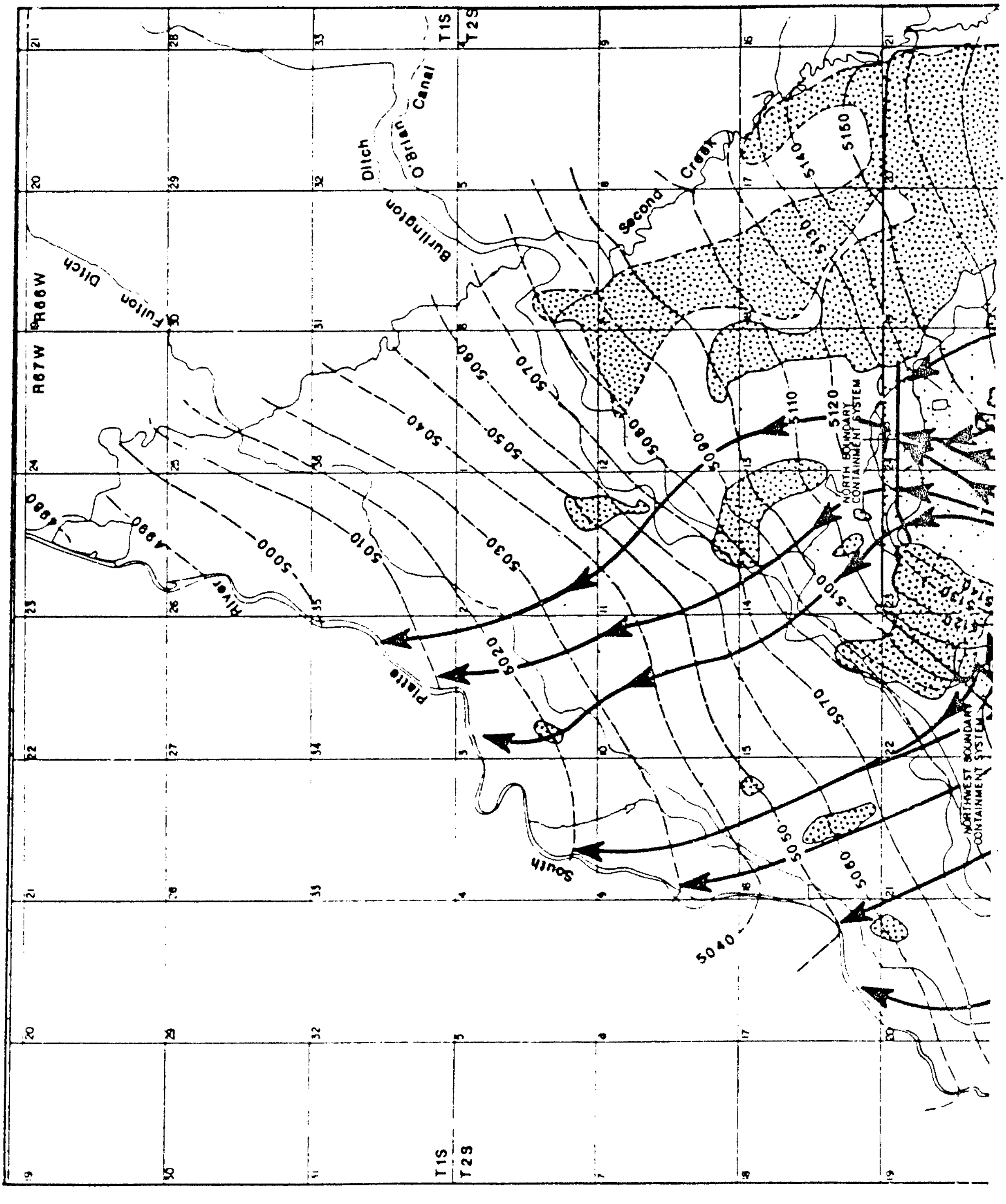
Sandstone zones 1 and 2 are generally separated by claystone (Plate 2). However, the two zones probably are directly connected at some points near Basins C and F. Where connected, a pathway for vertical migration would occur. Hydraulic conductivity for zones 1 and 2 (Appendix F, Table 2.4-2) is between 10 and 30 ft/day. Assuming the two zones are directly connected, these values of hydraulic conductivity are sufficiently large to interpret vertical migration beneath Basins C and F on the basis of matrix flow through sandstone. A single well screened in zone 3 of the Denver aquifer generally indicates that most contaminants detected in zones 1 and 2 are not present in zone 3. This indicates that sandstone zone 3 may not be directly connected to zone 2.

4.7.3 North Boundary Containment System

A large number of contaminants has been detected in the Denver aquifer beneath and immediately north of the North Boundary Containment System. Contaminants detected in several wells include benzene, chlorobenzene, chloroform, DBCP, dieldrin, diisopropylmethyl phosphonate, oxathiane, dithiane, trichloroethylene, and others. Concentrations of some contaminants, including benzene and chlorobenzene, are higher in the Denver aquifer than in the overlying Unconfined Flow System. The elevated concentrations in the Denver aquifer indicate that vertical migration occurred in the past, when concentrations in the Unconfined Flow System near the northern boundary of RMA probably were higher.

Contaminant concentrations above CRLs have been detected near the North Boundary Containment System in sandstone zones 2 through 5 of the Denver aquifer. These zones are interconnected or separated by thin intervals of claystone near the North Boundary Containment System. As a result, the mechanism for vertical migration between zones probably is by flow through the sandstone matrix. The sandstone zones are separated from the Unconfined Flow System by 10 to 20 ft of claystone. However, drilling near the North Boundary Containment System indicated that part of the claystone is fractured. As a result, vertical migration of contaminants from the Unconfined Flow System to the shallow sandstone zones probably occurs through fractures.

8-88, T 44



R67W
R66W
T1S
T2S
Fulton Ditch
Burlington Ditch
O'Brian Canal
Second Creek
South Platte River
NORTH BOUNDARY CONTAINMENT SYSTEM
NORTHWEST BOUNDARY CONTAINMENT SYSTEM
4880
4990
5000
5010
5020
5030
5040
5050
5060
5070
5080
5090
5100
5110
5120
5130
5140
5150

