

Final

**Summary Report
RCRA Facility Investigation
Contaminated Groundwater Site CG037
GWMU 1B and GWMU 1F
Tinker Air Force Base, Oklahoma**

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List of Acronyms

AAR	average absolute residual
AFB	Air Force Base
amsl	above mean sea level
AOC	area of concern
AR	average residual
ASTM	American Society for Testing and Materials
AWQC	ambient water quality criteria
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylene
BWGW	Basewide Groundwater
BX	base exchange
CAH	chlorinated aliphatic hydrocarbons
CG	contaminated groundwater
COPC	constituent of potential concern
COPEC	constituent of potential ecological concern
CSM	conceptual site model
DCA	dichloroethane
DCE	dichloroethylene
DNAPL	dense non-aqueous phase liquid
DR	degradation ratio
EDR	Environmental Data Resources, Inc.
EPA	U.S. Environmental Protection Agency
ERA	Ecological Risk Assessment
F	Fahrenheit
FSC	Federal species of concern
ft	foot/feet
GWMU	groundwater management unit
HHRA	Human Health Risk Assessment
HI	hazard index
HQ	hazard quotient
HWBZ	Hennessey water-bearing zone
IRP	Installation Restoration Program
IT	IT Corporation

List of Acronyms (Continued)

K	hydraulic conductivity
LSZ	lower saturated zone
MCL	maximum contaminant level
µg/L	micrograms per liter
OCC	Oklahoma Corporation Commission
OWQC	Oklahoma water quality criteria
PCB	polychlorinated biphenyls
PCE	Tetrachloroethylene
PES	Parsons Engineering Science, Inc.
PRG	preliminary remediation goal
PZ	producing zone
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RME	reasonable maximum exposure
SSSC	State species of special concern
SVOC	semivolatile organic compound
SWMU	solid waste management unit
TCA	1,1,1-trichloroethane
TCE	trichloroethylene
TCH	total chlorinated hydrocarbons
USACE	U.S. Army Corps of Engineers
USAF	U.S. Air Force
UST	underground storage tank
USZ	upper saturated zone
UTL	upper tolerance limit
VC	vinyl chloride
VOC	volatile organic compound
WS	water supply

Executive Summary

The purpose of this document is to provide the results of the Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) at Installation Restoration Program Contaminated Groundwater (CG) site 37, Tinker Air Force Base (AFB), Oklahoma. This document covers the portion of CG037 associated with Groundwater Management Units (GWMU) 1B and 1F in the north-central portion of the Base.

Tinker AFB is the home of the Oklahoma City Air Logistics Center and the 552nd Airborne Warning and Control Wing. Tinker AFB is located in the southeastern corporate limits of Oklahoma City, Oklahoma County, Oklahoma. Midwest City and Del City are located to the north and northwest of Tinker AFB. Tinker AFB is bounded on the west by Sooner Road, on the east by Douglas Road, on the north by I-40, and on the south by S.E. 74th Street.

Tinker AFB encompasses 5,041 acres and contains approximately 500 buildings. Operation of Tinker AFB as a major aircraft, weapons, engine repair depot, and logistics center began in 1942 and continues to the present. Past and current operations have required the use of petroleum products and hazardous materials. Operations particular to this investigation have included the bulk storage and use of petroleum fuels (gasoline and diesel) and the use of chlorinated solvents in Base operations.

The primary data set used in the RFI was compiled from wells sampled during the 1999 annual Basewide sampling round. In addition, these data were supplemented with data and information obtained from several other sources, as described and summarized in Chapter 3.0 of this report.

During the sampling activities performed in 1999, for the portion of CG037 associated with GWMU 1, groundwater samples were collected from monitoring wells completed in the upper saturated zone (USZ), the lower saturated zone (LSZ), and the producing zone (PZ), to determine the horizontal and vertical extent of groundwater contamination.

As part of the data gathering and review task completed during this RFI, all existing data, including previous data for trend analysis; data from other studies within the CG037 area; and results from a database records search and review for surrounding sites, receptor identification, and groundwater drinking water wells were compiled. Subsequently, a site conceptual model was constructed, identifying potential sources for groundwater contamination; characterizing the

geology of the area; characterizing the groundwater flow direction, velocities, and migration pathways; and determining the nature and extent of contamination was completed. In addition, potential human and ecological receptors were identified.

Next, a groundwater flow and contaminant transport model was constructed to evaluate varying hydrogeologic conditions. Tasks include setting up boundary conditions for the model, developing and calibrating the numerical model, and implementing the model under various scenarios. Results are used for predicting contaminant concentrations for risk assessment purposes and for evaluating potential removal alternatives.

Finally, a human health and ecological risk assessment were completed. This task was conducted to determine constituents of potential concern (COPC) to human health and the environment, to estimate the potential risks associated with groundwater and surface water exposures to human health and the environment, and to enable future determinations of remediation goals, if necessary. Ecological risk assessment was performed at the screening level.

Based on the analysis of data and observations made in the nature and extent of contamination, the following conclusions are made:

- The nature and extent of contamination of CG037 associated with GWMU 1 can be characterized as defined, particularly the lateral extent. The vertical extent of volatile organic compound contamination is less well-characterized; however, there is little concern that contamination has moved significantly into the lower portion of the LSZ at this time.
- Concentrations of major COPCs, especially fuel-related compounds and total chlorinated hydrocarbons (TCH), are generally higher in the LSZ than in the USZ in the area around GWMU 1B. This phenomenon is explained by the presence of a zone of increased vertical hydraulic conductivity in the vicinity of the Base Exchange Service Station in the USZ-LSZ aquitard. A vacuum enhanced pumping remediation system is currently in place in this vicinity, and was expanded in 1998 and 1999 to include additional extraction wells in the LSZ.
- Temporal trend analysis indicates that although reductive dechlorination is an ongoing process at most locations, little to no chlorinated aliphatic hydrocarbon (CAH) mass loss is observed. The constant, or at some well locations increasing, total CAH mass suggests that there may be a continuing source that is contributing solvents to the groundwater concurrently with degradation. Three potential sources

include desorption of solvents from sediments, a continuing source of solvents in overlying sediments, or the presence of a dense non-aqueous phase liquid (DNAPL) within the plume.

At GWMU 1, there is little evidence that DNAPL is present, other than the limited degree of reduction of chlorinated solvents and the slight increase in total chlorinated hydrocarbons mass. As discussed above, there is a zone of increased vertical hydraulic conductivity in the area around GWMU 1B in the USZ-LSZ aquitard that would serve as a conduit for the downward migration of dissolved constituents. However, the presence of a DNAPL or a continuing source of hydrocarbon contamination from the overlying soils cannot be ruled out based on the existing data.

- Concentrations of TCH are significantly lower in GWMU 1F than in 1B, and are generally confined to the USZ. Fuel-related compounds were not detected in groundwater at GWMU 1F.
- Groundwater at GWMU 1B and 1F contains slightly elevated concentrations of some metals. However, in every case where elevated metals were observed, significantly elevated turbidity of the sample was also observed. It has been shown that there is a strong correlation between elevated turbidity and elevated concentrations of some metals that tend to adsorb onto clay and iron oxide particles entrained in the water sample. Thus, elevated metals are not indicative of a contaminant source. In addition, it has been shown that elevated concentrations of nickel and chromium are related to issues associated with corrosion of steel well screens, and are not indicative of Base activities that contributed to contamination. There is no known activity within CG037 at the Base or suspected source for elevated concentrations of the other metals, such as barium and arsenic.

A conservative groundwater hydrologic model was prepared and used to estimate contaminant fate and transport for the CG037 site. The following conclusions from the contaminant fate and transport model are made:

- Low levels of contamination from GWMU 1B are predicted to reach USZ and LSZ receptor points at the Base boundary within the 30 year time frame calculated by the model. The primary contaminants that will reach the Base boundary include benzene and degradation products of trichloroethylene (TCE). These predictions are conservative, and assume that no effort is made to halt or slow down migration by remediation of the plume.
- Contamination from GWMU 1B and 1F is predicted move in a west-northwest direction, initially towards Crutch and Kuhlman Creeks, then northwest roughly parallel to Crutch Creek towards the boundary of the Base. Again, these predictions did not assume any remedial effort was conducted within the 30-year period of the model.

- Particle tracking calculations performed during the modeling exercise indicate a preferred downward vertical migration pathway in the area around GWMU 1B from the LSZ to the lower portion of the LSZ over time, followed by migration to the northwest coincident with Crutch Creek. It should be noted that particles could not continue to move vertically into the aquitard between the lower portion of the LSZ and the PZ due to the absence of that unit in the hydrologic model.

Based on the data and analysis presented in the baseline risk assessment, both for potential human health and ecological receptors, the following conclusions are made:

- **Current Risk and Hazard.** Cancer risk is in excess of 10^{-4} in the GWMU 1B plume, driven by benzene. The GWMU 1F plume does not exceed cancer risk of 10^{-4} . Carcinogens were not detected in any water supply well within the study area in the current monitoring well data.

Noncancer hazard exceeds 1.0 in both GWMU 1B and 1F. Hazard in GWMU 1B is driven by benzene and TCE; hazard in GWMU 1F is driven by chloroform and TCE. Noncarcinogens were not detected in any on-site water supply well within the study area. Although calculations show that risk and hazard exceed established values, there is no current exposure pathway for on-site workers or offsite residents.

- **Future Risk and Hazard.** A hypothetical future risk at compliance points was estimated by examining modeled groundwater concentrations at 30 years for the locations of on-site water supply wells, and in wells at the Base boundary. The groundwater model was conservative and did not allow for significant degradation, retardation, and other parameters, and did not allow for any effort at remediation during the 30-year time frame for the model. Residential risk downgradient from GWMU 1 in the vicinity of CG037 is significantly below 10^{-4} at well 69 (USZ well adjacent to Kuhlman Creek at the Base boundary), and slightly below 10^{-4} at well 68 (LSZ well adjacent to Crutch Creek at the Base boundary). Future risk to residents from LSZ groundwater at the Base boundary is less than 10^{-4} , and no constituents of concern are predicted in Base boundary wells in units below the LSZ. Future risk to on-site workers indicates that no potential exposure wells (i.e., water supply wells) exhibit cancer risk greater than 10^{-4} in the 30 year time period modeled.

Hypothetical future hazard to residents downgradient from GWMU 1 from USZ groundwater is less than 1.0. Hazard is less than 1.0 in LSZ wells downgradient of GWMU 1 in the vicinity of CG037, and no constituents of concern are predicted in Base boundary wells in units below the LSZ. In addition, no public water supply wells are known to be screened in the USZ in the vicinity of Tinker AFB. Future hazard to on-site workers is below 1.0 for all potential exposure points with the exception of water from water supply well WS-3 (HQ = 3.8). However, WS-3 is an inactive well; therefore, the potential exposure pathway is not complete.

- Cancer risk to the trespasser and maintenance worker for surface water in the vicinity of CG037 associated with GWMU 1 were estimated. Cancer risk to both receptors is less than 10^{-8} ; noncancer hazard is less than 10^{-4} .
- The results of the ecological assessment showed no hazard quotients (HQ) exceeding 1 for the receptor/chemical combinations for which HQs could be determined. HQs could not be determined for 55 of the 120 receptor/chemical combinations, principally due to the lack of toxicological data for plants and birds. However, because of the conservatism associated with the calculated HQs in the assessment and the low values of the majority of these HQs, the weight of evidence indicates that it is highly likely that the chemical contaminants in CG037 will have a negligible contribution to the chemical exposures in and subsequent risk to ecological receptors along these creeks over the next 30 years at least, and probably well beyond that time frame.

The following recommendations are made for the portions of the RFI at site CG037 within GWMU 1B and GWMU 1F:

- Continue monitoring groundwater wells in the vicinity of water supply wells in GWMU 1, particularly wells in the LSZ (including those in the lower portion of the LSZ) to ensure that the quality of water remains acceptable.
- Analyze samples collected from within GWMU 1B for the full Target Analyte List to enable determinations of metals background issues, consideration of issues associated with turbidity and suspended solids, and continued monitoring of well-screen degradation issues.
- Due to elevated risk and hazard in the mass centers of plumes at GWMU 1B and GWMU 1F, and the potential for contamination to migrate vertically to the lower portions of the LSZ, source control is recommended for consideration in a Corrective Measures Study.
- Contaminants have not been detected at the receptor monitoring wells downgradient from GWMU 1B and 1F; therefore, there is no current risk or hazard from exposure to groundwater at these points. Hypothetical future risk and hazard at the downgradient receptor wells near the Base boundary are also within acceptable levels; therefore, remediation techniques focused on capture of the leading edge of the plume may not be warranted.
- It is recommended that the inactive water supply well WS-3 be properly plugged and abandoned to preclude it serving as a possible conduit for contaminant migration from the USZ and LSZ to the PZ.

1.0 Introduction

The U.S. Air Force (USAF) is conducting an Installation Restoration Program (IRP) at Tinker Air Force Base (AFB), Oklahoma (Figure 1-1). The objective of the program is to characterize each solid waste management unit (SWMU), area of concern (AOC), and groundwater management unit (GWMU), study and select cleanup methods, if required, and implement a cleanup. The GWMU, SWMU, and AOC locations are shown on Figure 1-2.

This Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) summary report provides the results of the RFI for IRP contaminated groundwater (CG) site CG037 (Figure 1-3), Tinker AFB, Oklahoma. Specifically covered in this report is the RFI for GWMU 1B and GWMU 1F, within site CG037.

The primary data set used in the RFI was compiled during the basewide groundwater (BWGW) RFI, from wells sampled during the 1999 program year. In addition, the BWGW data were supplemented with data and information obtained from several sources, as described and summarized in Chapter 3.0 of this report.

During 1999, groundwater samples were collected from monitoring wells completed in the upper saturated zone (USZ), the lower saturated zone (LSZ), including wells in the lower portion of the LSZ, and the producing zone (PZ) to determine the horizontal and vertical extent of groundwater contamination. Analytical results and other data collected during the investigation were used in conjunction with existing data sets to prepare potentiometric surface maps, contaminant isopleths, and geologic cross-sections.

The scope of this project is limited to investigation of the nature and extent of groundwater contamination. Soil contamination at individual SWMUs and AOCs is addressed by previous investigations at Tinker AFB.

FIGURES

OKLAHOMA



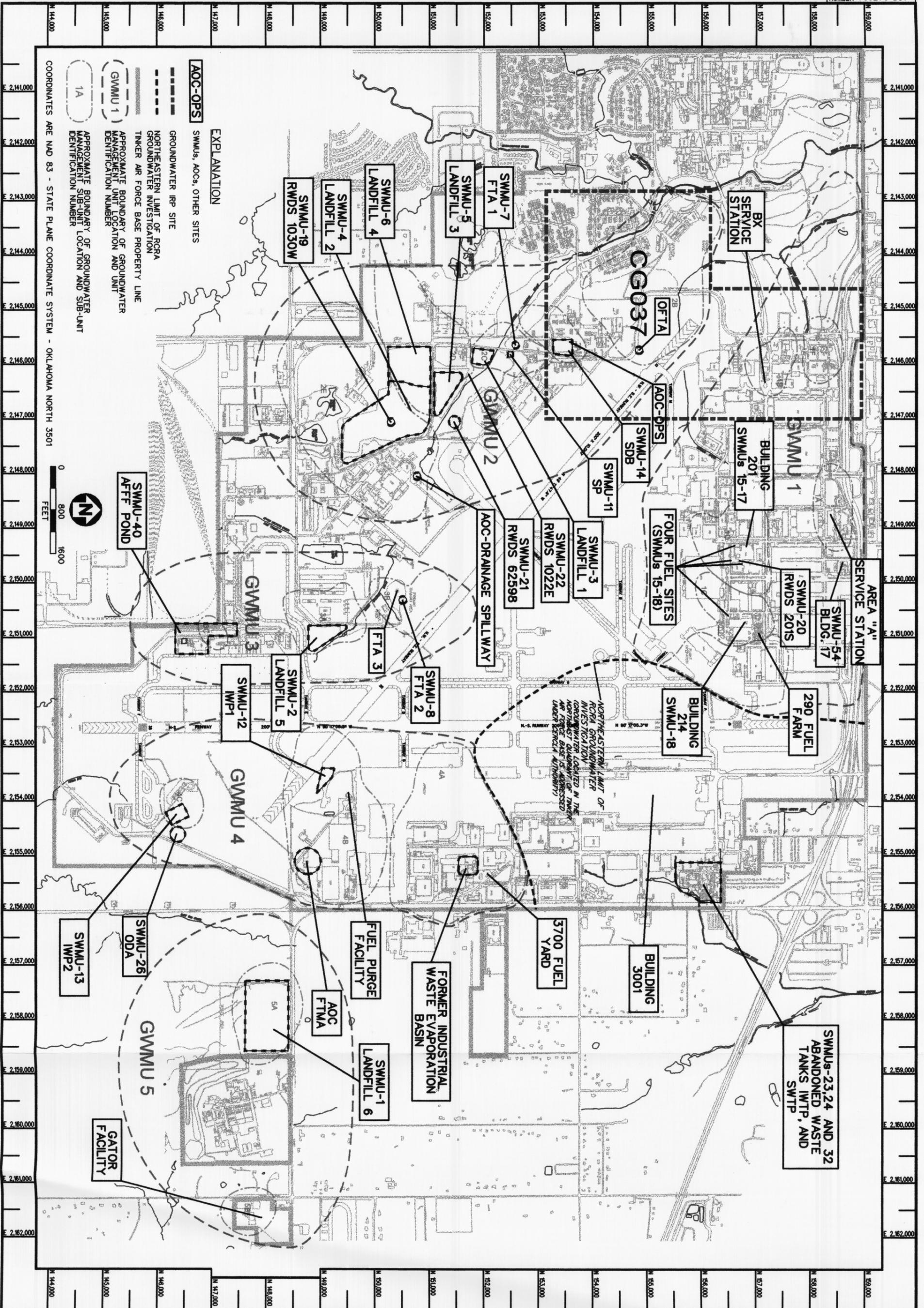
DRAWN BY: CFB
START DATE: 11/28/00
REVISED BY: CFB
LAST REV: 03/15/01
INITIATOR: MG
INT. DATE: 11/28/00

LOCATION MAP FOR
TINKER AIR FORCE BASE
CG037 RFI GWMU 1B AND 1F
PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

PROJ. NO. 799270

FIG. 1-1

UNIQUE NUMBER 799270-A03



DRAWN BY: CFB
 START DATE: 11/27/00
 REVISED BY: CFB
 LAST REV: 03/26/01

SITE LOCATION MAP FOR TINKER AFB

CG037 RFI GWMU 1B AND 1F

PROJ. NO. 799270

FIG. 1-2

2.0 Site Background

Tinker AFB is the home of the Oklahoma City Air Logistics Center and the 552nd Airborne Warning and Control Wing. Tinker AFB is located in the southeastern corporate limits of Oklahoma City, Oklahoma County, Oklahoma (Figure 1-1). Midwest City and Del City are located to the north and northwest, respectively, of Tinker AFB. Tinker AFB is bounded on the west by Sooner Road, on the east by Douglas Road, on the north by I-40, and on the south by S.E. 74th Street (Figure 1-2).

Tinker AFB encompasses 5,041 acres and contains approximately 500 buildings. Operation of Tinker AFB as a major aircraft, weapons, engine repair depot, and logistics center began in 1942 and continues to the present. Past and current operations have required the use of petroleum products and hazardous materials. Operations particular to this investigation have included the bulk storage and use of petroleum fuels (gasoline and diesel) and the use of chlorinated solvents in Base operations.

GWMU 1B and 1F are located in the western portion of GWMU 1 and comprise the northern portion of CG037 (Figure 1-3). This portion of CG037 is bounded on the north by the Tinker AFB boundary, on the south by the northwest-southeast runway in the airfield, on the east by "H" Avenue, and on the west by Kuhlman Creek and the eastern portions of the golf course.

Tinker AFB is an active military industrial facility responsible for the maintenance of a wide variety of military aircraft. In 1984, Congress reauthorized RCRA and amended the statute to allow the U.S. Environmental Protection Agency (EPA) to require a facility, as a permit condition, to take corrective action for any releases of hazardous waste or constituents from any SWMU at a treatment, storage, or disposal facility. These SWMUs do not have to be active units currently being used for treatment, disposal, or storage.

Many of the SWMUs at Tinker AFB are in close proximity to one another, resulting in difficulty in linking detected groundwater contaminants to specific contaminant sources. During the evaluation of data from the Phase II RFI and previous investigations performed at Tinker AFB, it was determined that the most efficient way to evaluate groundwater was to group together adjacent SWMUs, AOCs, and other potential sources that may have contributed to a general area of groundwater contamination. Within these areas, it was anticipated that it would be convenient to treat similar nearby plumes as a GWMU. Figure 1-2 shows the location of the SWMUs and

AOCs, as well as the groundwater IRP site CG037 established in 1996 and the associated portions of GWMU 1 established by Tinker AFB in 1996. The GWMUs were determined based on contaminant distribution and extent.

Based on the distribution of contamination in GWMU 1, six primary locations with groundwater contamination have been identified. These locations are referred to as subunits to GWMU 1. Two of these are located within site CG037, including GWMU 1B and 1F. Chapter 5 of this RFI report provides additional discussion on the GWMU 1 subunits.

Phase I RFIs have been completed at all known SWMUs and AOCs. During these investigations, soil and groundwater were characterized at each site. These investigations not only identified groundwater contamination associated with activities at the SWMU under investigation, but also identified impacts to groundwater that were apparently not associated with activities at the SWMU.

In July 1994, Tinker AFB and the EPA agreed that the most efficient way to investigate groundwater impacts was to perform a Phase II RFI that focused on determining the full extent of groundwater contamination resulting from RCRA units, as well as unknown sources. The fuel-related investigations have been updated under OCC status, with the few exceptions where mixed underground storage tank (UST) and other RCRA site plumes exist. Activities not regulated under the OCC are under the regulatory jurisdiction of the Oklahoma Department of Environmental Quality. The findings of the RFIs and UST investigations are summarized in separate reports. A more complete description of the past operations and results of past investigations is provided in the BWGW Phase II RFI Addendum 2 Work Plan (IT Corporation [IT], 1999a) and a more complete description of the studies utilized in the development of the RFI is presented in Chapter 3.0.

3.0 RFI Field Investigation Activities

Specific field sampling activities, such as groundwater monitoring well installation and associated soil and groundwater sampling, etc., were not performed for the RFI at CG037. However, field site visits were conducted to verify information gathered from other sources as described below.

3.1 Summary of Data Used in the RFI

The primary data source for the RFI at CG037 is the BWGW RFI, specifically data from the 1999 program year. These data include BWGW monitoring well fluid levels from May and October 1999, and analytical data from groundwater samples obtained during the December 1999 Basewide event. For the purposes of temporal trend analyses, the data from previous BWGW events were also used.

In addition to the BWGW data, other data and information were obtained from the following sources:

- Remedial Action Plan for UST Site 23, Tinker AFB, Oklahoma (Parsons Engineering Science [PES], 1997a), and supplemental remediation reports 1997 through 1999. Data from this program were used to supplement data from GWMU 1B and 1F to assist in the determination of the nature and extent of contamination at the unit and to facilitate development of the groundwater numerical model.
- Monitoring Report for UST Site 23, Tinker AFB, Oklahoma (PES, 2000).
- Crutcho and Kuhlman Creeks and Tributaries of Elm Creek, Final Remedial Investigation Report, Tinker AFB, Oklahoma (Halliburton NUS Corporation, 1992). Data from this study were used to assist in the ecological conceptual model formulation and risk assessment, as well as in the determination of the nature and extent of contamination.
- Final Letter Report, Crutcho Creek Influent/Effluent Study, Tinker AFB, Oklahoma (Battelle, 1995). Data from this study were used to assist in the ecological conceptual model formulation and risk assessment, as well as in the determination of the nature and extent of contamination and potential source evaluation.
- Plug, Abandon, and Construct Monitoring Wells No. 7 Final Report, Tinker AFB, Oklahoma (Tetra Tech Remediation and Construction Services, 1999). This report provided additional analytical results for new wells installed during the 1999 year and not sampled during the BWGW event.

- Storm Sewer Investigation for Crutchko and Kuhlman Creeks, Tinker AFB, Oklahoma (NUS Corporation, 1990). Data from this study were used to assist in the ecological conceptual model formulation and risk assessment, as well as in the determination of the nature and extent of contamination and potential source evaluation.
- Semiannual Report for the Long-Term Monitoring (IV) of Crutchko Creek, Kuhlman Creek, and Tributaries of Elm Creek, Tinker AFB, Oklahoma (PES, 1999a). Data from this study were used to assist in the ecological conceptual model formulation, as well as in the determination of the nature and extent of contamination.
- Habitat Assessment of Crutchko and Kuhlman Creeks, Tinker AFB, Oklahoma (PES, 1996). Information from this study was used to assist in the ecological conceptual model formulation and risk assessment.
- EDR Radius Map with GeoCheck[®], Tinker AFB, Oklahoma (EDR, 2000a). This study was performed as part of the RFI at CG037 and included a search of reasonably available and ascertainable government records and databases with any reference to the subject property or within a search radius around the property of two miles. Additional information regarding the records search is provided below in Section 3.2.
- EDR Offsite Receptor Report, Tinker AFB, Oklahoma (EDR, 2000b). This study was performed as part of the RFI at CG037 and included a search of reasonably available and ascertainable government records and databases within a 2 mile search radius to provide useful information regarding potential off-site receptors. The results of the EDR search were considered in the development of the human health and ecological conceptual site model formulation and risk assessment. Additional information regarding the Offsite Receptor Report is provided below in Section 3.3.
- Drawings from Air Force Master Plan, 1955 and 1963, Tinker AFB, Oklahoma. These drawings were used to develop the generalized conceptual site model and evaluate potential source areas for contamination within CG037. The drawings show general activities that took place in buildings and areas during the late 1950s, particularly in the vicinity of GWMU 1, that may have contributed to groundwater contamination currently present within the area.
- Aerial photographs, 1945 through 1995, Tinker AFB, Oklahoma. A study of aerial photographs from the late 1940s through 1995 provided valuable insight into potential source areas for the groundwater contamination found at CG037, particularly in evaluating potential sources of contamination for the southern portions of GWMU 1 and the northern portions of GWMU 2 within CG037.
- Maps of buried utility lines, including sanitary sewer, storm sewer, electrical, natural gas, communication, steam, and fuel, Tinker AFB, Oklahoma. An evaluation of buried utility lines at Tinker AFB for the potential for the lines to serve as either

sources of contamination or preferential conduits for the migration of contamination was performed.

3.2 Summary of EDR Search Results

A search of available environmental records was performed for the subject site by EDR (2000a). The search and report met the government records search requirements of the American Society for Testing and Materials (ASTM) Standard Practice for Environmental Site Assessments E1527-97. All publicly available databases that were relevant to Tinker AFB Site CG037 were included in the search.

The search provides information as to the identity of sites that are found in one or more of the databases; an approximate elevation of the site; and distance and direction from a reference point – in this case, the approximate northwest corner of Tinker AFB was used and a 2-mile radius search was performed. The potential impact from any and all sites was evaluated as part of the determination of the nature and extent of contamination and development of potential source determination for groundwater contamination, particularly as it relates to potential offsite sources. Finally, in addition to searching the databases discussed above for potential source areas for groundwater contamination migrating onto Tinker AFB, the EDR report includes the results of a search of Federal, State, and local groundwater wells to provide the location of known drinking water supply wells within a search radius.

The results of the EDR database searches revealed only one site is likely a potential source area for groundwater contamination within GWMU 1 (EDR, 2000a). The site is a Texaco station located just north of the Tinker AFB northern boundary that may have impacted USZ groundwater as it migrates onto the Base. The ramifications of this impact are discussed more fully in Chapter 5 of this RFI summary report.

3.3 EDR Offsite Receptor Report Results

A search of available environmental records was performed for the subject site by EDR (2000b). The purpose of the database search was to provide useful information regarding potential receptors in the area adjacent to the northwest corner of Tinker AFB, within a 2 mile radius. The EDR search provides data on population census, Federal land management information, day-care centers, nursing homes, schools, arenas, and other areas where individuals who are potential public receptors to the offsite migration of contamination are likely to be located. The results of the EDR search were considered in the development of the human health and ecological conceptual site model formulation and risk assessments.

The results of the Offsite Receptor search are as follows:

- Estimated population in the search radius is 35,694 persons
- A total of 43 daycare centers are located within the search radius
- A total of 29 schools (including elementary, middle, and secondary) are located within the search radius
- One nursing home is located within the search radius.

Because the CG037 site is related to contaminated groundwater, none of the potential receptors identified above are likely at increase risk of exposure as a result of location. All potential receptors in the vicinity of the northwest corner of Tinker AFB are included in the human health and ecological risk assessment conceptual models due to the potential for exposure to contaminated drinking water if contamination enters a local water supply well and, to a lesser degree, if the potential exists for exposure to contaminated surface water. Exposure pathways are evaluated in the risk assessment and groundwater model chapters (Chapters 6.0 and 7.0, respectively) of this RFI report.

4.0 Environmental Setting

4.1 Location and Surrounding Land Use

Tinker AFB is located in Oklahoma County, within the metropolitan area of Oklahoma City. Nearby communities also include Midwest City and Del City. The Oklahoma City area is located within the Central Redbed Plains section of the Central Lowland Physiographic Province (Curtis and Ham, 1972).

Land use surrounding Tinker AFB in the vicinity of CG037, particularly to the north of GWMU 1, is a mixture of residential and commercial/light manufacturing. The Base is bounded on the north by Interstate-40 and associated access roads. These access and feeder roads are well-developed with automobile service stations, automobile and truck sales lots, and strip-type shopping centers with commercial businesses. Residential areas are located north and northwest of the interstate and the business districts, and nearly adjacent to the Base boundary to the west.

4.2 Climate

The climate at Tinker AFB is characterized by long hot summers. Occasional droughts of varying duration occur. The average annual temperature is approximately 60° to 62° Fahrenheit (F). The hottest month is typically July with a mean monthly temperature of 82°F; the coolest month is typically January, with a mean monthly temperature of 37°F. Maximum precipitation generally occurs in May and decreases in June, setting the stage for hot, dry summers (U.S. Army Corps of Engineers [USACE], 1993). The average annual precipitation at Tinker AFB is approximately 33 inches. Evaporation, as measured in a U.S. Weather Bureau Class A pan, is approximately 85 inches per year.

4.3 Topography, Surface Water, and Surface Drainage

The area is characterized by nearly level plains to gently rolling hills. At Tinker AFB ground surface elevations range from 1,190 feet above mean sea level (amsl) near the northwest corner to over 1,300 feet amsl near the southeast corner of the Base. The native topography of parts of the Base has been somewhat altered by cut-and-fill activity during construction activities.

Tinker AFB is dissected by several tributaries of the North Canadian River, while the southeast part of the Base has been dissected by tributaries of the Little River. Thus, a drainage divide crosses the southern part of the base, separating these two major river basins.

Surface water runoff on Tinker AFB is conveyed through ditches and diversion structures to on-site streams. Runoff in the north and west sections of the Base, including the main instrument runway, drains to Crutcho Creek. Kuhlman Creek is a tributary of Crutcho Creek, crossing from east to west across GWMU 1 then turning northwest to exit the Base roughly parallel to Crutcho Creek. Kuhlman Creek flows into Crutcho Creek approximately 1 mile north of the Base boundary. Crutcho Creek is a tributary of the North Canadian River.

4.4 Geologic Setting

4.4.1 Regional Geology

The Central Oklahoma region is underlain by Pennsylvanian and Permian sedimentary rocks which are overlain in places by Quaternary alluvium and terrace deposits. The bedrock formations dip to the west at approximately 30 to 40 feet per mile. The formations generally strike slightly west of north. Older formations outcrop progressively farther east.

The bedrock geologic formations, which are important to an evaluation of the fate of surficial or near surface contaminant releases at Tinker AFB, include, from youngest to oldest, the Hennessey Group, the Garber Sandstone, and the Wellington Formation (Table 4-1). The Garber Sandstone and the Wellington Formation are the principal water-bearing units of the Central Oklahoma Aquifer. Underlying the Wellington Formation are Permian age rocks of the Chase, Council Grove, and Admire Groups, which are also considered to be a part of the aquifer. These Groups overlie the Vanoss Formation, which is the lower confining bed of the aquifer.

The Hennessey Group, Garber Sandstone, and Wellington Formation were deposited during the Permian Period. The units form a conformable sequence of sandstones, siltstones, and shales. The Hennessey Group consists of reddish-brown shale and mudstone, with a few thin, lenticular beds of very fine-grained sandstone.

The Garber Sandstone and Wellington Formation have similar lithologies. In Central Oklahoma, these units consist of lenticular beds of fine-grained, cross-bedded sandstone interbedded with siltstone and mudstone. The sand is predominantly quartz. These formations form approximately the upper 1,200 feet of the stratigraphic column at Tinker AFB (Christenson, et al., 1992). Both of these formations were deposited in a fluvial-deltaic environment at the margin of a broad Permian basin located to the west. A Permian delta is reported to have existed generally in the

vicinity of present day central Oklahoma County (Patterson, 1993), where as much as 75 percent of the Permian section is sandstone. Lithology is highly variable, with individual lithologic beds pinching out abruptly by grading laterally into a different lithology, making time-stratigraphic correlation difficult.

4.4.2 Geology of CG037

The geology of the GWMU 1 portion of CG037 is illustrated in the geologic cross-sections presented as Figures 4-1 through 4-4. The Hennessey Group crops out generally in the south and southwestern two thirds of the Base, reaching a maximum thickness of approximately 60 feet. The unit thins to an erosional edge in the northeast portion of the Base and in the northeast portion of CG037. The contact between the Hennessey Group and the underlying Garber Sandstone is often difficult to distinguish; thin remnants of the Hennessey Group are believed to be present at higher topographic elevations in the central, eastern, and northeastern parts of the Base. The Hennessey Group was deposited in a tidal flat environment cut by shallow, narrow channels. The unit is composed predominantly of red shale and thin beds of fine sandstone. Locally, the unit consists of clay, silty clay, and clayey silt with interbedded sandy clay and clayey sand layers up to 3 feet thick. The Hennessey Group sediments are only encountered in the far west and southern portion of the unit. Elsewhere within the area, the Hennessey Group sediments are missing and the Garber Sandstone outcrops at the surface.

The Garber Sandstone conformably underlies the Hennessey Group, and outcrops generally in the north-central and northeast part of CG037. Outcrops of the Garber located north of the Base are characterized by small to medium channels with cross-bedded sandstones featuring cut and fill structures. The Garber is composed dominantly of fine-grained sandstone, with lesser amounts of siltstone and shale, deposited in fluvial-deltaic environments. The sandstones are typically fine to very fine grained, friable, and poorly cemented. However, the sandstone intervals are cemented in places, typically at the base of sandstone lens, by silica, carbonate or iron-bearing minerals, forming horizons resistant to drilling. It is suggested that the silty clays, because of their reduced permeability, may have contributed to the extent of increased cementation in the overlying sands. In some areas the degree of cementation has progressed to the degree that the basal part of the sands can act as an aquitard. The shale intervals are generally discontinuous, and range in thickness from a few inches to 40 feet.

The Wellington Formation outcrops immediately east of the Base, and underlies the Garber Sandstone. The lithology of the Wellington is similar to that of the Garber, making it difficult to

differentiate between the two formations. The Wellington is composed predominantly of fine-grained sandstone, often in a clay matrix, cemented by silica, carbonate or iron-bearing minerals. The sandstone units are interbedded with shale. The combined thickness of the Garber Sandstone and the Wellington Formation is over 1,000 feet.

The overlapping silty clay layers which form the USZ aquitard are locally discontinuous in GWMU 1. These discontinuities, which result in “gaps” in the clay aquitard, are associated with lateral facies changes, or channel scours through the aquitard. These localized “gaps” in the aquitard provide potential conduits for migration of groundwater between saturated zones.

Four major soil associations (Table 4-2) have been mapped within the Base limits (U.S. Department of Agriculture, 1969; USAF, 1999). The residual soils associations are products of the weathering of underlying ancient bedrock. The alluvial materials are developed on younger silts and sands that are typically restricted to floodplains of area streams.

4.5 Hydrogeology

4.5.1 Regional Hydrogeology

The regional source of potable groundwater, the Central Oklahoma Aquifer, underlies about 3,000 square miles of central Oklahoma, including all of Oklahoma County, where Tinker AFB is located. The productive formations of the aquifer include the Permian red beds, including parts of the Permian Garber Sandstone, Wellington Formation, and the Chase, Council Grove, and Admire Groups, and Quaternary alluvium and terrace deposits. The eastern extent of this aquifer is delineated by outcrops of the Chase, Council Grove, and Admire Groups in Payne, Lincoln, and Pottawatomie Counties. All strata dip generally westward, while the topographic elevations decline toward the east. The western boundary of the aquifer occurs at the down-dip limits of freshwater circulation, near the Oklahoma-Canadian/Kingfisher-Logan county line. The northern and southern boundaries of the aquifer have been defined as the Cimarron River and Canadian River, respectively (Parkhurst et al., 1993) based on a reduction in transmissivity beyond these areas.

The highest capacity wells are completed in the Garber Sandstone and the Wellington Formation, often referred to collectively as the “Garber-Wellington” aquifer. The Hennessey Group overlies the Garber-Wellington aquifer, forming an upper confining bed where present. The underlying Vanoss Formation forms the lower confining bed of the Garber-Wellington aquifer.

Groundwater in the Central Oklahoma aquifer is derived primarily from precipitation that falls on the outcrops of the geologic units. Infiltration of water from streams crossing the outcrops is likely a minor source of recharge to the aquifer (Parkhurst et al., 1993). Tinker AFB is located in an outcrop area of the Garber Sandstone and within the recharge zone of this aquifer.

4.5.2 Hydrogeology of CG037

The primary water-bearing units identified and evaluated beneath CG037 are, in descending order, the USZ, the LSZ, and the PZ. In other areas at Tinker AFB, particularly to the south of GWMU 1, the Hennessey Group sediments are saturated or partially saturated; in these areas, the first water-bearing unit is known as the Hennessey Water-Bearing Zone (HWBZ). The LSZ is also subdivided into upper and lower parts for convenience in discussing monitoring wells screened at different depths in this zone, specifically as it relates to the groundwater model described in Chapter 7.0 of this report. The hydrogeology of these water-bearing zones at CG037 is described below; the chemical quality of the zones is discussed in Chapter 5.0 of this report.

In the portion of CG037 associated with GWMU 1, the HWBZ is present only to a limited extent near the western edge of the Base (i.e., near monitoring well cluster 40). Therefore, this unit is not included in further discussions of the hydrogeology at CG037.

The USZ and the LSZ intervals have been defined to include their lower bounding aquitards, the USZ-LSZ aquitard and the LSZ-PZ aquitard, respectively. These aquitard zones are composed of interbedded fine-grained beds that serve as partial hydraulic barriers to cross-aquifer flow of groundwater. The aquitards are shown on the geologic cross-sections (Figures 4-2 through 4-4).

Monitoring wells in the area around GWMU 1B and 1F are screened in the USZ, the LSZ, and the PZ. Potentiometric surface maps are provided in Figures 4-5 and 4-6 for the USZ and LSZ, respectively. A potentiometric map for the PZ was not prepared due to the lack of monitoring wells in this area. Profiles of these potentiometric surfaces are shown on the site-specific geologic cross-sections in Figures 4-2 through 4-4. Water level data for Tinker AFB monitoring wells collected in October 1999.

The water-bearing zones and aquitards that were evaluated as part of this study are described below in further detail for the portions of CG037 within and associated with GWMU 1B and 1F.

Surface Water. As shown in Figure 1-3, Crutch Creek approaches the far western edge of GWMU 1. The north and south tributaries of Kuhlman Creek drain the western part of the unit in the vicinity of GWMU 1B and 1F in CG037. Several studies have been conducted to determine stream characteristics, the degree of interaction of the creek with groundwater, and the presence or absence of contamination in and adjacent to the streams. The results of these studies are summarized below as they relate to surface water and groundwater within CG037.

A groundwater investigation was conducted for Crutch Creek to determine the degree of interaction of groundwater with the creek along several reaches, including sections in the vicinity of GWMU 1 (PES, 1999b). A total of 104 boreholes were completed immediately adjacent to Crutch Creek, and 85 water samples were collected and analyzed for volatile organic compounds (VOC). Static water levels were measured in the small-diameter borings, the locations were surveyed, and elevations determined. In addition to the groundwater study, a flow analysis study of Crutch and Kuhlman Creeks was performed (PES, 1997b). In the flow analysis study, piezometers and permeameters were installed, along with staff gauges, to determine average stream flow, seasonal flow gradients, and seasonal groundwater flux. Two additional studies provide information on stream physical characteristics, flow measurements, surface water drainage, and the interaction of surface water with groundwater. These include a habitat assessment of Crutch and Kuhlman Creeks conducted to support the determination of whether environmental impacts have occurred in the area (PES, 1996), and a remedial investigation for Crutch and Kuhlman Creeks and tributaries of Elm Creek to determine the presence or absence of contamination in those surface water bodies (Halliburton NUS, 1992).

The studies concluded that Crutch Creek remains a gaining stream in the vicinity of CG037, through all reaches passing from south to north through GWMU 2C, 2A, 2B and on through to the west of CG037 and GWMU 1 as it exits the Base boundary to the north (PES, 1999b, 1997b). Kuhlman Creek was shown to exhibit both gaining and losing characteristics, depending on location (PES, 1997b, 1996). These groundwater flow reversals may be attributed to drought conditions, unseasonably large amounts of rainfall, and/or discharges to the storm drains that make up the headwaters of Kuhlman Creek (PES, 1997b; Halliburton NUS, 1992). Three areas of Crutch Creek were found to be contaminated during the groundwater study, two of which are near CG037; however, these areas are located in the vicinity of GWMU 2A and 2C. Data indicate that, while groundwater has the potential to discharge to Crutch Creek west of GWMU 1, contaminated groundwater is not present in this area at this time (PES, 1999b). Contamination was not found in or adjacent to Kuhlman Creek or the tributary in the vicinity of

GWMU 1F during the studies. Additional discussion on the nature and extent of contamination is presented in Chapter 5.0 of this RFI report.

Hennessey Water-Bearing Zone. The HWBZ is not present in the portion of CG037 associated with GWMU 1. However, Hennessey Group sediments are present in the western edge of GWMU 1 and have an impact on infiltration and other hydrogeologic characteristics that affect the lower units. The unit receives recharge from precipitation that falls on its outcrop. The silty and sandy lenses within the Hennessey sediments are likely to have greater hydraulic conductivity than the formation as a whole; however, the lenses are laterally discontinuous as shown in the geologic cross-sections (Figures 4-2 through 4-4). Desiccation cracks are present that may increase infiltration rates in some areas of the Hennessey outcrop.

Upper Saturated Zone. The USZ is the uppermost water-bearing zone of the Garber-Wellington Aquifer within the study area. The USZ is approximately 50 feet thick, measured from the base of the overlying Hennessey Group to the base of the USZ-LSZ aquitard. The potentiometric level of the USZ occurs at different depths, ranging from the land surface in the northeastern part of the Base to approximately 60 feet below ground surface to the southwest of the study area. The base of the USZ-LSZ aquitard ranges from approximately 30 feet below ground surface in the east part of the Base to approximately 110 feet below ground surface in the southwest. The eastern edge of the USZ occurs immediately east of the Base. Although a large part of Tinker AFB is an area of recharge for the USZ, the area near the eastern Base boundary is the primary zone of recharge since the Hennessey Group sediments are thin or missing.

Due to its shallow nature, the gradient in the USZ at GWMU 1 is affected by pumping in USZ recovery wells near the former Base Exchange (BX) Service Station in GWMU 1B, surface drainage, and precipitation. Additional variations to gradient and flow are influenced by differences in hydraulic conductivity, thickness, or recharge rates. The USZ is primarily a water table aquifer in GWMU 1, although it may be locally confined in the Garber Formation.

Within the USZ, it is anticipated that because of the rapid lateral and vertical changes in grain size, amount of clay matrix, degree of cementation, etc. observed in the Garber-Wellington, marked changes in vertical flow rates and direction of groundwater and contaminant movement may exist. Thinning, and possibly gaps, in the USZ-LSZ aquitard in the area allow groundwater to flow vertically downward to the LSZ.