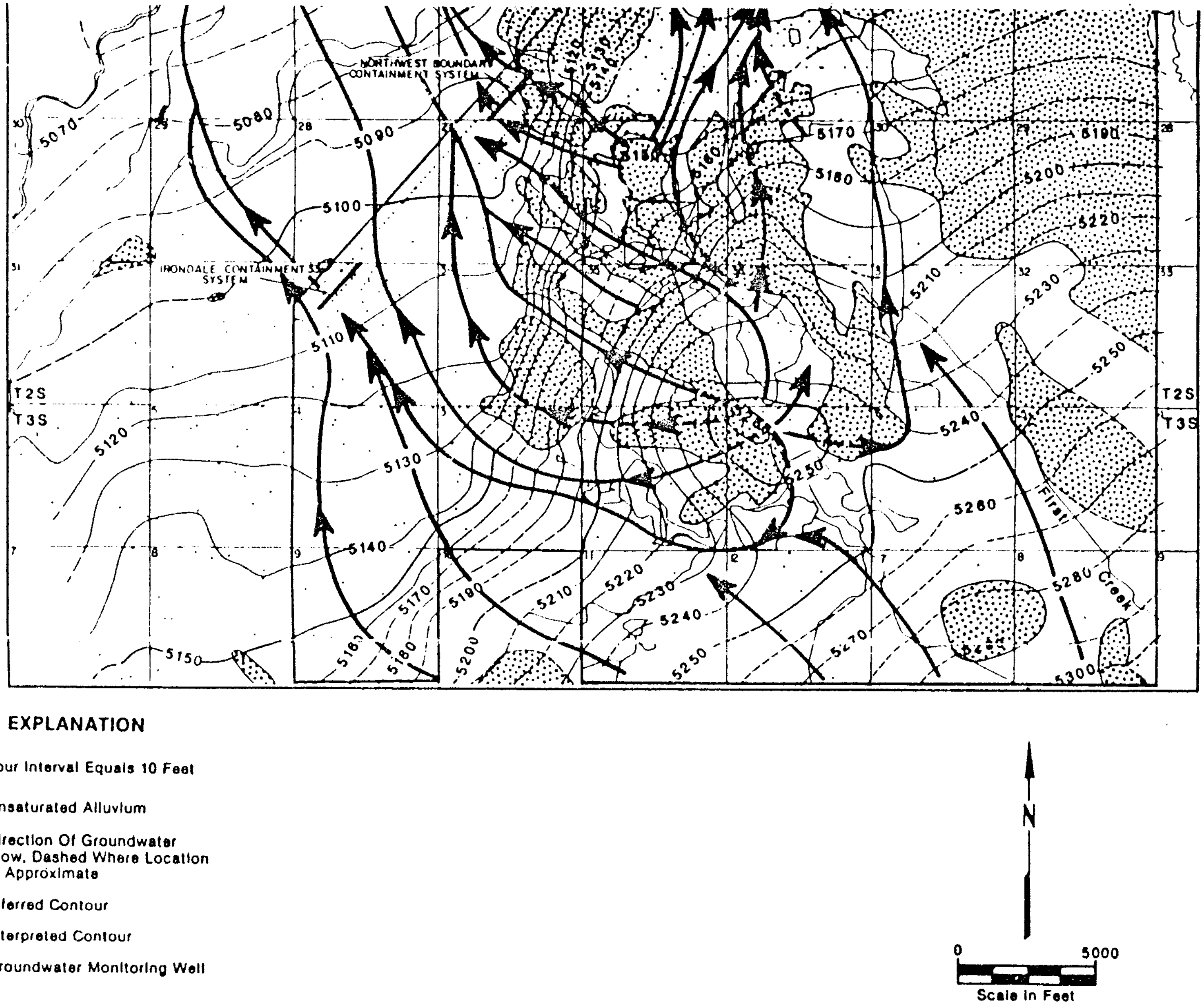


Figure 4.1

POTENTIOMETRIC SURFACE AND GROUNDWATER FLOW DIRECTIONS OF THE UNCONFINED FLOW SYSTEM

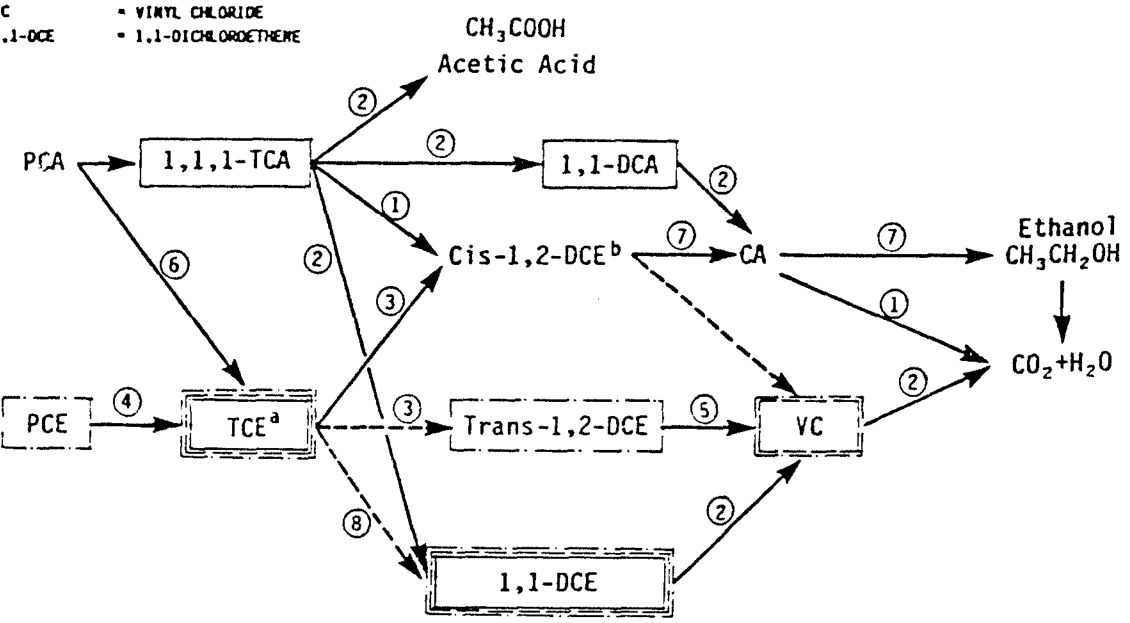
SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland

EXPLANATION

PCA = TERACHLOROETHANE
1,1,1-TCA = 1,1,1-TRICHLOROETHANE
1,1-DCA = 1,1-DICHLOROETHANE
CIS-1,2-DCE = CIS-1,2-DICHLOROETHENE
CA = CHLOROETHANE
PCE = TETRACHLOROETHENE
TCE = TRICHLOROETHENE
Trans-1,2-DCE = Trans-1,2-DICHLOROETHENE
VC = VINYL CHLORIDE
1,1-DCE = 1,1-DICHLOROETHENE



PATH REFERENCE

① McCarty (1986)
② Vogel & McCarty (1987 b)
③ Kloepfer et al (1985)
④ Parsons et al (1984)
⑤ Barrio-Lage et al (1986)
⑥ Cooper et al (1987)
⑦ Vogel et al (1987)
⑧ Wood et al (1985)

MAJOR MECHANISM

Biodegradation
↓
Abiotic Elimination
Biodegradation
↓

NOTES

– – – Minor Pathway

Half life reaction rates detailed in Table 4.3

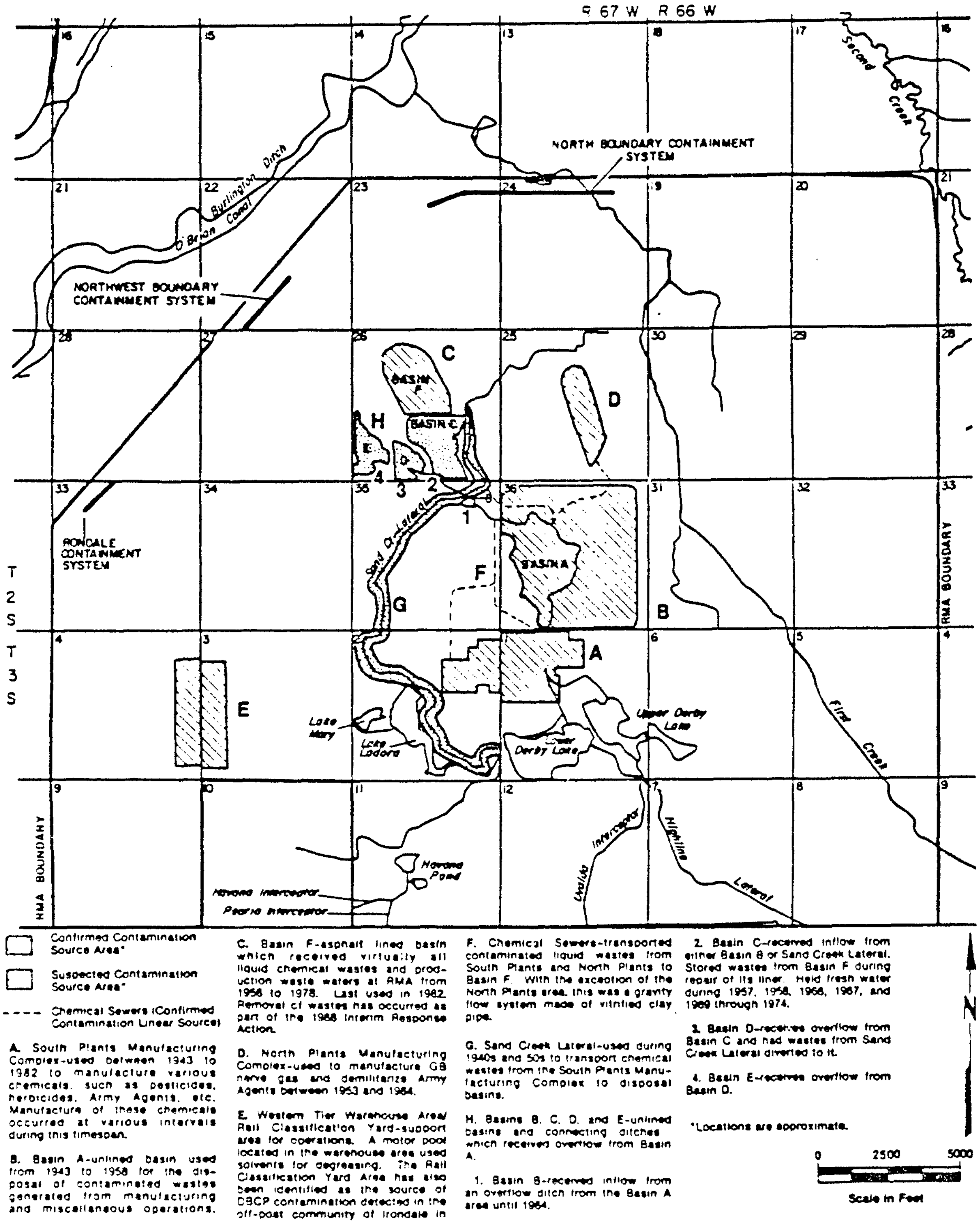
a Cis 1,2-DCE generated at approximately 30 times the concentration of Trans 1,2-DCE (3) and by a factor of 25:1 (8)

Figure 4.2

TRANSFORMATIONS OF CHLORINATED ALIPHATIC HYDROCARBONS

SOURCE: R. L. STOLLAR & ASSOCIATES, INC., 1989

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland



▢ Confirmed Contamination Source Area*

▢ Suspected Contamination Source Area*

- - - - Chemical Sewers (Confirmed Contamination Linear Source)

A. South Plants Manufacturing Complex-used between 1943 to 1982 to manufacture various chemicals, such as pesticides, herbicides, Army Agents, etc. Manufacture of these chemicals occurred at various intervals during this timespan.

B. Basin A-unlined basin used from 1943 to 1958 for the disposal of contaminated wastes generated from manufacturing and miscellaneous operations.

C. Basin F-asphalt lined basin which received virtually all liquid chemical wastes and production waste waters at RMA from 1956 to 1978. Last used in 1982. Removal of wastes has occurred as part of the 1988 Interim Response Action.

D. North Plants Manufacturing Complex-used to manufacture GB nerve gas and demilitarize Army Agents between 1953 and 1984.

E. Western Tier Warehouse Area/Rail Classification Yard-support area for operations. A motor pool located in the warehouse area used solvents for degreasing. The Rail Classification Yard Area has also been identified as the source of DBCP contamination detected in the off-post community of Irondale in 1980.

F. Chemical Sewers-transported contaminated liquid wastes from South Plants and North Plants to Basin F. With the exception of the North Plants area, this was a gravity flow system made of vitrified clay pipe.

G. Sand Creek Lateral-used during 1940s and 50s to transport chemical wastes from the South Plants Manufacturing Complex to disposal basins.

H. Basins B, C, D, and E-unlined basins and connecting ditches which received overflow from Basin A.

1. Basin B-received inflow from an overflow ditch from the Basin A area until 1964.

2. Basin C-received inflow from either Basin B or Sand Creek Lateral. Stored wastes from Basin F during repair of its liner. Held fresh water during 1957, 1958, 1966, 1967, and 1969 through 1974.

3. Basin D-receives overflow from Basin C and had wastes from Sand Creek Lateral diverted to it.

4. Basin E-receives overflow from Basin D.

*Locations are approximate.

Figure 4.3
LOCATION OF CONFIRMED AND SUSPECTED CONTAMINATION SOURCE AREAS

SOURCE: R. L. Stollar & Associates Inc., 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

5.0 SUMMARY AND CONCLUSIONS

The purpose of the Water Remedial Investigation Report is to assess contaminant occurrence and distribution within groundwater and surface water. To accomplish this, the RMA environmental setting was evaluated in terms of geology, hydrology, nature and extent of water-borne contamination, and contaminant migration.