USZ-LSZ Aquitard. The USZ-LSZ aquitard, a predominantly clayey unit, comprises the lower part of the USZ (Figures 4-2 through 4-4). This aquitard is not a continuous clay unit of uniform thickness, but rather consists of overlapping clay layers with interbedded thin sand lenses. The clay-rich aquitard interval varies in thickness from less than 10 feet to greater than 25 feet. In a few areas the aquitard interval is occupied mostly by sand and a few thin clayey beds. Immediately beneath this aquitard lies more fine-grained Garber Sandstone which is the top of the LSZ. The USZ-LSZ aquitard allows some hydraulic communication between the USZ and the LSZ, possibly due to gaps in the aquitard that may allow groundwater to flow vertically downward to the LSZ, as indicated by the distribution of chemical contaminants in the LSZ described in Chapter 5.0 of this report. The overlapping nature of the clays which make up this aquitard probably contribute to some variability in its overall hydraulic conductivity and its ability to restrict vertical leakage from the USZ to the LSZ.

Lower Saturated Zone. The LSZ at GWMU 1, a part of the Garber-Wellington Aquifer, underlies the USZ-LSZ aquitard. The stratigraphic interval occupied by the LSZ is approximately 200 feet thick, thinning to 140 feet due to erosion of shallower units. The LSZ is areally extensive and is found throughout the study area.

Recharge of the LSZ at CG037 occurs by downward movement of groundwater from the USZ through the USZ-LSZ aquitard and by lateral inflow of LSZ groundwater from east of the Base. Vertical recharge is probably enhanced locally along the eastern Base boundary where the edge of the USZ occurs and where the USZ-LSZ aquitard is thin or absent.

There is a downward hydraulic gradient within the LSZ on the eastern side of the Base, where water levels in the lower portions of the LSZ may be as much as 10 feet to 15 feet below water levels in the upper portion of the aquifer. However, on the west side of the Base there is little, if any, difference in water-level elevations in the upper and the lower portions of the LSZ. This is in part the result of frictional loss due to the distance from recharge areas, but also indicates that hydraulic communication between the zones is good. Groundwater in the LSZ generally flows to the southwest, except on the west side of the base where the groundwater gradient flattens and turns to the northwest near a flow divide. This divide is in response to the presence of two different discharge areas, one to the north (Deep River) and one to the south (Canadian River).

Elevations of the potentiometric surface of the LSZ at GWMU 1 during October 1999 are shown on Figure 4-6. The general groundwater flow is toward the west except in the western part of the

GWMU where the LSZ flattens and turns to the northwest. Local variations in the hydraulic gradient and groundwater flow direction as shown on Figure 4-6 are potentially due to differences in hydraulic conductivity or formation thickness, the influence of water withdrawals for remediation activities in the area around the former BX Service Station, or differences in recharge rates from one area to another.

LSZ-PZ Aquitard. The LSZ-PZ aquitard occurs at the base of the LSZ and separates the LSZ from the underlying PZ. The aquitard appears to be similar to the USZ-LSZ aquitard in that it is made up of a series of overlapping clays with interbedded sand lenses. The LSZ-PZ aquitard is likely present beneath all of CG037. The continuity and thickness of the clays in the aquitard are difficult to assess due to the relatively few number of wells drilled into the PZ. Cross-sections constructed during the investigation indicate that this aquitard is approximately 30 feet thick (Figures 4-2 through 4-4); however, regional studies of the Garber-Wellington Aquifer suggest this aquitard may be 80 to 100 feet thick.

Producing Zone. Beneath the LSZ aquitard is a water-bearing zone that is known at Tinker AFB as the PZ. The top of the PZ, based on well and cross section data, ranges from approximately 200 to 280 feet below ground level, and extends to over 1,000 feet below ground surface. Due to the very limited number of PZ wells installed in and around GWMU 1, no hydrogeologic evaluation of this water-bearing zone was performed.

This zone is tapped by water supply wells on both Tinker AFB and elsewhere in the Oklahoma City area. Data supplied by Wood and Burton (1968) from the Nichols Hills area to the west of the Base support a conclusion that there is little vertical communication between the PZ and shallower zones. Only one monitoring well is screened in the PZ within the CG037 study area. The direction of groundwater flow is strongly influenced by production from water supply wells. A total of 3 water supply (WS) wells are screened within the PZ in the vicinity of GWMU 1 (WS-1, -2, and -3); however, WS-3 is inactive. Where not affected by production wells, groundwater flow in the PZ divides in the north central part of the Base with a predominant southeast component and a lesser southwest component (IT, 2000).

4.5.3 Groundwater Usage at CG037

Tinker AFB presently obtains approximately 75 percent of its water through a series of wells completed in the lower part of the aquifer, though supplementary water is purchased from the Oklahoma City Water Department. Eight Tinker AFB water supply wells completed in the PZ

are located within CG037, four of which are located in the vicinity of GWMU 1B and 1F. One of these wells, WS-3, is not presently in use. All water supply wells at the Base are completed in the Garber and Wellington units, with multiple screened or perforated intervals that typically range from 400 to 800 feet in depth. The deeper screened intervals of some of the wells have been plugged to prevent entry of saline water. Yields range from approximately 150 to 250 gallons per minute. Some of the wells have been perforated since their initial construction in order to increase water yield.

The nearby communities of Midwest City and Del City obtain their water supplies from both surface waters and groundwater. Outside the western edge of the Tinker AFB boundary there is one Del City water supply well (DC-20) completed below the LSZ-PZ aquitard. Many households, farms, small communities and industries not served by a municipal distribution system also depend on wells completed in the aquifer. Some of these wells are likely completed in water-bearing zones above the PZ.

Water produced from the aquifer is of sufficient quality to be used for most industrial, agricultural, and domestic purposes, although the water locally may be hard, or high in sulfate, chloride, nitrate, or dissolved solids.

4.6 General Conceptual Site Model

A generalized, conceptual site model (CSM) block diagram for CG037 is provided in Figure 4-7. The area shown in the three-dimensional conceptual diagram includes the range of potential migration pathways for groundwater contamination occurring within the site, including vertical and horizontal migration of groundwater; potential interaction of groundwater with surface water; approximate location of groundwater contaminant plumes; approximate potentiometric surface elevations; general direction of groundwater flow; surface topographic expression; and structural geologic bedding.

As is shown in the general CSM, contamination released into the groundwater in upper zones within CG037 has the potential to migrate downward vertically and horizontally to the LSZ. Contamination within the LSZ has the potential to migrate vertically through the LSZ-PZ aquitard into the PZ. Contamination within the USZ and the LSZ has the potential to migrate horizontally to surface water exit points, particularly to Crutchko and Kuhlman creeks. The CSM generally shows the location and possible migration mechanism for dissolved-phase

contaminants; however, the possible migration of non-aqueous phase liquids through one or more pathways is not ruled out.

4.7 Potential Groundwater Contamination Receptors

Potential human and ecological receptors of groundwater contamination at Tinker AFB are discussed below.

Human Receptors. Tinker AFB is situated on a relatively flat expanse of grassland. Prior to the development of the Base, the area was characterized by large tracts of private agricultural land. The Base currently occupies approximately 5,041 acres of semi-improved and unimproved grounds that are used for the airfield, golf course, housing area, offices, shops, and other uses characteristic of military installations.

In 1989, approximately 26,000 military and civilian personnel worked at Tinker AFB. Of these personnel, approximately 2,722 personnel occupied on-Base housing, which consisted of 530 family housing units and seven dormitories. At that time, 1,262 of these residents were children. Military personnel and their families who reside on Base represent the nearest receptors to releases from Tinker AFB. However, access to areas impacted by Base activities is restricted in most cases, and direct contact by Base residents is not likely. The current land use at and near the Base is not expected to change because the facilities have decades of useful life remaining and the Base has an important and continuing mission.

Ecological Receptors. Tinker AFB lies within a grassland ecosystem, which is typically composed of grasses and riparian (trees, shrubs, and vines associated with water courses) vegetation. This ecosystem has generally experienced fragmentation and disturbance as a result of urbanization and industrialization at and near the Base. While no threatened or endangered plant species occur on the Base, the Oklahoma penstemon (*Penstemon oklahomensis*), identified as a rare plant under the Oklahoma Natural Heritage Inventory Program (USAF, 1999), thrives in several locations on Base. Tinker AFB policy (AFR 126-1) is to treat rare species as if they were threatened or endangered and provide equivalent protection for these species. In general, wildlife on the Base is tolerant of human activities and urban environments. No federal threatened or endangered species have been reported at the Base.

The Oklahoma Department of Wildlife Conservation also lists several species within the state as Species of Special Concern. Information on these species suggests declining populations but

information is inadequate to support listing, and additional monitoring of populations is needed to determine the species status. These species also receive protection by Tinker AFB as if they were threatened or endangered. Of these species, the Swainson's hawk (*Buteo swainsoni*) and the burrowing owl (*Athene cunicularia*) have been sighted on Tinker AFB (USAF, 1999). Swainson's hawk, a summer visitor and prairie/meadow inhabitant, has been encountered Basewide. The burrowing owl has been known to inhabit the airfield at the Base.

TABLES

Table 4-1

Major Geologic Units in the Vicinity of Tinker AFB
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma

System	Series	Stratigraphic Unit	Thickness (feet)	Description and Distribution	Water-Bearing Properties
Q U A T E R N A R Y	P L E I S T O C E N E A N D R E C E N T	Alluvium	0-70	Unconsolidated and interfingering lenses of sand, silt, clay, and gravel in the flood plains and channels of stream.	Moderately permeable. Yields small to moderate quantities of water in valleys of larger streams. Water is very hard, but suitable for most uses, unless contaminated by industrial wastes or oil field brines.
		Terrace deposits	0-100	Unconsolidated and interfingering lenses of sand, silt, gravel, and clay that occur at one or more levels above the flood plains of the principal streams.	Moderately permeable. Locally above the water table and not saturated. Where deposits have sufficient saturated thickness, they are capable of yielding moderate quantities of water to wells. Water is moderately hard to very hard, but less mineralized than water in other aquifers. Suitable for most uses unless contaminated by oil field brines.

Table 4-1
Major Geologic Units in the Vicinity of Tinker AFB
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

System	Series	Stratigraphic Unit	Thickness (feet)	Description and Distribution	Water-Bearing Properties
P E R M I A N	L O W E R P E R M I A N	Hennessey Group (includes Kingmen Siltstone and Fairmont Shale)	700	Deep-red clay shale containing thin beds of red sandstone and white or greenish bands of sandy or limey shale. Forms relatively flat to gently rolling grass-covered prairie. Thickness of this unit ranges from zero to about 60 feet at Tinker AFB.	Poorly permeable. Yields meager quantities or very hard, moderately to highly mineralized water to shallow domestic and stock wells. In places water contains larger amounts of sulfate. HWBZ occurs within this unit to the west of GWMU 1 at Tinker AFB.
		Garber Sandstone	500	Deep-red clay to reddish-orange, massive and cross-bedded and interfingered with red shale and siltstone.	Poorly to moderately permeable. Important source of groundwater in Cleveland and Oklahoma counties. Yields small to moderate quantities of water to deep wells; heavily pumped for industrial and municipal uses in the Norman and Midwest City areas. Water from shallow wells hard to very hard; water from deep wells moderately hard to soft.
		Wellington Formation	500	Deep-red to reddish-orange massive and cross-bedded fine-grained sandstone interbedded with red, purple, maroon, and gray shale. Base of formation not exposed in the area.	Lower part contains water too salty for domestic and most industrial uses. The USZ occurs within the upper 50 feet of the Garber Sandstone at Tinker AFB. The LSZ (including the LLSZ) also occurs within the Garber Sandstone and is typically 160 feet thick. The production wells at Tinker AFB penetrate the lower part of the Garber Sandstone and the upper part of the Wellington Formation.

Source: Modified from Wood and Burton, 1968.

Table 4-2

**Tinker AFB Soil Associations
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

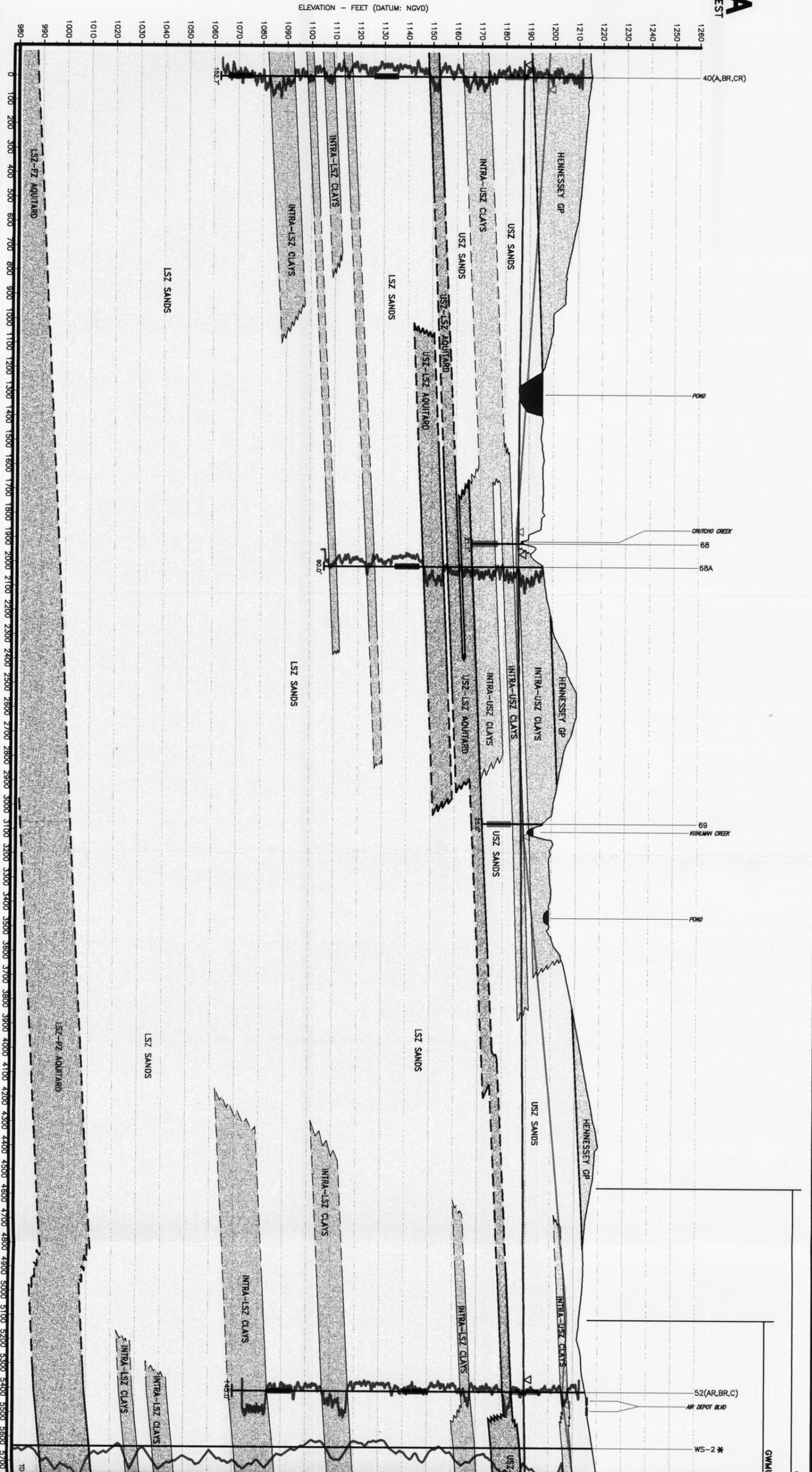
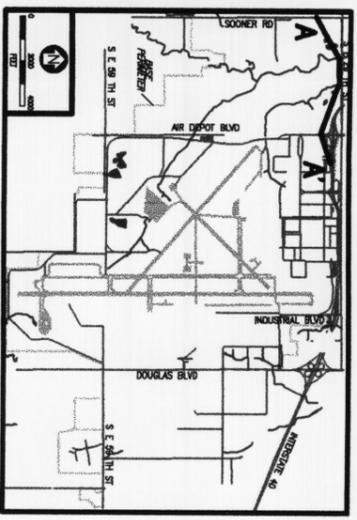
Association	Description	Thickness (in.)	United Classification	Permeability (in./hr)
Darnell-Stephenville: loamy soils of wooded uplands	Sandy loam Sandy clay loam Soft sandstone (Garber Sandstone)	12-54	SM,ML,SC	2.0-6.30
Renfrow-Vernon- Bethany: loamy and clayey soils on prairie uplands	Silt loam – clay Clay loam Mudstone (Hennessey Group)	12-60	ML,CL,MH,CH	<0.06-0.20
Dale-Canadian-Port: loamy soil on low benches near large streams	Fine sandy loam Silty clay loam Loam Clay loam	12-60	SM,ML,CL	0.05-6.3
Doughtery-Norge-Teller: sandy and loamy soils on wooded and prairie uplands	Loam Clay loam Mudstone (Hennessey Group)	12-50	ML,CL	<0.06-0.20

Source: USDA, 1969; and Tinker, 1991.

in. - Inch.

in./hr - Inches per hour.

FIGURES

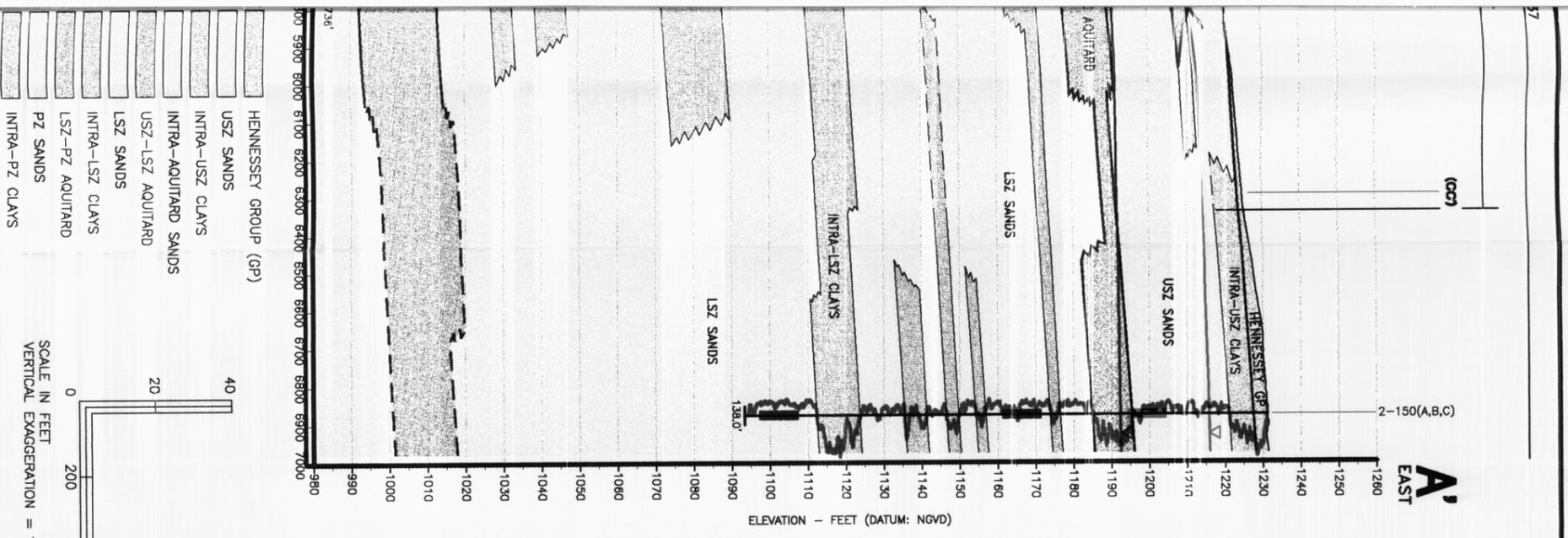


NOTES:

1. ABBREVIATIONS USED ON CROSS-SECTIONS:
 USZ → UPPER SATURATED ZONE
 LSZ → LOWER SATURATED ZONE
 PZ → PRODUCING ZONE
2. "X" WELL IDENTIFIER INDICATES THAT WELL WAS DRILLED, THEN PLUGGED AND ABANDONED.
3. "P" IDENTIFIER INDICATES DEEP PILOT HOLE DRILLED FOR GEOPHYSICAL LOGGING PURPOSES.