Surface water at RMA flows within several small drainage basins that are tributaries of the South Platte River. The major drainages within RMA are First Creek and Irondale Gulch. Man-made structures, including diversion ditches, lakes, and water retention basins, have modified the natural drainage patterns. The land surface consists of gently rolling hills with a total change in altitude of 220 ft.

Groundwater at RMA occurs under both confined and unconfined conditions. The Unconfined Flow System includes saturated alluvium, eolian deposits, and subcropping parts of the Denver Formation where lithologic data indicate the presence of sandstone or relatively permeable material. In areas where alluvial and eolian deposits are unsaturated, the Unconfined Flow System consists solely of sandstone and fractured rock within shallow parts of the Denver Formation. Saturated thickness varies from less than 10 ft to approximately 70 ft. Hydraulic conductivity estimates from aquifer tests range from 0.3 ft/d in areas where the Denver Formation is unconfined to greater than 900 ft/d in alluvial terrace gravel.

Groundwater in the Unconfined Flow System generally flows toward the north and northwest. Spatial variations in hydraulic gradients and direction of flow is a result of variations in saturated thickness, hydraulic conductivity, locations of recharge and discharge, and configuration of the bedrock surface. Water level fluctuations generally are small; however, seasonal fluctuations as large as 6 ft have been measured beneath South Plants. Historical water level fluctuations have been large in the vicinity of Basin C. During the late 1950s and from 1969 through 1975, water levels beneath Basin C rose 20 to 30 ft in response to artificial recharge. Present day recharge to the Unconfined Flow System occurs as infiltration of precipitation and irrigation, seepage from lakes, streams, reservoirs, canals, buried pipelines, and flow from the underlying Denver aquifer. Discharge occurs primarily as seepage to lakes and the South Platte River, groundwater withdrawals by wells, and flow into the Denver aquifer.

A numerical model of groundwater flow in the Unconfined Flow System has been developed to evaluate hydrologic concepts and refine hydraulic conductivity estimates. Model results confirmed that paleochannels and terrace deposits generally convey larger flow than interfluvial zones. Hydraulic conductivity estimates in the Basin A Neck and areas immediately northwest obtained during model calibration were smaller than initial estimates. Sensitivity analyses indicated that the areas of greatest model uncertainty within the boundaries of RMA are near South Plants and Basins A through F.

The Denver aquifer in the vicinity of RMA consists of parts of the Denver Formation where permeable sandstone or lignitic beds are separated from the Unconfined Flow System by relatively impermeable shale or claystone. The hydraulic conductivity of the shale and claystone matrix is small, probably 10^{-2} to 10^{-4} ft/d. The hydraulic conductivity for sandstone in the Denver aquifer has been estimated by aquifer test analyses to range from 1.1 to 7.7 ft/d. The hydraulic conductivity of fractured lignitic beds may be an order of magnitude greater than the hydraulic conductivity of sandstone.

Water in the Denver aquifer moves downward and laterally toward the northwest. The smaller hydraulic conductivity of shale relative to sandstone, as well as the stratification of the Denver aquifer, probably restricts the rate of vertical flow while enhancing lateral flow. Water in transmissive strata of the Denver aquifer returns to the Unconfined Flow System by lateral flow where the elevation of the bedrock varies appreciably in a short distance and the transmissive strata subcrop.

Areas where surface water contamination was detected include South Plants, Basin A, and the sewage treatment plant. Organochlorine pesticides and organosulfur compounds were the most frequently detected analytes. Fewer contaminants were detected from water entering RMA along the Peoria Interceptor. Comparisons of Third Quarter FY87 data with previously collected data indicate that there is little difference in analyte concentration at a site through time.

The majority of contamination by organic compounds occurs in the Unconfined Flow System. Plumes of organochlorine pesticides with peak concentrations greater than 1.0 ug/l have been identified in the South Plants, Basin A-Basin A Neck, central, and Basin F pathways. Plumes of organosulfur compounds occur along the Basin A-Basin A

Neck and Basin F. Peak concentrations of 56,200 ug/l have been detected near Basin A for volatile aromatic organics. Plumes of volatile aromatic organics occur along South Plants, Basin A-Basin A Neck and Basin F pathways. Volatile halogenated organic plumes have been identified along all major pathways with peak concentrations of 39,800 mg/l occurring along the Basin F pathway. Numerous organic plumes have migrated along off-post pathways.

Inorganic contaminants are more areally extensive in the Unconfined Flow System than organic compounds. Arsenic plumes have been delineated in the Basin A-Basin A Neck and Basin F pathways. The peak concentration of arsenic, 410 ug/l, occurred in the Basin F pathway. Fluoride concentrations greater than 5,000 ug/l were measured in the vicinity of Basin A and Basin F. Chloride concentrations greater than 1,000,000 ug/l were measured along the Basin A-Basin A Neck, central, and Basin F pathways. The distribution of inorganic contaminants is complicated by the natural occurrence of these compounds.

Concentrations of organic compounds in the Denver aquifer generally are less than concentrations in the overlying Unconfined Flow System. Organochlorine pesticides generally occur in isolated areas, rather than plumes. Organosulfur compounds are common in upper stratigraphic zones of the Denver aquifer beneath the Basin A-Basin A Neck pathway and beneath Basin C. Volatile aromatic organics have been identified over a more extensive area than other organic groups. In many parts of RMA, samples from the deepest wells in the Denver aquifer contained measurable concentrations of one or more organic contaminants. Inorganic analytes above background levels are common in water of the Denver aquifer; however, concentrations generally decrease with increasing depth.

Average linear velocity of groundwater calculated on the basis of available hydraulic information generally is consistent with observed rates of migration for weakly sorbing contaminants in the Unconfined Flow System. Dithiane and oxathiane are weakly sorbing contaminants that form plumes in the Basin A-Basin A Neck pathway. Average linear velocity of groundwater calculated from available hydraulic information compares favorably with actual contaminant migration rate, assuming an effective porosity of 0.31. Other areas where average linear velocity compares favorably with observed migration rates of slightly sorbing contaminants include the central and Basin F pathways.

The predominant hydrochemical processes affecting changes in contaminant concentration are sorption, vaporization, and degradation. Distribution coefficients (K_d) for RMA contaminants indicate that organochlorine pesticides are generally sorbed strongly while organosulfur compounds are generally sorbed weakly. Volatile aromatic organics and volatile halogenated organics tend to vaporize readily in the unsaturated zone but there is no evidence of volatilization in the saturated zone. Hydrodynamic processes affecting changes in contaminant concentration are advection, dispersion, and dilution.

6.0 REFERENCES

Barker, J. F. and Patrick, G. C. 1985. Natural Attenuation of Aromatic Hydrocarbons in a Shallow Sand Aquifer. In, Proceedings of the NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water - Prevention, Detection and Restoration. National Water Well Association, Dublin, Ohio.

Barrio-Lage, G., Parsons, F. Z., Nassar, R. J. and Lorenzo, P. A. 1986. Sequential Dehalogenation of Chlorinated Ethenes. Environ. Sci. Technol. 20, 96-99.

Barrio-Lage, G., Parsons, F. Z. and Nassar, R. J. 1987. Kinetics of the Depletion of Trichloroethene. Environ. Sci. Technol. 21, 366-370.

RIC#88195R01
Berry, E., et al. June 1988. Evaluation of Shell Chemical Company's Ground Water DBCP Control System at Rocky Mountain Arsenal, FY85/86. Waterways Experiment Station.

RIC#81266R25
Black and Veatch Consulting Engineers, Inc. 1980. Final Design Analysis, Liquid Waste Disposal Facility. North Boundary Expansion, Rocky Mountain Arsenal, Commerce City, Colorado, FY80, Project No. 34. Prepared for U.S. Army Corps of Engineers, Omaha District. Kansas City, Missouri.

Bopp, et al., 1979. Hydrogeology and Water Quality of Basin A Neck Area, Rocky Mountain Arsenal, Denver, Colorado, Draft Report, U.S. Army Engineer Waterways Experiment Station, C.E. Vicksburg, Mississppi.

Bouwer, E. J. and McCarty, P. L. 1984. Modeling of Trace Organics Biotransformation in the Subsurface. Ground Water, 22, 433-440.

Bouwer, Herman, and Rice, R.C. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells, Water Resources Research, V. 12, No. 3, p.423-428.

Brakensiek, D.L; H.B. Osborn and W.J. Rawls. 1979. Field Manual for Research in Agricultural Hydrology. Science and Education Administration USDA, Agriculture Handbook No. 224. U.S. Government Printing Office, Washington, D.C.

RIC#81266R27
Broughton, J., W. Miller, and G. Mitchell. 1979. Geology and Groundwater Definition, Basin A Area, Rocky Mountain Arsenal, Denver, Colorado. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

Burlinson, N. E., Lee, L. A. and Rosenblatt, D. H. 1982. Kinetics and Products of 1,2-dibromo-3-chloropropane. Environ. Sci. Technol. 16, 627-632.

Callahan, M.A., et al. 1979. "Water-Related Environmental Fate of 129 Priority Pollutants," EPA-440/4-79-029A, United States Environmental Protection Agency, Washington, D.C.

CDM (Camp Dresser McKee), 1986. Performance of Remedial Response Activities at Uncontrolled Hazardous Waste Sites (REM II), Remedial Investigation First Operable Unit. EPA's Rocky Mountain Arsenal off-post RI/FS site, Commerce City, Colorado.

Cherry, J.A., 1984. "Groundwater Contamination," in Short Course in Environmental Geochemistry. Mineral Association of Canada. ON, Canada.

COE (U.S. Army Corps of Engineers). 1987. Unpublished Data Sheet of Cherry Creek Dam Pan Evaporation. Omaha District, COE, Omaha, Nebraska.

RIC#84066R01
COE. 1983. Evaluation of the Existing and Future Flood Potential on the Rocky Mountain Arsenal, Denver, Colorado. Omaha, Nebraska.

COE. 1982. HEC-2 Water Surface Profiles: Programmers Manual. The Hydrologic Engineering Center, Davis, California.

Colorado Climate Center. 1988. Public Access Meteorological Data Base. Fort Collins, CO.

Cooper, H.H., Jr., J.D. Bredehoeft, and I.S. Papadopulos. 1967. Response of a Finite-Diameter Well to an Instantaneous Charge of Water. Water Resources Research, Vol. III, No. 1, p. 263.

Cooper, W. J., Mehran, M., Riusech, D. J. and Joens, J. A. 1987. Abiotic Tranformations of Halogenated Organics. I. Elimination Reaction of 1,1,2,2-tetrachloroethylene and Formation of 1,1,2-Trichloroethene. Environ. Sci. Technol. 21, 1112-1114.

RIC#84291R01
Devoto, R.H. 1968. Quaternary History of the Rocky Mountain Arsenal and Environs, Adams County, Colorado: Quarterly of the Colorado School of Mines.

RIC#85350R01
Dildine J. 1984. Rocky Mountain Arsenal Suface Water Runoff and Water Balances 1984. Waterways Experiment Station.

Dragun, J. 1988. The Soil Chemistry of Hazardous Materials. Hazardous Materials Control Research Institute, Silver Springs, Maryland.

Drever, J.I., 1982. The Geochemistry of Natural Waters. Prentice Hall Inc. Englewood Cliffs, New Jersey.

RIC#88357R01
Ebasco. 1988a, May. Rocky Mountain Arsenal Chemical Index, Volumes I and II. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88286R08
Ebasco. 1988b, September. Final Contamination Assessment Report. Chemical Sewers-North Plants and South Plants. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88306R02
Ebasco. 1988c, October. Final Summary of Results, Structures Survey Report. October 1988.

RIC#87197R05
Ebasco. June 1987. Toxicity Assessment for Rocky Mountain Arsenal Target Contaminants. Task 35. Draft Final Report.

RIC#81352R135
ERTEC (The Earth Technology Corporation). 1981. Hydraulic Conductivity and the Unified Soils Classification System at Rocky Mountain Arsenal, Denver, Colorado. Project Number 82-169. Prepared for U.S. Army Toxic and Hazardous Materials Agency and Computer Sciences Corporation. Long Beach, California.

Emmons, S.F., *et al*, 1896 Geology of the Denver Basin in Colorado. U.S. Geological Survey Monographs Vol. 27.

RIC#89054R01
ESE (Environmental Science and Engineering, Inc.). 1989a, May. Biota Remedial Investigation. Final Report. Task 9.

RIC#89024R01
ESE. 1989b, August. Off-post Operable Unit Remedial Investigation and Chemical Applicable or Relevant and Appropriate Requirements, Draft Final Report. Task 39.

RIC#88173R06
ESE. 1988a, May. Final Screening Program Third and Fourth Quarters, Final Report. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88173R02
ESE. 1988b, May. Site 26-6: Basin F. Contamination Assessment Report. Final Phase I. Prepared for Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88244R02
ESE. 1988c, July. Rocky Mountain Arsenal Composite Well Program, Draft Final Report, Task 44. Prepared for Office of the Program Managers, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88263R01
ESE. 1988d, August. Air Remedial Investigation Final Report. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88173R02A
ESE. 1988e. September. Site 26-6: Basin F. Contamination Assessment Report. Final Phase II Data Addendum. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88344R01
ESE. 1988f, September. Overall Soil Assessment and Groundwater Integration Determination of Partition Coefficients from the Primary Contaminant Sources of Section 36. Draft Final Report. Task 23. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88344R02
ESE. 1988g, November. Rocky Mountain Arsenal North Boundary System Component Response Action Assessment. Draft Final Report. Task 36. Prepared for the Office of the Program Manager, RMA Contamination Cleanup.