EXPLANATION

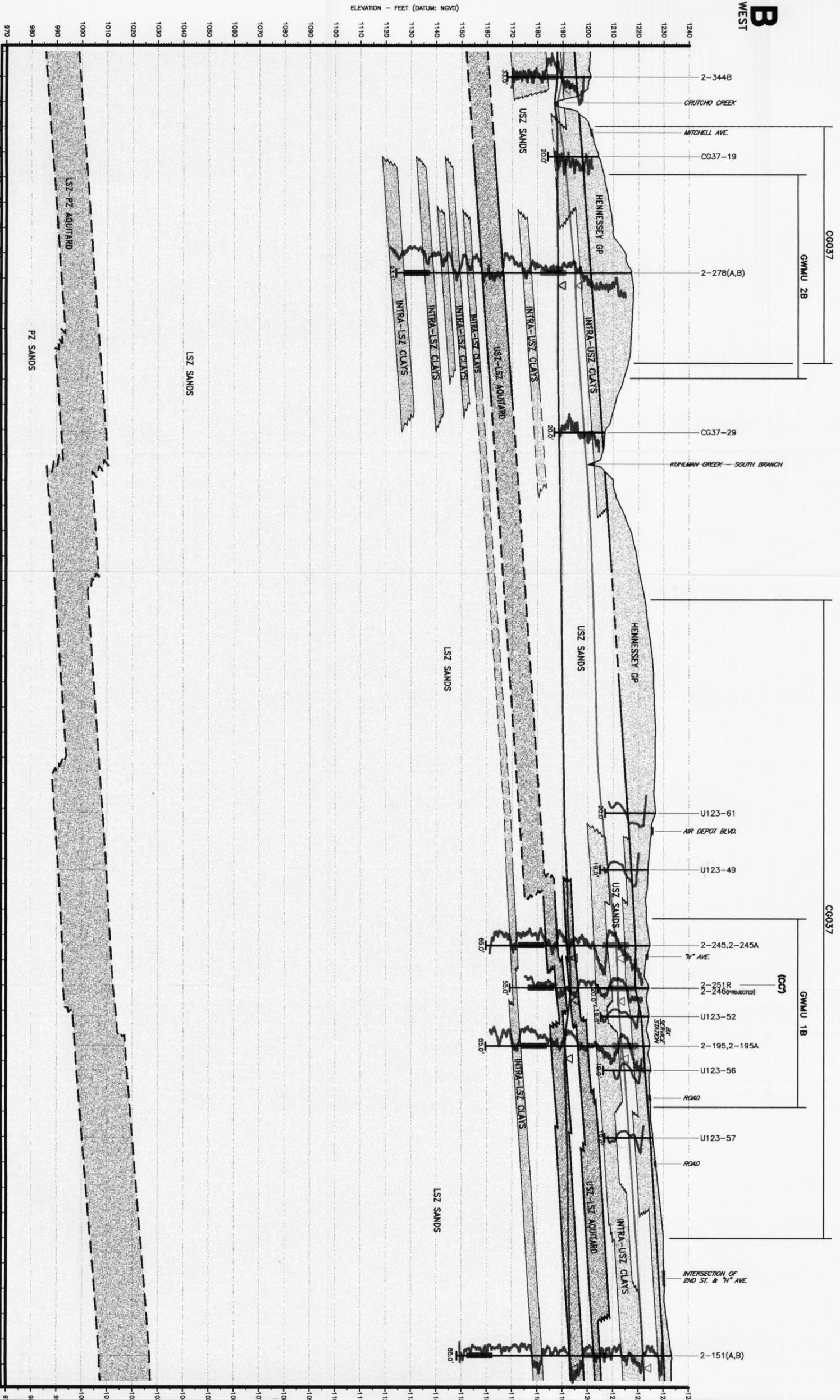
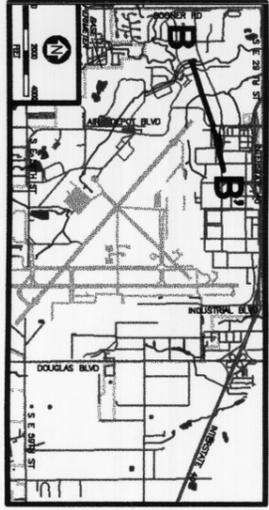
- | | | | |
|-------|------------------------------------|---|----------------------------|
| (AAA) | CROSS-SECTION TIE POINT(S) | ▽ | UPPER SATURATED ZONE |
| ○ | WELL IDENTIFICATION | ▽ | USZ POTENTIOMETRIC SURFACE |
| ▽ | WELL | ▬ | LOWER SATURATED ZONE |
| ▽ | WATER LEVEL ELEVATION (JUNE, 1997) | ▽ | LSZ POTENTIOMETRIC SURFACE |
| ▽ | SCREENED INTERVAL | ▬ | PRODUCING ZONE |
| ▽ | GAMMA LOG | ▬ | PZ POTENTIOMETRIC SURFACE |
| ▽ | TOTAL DEPTH DRILLED | | |
| * | DIGITIZED ANALOG GAMMA LOGS | | |
-
- | | |
|---|--------------------------|
| ▬ | DRY WELL |
| ▬ | HYDROGEOLOGIC BOUNDARIES |
| ▬ | LITHOLOGIC CONTACTS |
- NOTE:
 POTENTIOMETRIC SURFACES, HYDROGEOLOGIC BOUNDARIES, AND LITHOLOGIC CONTACTS DASHED WHERE INFERRED.
- GARBER-WELLMINGTON AQUIFER



DRAWN BY: CFB
START DATE: 12/05/00
REVISED BY: CFB
LAST REV: 03/27/01
INITIATOR: MG
INIT. DATE: 02/05/00

GEOLOGIC CROSS-SECTION A-A'
CG037 RFI GWMU 1B AND 1F
 PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

PROJ. NO. 799270
FIG. 4-2
UNIQUE NUMBER 799270-D02



NOTE:

1. ABBREVIATIONS USED ON CROSS-SECTIONS:

- USZ → UPPER SATURATED ZONE
 - LSZ → LOWER SATURATED ZONE
 - PZ → PRODUCING ZONE
2. "X" WELL IDENTIFIER INDICATES THAT WELL WAS DRILLED, THEN PLUGGED AND ABANDONED.
3. "P" IDENTIFIER INDICATES DEEP PILOT HOLE DRILLED FOR GEOPHYSICAL LOGGING PURPOSES.

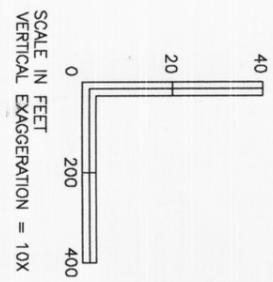
EXPLANATION

- | | | | |
|-------|------------------------------------|-----|----------------------------|
| (444) | CROSS-SECTION TIE POINT(S) | ▽ | UPPER SATURATED ZONE |
| □ | WELL IDENTIFICATION | ▽ | USZ POTENTIOMETRIC SURFACE |
| ▽ | WATER LEVEL ELEVATION (JUNE, 1997) | ▽ | LOWER SATURATED ZONE |
| ▽ | SCREENED INTERVAL | ▽ | LSZ POTENTIOMETRIC SURFACE |
| ▽ | GAMMA LOG | ▽ | PRODUCING ZONE |
| ▽ | TOTAL DEPTH DRILLED | ▽ | PZ POTENTIOMETRIC SURFACE |
| * | DIGITIZED ANALOG GAMMA LOGS | --- | DRY WELL |
| | | --- | HYDROGEOLOGIC BOUNDARIES |
| | | --- | LITHOLOGIC CONTACTS |
- NOTE: POTENTIOMETRIC SURFACES, HYDROGEOLOGIC BOUNDARIES, AND LITHOLOGIC CONTACTS DASHED WHERE INFERRED.
- GARBER-WELLINGTON AQUIFER

B'
EAST

ELEVATION - FEET (DATUM: NGVD)

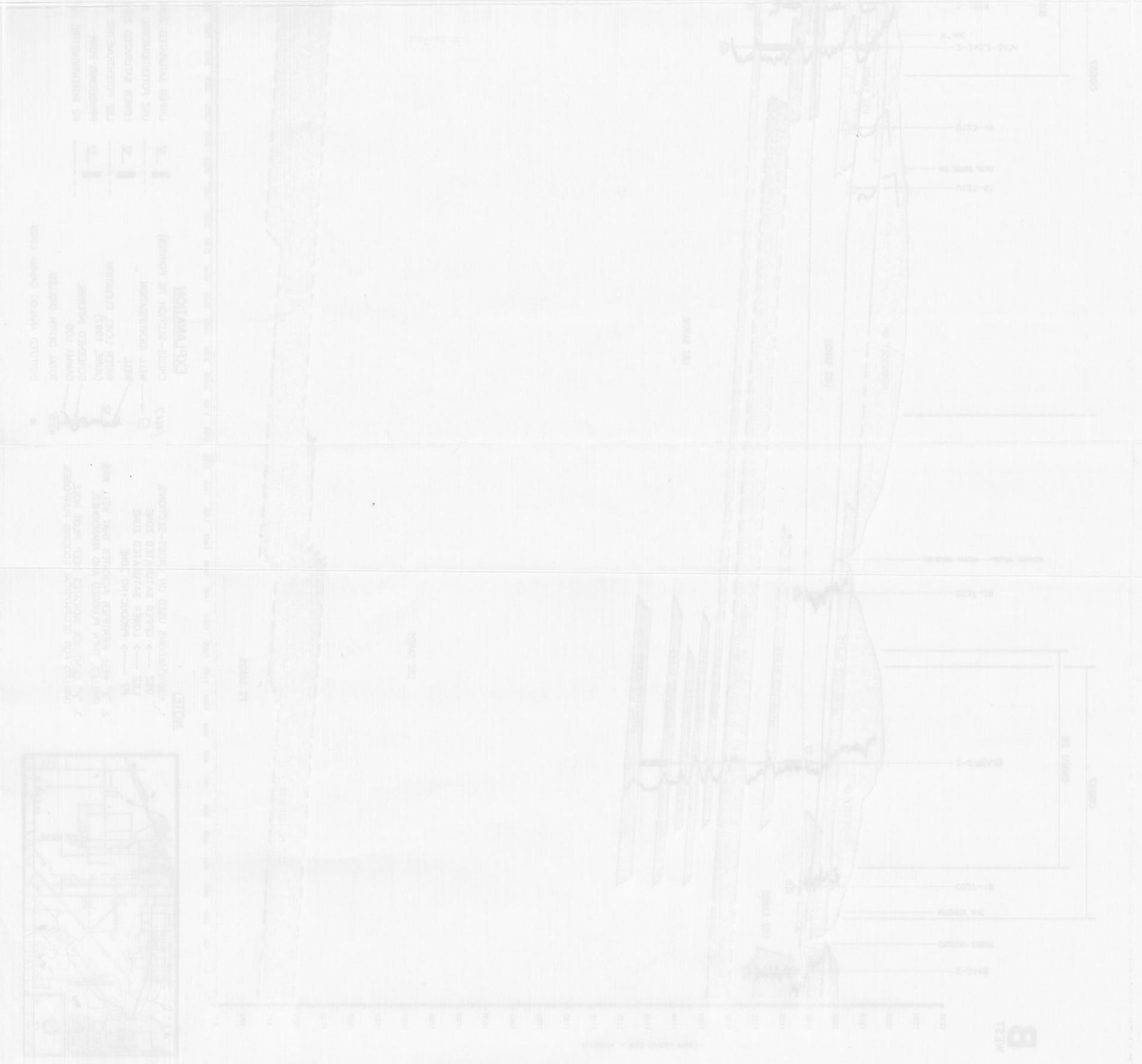
- HENNESSEY GROUP (GP)
- USZ SANDS
- INTRA-USZ CLAYS
- INTRA-AQUITARD SANDS
- USZ-USZ AQUITARD
- LSZ SANDS
- INTRA-USZ CLAYS
- LSZ-PZ AQUITARD
- PZ SANDS
- INTRA-PZ CLAYS



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START DATE: 12/05/00
REVISED BY: CFB
LAST REV: 11/14/01
INITIATOR: MG
INT. DATE: 12/05/00

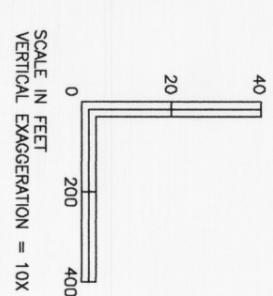
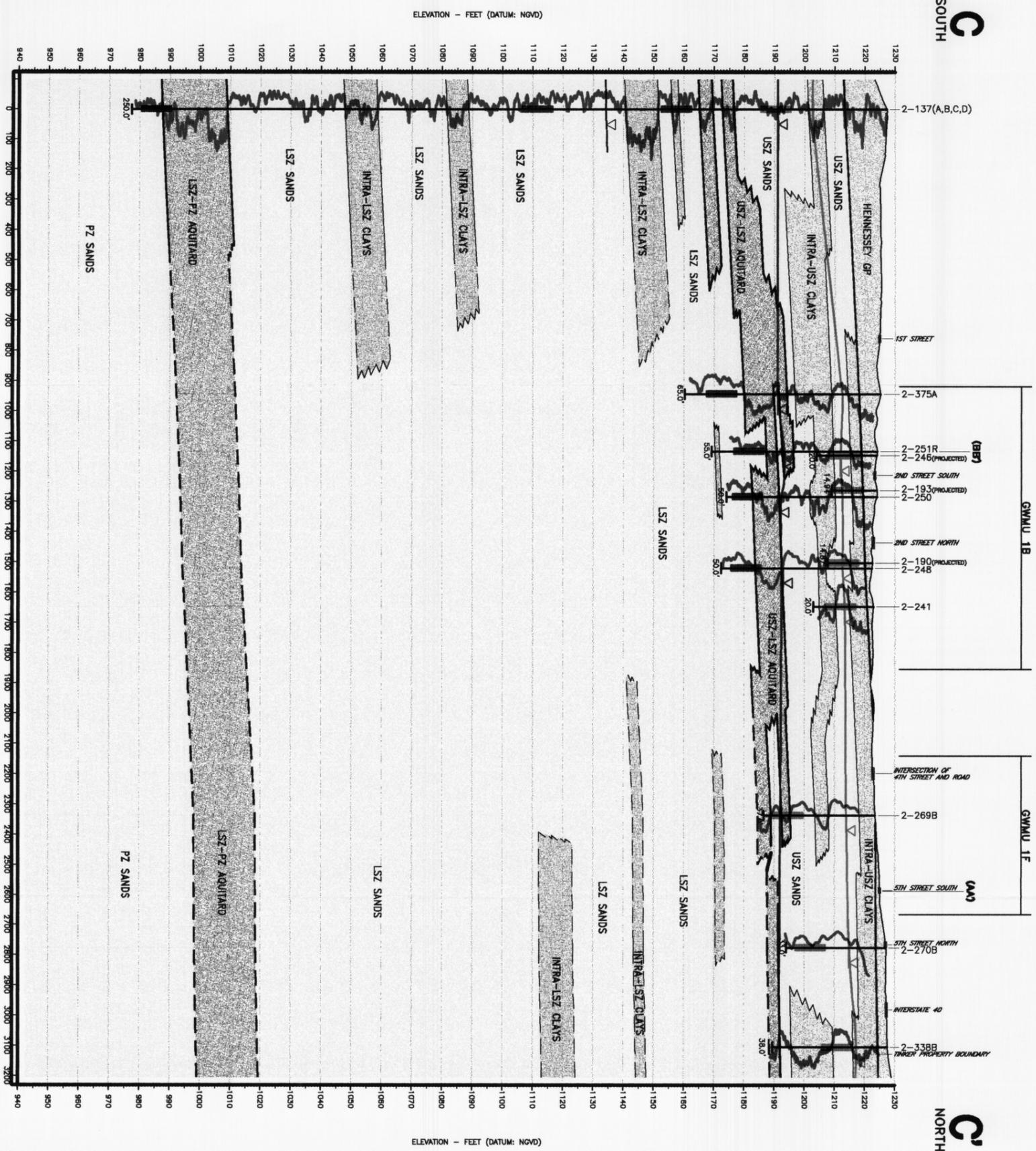
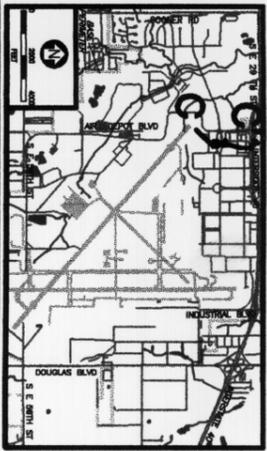
GEOLOGIC CROSS-SECTION B-B'
CG037 RFI GWMU 1B AND 1F
 PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

PROJ. NO. 799270
FIG. 4-3
 UNIQUE NUMBER 799270-D03



B
WEST

UNIQUE NUMBER 799270-D03



NOTE:

- ABBREVIATIONS USED ON CROSS-SECTIONS:
 USZ → UPPER SATURATED ZONE
 LSZ → LOWER SATURATED ZONE
 PZ → PRODUCING ZONE
- "X" WELL IDENTIFIER INDICATES THAT WELL WAS DRILLED, THEN PLUGGED AND ABANDONED.
- "P" IDENTIFIER INDICATES DEEP PILOT HOLE DRILLED FOR GEOPHYSICAL LOGGING PURPOSES.

EXPLANATION

- (444) CROSS-SECTION TIE POINT(S)
- WELL IDENTIFICATION
- WELL
- WATER LEVEL ELEVATION (JUNE, 1997)
- SCREENED INTERVAL
- GAMMA LOG
- TOTAL DEPTH DRILLED
- * DIGITIZED ANALOG GAMMA LOSS
- UPPER SATURATED ZONE
- USZ POTENTIOMETRIC SURFACE
- LOWER SATURATED ZONE
- LSZ POTENTIOMETRIC SURFACE
- PRODUCING ZONE
- PZ POTENTIOMETRIC SURFACE
- DRY WELL
- HYDROGEOLOGIC BOUNDARIES
- LITHOLOGIC CONTACTS

NOTE: POTENTIOMETRIC SURFACES, HYDROGEOLOGIC BOUNDARIES, AND LITHOLOGIC CONTACTS DASHED WHERE INFERRED.

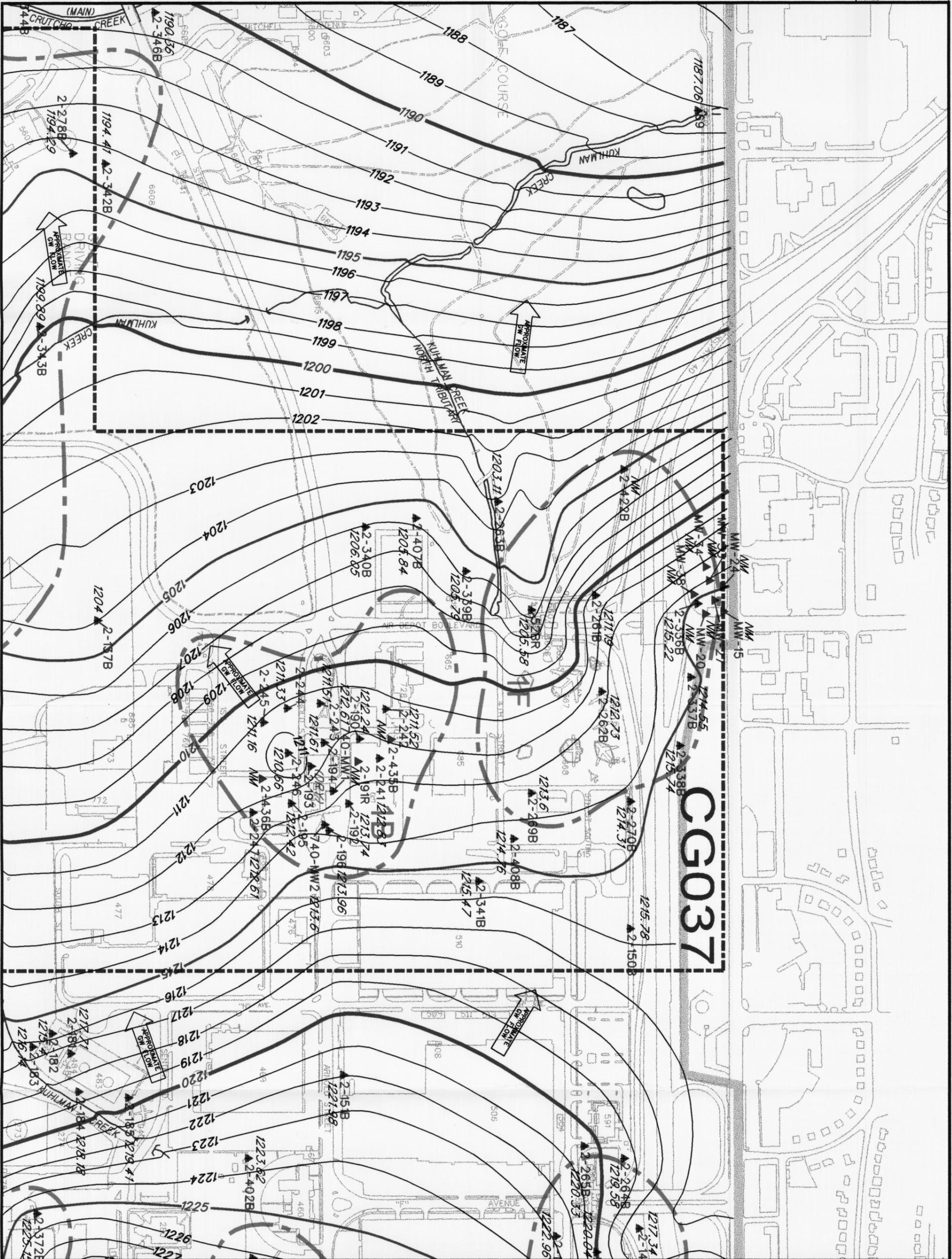
- HENNESSEY GROUP (GP)
- USZ SANDS
- INTRA-USZ CLAYS
- INTRA-AQUIFARD SANDS
- USZ-LSZ AQUIFARD
- LSZ SANDS
- INTRA-LSZ CLAYS
- LSZ-PZ AQUIFARD
- PZ SANDS
- INTRA-PZ CLAYS

DRAWN BY: CFB
 START DATE: 12/05/00
 REVISED BY: CFB
 LAST REV: 10/01/01
 INITIATOR: MC

GEOLOGIC CROSS-SECTION C-C'
CG037 RFI GWMU 1B AND 1F

PROJ. NO. 799270

FIG. 4-4



EXPLANATION

- 45B ▲ MONITORING WELL LOCATION
- 1261.66 + GROUNDWATER ELEVATION
- (1260.43) + GROUNDWATER ELEVATION NOT USED IN CONTOURING
- 1 FOOT CONTOUR (NGVD)
- 5 FOOT CONTOUR (NGVD)
- 10 FOOT CONTOUR (NGVD)
- TINKER AIR FORCE BASE PROPERTY LINE
- GROUNDWATER IRR SITE

- NM NOT MEASURED
- 1A APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER
- ← APPROXIMATE GW FLOW APPROXIMATE DIRECTION OF GROUNDWATER FLOW



DRAWN BY: CFB
 START DATE: 11/29/00
 REVISED BY: CFB
 LAST REV: 10/01/01

GROUNDWATER POTENTIOMETRIC SURFACE MAP FOR USZ, OCTOBER 1999

CG037 RFI GWMU 1B AND 1F

PROJ. NO. 799270

FIG. 4-5



EXPLANATION

- 45B▲ MONITORING WELL LOCATION
- 1261.66+ GROUNDWATER ELEVATION
- (1260.43)+ GROUNDWATER ELEVATION NOT USED IN CONTOURING
- 1 FOOT CONTOUR (NGVD)
- 5 FOOT CONTOUR (NGVD)
- 10 FOOT CONTOUR (NGVD)
- █ TINKER AIR FORCE BASE PROPERTY LINE
- GROUNDWATER IRR SITE

- NM NOT MEASURED
- 1A APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER
- ← APPROXIMATE GW FLOW APPROXIMATE DIRECTION OF GROUNDWATER FLOW



DRAWN BY: CFB
 START DATE: 11/29/00
 REVISED BY: CFB
 LAST REV: 10/01/01

GROUNDWATER POTENTIOMETRIC SURFACE MAP FOR LSZ, OCTOBER 1999

CG037 RFI GWMU 1B AND 1F

PROJ. NO. 799270

FIG. 4-6

5.0 Site Characterization

The following sections of this RFI summary report provide the results of the evaluation of data pertinent to site CG037, including the nature and extent of groundwater contamination and an analysis of potential source areas for the groundwater contamination. The evaluation included the data from the 1999 round of groundwater well sampling at Tinker AFB, as well as data from the other sources listed in Section 3.1 of this report. These data were used to prepare geologic cross-sections, potentiometric surface maps, and contaminant distribution maps. In general, 1999 data were used to characterize the current nature and extent of contamination, and are presented in data tables and on isopleth maps. Where appropriate, data from previous Basewide events from 1996 through 1999 were used for temporal trend analyses. Finally, data from appropriate sources outside the Basewide program, such as the BX Service Station, offsite investigations (e.g., Texaco Service Station north of the Base boundary), and data from the annual stream sampling, were used to supplement the Basewide data.