RIC#89024R02
ESE. 1988h, December. Rocky Mountain Arsenal. Boundary Control Systems Assessment Remedial Investigation. Draft Final Report. Volumes I, II and III. Task 25. Prepared for Program Manager, RMA Contamination Cleanup.

RIC#87253R01
ESE. 1987a, August. Final Initial Screening Program Report. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#88015R01
ESE. 1987b, August. Water Level Data, Summary Statistics, and Hydrographs.

RIC#88343R01
ESE. 1987c, December. Rocky Mountain Arsenal Off-post Assessment. Contamination Assessment Report. Final Report. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#87343R03
ESE. 1987d, December. Final Phase I Contamination Assessment Report. Site 26-3. Basin C. Task 6. Prepared for Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#87016R05
ESE. 1986. Rocky Mountain Arsenal Continued Off-post Groundwater Monitoring Program. (Revision III - 360^{0} Monitoring Program). Commerce City, Colorado. Prepared for the Office of the Program Manager, Rocky Mountain Arsenal Contamination Cleanup.

RIC#81356R32
Evans, D.M. 1965. Denver Area Earthquakes and the Rocky Mountain Arsenal Disposal Well. Mountain Geologist V. 3, no. 1, p.23-36.

FRICO (Farmer's Reservoir and Irrigation Company). 1988. Personal Communication.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. 1st Edition. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Fulton Ditch Company. 1988. Personal Communication.

Hamilton, John. 1988. Muller Engineering Company. Oral Communication.

Hansen, W.R and E.J. Crosby, 1982. Environmental Geology of the Front Range Urban Corridor and Vicinity, Colorado. USGS Professional Paper No. 1230.

Harding Lawson Associates, 1989. Regional Ground-Water Flow Modeling at the Rocky Mountain Arsenal, Denver, Colorado. Draft Final Report, Version 2.1.

HRS Water Consultants, Inc., 1986. Aquifer Test on Alluvial Well at 64th Avenue and Quebec Street, August 1986.

Hurr, R.T., P.A. Schneider,Jr., and D.R. Minges, 1975. Hydrology of the South Platte River Valley, Northeastern Colorado. Colorado Water Conservation Board Water Resources Circular 28.

Hutzinger, O., and Roof, A. A. M. 1980. Hydrocarbons and Halogenated Hydrocarbons in the Aquatic Environment: Some Thoughts on the Philosophy and Practice of Environmental Analytical Chemistry. pp. 9-28. B. K. and D. MacKay (eds). Hydrocarbons and Halogenated Hydrocarbons in the Aquatic Environment. Plenum Publishing. New York.

Karickhoff, Samuel W. 1981. Semi Epirical Estimation of Sorption of Hydrophobic Pollutants in Natural Sediments. Chemosphere, Vol 10, No. 8, p. 833.

Kirkham, R.J. and Rogers, W.P. 1981. Earthquake Potential in Colorado: Colorado Geological Survey, Bulletin 43.

Kleopfer, R. D., Easley, D. M., Haas, Jr., B. H. and Delhl, T. G. (1985). Anaerobic Degradation of Trichloroethylene in Soil. Environ. Sci. Technol. 19, 277-280.

Konikow, Leonard F. 1977. Modeling Chloride Movement in the Alluvial Aquifer at the Rocky Mountain Arsenal, Colorado. U.S. Geological Survey Water-Supply Paper Paper 2044, 43 p.

RIC#84324M01
Konikow, L.R. 1975. Hydrogeologic Maps of the Alluvial Aquifer In and Adjacent to the Rocky Mountain Arsenal, Denver, Colorado. U.S. Geological Survey Open-File Report 74-342, 1 Sheet.

Lindvall, R.M. 1980. Geological Map of the Commerce City Quadrangle, Adams and Denver Counties, Colorado: U.S. Geological Survey Map CQ-1541.

Lindvall, R.M. 1983. Geological Map of the Sable Quadrangle, Adams and Denver Counties, Colorado: U.S. Geological Survey Map MF-1180.

RIC#81295R16
Little, 1979. Hydrogeologic Description of Rocky Mountain Arsenal Groundwater Module,

RIC#81295R16
Little, 1979. Hydrogeologic Description of Rocky Mountain Arsenal Groundwater Module, Fourth Interim Report, Installation, Restoration, Simulation and Cost Benefit Analysis. Prepared by Geraghty and Miller.

Lombe T. and Robert V. Whitman. 1969. Soil Mechanics John Wiley and Sons. New York and London.

Mabey, W. R., Barich, V. and Mill, T. (1983) Presentation at the Annual Meeting of the American Chemical Society, Division of Environmental Chemistry.

McCarty, P. L. 1986. Anaerobic biotransformations of chlorinated solvents. Abstract, in. Biological Approaches to Aquifer Restoration. Recent Advances and New Opportunities. Stanford University, California.

Mackay, D.M. and P.V. Roberts. 1985. "A Natural-Gradient Experiment on Organic Solute Transport in a Sand Aquifer; Synopsis of Results," in Proceedings; Second Canadian/American Conference on Hydrology; Hazardous Wastes in Ground Water; A Soluble Dilemma. National Water Well Association. Banff, AB, Canada.

RIC#83299R01
May, J.H., J.D. Crabtree, R.W. Hunt, and M.L. Murphy. 1983. Hydrogeology of Basin A/South Plants Area, Rocky Mountain Arsenal, Denver, Colorado, Phase I. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

RIC#82295R01
May J.H. 1982, July. Regional Groundwater Study of Rocky Mountain Arsenal, Denver, Colorado. Report 1, Hydrogeological Definition. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

RIC#82350R03
May, J.H. and C.B. Whitten. 1982, October. Evaluation of Shell Chemical Company's Groundwater DBCP Control System, Phase I Final Report. Rocky Mountain Arsenal, Colorado. U.S. Army Corps of Engineers Waterways Experiment Station.

RIC#81266R48
May, J.H., D.W. Thompson, P.K. Law, and R.E. Wahl. 1980. Hydrogeologic Assessment of Denver Sands Along the North Boundary of Rocky Mountain Arsenal. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

Miller, C.H. et al. 1979. Preliminary Magnetic, Seismic, and Petrographic Investigation of a Possible Igneous Dike at the Rocky Mountain Arsenal. Denver, Colorado: U.S. Geological Survey, Open File Report 79-1685.

Miller, W.R. 1979. "Application of Hydrogeochemistry to the Search for Base Metals," in Exploration 77; an International Synposium. Ottowa, Ont., Canada.

RIC#81281R04
Mitchell, G.B. 1976. Interim Containment System RMA Memorandum for Record. Prepared for Decontamination Systems Technical Working Group. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

Mabey, W. R., Barich, V. and Mill, T. (1983) Presentation at the Annual Meeting of the American Chemical Society, Division of Environmental Chemistry.

McCarty, P. L. 1986. Anaerobic biotransformations of chlorinated solvents. Abstract, in. Biological Approaches to Aquifer Restoration. Recent Advances and New Opportunities. Stanford University, California.

Mackay, D.M. and P.V. Roberts. 1985. "A Natural-Gradient Experiment on Organic Solute Transport in a Sand Aquifer; Synopsis of Results," in Proceedings; Second Canadian/American Conference on Hydrology; Hazardous Wastes in Ground Water; A Soluble Dilemma. National Water Well Association. Banff, AB, Canada.

RIC#83299R01
May, J.H., J.D. Crabtree, R.W. Hunt, and M.L. Murphy. 1983. Hydrogeology of Basin A/South Plants Area, Rocky Mountain Arsenal, Denver, Colorado, Phase I. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

RIC#82295R01
May J.H. 1982, July. Regional Groundwater Study of Rocky Mountain Arsenal, Denver, Colorado. Report 1, Hydrogeological Definition. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

RIC#82350R03
May, J.H. and C.B. Whitten. 1982, October. Evaluation of Shell Chemical Company's Groundwater DBCP Control System, Phase I Final Report. Rocky Mountain Arsenal, Colorado. U.S. Army Corps of Engineers Waterways Experiment Station.

RIC#81266R48
May, J.H., D.W. Thompson, P.K. Law, and R.E. Wahl. 1980. Hydrogeologic Assessment of Denver Sands Along the North Boundary of Rocky Mountain Arsenal. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

Miller, C.H. et al. 1979. Preliminary Magnetic, Seismic, and Petrographic Investigation of a Possible Igneous Dike at the Rocky Mountain Arsenal. Denver, Colorado: U.S. Geological Survey, Open File Report 79-1685.

Miller, W.R. 1979. "Application of Hydrogeochemistry to the Search for Base Metals," in Exploration 77; an International Synposium. Ottowa, Ont., Canada.

RIC#81281R04
Mitchell, G.B. 1976. Interim Containment System RMA Memorandum for Record. Prepared for Decontamination Systems Technical Working Group. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

MKE (Morrison-Knudsen Engineers, Inc.). 1988. Geology of the Rocky Mountain Arsenal, Adams County, Colorado. Prepared for Holme, Roberts, and Owens. Denver, Colorado.

MKE. 1987. Preliminary Recharge Estimates for RMA Regional Flow Model, Final Version.

RIC#85085R01
Moloney, W. 1982. Assessment of Historical Waste Disposal in Section 36 of the Rocky Mountain Arsenal.

Molz, F.J. and O. Gueven. 1983. An Examination of Scale-Dependent Dispersion Coefficients. Ground Water, Vol. 21, No. 6, p. 715.

Morris, D.A. and A.I. Johnson. 1967. Summary of Hydrologic and Physical Properties of Rock and Soil Materials, as Analyzed by the Hydrologic Laboratory of the United States Geologic Survey, 1948-60. United States Geological Survey Water-Supply Paper1839-D.

National Oceanic and Atmospheric Administration (NOAA). 1957-1976. Climatic Data.

Nelson, M. J. K., Montgomery, S. O., O'Neill, E. J. and Pritchard, P. H. (1986). Aerobic Metabolism of Trichloroethylene by a Bacterial Isolate. Appl. Env. Microbiol. 52, 383-384.

Newsom, J.M. 1985. Transport of Organic Compounds Dissolved in Ground Water. Ground Water Moitoring Review, Vol. 5, No. 2, p. 28.

Olsen, R. L. and Davis, A. O. 1989. Predicting the Fate and Transport of Organic Compounds in Ground Water. Hazardous Materials Control Research Institute, Washington D.C. Manuscript in preparation.

Parker, J.C., and M. Th. van Genuchten. 1984. Flux-averaged and Volume-averaged Concentrations in Continuous Approaches to Solute Transport. Water Resources Research, Vol. 20, p 866-982.

Parsons, F., Wood, P. R. and DeMarco, J. 1984. Transformations of Tetrachloroethylene and Trichloroethene in Microcosms and Groundwater. Jour. AWWA. 76, 56-59

RIC#88131R01
Program Managers Office. 1988. Final Technical Program Plan FY88-FY92. Remedial Investigation/Feasibility Study/Interim Response Actions.

Ramanoorthy, S. and W.S. Molore. 1984. Mechanism of Transport of U-Th Series Radioisotpes from Solids into Ground Water Geochimica et Cosmochimica Acta, Vol 48, No. 2, p 395.

Rao, P. S. C. and Davidson, J. M., eds. 1982. "Retention and Transformation of Selected Pesticides and Phosphorus in Soil-water Systems: a Critical Review". EPA-600/3-82-060. U.S. Environmental Protection Agency, Athens, Georgia.

Roberts, P. V., Schreiner, J. E. and Hopkins, G. D. 1982. Field Studies of Organic Water Quality Changes During Ground Water Recharge in the Palo Alto Baylands. Wat. Res. 16, 1025-1035.

Rochkind, M. L. and Blackburn, J. W. 1986. Microbial Decomposition of Chlorinated Aromatic Compounds. EPA/600/2-86/090. U. S. Environmental Protection Agency, Cicinnati, Ohio.

RIC#84192R06
The Ralph M. Parsons Co., 1955. Final Report Disposal of Chemical Wastes, Rocky Mountain Arsenal. Prepared for the U.S. Army Corps of Engineers.

RCI. 1986. Review and Proposed Revisions of State-Volume Curves for Rocky Mountain Arsenal's Lower Lakes. Ft. Collins, Colorado.

RIC#85128R04
RCI. 1984. Rocky Mountain Arsenal Surface-Water Gaging Report: October 1982-September 1983. Final Report. Ft. Collins, Colorado.

RIC#82096R01
RCI. 1982. Surface-Water Hydrologic Analysis Rocky Mountain Arsenal Denver, Colorado. Fort Collins, Colorado.

RIC#84034R01
RMACCPMT, 1984. Decontamination Assessment of Land and Facilities at Rocky Mountain Arsenal. Draft Final Report.

RIC#83326R01
RMACCPMT, 1983. Selection of a Contamination Control Strategy for Rocky Mountain Arsenal. Final Report.

Robson, S.G. 1987. Bedrock Aquifers in the Denver Basin, Colorado - A Quantitative Water-Resources Appraisal. U.S. Geological Survey. Professional Paper 1257, p.73.

Robson, S.G. 1981. Computer Simulation of Movement of DIMP-contaminated Groundwater Near the Rocky Mountain Arsenal, Colorado, in Permeability and Groundwater Contaminant Transport, ASTM STP 746. T.F. Zimmie and C.O. Riggs, Eds., American Society for Testing and Materials. pp. 209-220.