5.1 Overview

Groundwater samples were collected from monitoring wells installed in the USZ, LSZ, and PZ. Groundwater samples were collected during the 1999 annual Basewide monitoring well sampling event, from temporary well points and wells installed in 1999, and from additional sources discussed previously in Section 3.1 of this report (e.g., UST data). Groundwater samples were analyzed for the following parameters: VOCs, semivolatile organic compounds (SVOC), metals, and pesticides/polychlorinated biphenyls (PCB). Analytical data underwent a thorough laboratory review process, and 100 percent of the data used in this study from the 1999 Basewide event were validated.

Results of the laboratory analyses of groundwater samples from monitoring wells are summarized in Tables 5-1 through 5-4, for VOCs, SVOCs, pesticides/PCBs, and metals, respectively. Maximum Contaminant Levels (MCL), as promulgated under the Safe Drinking Water Act, and preliminary remediation goals (PRG) developed by EPA Region IX (EPA, 1999) and Oklahoma water quality criteria standards (OWQC) provided by the Oklahoma Water Resources Board (1999) are presented in these tables for comparison. Results provided in these tables only include those constituents with concentrations above reporting limits. Results in bold face type are values above standards cited previously, in the following order of precedence: MCLs, PRGs, or OWQC. Metals in groundwater are also compared with naturally occurring background concentrations, as described below. Table 5-5 provides a summary of analytical

results for wells not sampled as part of the 1999 annual Basewide sampling round (e.g., data from the Texaco station investigation north of the Base boundary).

Evaluation of the analytical data for each water-bearing zone revealed that groundwater contamination exists at various locations within GWMU 1 at CG037. Potential source areas for contamination are shown in Figure 5-1. For groundwater zones where concentrations for benzene, toluene, ethylbenzene, and total xylenes (BTEX) and total chlorinated hydrocarbons (TCH) compounds were detected above MCLs, isopleth maps showing the distribution of these contaminants were prepared. Figures 5-2 through 5-5 provide isopleth maps of significant compounds found in GWMU 1. Direct and indirect evidence indicates that natural attenuation through degradation of chlorinated solvents and fuel hydrocarbons is occurring selectively in the groundwater at Tinker AFB (IT, 1999b). Metals contamination was listed for a unit if the concentration of the indicated metal exceeded the MCL and 95 percent of the upper tolerance limit (UTL) in at least one groundwater sample collected from within the GWMU. Exceedance of an MCL does not necessarily indicate an impact from Base activities.

The distribution and potential migration of contaminant plumes are influenced by the direction and rate (average linear velocity) of groundwater flow. The average linear velocity represents the average rate at which groundwater will move within an aquifer pore space. However, certain natural groundwater constituents and contaminants (solutes) within the groundwater may migrate at a slower rate than this average linear velocity due to processes such as adsorption. Mass transfer by adsorption or other chemical processes from the pore water to the solid part of the porous aquifer medium causes the advance rate of the solute front to be reduced. Other processes such as chemical precipitation or biodegradation may cause a reduction in the solute mass, which also may cause the apparent transport rate to be less than the average linear flow velocity. In addition to geochemical considerations affecting plume migration, preferred pathways for groundwater flow exist within the Garber-Wellington Aquifer and can create channels for flow that are not in a uniform downgradient direction. These pathways arise through textural variations in the rock such as grain size, differences in amount of clay matrix, degree of cementation, etc. Additional discussion on contamination fate and transport is provided in Chapter 7.0 of this RFI report.

5.1.1 Treatment of Analytical Data

Analytical data used for this report were received electronically from the analytical laboratory with the associated laboratory data qualifiers. If the compound tested for was not detected, then

a “U” laboratory qualifier was attached. If the result was greater than 0, but less than the reporting limit, that result was assigned a “J” laboratory qualifier. “B” qualifiers for method blank contamination for organics was applied if the analyte was detected in the laboratory method blank. These data are usable for the objectives of this RFI report. In instances where detected concentrations were such that both an undiluted and diluted sample was required, the results of the diluted run were evaluated and a “D” qualifier was assigned. Data from the 1996 Basewide event, used for temporal trend analysis in this report, were treated as described in the Basewide RFI Phase II, Addendum II report (IT, 2000). One hundred percent of the data for CG037 from the 1999 Basewide sampling round were validated.

Groundwater contamination at Tinker AFB was evaluated using data on contaminant distribution and knowledge of the types and physical characteristics of contaminants potentially present. Chemicals which comprise groundwater contamination at Tinker AFB were primarily used during one of two activities: fuel storage and handling, and aircraft and vehicle maintenance. These activities have resulted in the presence of two principal organic contaminant groups: fuel hydrocarbons and chlorinated solvents. In addition to organic compounds, the potential for metals contamination was also evaluated.

Statistical analysis has been performed on analytical results from select monitoring wells in order to determine the 95 percent UTL for metals in groundwater at Tinker AFB. The results of this study are presented in a draft report entitled *Background Metals Concentrations in Groundwater, Tinker AFB, Oklahoma* (IT, 1999c). The results of background metals calculations at the Base are summarized and provided with MCLs in Table 5-4. Concentrations that exceed background levels and a particular MCL are noted in the table by bold type. In most cases, the background concentration is less than (more conservative) than the MCL; therefore, most metals values were compared to MCLs.

5.1.2 Organic Constituents

In order to aid in the evaluation of the nature and extent of contamination in groundwater at the Base, isopleth maps were constructed that depict the sum of the concentrations of the constituents in two principal contaminant groups (fuel hydrocarbons and chlorinated solvents) at each sampling point. The specific compounds considered to be the primary components of these two contaminant groups include, for the fuel hydrocarbons or BTEX group:

Benzene	Toluene
Ethylbenzene	Xylenes

and for the chlorinated solvents or TCH group:

Chloroform	Carbon tetrachloride
1,1,1-Trichloroethane (TCA)	Chloroethane
1,1,2,2-Tetrachloroethane	Tetrachloroethylene (PCE)
1,1,2-TCA	Trichloroethene (TCE)
1,1-Dichloroethane (DCA)	Vinyl chloride (VC)
1,1-Dichloroethylene (DCE)	Cis-1,2-DCE
1,2-DCA	trans-1,2-DCE.

In addition to the broad look at the contaminant groups listed above, several additional contaminants in the portion of GWMU 1 associated with CG037 were evaluated by preparing constituent specific isopleth maps. For the RFI report, maps were prepared for constituents for which a meaningful spatial distribution exists. These constituents include benzene, TCE, PCE, carbon tetrachloride, cis-1,2-DCE, and 1,2-DCA. These maps are not included in this summary report. All data where a "U" data qualifier was assigned indicating a non-detect were assigned a "ND" qualifier on the constituent isopleth maps. On the isopleth maps (Figures 5-2 through 5-5), all groundwater monitoring wells present at the time of the 1999 Basewide groundwater sampling event are identified in red. Analytical data for these wells are shown in black.

Groundwater contamination has been defined on isopleth maps to exist where one or more groundwater samples contains a concentration of TCH or total BTEX which exceeds 5 micrograms per liter ($\mu\text{g/L}$). The basis for the 5 $\mu\text{g/L}$ closing contour defining contamination stems from the 5 $\mu\text{g/L}$ MCL for TCE and PCE and the 5 $\mu\text{g/L}$ MCL for benzene. It is pointed out, however, that although benzene, with an MCL of 5 $\mu\text{g/L}$, has the lowest MCL of the fuel BTEX constituents, MCLs within the group range from 5 $\mu\text{g/L}$ (benzene) to 10,000 $\mu\text{g/L}$ (total xylenes). Similarly, within the 14 chlorinated compounds comprising the TCH group, MCLs range from 2 $\mu\text{g/L}$ (VC) to 5 $\mu\text{g/L}$ (TCE) to 200 $\mu\text{g/L}$ (1,1,1-TCA), and there is no MCL for 1,1-DCA. For TCH isopleths it is also important to remember that, because of the number of chlorinated compounds analyzed for (14), the TCH value shown at a given well may exceed the concentration of TCE or one of the other chlorinated hydrocarbon concentrations. Other VOCs of potential concern that were not presented on isopleth maps are discussed in the text for each GWMU subunit where they were detected.

All wells were also sampled for semivolatile compounds; however, contaminants from that group of constituents were only found in a relatively small number of samples. Although isopleth maps were not prepared for SVOCs, these compounds are discussed in the text for each GWMU subunit where they were detected. Pesticides/PCBs were also analyzed, but were only present in a limited number of wells, generally at or below MCL or PRG concentrations, and were not evaluated by isopleth maps. Additionally, many of the results were qualified.

5.1.3 Inorganic Constituents

In addition to organic compounds, metals were also evaluated. Concentrations of metals in groundwater samples were compared to MCLs and PRGs as were organic compounds. All samples were analyzed for the nine RCRA Appendix IX metals and the results are provided in Table 5-4. Isopleth maps were not prepared for any inorganic constituents due to a lack of any meaningful spatial distribution. Samples were also analyzed for the following water quality parameters: dissolved oxygen, oxidation-reduction potential, pH, filterable residues, specific conductivity, temperature, total organic carbon, and turbidity. This information is provided in the RFI report, but has not been included in this summary report.

In general, chromium analysis was not speciated between trivalent and hexavalent chromium. However, as part of the ongoing evaluation of metals, the occurrence of chromium and nickel in groundwater as a possible result of corrosion of stainless-steel well construction material was evaluated (IT, 1999d). In that study, a number of samples from wells with elevated chromium were speciated for hexavalent chromium; the results indicated that the hexavalent chromium was not present. It now seems likely that the elevated concentrations of these metals, along with high concentrations of iron, observed in groundwater in most instances are the result of corrosion of stainless-steel well screens and dedicated pumps used in monitoring well installation and sampling. In the study a direct association between chromium and iron concentrations was observed. Concentrations of both metals rapidly decreased during purging and showed a marked decrease with filtration of the samples. This data, and the overall lack of hexavalent chromium, suggest a noncontaminant source for the chromium. Similar results were observed also for nickel, which could be explained generally by either corrosion of stainless-steel well materials or by the presence of naturally-occurring suspended clay particulates (IT, 1999d).

Several metals occur naturally in deep (depths greater than 300 feet) groundwater at Tinker AFB at concentrations above their MCLs, and metals were detected in this RFI at concentrations above MCLs at locations where no Base operations are believed to have occurred. In addition,

complexities in the evaluation of the presence and distribution of metals arise through the fact that only total (unfiltered) metals samples were analyzed for a majority of samples; however, both filtered and unfiltered samples were analyzed as part of the chromium-nickel study (IT, 1999c). Because of this, it is not known to what extent analyses include metals which may be adsorbed to suspended clays or iron oxide particulates. In most cases, elevated levels of metals in the groundwater also coincided with significantly elevated turbidity of the samples. Exceedance of MCLs for metals, therefore, is not a clear indicator of impacts from Base operations. Background metals concentrations in groundwater have been evaluated and calculated to the 95 percent UTL; these values are provided for comparison with the analytical data in Table 5-4.

5.2 Analysis of Potential Source Areas

Several potential source areas for groundwater contamination at CG037 exist and were evaluated during the RFI. Of the potential sources observed during the data collection and review stage of the RFI, described in Chapter 3 of this report, the following are considered the likely sources of contamination for groundwater contamination within GWMU 1 at CG037:

- ***BX Service Station (GWMU 1B)***. Characterization of the BX Service Station has been completed during previous studies, and a groundwater remediation system has been installed and is operating to remediate the USZ and LSZ in the vicinity of the station. The remediation system is a vacuum-enhanced pumping system that was initially installed to recover non-aqueous phase liquids and groundwater from the USZ contaminated with BTEX constituents. The system was expanded in 1999 with the installation of additional extraction wells in the LSZ, along with additional wells in the USZ (PES, 2000).

In addition to fuel constituents, contaminants of concern in the vicinity of the BX Service Station include chlorinated solvents. There is no documented release of solvents at the site; however, solvents were routinely used at the station to clean metal parts and remove grease during the time of operation when fuel releases occurred. Other possible sources of solvent contamination are discussed below.

- ***Shops in the Vicinity of Arnold Street, N Street, and Air Depot Boulevard (GWMU 1B)***. Documentation of actual chemicals used and releases from these facilities does not exist. However, these various shops are labeled on Base drawings from the 1950s to early 1960s as "Auto Shop," "Parts," "Cleaning," "Base Laundry," and other similar labels and are the only plausible source areas for the solvent contamination found in the area. Figure 5-1 shows the approximate locations of these facilities on the current Base map, along with what were thought to be the building numbers at the time.

- **Shops in the Vicinity of N Street Between 4th and 5th Streets (GWMU 1F).** Documentation of actual chemicals used and releases from these facilities does not exist. However, these various shops are labeled on Base drawings from the 1950s to early 1960s as “Auto Shop,” “Parts,” “Cleaning” and other similar labels and are the only plausible source areas for the solvent contamination found in the area. Figure 5-1 shows the approximate locations of these facilities on the current Base map, along with what were thought to be the building numbers at the time.
- **Buried Utility Lines.** These utilities, including sanitary sewer, storm sewer, electrical, natural gas, communication, steam, and fuel lines, cross through both GWMU 1B and 1F in virtually all directions through the vadose zone above the contaminated areas. Analysis of the direction of trend for these various utility lines indicates that, while the lines themselves may not be actual sources of contamination (i.e., likely did not transport constituents of concern or the constituents did not leak from the utility line), there are several cases where the trend of the contaminant plume suggests that the trenches the utility lines are buried in may have served as conduits enabling the migration of contaminants along the preferential pathway until a vertical pathway into the subsurface was reached.

5.3 Groundwater Assessment Results

Groundwater samples were collected from monitoring wells installed in the USZ, LSZ, and PZ at the portion of GWMU 1 associated with CG037. A total of 52 USZ monitoring wells associated with the CG037 study in the vicinity of GWMU 1B and 1F were sampled during the annual sampling round. In addition, data from five USZ wells associated with the investigation at a Texaco Service Station immediately north of the Base boundary were evaluated for this study. For the LSZ, a total of 30 monitoring wells associated with the CG037 study in the vicinity of GWMU 1B and 1F were sampled during the 1999 sampling round. One PZ monitoring well, and one Tinker AFB water supply well in the vicinity of GWMU 1B and 1F were sampled during the event. The HWBZ is not present in the vicinity of GWMU 1B and 1F; therefore, no wells are installed in this unit.

Results of the laboratory analyses of groundwater samples collected from monitoring wells are summarized in Tables 5-1 through 5-5. Tables 5-1 through 5-4 provide data collected as part of the annual Basewide sampling events. The results provided in these tables are only for those constituents with concentrations above the reporting limits. If a particular constituent is not included in the results tables, it was not detected in any groundwater sample collected from the wells associated with the CG037 RFI. Table 5-5 provides a summary of data collected as part of programs other than the annual Basewide sampling rounds. Contaminant isopleth maps for

selected compounds in GWMU 1 groundwater are provided in Figures 5-2 through 5-5, and are discussed individually in the following sections. Section 5.4 also discusses the data trends established from this data set as well as data from previous sampling events. The temporal trend data are provided in Tables 5-6a and b, and 5-7a and b.

Based on the distribution of contamination in GWMU 1, six primary locations with groundwater contamination have been identified. These locations are referred to as subunits to GWMU 1. Of the six GWMU 1 subunits, GWMU 1B and 1F are located within CG037 and are discussed in this RFI summary report.

5.3.1 GWMU 1B Nature and Extent of Contamination

GWMU 1B is in the west central part of GWMU 1 in the vicinity of the BX Service Station which is being investigated under authority of the OCC. Impacts to groundwater are based on groundwater samples collected from monitoring wells installed in the USZ and LSZ. No HWBZ is present in this area, and no PZ wells have been installed as of the date of this investigation. However, there is one well cluster to the southwest of GWMU 1B that contains wells screened in the lower portion of the LSZ and in the PZ, and there are two Tinker AFB water supply wells in the vicinity of the unit (WS-2 in GWMU 1F, WS-3 southwest of GWMU 1B). WS-3 is currently inactive. Results of laboratory analyses of groundwater samples from monitoring wells in GWMU 1B are summarized in Tables 5-1 through 5-4. Table 5-5 provides results from studies other than the annual Basewide sampling round.

GWMU 1B is characterized by groundwater impacted with organic compounds (primarily fuels and chlorinated hydrocarbons). Metals were also detected in groundwater samples at GWMU 1B. Potential sources of contamination include releases related to activities at the BX Service Station and/or past activities or spills south of and in the vicinity of the service station. This facility is still active; in 1995 existing USTs were removed and replaced with vaulted tanks. Potential releases to soil and groundwater from this facility have been investigated but the results are not included as part of this study. At the time of preparation of this RFI report, a remedial design had been completed to address fuel contamination at the site under OCC guidance, and the groundwater pump-and-treat system has been installed and is currently operating. Additional extraction and monitoring wells associated with the pump-and-treat system were installed in 1998 and 1999, including wells in the LSZ (PES, 2000).

5.3.1.1 Upper Saturated Zone

Table 5-1 shows BTEX constituents detected above their respective MCLs for USZ wells. The highest concentrations were found in the immediate vicinity of the BX Service Station. Total BTEX distribution is shown on Figure 5-2. Other fuel constituents detected (e.g., trimethyl benzene) which do not have MCLs were detected at their PRG. Free-phase fuel product was reported in groundwater monitoring well 740-MW1; this well was not sampled for dissolved constituents as part of the 1999 sampling event. However, well 740-MW1 was sampled during 1999 as part of the ongoing UST remediation project; benzene concentrations were found to be 4,600 µg/L.

TCH constituents detected above their respective MCLs or, as appropriate, PRGs are shown in Table 5-1. The distribution of dissolved-phase chlorinated hydrocarbons, represented by TCHs, in the USZ at GWMU 1B is shown on Figure 5-4. The highest concentrations of TCH were south-southwest of the BX Station. The downgradient extent of TCH contamination in the USZ has been reasonably well defined. Carbon tetrachloride was also detected in significant concentrations and with significant spatial distributions in the USZ.

Table 5-2 shows SVOCs detected above their respective action levels. Two SVOCs and three pesticides were detected in groundwater samples collected from monitoring wells sampled at GWMU 1B. Only the compounds 4-chloro-3-methylphenol (1 well) and di-n-butylphthlate (six wells) were detected above reporting limits; all are estimated values and are significantly below the PRGs. The only pesticide/PCB detected above its PRG was dieldrin (Table 5-3).

Arsenic, barium, chromium, nickel, and lead were detected above their MCLs in one or more of the monitoring wells sampled within the study area (Table 5-4). The presence of lead potentially relates to fuel releases at the service station. In every case, elevated turbidity levels were also present at the time of sampling. It has been shown that there is a strong correlation between elevated turbidity, typically caused by clay and iron oxide particles in the water sample, and elevated levels of arsenic, barium, and lead that tend to readily adsorb to the particles (IT, 1999c). Due to a lack of meaningful spatial distributions for the metals specified above, isopleth maps were not prepared. In addition, a study of monitoring well screen corrosion indicates that elevated nickel and chromium concentrations are likely not due to contamination (IT, 1999d).

5.3.1.2 Lower Saturated Zone

Total BTEX distribution in the LSZ is shown on Figure 5-3. BTEX concentrations are shown in Table 5-1. The highest concentrations were found in the immediate vicinity of the BX Service Station.

TCH constituents detected above their respective MCLs or, as appropriate, PRGs are shown in Table 5-1. The distribution of dissolved-phase chlorinated hydrocarbons, represented by TCHs, in the LSZ at GWMU 1B is shown on Figure 5-5. The downgradient extent of TCH contamination in the LSZ has been reasonably well defined. However, the contaminant plume is apparently migrating to the south-southwest in the direction of GWMU 2B. Other chlorinated hydrocarbons detected in significant concentrations and with significant spatial distributions in the LSZ included PCE, carbon tetrachloride, cis-1,2-DCE, and 1,2-DCA. In general, concentrations of chlorinated compounds are higher in the LSZ than was seen in the USZ. As discussed in Chapter 4.0 of this report, potentiometric surface maps indicate there may be a zone of increased downward hydraulic conductivity in this vicinity. This apparent tendency would explain the vertical concentration trend for dissolved TCH at GWMU 1B.

Table 5-2 shows SVOCs detected above their respective action levels. Three compounds (di-n-butylphthalate, 2-methylnaphthalene, and naphthalene) were detected in one or more wells within the LSZ. Of these, only the compound naphthalene was detected above its PRG at one well (2-251R). This could be expected as this well is very near the center of the BTEX plume discussed above. Pesticides/PCBs were not detected in any groundwater sample from GWMU 1B (Table 5-3).

Barium, cadmium, chromium, and nickel were detected above their MCLs in one or more of the monitoring wells sampled within the study area (Table 5-4). Lead was detected in two wells below its MCL (2-195 and 2-244); the presence of lead potentially relates to fuel releases at the service station. In every case where metals were above MCLs, elevated turbidity levels were also present at the time of sampling. It has been shown that there is a strong correlation between turbidity, typically caused by clay and iron oxide particles in the water sample, and elevated concentrations of arsenic, barium, and trace metals (e.g., cadmium) that tend to readily adsorb to these particles (IT, 1999c). As with the metals in the USZ, there was a lack of meaningful spatial distributions for metals; therefore, isopleth maps were not prepared. In addition, a study of monitoring well screen corrosion indicates that elevated nickel and chromium concentrations are likely not due to contamination (IT, 1999d).

Tables 5-1 through 5-4 also summarize analytical results for groundwater samples from wells that are completed within the lower portions of the LSZ at GWMU 1B. Groundwater within the lower portions of the LSZ has not been impacted by VOCs, pesticides/PCBs, or metals at GWMU 1B. SVOC constituents were not detected in samples from the unit, with the exception of di-n-butylphthalate detected in one well (2-150C) with an estimated concentration of 1 µg/L; this concentration is many orders of magnitude below the PRG. In addition, phthalates are very common laboratory contaminants.

5.3.1.3 Producing Zone

Tables 5-1 through 5-4 show analytical results for groundwater samples from within the PZ at GWMU 1B. Groundwater within the PZ has not been impacted by VOCs, pesticides/PCBs, or metals at the unit. SVOC constituents were not detected in samples from the unit, with the exception of di-n-butylphthalate detected in one well to the south-southwest of the unit (2-137D) with an estimated concentration of 1.9 µg/L; this concentration is many orders of magnitude below the PRG. In addition, phthalates are very common laboratory contaminants.

5.3.2 GWMU 1F Nature and Extent of Contamination

GWMU 1F is in the western part of GWMU 1 in the vicinity of Kuhlman Creek and near the Tinker AFB main gate. This subunit was delineated during the Addendum 1 RFI investigation (IT, 1998). Potential impacts to groundwater are based on groundwater samples collected mainly from monitoring wells in the USZ and LSZ, and one PZ well in the study area. No HWBZ is present in this area. Results of laboratory analyses of groundwater samples collected from monitoring wells at GWMU 1F during this investigation are summarized in Tables 5-1 through 5-4. Table 5-5 provides results from studies other than the Basewide sampling round.

GWMU 1F is characterized by groundwater impacted with organic compounds (chlorinated hydrocarbons) and metals. At this time, no known ongoing sources for contamination exist within the subunit. There is one apparent off-Base source for BTEX constituents as discussed in Section 5.3.2.1 below. Figure 5-1 provided approximate locations of potential sources from historical operations at the Base in the vicinity of GWMU 1F.

5.3.2.1 Upper Saturated Zone

BTEX constituents were not detected in Tinker AFB monitoring wells within GWMU 1F. However, BTEX constituents were detected in USZ groundwater monitoring wells installed just

north and west of GWMU 1F associated with the investigation of a leaking UST north of the Base boundary in this vicinity (Figure 5-2).

Table 5-1 shows TCH constituents detected above their respective MCLs or, as appropriate, PRGs. The distribution of dissolved-phase chlorinated hydrocarbons, represented by TCHs, in the USZ at GWMU 1F is shown on Figures 5-4. The downgradient extent of TCH contamination in the USZ has been reasonably well defined. The remote potential for downgradient migration of TCH toward the Kuhlman Creek tributary and also westward of monitoring well 2-422B exists. Detections of TCH along the northern edge of the Base (e.g., well 2-336B) may indicate the presence of an offsite source of contamination, as the groundwater flow direction is generally toward Tinker AFB at that location. Carbon tetrachloride was detected in significant concentrations and with significant spatial distributions in the USZ.

Table 5-2 shows SVOCs detected above their respective action levels. Only the compounds 4-chloro-3-methylphenol (1 well) and di-n-butylphthalate (4 wells) were detected above reporting limits; all are estimated values and significantly below the PRGs. In addition, phthalates are very common laboratory contaminants. Pesticides/PCBs were not detected in any well in the study area (Table 5-3).

Arsenic, barium, chromium, lead, and nickel were detected above their MCLs in one or more of the monitoring wells sampled within the study area (Table 5-4). In every case, elevated turbidity levels were also present at the time of sampling. It has been shown that there is a strong correlation between elevated turbidity, typically caused by clay and iron oxide particles in the water sample, and elevated levels of arsenic, barium, and lead that tend to readily adsorb to the particles (IT, 1999c). Due to a lack of meaningful spatial distributions for metals, isopleth maps were not prepared. In addition, a study of monitoring well screen corrosion indicates that elevated nickel and chromium concentrations are likely not due to contamination (IT, 1999d).

5.3.2.2 Lower Saturated Zone

Tables 5-1 through 5-4 show analytical results for LSZ groundwater samples collected from within GWMU 1F. Based on the data from four wells (52AR, 52C, 2-150A, and 2-150C), groundwater within the LSZ has not been impacted by VOCs, pesticides/PCBs, or metals within the GWMU 1F study area. The SVOC compound di-n-butylphthalate was detected in well 52AR, significantly below the PRG. Phthalates are also very common laboratory contaminants.

Spatial distributions of VOCs are represented by BTEX (Figure 5-3) and by TCH (Figure 5-5) for the LSZ in the study area.

5.3.2.3 Producing Zone

Tables 5-1 through 5-4 show analytical results for groundwater samples from within the PZ at GWMU 1F. Groundwater within the PZ has not been impacted by organic or inorganic compounds at the unit.

5.4 Temporal Trend Analysis

In addition to the data used in the previous analyses, many of the CG037 wells have been sampled multiple times over monitoring periods up to 4 years. These data have been presented in various previous reports, including the Phase I, Phase II, Addendum I, and Addendum II Basewide RFI reports (IT, 1994a,b; 1997; 1999e; and 2000, respectively). Additional data may be available for some wells that are part of individual monitoring programs, for example the UST Site 23 monitoring and remediation. However, because these data are collected at different times, with different methods, and under different analytical programs and may not be directly comparable to the BWGW data, they were not used for this analysis. With such time-series data available, a useful analysis for evaluating the extent of contamination is conducting a temporal analysis of both concentration of contaminants, as well as degradation products to observe changes in concentrations over time. A summary discussion of temporal trends and the significance of biodegradation potential is provided below for the purposes of evaluating the nature and extent of contamination, particularly with respect to the presence or absence of dense non-aqueous phase liquids (DNAPL).

Direct evidence for the natural attenuation for chlorinated aliphatic hydrocarbons (CAH) compounds is the observation of degradation products, and decreases in concentrations of the primary contaminants over time. A useful parameter for evaluating the extent of CAH degradation is the degradation ratio (DR), which is defined as the ratio of the sum of the concentrations of degradation products to the sum of the concentrations of primary solvents. The DR serves as an indicator of the extent of reductive dechlorination that is occurring. Samples with detectable PCE and/or TCE with no detectable degradation products (DCE and VC) do not exhibit evidence of microbial degradation. Conversely, samples that have a DR of 0.001 to 1.0 indicate limited degradation, and samples that have a DR greater than 1.0 indicate advanced degradation. Samples with detectable degradation products, but no detectable primary solvents, indicate near-complete degradation of the primary solvents.

A second useful parameter in evaluating the degradation rate of chlorinated solvents in groundwater is the sum of the concentrations of CAH compounds (Σ_{CAH}), which is defined as the sum of PCE, TCE, DCE, and VC. Microbial degradation of chlorinated solvents via reductive dechlorination is indicated by a DR that increases with time, and a Σ_{CAH} that decreases with time.

An increasing DR indicates that reductive dechlorination is proceeding, but does not necessarily imply complete mineralization to CO_2 and water. An increasing DR accompanied by a significant mass loss over time suggests that reductive dechlorination as well as mineralization is occurring.

Loss of CAH mass in groundwater can also be caused by adsorption, volatilization, dispersion, oxidation, or dilution. If these processes affect all of the CAH compounds present to a similar extent, there may be little to no effect on the DR. The total CAH mass is subject to seasonal dilution effects that can mask real trends, but the DR is relatively immune to such effects as long as the ratios of all of the CAH compounds are maintained.

Another important process that can affect the mass of CAH in groundwater is the desorption of contaminants. A groundwater contaminant such as TCE will adsorb to some extent on sediments. At equilibrium, some fraction of the TCE will be in an adsorbed state, and the remaining fraction will remain dissolved in the groundwater. The equilibrium ratio of the adsorbed mass to the dissolved mass is described by the adsorption coefficient (K_d), which is a function of a number of compound- and site-specific parameters. Microbes will preferentially degrade the dissolved fraction. If some of the dissolved TCE is degraded to DCE, then the distribution ratio of adsorbed-to-dissolved TCE is disturbed from equilibrium. The system will respond by desorbing additional TCE from the sediments into the groundwater so that the equilibrium ratio is maintained. In such a two-phase (groundwater and sediment) system, the dissolved TCE concentration is partially replenished by desorption as degradation proceeds. This process will continue until both the adsorbed and dissolved fractions of TCE are completely degraded. This process is identified by an increasing DR with no significant total CAH mass loss over time. The CAH and DR observations are made at each well point using the time series data. Therefore, groundwater movement is accounted for in the interpretation of the results.

To summarize the evaluation methodology, the Σ_{CAH} and DR parameters, and their changes over time, are used in concert to identify the natural attenuation processes that are occurring. The

following table provides a general guide to the interpretation of observed trends in these parameters:

Observation	Steady DR	Increasing DR
Decreasing Σ_{CAH}	Natural attenuation is occurring by processes other than reductive dechlorination	Natural attenuation is occurring by reductive dechlorination
Steady Σ_{CAH}	Little to no natural attenuation	Continual contaminant source, contaminant migration toward well, or desorption with ongoing reductive dechlorination
Increasing Σ_{CAH}	Continual contaminant source or contaminant migration toward well with little to no natural attenuation	Continual contaminant source or contaminant migration toward well with ongoing but slow reductive dechlorination

It should be noted that, although degradation ratios can be calculated on a single data point, the data used in this trend analysis span a period of time of only 0.9 to 2.1 years. Therefore, additional sequential sampling events may provide data that would change the conclusions of this analysis.

5.4.1 Temporal Trends at GWMU 1B

The following discussion provides an analysis of temporal trends for chlorinated hydrocarbons and for BTEX constituents at GWMU 1B. For the purposes of the temporal trend analyses, the portion of TCH that is comprised of chlorinated aliphatic hydrocarbons has been used to simplify the discussion and to focus directly on TCE and the plausible degradation byproducts.

Chlorinated Aliphatic Hydrocarbons. There are ten wells in GWMU 1B that are impacted with CAH. Wells 2-245A and 2-237A, which are both completed in the LSZ, and well 2-340B, which is completed in the USZ, were sampled twice in 1999 (January and November); the remaining seven wells were sampled once in the latter part of 1999 as part of the annual sampling event. Table 5-6a provides a summary of the detected CAH concentrations, the calculated Σ_{CAH} at these locations (in $\mu\text{g/L}$), and the DR. Both of the LSZ wells and the USZ well that were sampled twice show significant increases in Σ_{CAH} in the intervening 0.9 year period between samples. Most of the changes are due to increases in TCE, with lesser increases in the daughter product DCE.

Degradation ratios calculated for 15 samples from CAH-impacted wells at GWMU 1B are all 0.5 or less, except for a single sample from well 2-248 which had a DR of 2.78. This well is also

impacted by fuel hydrocarbons from a leaking UST at the BX Service Station, which probably accounts for the high DR. The degradation rate of CAH is often limited by the availability of organic carbon. The presence of fuel hydrocarbons can provide an additional source of organic carbon that can stimulate the reductive dechlorination of CAH.

The low DRs observed at the other locations at GWMU 1B could be the result of the active remediation systems that are in place to reduce fuel hydrocarbon concentrations at the BX Service Station site. Vacuum enhanced pumping was initiated in 1996 to capture and remove free product, contaminated groundwater, and soil gas containing fuel vapors from the USZ vadose and dewatered zones; the extraction well network was expanded in 1998 and 1999 to include additional wells in both the USZ and the LSZ (PES, 2000). Extraction of soil gas from the base of the vadose zone results in a vertical gas-phase pressure gradient within the vadose zone. Fresh oxygen-bearing air moves downward toward the water table in response to the soil gas extraction. The presence of fresh air at the top of the water table allows for local replenishment of dissolved oxygen in the groundwater, thus preventing the establishment of anaerobic conditions that are required for reductive dechlorination of the CAH compounds.

The increasing Σ_{CAH} over time and the low average DR values indicate that natural attenuation of CAH is not a significant process at GWMU 1B.

BTEX. Seven BTEX-impacted wells were sampled during the sampling rounds at GWMU 1B, as shown in Table 5-6b. The wells were sampled two or three times, as shown in the table. Elapsed times between the first and last samples at these locations ranged from 0.9 to 2.1 years. Three of the wells showed increased concentrations, and four showed decreased concentrations over the monitoring period. The average change in the total BTEX concentrations over time at these locations is a loss of 1,603 $\mu\text{g/L}$ over an average period of 1.3 years. Some of this loss is due to the active remediation systems that have been operating in this area since 1996.

It is difficult to determine the relative contributions of natural attenuation versus active remediation at a location where active remediation is in progress. As discussed previously, vacuum enhanced pumping was initiated in 1996 to capture and remove free product, contaminated groundwater, and soil gas from the vadose and dewatered zones. The presence of fresh air at the top of the water table allows for replenishment of dissolved oxygen that is consumed by microbial activity, which affects the natural attenuation of BTEX and CAH in

different ways. Unlike the case of CAH compounds, for BTEX constituents aerobic conditions that are favorable for microbial degradation of the fuel hydrocarbon compounds are maintained.

5.4.2 Temporal Trends at GWMU 1F

The following discussion provides an analysis of temporal trends for chlorinated hydrocarbons and for BTEX constituents at GWMU 1F.

Chlorinated Aliphatic Hydrocarbons. There are four CAH-impacted wells at GWMU 1F that were sampled between two and four times, as shown in Table 5-7a. The elapsed times between first and last samples range from 0.9 to 3.3 years. Table 5-7a provides a summary of the detected CAH concentrations, Σ_{CAH} , and DRs, at these locations. Three of the wells are completed in the USZ, and one in the LSZ. One of the USZ wells (52BR) shows approximately steady-state Σ_{CAH} concentrations ($\sim 42 \mu\text{g/L}$) over a 3.3 year period. Another USZ well (2-261B) shows a small Σ_{CAH} decrease from 16.6 to 11.5 $\mu\text{g/L}$ over a 2.1 year period. The third USZ well (2-269B) shows Σ_{CAH} increasing from 21 to 60 $\mu\text{g/L}$ over a 2 year period. The only LSZ well that was sampled multiple times (2-251R) shows the highest Σ_{CAH} concentrations and the largest increase in Σ_{CAH} over time. This well had Σ_{CAH} increasing from 930 to 1,483 $\mu\text{g/L}$ over 0.9 years. The DRs of these samples are uniformly low, ranging from 0.09 to 0.38. The steady-state or increasing Σ_{CAH} over time, and the low DR values, indicate that natural attenuation is not a significant process at GWMU 1F.

BTEX. There was only one sample from GWMU 1F that had detectable concentrations of a BTEX compound. Analyses from this well are provided in Table 5-7b. The sample obtained at well 2-337B on November 3, 1999 had an estimated toluene concentration of 0.6 $\mu\text{g/L}$, which is below the practical quantitation limit of 1.0 $\mu\text{g/L}$. A previous sample obtained on January 6, 1999, from the same well did not have any detectable concentrations of BTEX compounds.

5.5 Conclusions of Characterization

5.5.1 General Conclusions

The following general conclusions regarding groundwater contamination have been made from the collected data:

- The metals most commonly detected above MCLs in the monitoring wells at Tinker AFB are barium, chromium, and nickel. Serial sampling and other considerations,

strongly support the conclusion that the presence of chromium and nickel in the groundwater may be from the degradation of stainless-steel well screens and well pumps used in the installation of wells. In addition, barium occurs in the mineral barite, which is prevalent in the red beds of the Hennessey and Garber-Wellington. Similarly iron, which occurs above its PRG at a lesser frequency, may be related to the desorption of iron oxides in the Garber-Wellington (IT, 1999d; 1999c). Finally, there is a strong correlation between elevated turbidity and elevated concentrations of barium, chromium, and nickel, as well as other trace metals such as lead and arsenic. This is due to the tendency of these metals to adsorb to clay and iron oxide particles contained in the water sample (IT, 1999c). These data suggest that the occurrences of metals above regulatory levels are not widespread, and are not related to sources of contamination from Tinker AFB mission-related activities.

- Contaminant migration pathways are directly related to the permeabilities of the lithologies making up the water-bearing zones and aquitards at the Base. This is because coarser (sandy), more permeable sediments representing channel sand deposition control dominant flow paths in both the horizontal and vertical directions.
- There is a general correlation between hydraulic conductivity within GWMU subunits and the distance over which plumes have apparently migrated. In areas where the hydraulic conductivity was found to be the lowest on Base, such as GWMU 1, migration of plumes has occurred over relatively short distances. Vertical migration in certain specific areas of GWMU subunits may be enhanced by the presence of zones of increased hydraulic conductivity leading to the downward migration of TCH (discussed in more detail below).
- Natural attenuation of organic contaminants is believed to have taken place within individual plumes. However, a complete evaluation is needed to determine its potential for remediation and the extent to which attenuation of solvents and fuels has occurred across the Base. Preliminary analyses based on temporal trends presented in this report indicate the potential for natural attenuation of organic contaminants in the portion of CG037 within GWMU 1 may be low.

5.5.2 Specific Subunit Conclusions

GWMU 1B

- Both free-phase fuel product in one well and dissolved fuel constituents in groundwater in several wells were found in the USZ at GWMU 1B. Additional data from UST program wells that were installed under OCC regulations were also included in this report. A hydrocarbon recovery system has been installed at the BX Service Station, and was expanded in 1998 and 1999 to include more wells in both the USZ and the LSZ (PES, 2000).

- Groundwater in the USZ at GWMU 1B has been impacted by dissolved-phase chlorinated hydrocarbons. The downgradient extent of chlorinated hydrocarbons in the USZ in GWMU 1B is defined, particularly in the lateral extent. There is no evidence of vertical migration of TCH below the upper portions of the LSZ. The likely source of the TCH contamination is the BX Service Station or activities that occurred at or in the vicinity of this site prior to construction of that facility. Additional possible sources are former facilities in the vicinity as shown on Figure 5-1, particularly the “Base Laundry” facility relative to carbon tetrachloride contamination.
- Arsenic, barium, chromium, nickel, and lead were detected above their MCLs and/or PRGs in one or more of the monitoring wells sampled within the study area. The presence of lead potentially relates to fuel releases at the BX Service Station. Because elevated turbidity levels were also present at the time of sampling in every case, evidence of corrosion of well screens contributing to concentrations of nickel and chromium observed in some of the wells, and due to a lack of meaningful spatial distributions for metals, it appears that, except for lead in the vicinity of the BX Service Station, activities at Tinker AFB did not contribute to metals contamination in groundwater at GWMU 1B. As discussed under general conclusions above, the presence of some metals is related to geologic formation chemistry and the geochemistry of the interaction of the formation with groundwater.
- BTEX and TCH constituents were present in the LSZ in GWMU 1B. The lateral extent of this contamination has been defined downgradient from the unit. There are increases in concentrations of both BTEX and TCH constituents in the LSZ compared with the USZ; these increases are likely due to a zone of increased vertical hydraulic conductivity observed in the vicinity of the BX Service Station. There are a limited number of wells screened in the deeper portion of the LSZ at GWMU 1B; however, it appears that contamination does not currently extend vertically beyond the upper portions of the LSZ.
- Contamination has not been observed in the PZ at GWMU 1B.

GWMU 1F

- No fuel constituents were detected above their respective MCLs at this location at Tinker AFB wells. There is fuel-related contamination moving onto Tinker AFB from north of the Base boundary from the site of a leaking UST.
- Groundwater in the USZ at GWMU 1F has been impacted by dissolved-phase chlorinated hydrocarbons. The downgradient westward extent of this plume has been defined, with the possible exception of the lateral extent of migration west of well 2-422B. The potential source(s) for the TCH plume are unknown, but are likely related to former facilities in the vicinity as shown on Figure 5-1, or possibly to an off-Base source of TCE along the northern Base boundary.

- Arsenic, barium, chromium, lead, and nickel were detected above their MCLs and/or PRGs in one or more of the monitoring wells sampled within the study area. Because elevated turbidity levels were also present at the time of sampling in every case, evidence of corrosion of well screens contributing to concentrations of nickel and chromium observed in some of the wells, and due to a lack of meaningful spatial distributions for metals, it appears that activities at Tinker AFB did not contribute to metals contamination in groundwater at GWMU 1F.
- Based on the data from well cluster 52 and upgradient wells, groundwater in the LSZ and PZ has not been impacted by organic or inorganic compounds at GWMU 1F.

5.5.3 Conclusions of Temporal Trend Analysis

The following discussion provides conclusions of temporal trend analysis for BTEX constituents and for chlorinated hydrocarbons at GWMU 1.

BTEX. Total BTEX concentrations at GWMU 1B are decreasing over time, most likely due to a combination of active remediation and natural attenuation processes. Only minor detections of BTEX constituents at concentrations below the MCLs were found at GWMU 1F.

Chlorinated Aliphatic Hydrocarbons. The main observation from the temporal trend evaluation is that the CAH-impacted wells that were sampled multiple times exhibit a wide range of CAH degradation behavior. Some of these wells show no evidence of degradation based on detectable primary solvents but no detectable degradation products. Other wells show advanced degradation as evidenced by detectable degradation products and no primary solvents. The remaining wells show varying degrees of degradation based on the degradation ratios. In many cases, the sample data indicate that the degradation of chlorinated compounds is enhanced by the presence of hydrocarbon-based fuel constituents in the groundwater.

A second observation from the temporal trend analysis is that although reductive dechlorination is an ongoing process, little to no CAH mass loss is observed. The constant, or at some locations increasing, total CAH mass suggests that there is some continuing source that is contributing solvents to the groundwater concurrently with degradation. Three potential sources include:

- **Desorption of solvents from sediments.** Partial or complete degradation of a CAH compound in a sediment-groundwater system will result in the desorption of additional mass of that compound from the sediment to the groundwater, thus

partially replenishing the mass of degraded CAH. This process will continue until the total mass of the compound (both adsorbed and dissolved) is degraded.