Robson, S.G. 1977. Digital-Model Study of Groundwater Contamination by Diisopropylmethyl Phosphonate, Rocky Mountain Arsenal Near Denver, Colorado. Progress Report - Phase I. Prepared for the U.S. Department of the Army by the U.S. Geological Survey.

RIC#82350M02
Robson, S.G., and J.C. Romero. 1981. Geologic Structure, Hydrology, and Water Quality of the Denver Aquifer in the Denver Basin, Colorado. Prepared for the United States Geological Survey (USGS) and the Colorado Division of Water Resources.

RIC#81266R69
Romero, J.C. 1976. Report on the Groundwater Resources of the Bedrock Aquifers of the Denver Basin, Colorado. Colorado Department of Natural Resources. Denver, Colorado.

RIC#81266R54
Sampson, J., T. Babor, and C. Prentiss., 1974. Soil Survey of Adams County, Colorado. CSU, USDA.

Shepherd, W. D., 1982. Letter to Commander of RMA from J.H. Knaus, Shell Oil CO., including data from aquifer tests dated May 5, 1982.

Smith, J.H., et al. 1978. Environmental Pathways of Selected Chemicals in Freshwater Systems: Part III, Laboratory Status. EPA-600/7-78-074. SRI Int., Menlc Par, CA.

RIC#84324RO2
Smith R., P. Schneider, and L. Petri, 1963. Ground Water Resources of the South Platte River Basin in Western Adams and Southwestern Weld Counties, Colorado. USGS.

RIC#85133R04
Spaine, P.A., D.W. Thompson, and J.H. Dildane. 1984. Regional Groundwater Study of Rocky Mountain Arsenal, Denver, Colorado. Report 2: Contamination Distribution. U.S. Army Corps of Engineers Waterways Experiment Station, Environmental Laboratory. Vicksburg, Mississippi.

RIC#81293R05
Stollar, R.L. and F. Van der Leeden. 1981. Evaluation of the Hydrogeologic System and Contaminant Migration Patterns, Rocky Mountain Arsenal. Final Report. Geraghty and Miller, Inc. Prepared for U.S. Army Toxic and Hazardous Materials Agency (USATHAMA). Denver, Colorado.

RIC#85130R01
Thompson, D.W., and C.B. Whitten. 1984. Evaluation of Shell Chemical Company's Ground Water DBCP Control System at Rocky Mountain Arsenal for the period of January 1984 September 1984. U.S. Army Corps of Engineers Waterways Experiment Station.

Trimble, and Machette, 1979. Geologic Map of the Greater Denver Area, Front Range Urban Corridor, Colorado. USGS Map I-856-H.

U.S.EPA (1979). Water Related Environmental Fate of 129 Priority Pollutants. Vol II. EPA-440/4-79-029b.

U.S. Geological Survey. 1977. National Handbook of Recommended Methods for Water-Data Acquisition. Office of Water Data Coordination, USGS, Reston, Virginia.

U.S. Soil Conservation Service (SCS). 1970. Irrigation Water Requirements. USDA Technical Release No. 21, U.S. Government Printing Office, Washington, D.C.

RIC#81266R70
Vispi, M.A. 1978. Report of Findings. RMA Pumping Tests. USAEWES Report. U.S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

Vogel, T. M. and McCarty, P.L. 1985. Biotransformation of Tetrachloroethylene to Trichloroethylene, Dichloroethylene, Vinyl Chloride, and Carbon Dioxide Under Methanogenic Conditions. Appl. Env. Microbiol. 49, 1080-1083.

Vogel, T. M. and McCarty, P.L. 1987a. J. Cont. Hydrol. 1, 299-

Vogel, T. M. and McCarty, P.L. 1987b. Abiotic and Biotic Transformations of 1,1,1-trichloroethane under Methanogenic Conditions. Environ. Sci. Technol. 12, 1208-1213.

Vogel, T. M., Criddle, C. S. and McCarty, P. L. 1987. Transformations of Halogenated Aliphatic Compounds. Environ. Sci. Technol. 21, 722-735.

Walton, W. 1987. Groundwater Pumping Tests. Design and Analysis, First Edition. Lewis Publishers, Inc. and NWWA, Chelsea, Michigan.

Walton, William C. and Earl A. Ackroyd. 1966. Effects of Induced Streambed Infiltration on Water Levels in Wells During Aquifer Tests. m Water Resources Research Center Bull. 2.

RIC#84088R01
Ward G. 1984. The 360° Water Monitoring Program, 1983 Review. Rocky Mountain Arsenal, Commerce City, Colorado.

RIC#81266R59
Weimer, R., 1973. A Guide to Uppermost Cretaceous Stratigraphy, Central Front Range, Colorado. Department of Geology, Colorado School of Mines, Golden, Colorado.

Whitman, et. al.,1943. Rocky Mountain Arsenal Water Supply Facilities, Sanitary Department-Graphs of Storage, Area, and Time of Filling for Process Water Storage Lakes. For Kuljian and Co., Engineers. Plan Number 7164-2222.

RIC#88162R03
Wilson, R., Topi, J., Steeples, D. 1987. Feasibility Analysis Basin F Interim Well System Rocky Mountain Arsenal and Results from Shallow Seismic Reflection Surveys near Reservoir F. Omaha District, Corps of Engineers, Omaha, Nebraska.

RIC#81266R68
Wingfield, D. 1977. Installation Assessment of Rocky Mountain Arsenal, Records Evaluation Report No. 107, Volumes, I, II, and Appendices. Prepared for U.S. Army Toxic and Hazardous Materials Agency. Edgewood, Maryland.

RIC#84065R01
Whitten, C.B. and J.H. May, 1983. Evaluation of Shell Chemical Company's Groundwater DBCP System, Rocky Mountain Arsenal, Phase II Report. U.S. Army Corps of Engineers Waterways Experiment Station.

Wood, P. R., Lang, R. F. and Payan, I. L. 1985. Anaerobic Transformation, Transport, and Removal of Volatile Chlorinated Organics in Ground Water. In C. H. Ward, W. Giger and P. L. McCarty (eds). Ground Water Quality. Wiley, New York.

RIC#81266R19
Zebell, R.A., D.W. Thompson, and P.K. Law. 1979. Basin F to North Boundary Area, RMA; Volume I: Geotechnical Definitions; Volume II: Ground Water Analysis. Prepared for U.S. Army Waterways Experiment Station. Vicksburg, Mississippi.

Zoeteman, B. C. J., DeGreef, E. and Brinkmann, F. J. J. 1981. Persistency of Organic Contaminants in Ground Water, Lessons from Soil Pollutant Incidents in the Netherlands. Sci. Tot. Env. 21, 187-202.