- ***Continuing source of solvents in overlying sediments.*** If solvents still remain in the unsaturated zone above the CAH plumes, then they may serve as continuing sources that slowly replenish the primary solvents by vertical infiltration. If the rate of replenishment is similar to the rate of degradation within the plume, then total CAH mass will remain constant even though degradation is proceeding.
- ***The presence of a dense non-aqueous solvent phase within the plume.*** If chlorinated solvents are released to groundwater at concentrations that locally exceed their solubilities, then a separate non-aqueous phase will persist. The densities of these compounds are greater than water (PCE = 1.62, TCE = 1.46, H₂O = 1.00 grams per cubic centimeter at 20° Celsius) and will therefore tend to migrate downward below the water table, where they will slowly dissolve. If the rate of dissolution from the non-aqueous phase is similar to the rate of degradation within the plume, then total CAH mass in the aqueous phase will remain constant even though degradation is proceeding.

At GWMU 1B, there is little evidence that DNAPL is present, other than the limited degree of reduction of chlorinated solvents and the slight increase in total chlorinated hydrocarbons mass. There is a zone of increased vertical hydraulic conductivity in the area around GWMU 1B in the USZ-LSZ aquitard that would serve as a conduit for the downward migration of dissolved constituents. However, the presence of a DNAPL or a continuing source of hydrocarbon contamination from the overlying soils cannot be ruled out based on the existing data.

TABLES

Table 5-1
Volatile Organic Compounds
Analytical Data for Groundwater Samples
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Sampling Zone	Location ID	Sample Date	GWMU	Regulatory Standards		Maximum Contaminant Levels (MCLs)		Preliminary Remediation Goals (PRGs)		Oklahoma Water Quality Standards (OWQS)	
				5	7	0.2	0.6	0.7	0.7		
USZ	2-181	11/19/99	GWMU 1	1,1,2-Trichloroethane	5	7	0.2	0.6	0.7	0.7	
USZ	2-182	11/19/99	GWMU 1	1,1-Dichloroethane	810	810	0.3	0.3			
USZ	2-184	11/19/99	GWMU 1	1,1-Dichloroethane	0.046	0.046	0.6	0.6			
USZ	2-284B	11/17/99	GWMU 1	1,2,4-Trimethylbenzene	12	12					
USZ	2-336B	11/3/99	GWMU 1	1,2-Dibromoethane	0.05	0.05	0.00076	0.00076			
USZ	2-337B	11/3/99	GWMU 1	1,2-Dichloroethane	5	5	0.12	0.12			
USZ	2-339B	11/30/99	GWMU 1	1,3,5-Trimethylbenzene	12	12					
USZ	2-340B	11/30/99	GWMU 1	Benzene	5	5	0.39	0.39			
USZ	2-341B	11/30/99	GWMU 1	Carbon Tetrachloride	5	5	0.17	0.17			
USZ	2-371B	12/2/99	GWMU 1	Chloroethane	8600	8600	2.1	2.1			
USZ	2-372B	11/18/99	GWMU 1	Chloroform	100	100	0.16	0.16			
USZ	2-373B	11/18/99	GWMU 1	cis-1,2-Dichloroethane	70	70	61	61			
USZ	2-402B	11/16/99	GWMU 1A	Ethylbenzene	700	700	0.4	0.4			
USZ	2-163B	11/16/99	GWMU 1A	Isopropylbenzene	660	660	100 D	100 D			
USZ	2-164B	11/16/99	GWMU 1A	m,p-Xylenes	10000	10000	1400	1400			
USZ	2-166B	11/16/99	GWMU 1A								
USZ	2-195	11/22/99	GWMU 1B								
USZ	2-243	11/22/99	GWMU 1B								
USZ	2-245	11/23/99	GWMU 1B								
USZ	2-246	11/23/99	GWMU 1B								
USZ	2-370B	11/24/99	GWMU 1D								
USZ	2-261B	12/1/99	GWMU 1F								
USZ	2-269B	11/3/99	GWMU 1F								
USZ	52BR	12/1/99	GWMU 1F								
LSZ	2-371A	11/24/99	GWMU 1								
LSZ	2-403A	11/24/99	GWMU 1								
LSZ	2-414A	11/23/99	GWMU 1								
LSZ	2-415A	11/23/99	GWMU 1								
LSZ	2-248	11/23/99	GWMU 1B								
LSZ	2-249	11/24/99	GWMU 1B								
LSZ	2-250	12/29/99	GWMU 1B								
LSZ	2-251R	11/23/99	GWMU 1B								
LSZ	2-375A	11/24/99	GWMU 1B								
LSZ	2-370A	11/24/99	GWMU 1D								
LSZ	2-137A	11/5/99	GWMU PRM								

Table 5-1
Volatile Organic Compounds
Analytical Data for Groundwater Samples
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Sampling Zone	Location ID	Sample Date	GWMU	Regulatory Standards		Maximum Contaminant Levels (MCLs)		Preliminary Remediation Goals (PRGs)		Oklahoma Water Quality Standards (OWQS)	
				µg/L	Qual	µg/L	Qual	µg/L	Qual	µg/L	Qual
USZ	2-181	11/19/99	GWMU 1								
USZ	2-182	11/19/99	GWMU 1								
USZ	2-184	11/19/99	GWMU 1								
USZ	2-264B	11/17/99	GWMU 1	1.7							
USZ	2-336B	11/3/99	GWMU 1								
USZ	2-337B	11/3/99	GWMU 1								
USZ	2-339B	11/30/99	GWMU 1	1.5							
USZ	2-340B	11/30/99	GWMU 1								
USZ	2-341B	11/30/99	GWMU 1	2.2							
USZ	2-371B	12/2/99	GWMU 1								
USZ	2-372B	11/18/99	GWMU 1								
USZ	2-373B	11/18/99	GWMU 1								
USZ	2-402B	11/19/99	GWMU 1								
USZ	2-163B	11/16/99	GWMU 1A								
USZ	2-164B	11/16/99	GWMU 1A	1.5							
USZ	2-195	11/22/99	GWMU 1B								
USZ	2-243	11/24/99	GWMU 1B								
USZ	2-245	11/23/99	GWMU 1B								
USZ	2-246	11/23/99	GWMU 1B								
USZ	2-370B	11/24/99	GWMU 1D								
USZ	2-261B	12/1/99	GWMU 1F								
USZ	2-269B	11/3/99	GWMU 1F								
USZ	52BR	12/1/99	GWMU 1F								
LSZ	2-371A	12/2/99	GWMU 1								
LSZ	2-403A	11/24/99	GWMU 1								
LSZ	2-414A	11/23/99	GWMU 1								
LSZ	2-415A	11/23/99	GWMU 1								
LSZ	2-248	11/23/99	GWMU 1B								
LSZ	2-249	11/23/99	GWMU 1B	7.5							
LSZ	2-250	12/29/99	GWMU 1B								
LSZ	2-251R	11/23/99	GWMU 1B								
LSZ	2-375A	11/24/99	GWMU 1B								
LSZ	2-370A	11/24/99	GWMU 1D								
LSZ	2-137A	11/5/99	GWMU PRM								

Qualifiers
 J - Result was less than the reporting limit but greater than the method detection limit (estimated value)
 D - Sample was diluted prior to quantification.
 Regulatory standards in µg/L.
 µg/L - Micrograms per liter.
 USZ - Upper saturated zone.
 LSZ - Lower saturated zone.

Table 5-2
Semivolatile Organic Compounds
Analytical Data for Groundwater Samples
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Regulatory Standards				Maximum Contaminant Levels (MCLs)		Preliminary Remediation Goals (PRGs)		Oklahoma Water Quality Standards (OWQS)	
Sampling Zone	Location ID	Sample Date	GWMU	2-Methylnaphthalene	4-Chloro-3-methylphenol	Di-n-butylphthalate	Naphthalene	µg/L Qual	µg/L Qual
USZ	2-181	11/19/99	GWMU 1						
USZ	2-264B	11/17/99	GWMU 1					16	
USZ	2-270B	11/3/99	GWMU 1					8.7 J	
USZ	2-336B	11/3/99	GWMU 1					1.2 J	
USZ	2-337B	11/3/99	GWMU 1					1.4 J	
USZ	2-338B	11/3/99	GWMU 1					2 J	
USZ	2-408B	11/3/99	GWMU 1					1.1 J	
USZ	2-163B	11/16/99	GWMU 1A					1.3 J	
USZ	2-262B	11/5/99	GWMU 1F		1.1 J			1.9 J	
USZ	2-269B	11/3/99	GWMU 1F					2 J	
LSZ	2-150A	11/3/99	GWMU 1					2.3 J	
LSZ	2-251R	11/23/99	GWMU 1B					1.1 J	
LSZ	52AR	12/1/99	GWMU 1F						
LSZ	2-137A	11/5/99	GWMU PRM	5.5 J				1.7 J	
LSZ	2-137C	11/5/99	GWMU PRM					7.8 J	
LLSZ	2-150C	11/3/99	GWMU 1					3.5 J	
PROD	2-137D	11/5/99	GWMU PRM					1 J	
								1.9 J	
									30

Qualifier
 J - Result was less than the reporting limit but greater than the method instrument limit (estimated value).
 Regulatory standards in µg/L
 USZ - Upper saturated zone
 LSZ - Lower saturated zone
 LLSZ - Used to describe wells completed in the lower portions of the LSZ.
 P.Z. - Producing zone.
 µg/L - Micrograms per liter.

Table 5-3

**Pesticides/Polychlorinated Biphenyls
Analytical Data for Groundwater Samples
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma**

CG037 RFI, GWMU 1B and 1F
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Regulatory Standards				alpha-Chlordane	Dieldrin	gamma-Chlordane
Maximum Contaminant Levels (MCLs)				2	0.0042	2
Preliminary Remediation Goals (PRGs)				0.19		0.19
Oklahoma Water Quality Standards (OWQS)						
Sampling Zone	Location ID	Sample Date	GWMU	µg/L Qual	µg/L Qual	µg/L Qual
USZ	2-165B	11/16/99	GWMU 1	0.19	0.065 J	0.16
USZ	2-402B	11/19/99	GWMU 1	0.034 P		0.044
USZ	2-149B	11/16/99	GWMU 1A	0.046		0.12 P

Qualifier

J - Result is less than reporting limit but greater than the method detection limit (estimated value)
P - Target analyte where there is greater than 25% difference for detected compounds between the two gas chromatograph columns; the lower of the two values is reported on the Form I.

Regulatory standards reported in µg/L.
USZ - Upper saturated zone.
µg/L - Micrograms per liter.

Table 5-4

Metals

Analytical Data for Groundwater Samples

CG037 RFI, GWMU 1B and 1F

Tinker AFB, Oklahoma

CG037 RFI, GWMU 1B and GWMU 1F
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Regulatory Standards		Sampling Zone	Location ID	Sample Date	GWMU	Arsenic	Barium	Cadmium	Chromium	Lead	Nickel	Selenium	Silver
Maximum Contaminant Levels (MCLs)	Preliminary Remediation Goals (PRGs)												
USZ Background 95% Upper Tolerance Limits (UTLs)													
USZ		2-150B		11/3/99	GWMU 1	0.0037	2.7		0.042	0.0032	24	0.0043	
USZ		2-151B		12/1/99	GWMU 1		0.539		0.0266		0.602		
USZ		2-155B		11/19/99	GWMU 1		0.547						
USZ		2-165B		11/16/99	GWMU 1		0.0682		0.0336		0.0931		
USZ		2-181		11/19/99	GWMU 1		0.0393				0.0142		
USZ		2-182		11/19/99	GWMU 1		2.77			0.0093	0.0044		
USZ		2-183		11/19/99	GWMU 1	0.0219	2.55						
USZ		2-184		11/19/99	GWMU 1		0.0846		0.0192		0.0048		
USZ		2-185		11/19/99	GWMU 1		0.066				0.0164		
USZ		2-238		11/19/99	GWMU 1		1.57						
USZ		2-247		12/2/99	GWMU 1	0.0758	1.09			0.003			
USZ		2-263B		11/22/99	GWMU 1		0.382		0.0241	0.0114			
USZ		2-264B		12/1/99	GWMU 1		0.429				0.0282		
USZ		2-265B		11/17/99	GWMU 1		0.077		0.0092		0.0241		
USZ		2-270B		11/17/99	GWMU 1	0.0423	0.452		0.0092		0.0091		
USZ		2-336B		11/3/99	GWMU 1	0.399	2.98		0.399		0.274		
USZ		2-337B		11/3/99	GWMU 1		0.0756 B		6.08	0.0244	3.94		
USZ		2-338B		11/3/99	GWMU 1		0.0771 B		0.11		0.108		
USZ		2-339B		11/30/99	GWMU 1		0.0879 B		0.851		0.277		
USZ		2-340B		11/30/99	GWMU 1		0.621				1.13		
USZ		2-341B		11/30/99	GWMU 1		0.385		0.286		0.578		
USZ		2-371B		12/2/99	GWMU 1		1.16				0.173		
USZ		2-372B		11/18/99	GWMU 1		1.25		0.092		0.67		
USZ		2-373B		11/18/99	GWMU 1		0.293		0.0214		0.201		
USZ		2-402B		11/19/99	GWMU 1		0.393						
USZ		2-407B		11/30/99	GWMU 1		0.647		0.0697		0.362		
USZ		2-408B		11/3/99	GWMU 1	0.0655	0.147		0.104		0.587		
USZ		69		11/22/99	GWMU 1		1.48		0.577		0.104		
USZ		2-149B		11/16/99	GWMU 1A		2.21			0.0043			
USZ		2-163B		11/16/99	GWMU 1A		0.122						
USZ		2-164B		11/16/99	GWMU 1A		0.82						
USZ		2-166B		11/16/99	GWMU 1A		0.325						
USZ		2-173B		11/16/99	GWMU 1A		0.0361		0.151		0.0057		
USZ		2-192		11/23/99	GWMU 1B		0.59			0.0041			
USZ		2-195		11/22/99	GWMU 1B	0.016 *	0.259						
USZ		2-196		11/23/99	GWMU 1B		2.36		0.0066				
USZ		2-241		11/23/99	GWMU 1B		0.21			0.0135			
USZ		2-242		11/23/99	GWMU 1B		0.714						
USZ		2-243		11/24/99	GWMU 1B		0.574		0.0135				
USZ							0.0314						

Table 5-4

Metals

Analytical Data for Groundwater Samples

CG037 RFI, GWMU 1B and 1F

Tinker AFB, Oklahoma

CG037 RFI, GWMU 1B and GWMU 1F
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Regulatory Standards		GWMU							
Maximum Contaminant Levels (MCLs)	Preliminary Remediation Goals (PRGs)	Location ID	Sample Date						
Sampling Zone	Location ID	Sample Date	GWMU						
0.05	2	0.000045	2.6	0.01	0.015	0.1	0.1	0.05	0.1
0.000045	2.6	0.000045	2.6	0.000045	0.004	0.73	0.73	0.18	0.18
0.0538	0.132	0.0538	0.132	0.0538	0.0058	0.0098	0.0098	0.0123	0.0123
0.0098	0.0095	0.0098	0.0095	0.0098	0.0063	0.0064	0.0064	0.0056	0.0056
0.0308	0.033	0.0308	0.033	0.0308	0.0308	0.0116	0.0116	0.0064	0.0064
0.0356	0.179	0.0356	0.179	0.0356	0.0356	0.0905	0.0905	0.0164	0.0164
0.921	0.807	0.921	0.807	0.921	0.921	0.0475	0.0475	0.047	0.047
1.36	0.756	1.36	0.756	1.36	0.076	0.0199	0.0199	0.064	0.064
1.33	0.937	1.33	0.937	1.33	0.076	0.043	0.043	0.08	0.08
0.634	0.0116	0.634	0.0116	0.634	0.064	0.043	0.043	0.08	0.08
0.787	0.0064	0.787	0.0064	0.787	0.064	0.043	0.043	0.08	0.08
0.658	0.0905	0.658	0.0905	0.658	0.064	0.043	0.043	0.08	0.08
0.475	0.0164	0.475	0.0164	0.475	0.064	0.043	0.043	0.08	0.08
3.3	Not Established	3.3	Not Established	3.3	0.064	0.043	0.043	0.08	0.08
0.018	0.018	0.018	0.018	0.018	0.064	0.043	0.043	0.08	0.08
0.32	0.32	0.32	0.32	0.32	0.0358	0.516	0.516	0.104	0.104
0.393	0.393	0.393	0.393	0.393	0.0225	0.104	0.104	0.018	0.018
0.363	0.363	0.363	0.363	0.363	0.0327	0.018	0.018	0.448	0.448
0.588	0.588	0.588	0.588	0.588	0.102	0.448	0.448	0.271	0.271
0.496	0.496	0.496	0.496	0.496	0.0725	0.271	0.271	0.276	0.276
0.366	0.366	0.366	0.366	0.366	0.334	0.276	0.276	0.354	0.354
0.289	0.289	0.289	0.289	0.289	0.0298	0.354	0.354	0.116	0.116
0.747	0.747	0.747	0.747	0.747	0.0122	0.116	0.116	0.0072	0.0072
0.456	0.456	0.456	0.456	0.456	0.0118	0.0072	0.0072	0.0048	0.0048
0.374	0.374	0.374	0.374	0.374	0.0118	0.0048	0.0048	0.027	0.027
0.601	0.601	0.601	0.601	0.601	0.0118	0.027	0.027		
2.69	2.69	2.69	2.69	2.69					
0.605	0.605	0.605	0.605	0.605					
0.524	0.524	0.524	0.524	0.524					
0.829	0.829	0.829	0.829	0.829					
0.521	0.521	0.521	0.521	0.521					
0.896	0.896	0.896	0.896	0.896					

LSZ Background 95% Upper Tolerance Limits (UTLs)

LSZ	2-150A	11/23/99	GWMU 1	0.32	0.018	0.064	0.043	0.08	0.08
LSZ	2-151A	12/1/99	GWMU 1	0.393	0.018	0.064	0.043	0.08	0.08
LSZ	2-155A	11/19/99	GWMU 1	0.363	0.018	0.064	0.043	0.08	0.08
LSZ	2-371A	12/2/99	GWMU 1	0.588	0.018	0.064	0.043	0.08	0.08
LSZ	2-402A	11/19/99	GWMU 1	0.496	0.018	0.064	0.043	0.08	0.08
LSZ	2-403A	11/24/99	GWMU 1	0.535	0.018	0.064	0.043	0.08	0.08
LSZ	2-413A	11/19/99	GWMU 1	0.366	0.018	0.064	0.043	0.08	0.08
LSZ	2-414A	11/23/99	GWMU 1	0.289	0.018	0.064	0.043	0.08	0.08
LSZ	2-415A	11/23/99	GWMU 1	0.747	0.018	0.064	0.043	0.08	0.08
LSZ	2-149A	11/16/99	GWMU 1A	0.456	0.018	0.064	0.043	0.08	0.08
LSZ	2-195A	11/22/99	GWMU 1B	0.374	0.018	0.064	0.043	0.08	0.08
LSZ	2-245A	11/23/99	GWMU 1B	0.601	0.018	0.064	0.043	0.08	0.08
LSZ	2-248	11/23/99	GWMU 1B	2.69	0.0139 *	0.064	0.043	0.08	0.08
LSZ	2-249	11/24/99	GWMU 1B	0.605	0.0139 *	0.064	0.043	0.08	0.08
LSZ	2-250	12/29/99	GWMU 1B	0.524	0.0139 *	0.064	0.043	0.08	0.08
LSZ	2-251R	11/23/99	GWMU 1B	0.829	0.0139 *	0.064	0.043	0.08	0.08
LSZ	2-252	11/23/99	GWMU 1B	0.521	0.0139 *	0.064	0.043	0.08	0.08
LSZ	2-375A	11/24/99	GWMU 1B	0.896	0.0139 *	0.064	0.043	0.08	0.08

Table 5-4

Metals

Analytical Data for Groundwater Samples

CG037 RFI, GWMU 1B and 1F

Tinker AFB, Oklahoma

Regulatory Standards		Sample Date		GWMU		Arsenic		Barium		Cadmium		Chromium		Lead		Nickel		Selenium		Silver	
Maximum Contaminant Levels (MCLs)	Preliminary Remediation Goals (PRGs)	Location ID	Sample Date	GWMU	mg/L	Qual	mg/L	Qual	mg/L	Qual	mg/L	Qual	mg/L	Qual	mg/L	Qual	mg/L	Qual	mg/L	Qual	
		2-370A	11/24/99	GWMU 1D	0.05		0.516		0.005		0.087		0.015		1		0.05		0.1		
		52AR	12/1/99	GWMU 1F	0.000045		0.309		0.018		0.0101		0.004		0.0173		0.18		0.1		
		2-137A	11/5/99	GWMU PRM			1.04				0.0621				0.0074						
		2-137C	11/5/99	GWMU PRM			0.52								0.137						
		40CR	11/29/99	GWMU PRM			0.246								0.17						
		68A	11/22/99	GWMU PRM			0.75														
LLSZ Background 95% Upper Tolerance Limits (UTLs)																					
		2-150C	11/3/99	GWMU 1			Not Established														
		2-149C	11/16/99	GWMU 1A			0.431														
		52C	12/1/99	GWMU 1F			0.332														
		40A	11/29/99	GWMU PRM			0.192								0.0067						
							0.339														
PZ Background 95% Upper Tolerance Limits (UTLs)																					
		2-137D	11/5/99	GWMU PRM			Not Established														
		WS-2	8/20/99	GWMU WSW			0.345								0.0101						
		WS-30	8/20/99	GWMU WSW			0.399														
							0.465														

Qualifier

B - Result is less than the reporting limit but greater than the instrument detection limit (estimated value).
 * - Duplicate analysis was not within control limits

Regulatory standards in mg/L, background values from IT, 1999 and are specific for each sample zone
 USZ - Upper saturated zone
 LSZ - Lower saturated zone
 LLSZ - Used to describe wells completed in the lower portion of the LSZ
 PZ - Producing zone
 mg/L - Milligrams per liter

**Table 5-5
 Summary of Analytical Results for Wells Not Sampled as Part of the
 1999 Annual Basewide Sampling Round
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Well #	Sample Zone	Date Sampled	Detected Constituents	Concentrations µg/L
Data from: Brown and Root, 1999				
2-422B	USZ	10/15/99	Carbon Tetrachloride Trichloroethene bis(2-Ethylhexyl)phthalate Diethylphthalate	2.3J 16 4.6J 10J
Data from: Parsons, UST 23, 1999				
2-191R	USZ	August 1999	No VOCs detected	ND
2-432A	LSZ	August 1999	Carbon Disulfide Carbon Tetrachloride	8.2 4.4
2-433A	LSZ	August 1999	No VOCs detected	
2-434A	LSZ	August 1999	1,1-Dichloroethene Carbon Disulfide Carbon Tetrachloride Chloroform Tetrachloroethene Trichloroethene	12 23 27 6.3 2.8 240
2-242A	LSZ	August 1999	1,1-Dichloroethene Carbon Disulfide cis-1,2-Dichloroethene Trichloroethene	22(D) 86 5.1 42
2-435B	USZ	August 1999	Naphthalene	8.4
2-436B	USZ	August 1999	No VOCs detected	ND
Arcadis, 1999				
MW-15	USZ	12/9/99	Benzene BTEX	484 607
MW-24	USZ	12/9/99	Benzene BTEX	ND ND
MW-27	USZ	12/9/99	Benzene BTEX	107 136.5
MW-33	USZ	12/9/99	Benzene BTEX	112.3 121.5

BTEX - Benzene, toluene, ethylbenzene, and total xylenes.
 D - Sample was diluted prior to quantification.
 J - Result was less than the reporting limit but greater than the method detection limit.
 LSZ - Lower Saturated Zone.
 µg/L - Micrograms per liter.
 ND - Not detected.
 UST - Underground storage tank.
 USZ - Upper Saturated Zone.
 VOC - Volatile organic compound.

Table 5-6a

**Chlorinated Aliphatic Hydrocarbon Concentrations at GWMU 1B
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

(concentrations in micrograms per liter)

Well	Sample Zone	Sample Date	PCE	TCE	1,1-DCE	cis-DCE	trans-DCE	VC	DR	Sum CAH
2-248	LSZ	11/23/99	ND	5.4	ND	15	ND	ND	2.78	20.4
2-249	LSZ	11/24/99	1.6	35	ND	3.9	ND	ND	0.11	40.5
2-250	LSZ	12/29/99	0.8	13	ND	3.3	ND	ND	0.24	17.1
2-245	USZ	11/23/99	ND	84	ND	9.1	ND	ND	0.11	93.1
2-245A	LSZ	01/07/99	0.8	21	ND	ND	ND	ND	0.00	21.8
		11/23/99	9.7	980	53	54	ND	ND	0.11	1,096.7
2-190	USZ	10/10/97	ND	4	ND	2	ND	ND	0.50	6.0
2-340B	USZ	01/05/99	ND	2	ND	ND	ND	ND	0.00	2.0
		11/30/99	ND	15	ND	ND	ND	ND	0.00	15.0
2-414A	LSZ	01/05/99	ND	23	2.4	7.1	ND	ND	0.41	32.5
		11/23/99	0.9	26	2.7	6.7	ND	ND	0.35	36.3
2-415A	LSZ	01/05/99	3.8	410	20	2.8	ND	ND	0.06	436.6
		11/23/99	3.8	360	19	3	ND	ND	0.06	385.8
2-375A	LSZ	01/07/99	ND	3.8	ND	ND	ND	ND	0.00	3.8
		11/24/99	ND	94	ND	1.7	ND	ND	0.02	95.7

- CAH - Chlorinated aliphatic hydrocarbon.
- 1,1-DCE - 1,1-Dichloroethylene.
- cis-DCE - cis-1,2-Dichloroethylene.
- trans-DCE - trans-1,2-Dichloroethylene.
- DR - Degradation ratio.
- LSZ - Lower Saturated Zone.
- ND - Not detected
- PCE - Tetrachloroethylene.
- TCE - Trichloroethylene.
- USZ - Upper Saturated Zone.
- VC - Vinyl chloride.

Table 5-6b

**BTEX Concentrations at GWMU 1B
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

(concentrations in micrograms per liter)

Well	Sample Zone	Sample Date	Benzene	Ethyl benzene	Toluene	Xylene	Total BTEX
2-192	USZ	10/10/97	100	140	830	830	1900.0
		12/31/98	ND	ND	ND	ND	0.0
		11/23/99	ND	ND	ND	ND	0.0
2-194	USZ	10/10/97	15,000	1,200	770	2,830	19,800.0
		01/05/99	3,100	86	12	70.8	3,268.8
2-195	USZ	10/10/97	32	4	2	8	46.0
		01/05/99	90	55	9.2	78	232.2
		11/22/99	180	110	ND	60	350
2-195A	LSZ	01/05/99	1.9	ND	ND	ND	1.9
		11/22/99	ND	ND	ND	ND	0.0
2-245A	LSZ	01/07/99	16	ND	ND	ND	16.0
		11/23/99	380	ND	ND	3.3	383.3
2-251R	LSZ	01/07/99	2,200	0.9	5.7	5	2,211.6
		11/23/99	8,600	31	48	27	8706
2-340B	USZ	01/05/99	0.6	ND	ND	ND	0.6
		11/30/99	ND	ND	ND	ND	0.0

BTEX - Benzene, toluene, ethyl benzene, and total xylenes.
 LSZ - Lower saturated zone.
 ND - Not detected.
 USZ - Upper saturated zone.

Table 5-7a

**Chlorinated Aliphatic Hydrocarbon Concentrations at GWMU 1F
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

(concentrations in micrograms per liter)

Well	Sample Zone	Sample Date	PCE	TCE	1,1-DCE	cis-DCE	trans-DCE	VC	DR	Sum CAH
52BR	USZ	08/05/96	ND	36	ND	5	ND	ND	0.14	41.0
		10/22/97	ND	39	ND	5	ND	ND	0.13	44.0
		01/05/99	ND	38	ND	4.7	ND	ND	0.12	42.7
		12/01/99	ND	34	ND	5.1	ND	ND	0.15	39.1
2-251R	LSZ	01/07/99	15	840	60	15	ND	ND	0.09	930.0
		11/23/99	34	1,200	140	59	25	25	0.20	1,483.0
2-261B	USZ	10/21/97	ND	12	ND	4	0.6	ND	0.38	16.6
		01/06/99	ND	10	ND	2.9	ND	ND	0.29	12.9
		12/01/99	ND	8.5	ND	3	ND	ND	0.35	11.5
2-269B	USZ	10/21/97	ND	19	ND	2	ND	ND	0.11	21.0
		01/06/99	ND	43	ND	4.6	0.8	ND	0.13	48.4
		11/03/99	ND	52	ND	7.1	1.1	ND	0.16	60.2

- CAH - Chlorinated aliphatic hydrocarbon.
- 1,1-DCE - 1,1-Dichloroethylene.
- cis-DCE - cis-1,2-Dichloroethylene.
- trans-DCE - trans-1,2-Dichloroethylene.
- DR - Degradation ratio.
- LSZ - Lower Saturated Zone.
- ND - Not detected.
- PCE - Tetrachloroethylene.
- TCE - Trichloroethylene.
- USZ - Upper Saturated Zone.
- VC - Vinyl chloride.

Table 5-7b

**BTEX Concentrations at GWMU 1F
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

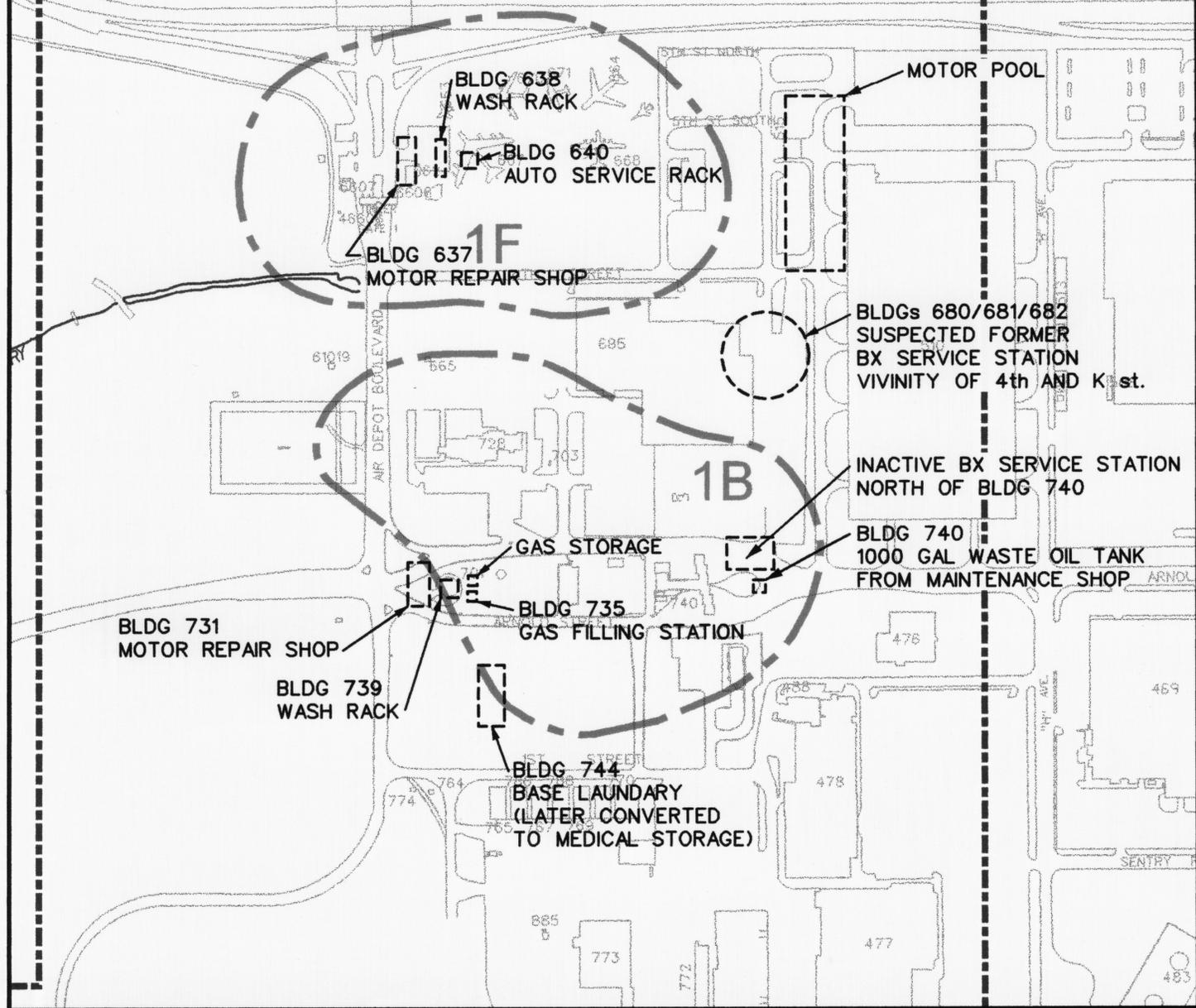
(concentrations in micrograms per liter)

Well	Sample Zone	Sample Date	Benzene	Ethyl benzene	Toluene	Xylene	Total BTEX
2-337B	USZ	01/06/99	ND	ND	ND	ND	0.0
		11/03/99	ND	ND	0.6	ND	0.6

- BTEX - Benzene, toluene, ethyl benzene, and total xylenes.
- ND - Not detected.
- USZ - Upper saturated zone.

FIGURES

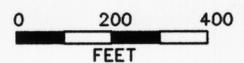
CG037



EXPLANATION

- POTENTIAL SOURCE AREA
- GROUNDWATER IRP SITE
- ▨ TINKER AIR FORCE BASE PROPERTY LINE

1A APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



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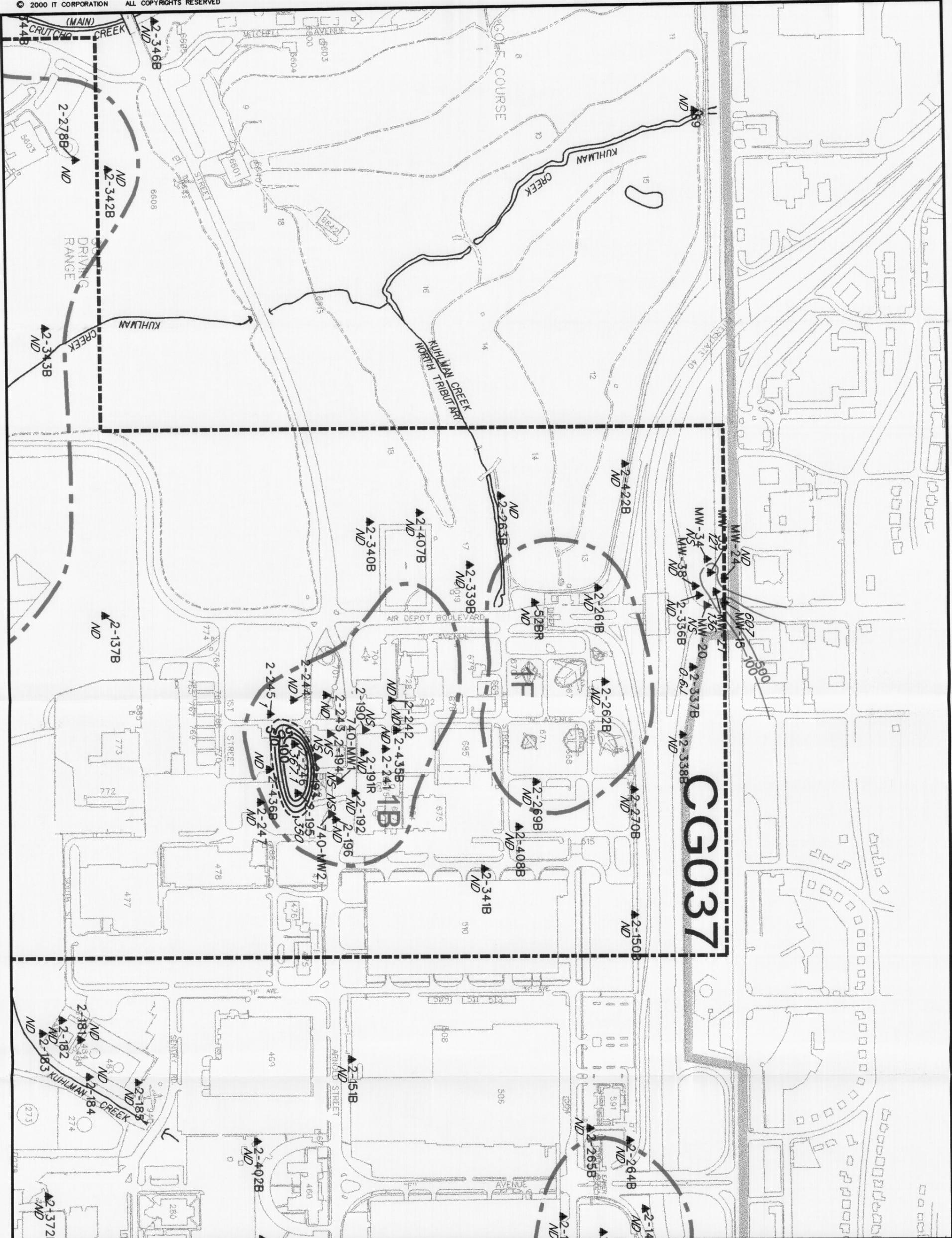
DRAWN BY: CFB
START DATE: 12/06/00
REVISED BY: CFB
LAST REV: 03/26/01
INITIATOR: MG
INT. DATE: 12/06/00

APPROXIMATE LOCATIONS OF POTENTIAL SOURCE AREAS FOR CONTAMINATION

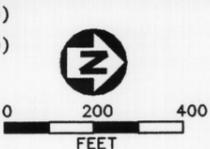
CG037 RFI GWMU 1B AND 1F

PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

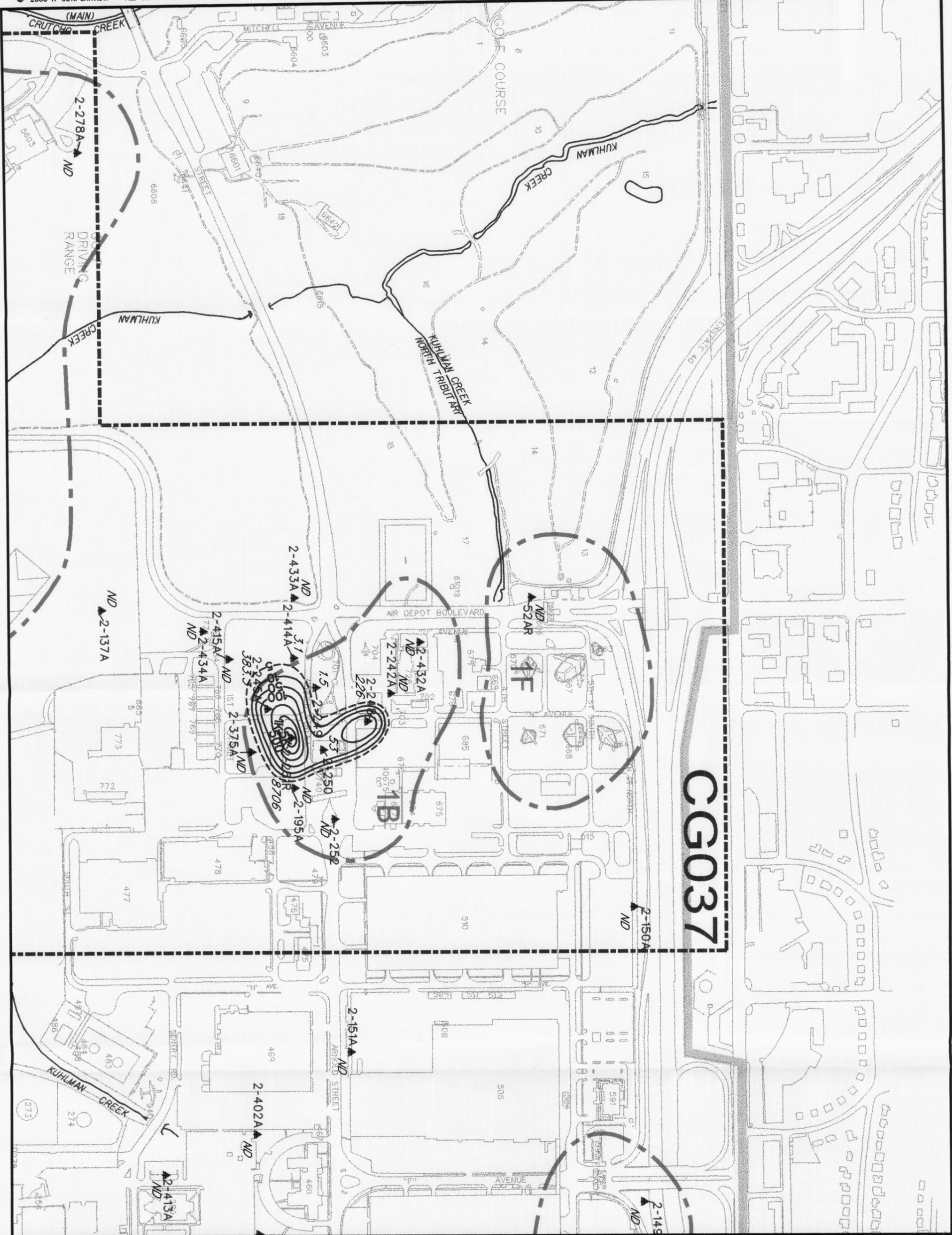
PROJ. NO. 799270
FIG. 5-1
UNIQUE NUMBER 799270-A15



EXPLANATION	
45B▲	MONITORING WELL LOCATION
S +	BWG 1999 ANALYTICAL DATA (µg/L)
(S) +	LOWER CONCENTRATION OF NESTED WELLS NOT USED IN CONTOURING
ND	ANALYTE NOT DETECTED
NA	CONSTITUENT NOT ANALYZED FOR IN 1999
NS	WELL NOT SAMPLED
D	SAMPLE WAS DILUTED FOR QUANTITATION
✓	VALUE IS ESTIMATED
---	GROUNDWATER IRP SITE
---	TINKER AIR FORCE BASE PROPERTY LINE
---	LINE OF EQUAL CONCENTRATION (µg/L) (DASHED WHERE INFERRED)
---	LINE OF EQUAL CONCENTRATION (µg/L) (DASHED WHERE INFERRED) DATA FROM ARCADIS 1999 INVESTIGATION OF MOBILE SERVICE STATION LOCATED NORTH OF BASE BOUNDARY
1A	APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



DRAWN BY: CFB START DATE: 11/29/00 REVISED BY: CFB LAST REV: 03/26/01 INITIATOR: MG INT. DATE: 11/29/00	BTEX ISOPLETH MAP FOR USZ CG037 RFI GWMU 1B AND 1F PREPARED FOR TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA	PROJ. NO. 799270 FIG. 5-2 UNIQUE NUMBER 799270-B06
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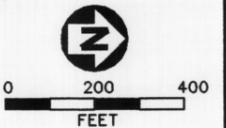


EXPLANATION

- 45B▲ MONITORING WELL LOCATION
- 5+ BWGW 1999 ANALYTICAL DATA (µg/L)
- (5)+ LOWER CONCENTRATION OF NESTED WELLS NOT USED IN CONTOURING
- ND+ ANALYTE NOT DETECTED
- NA CONSTITUENT NOT ANALYZED FOR IN 1999
- NS WELL NOT SAMPLED
- D SAMPLE WAS DILUTED FOR QUANTITATION
- ✓ VALUE IS ESTIMATED
- GROUNDWATER IRP SITE
- TINKER AIR FORCE BASE PROPERTY LINE

--5-- LINE OF EQUAL CONCENTRATION (µg/L) (DASHED WHERE INFERRED)

1A APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



DRAWN BY: CFB
START DATE: 11/29/00
REVISED BY: CFB
LAST REV: 03/27/01
INITIATOR: MG
INT. DATE: 11/29/00

BTEX ISOPLETH MAP FOR LSZ

CG037 RFI GWMU 1B AND 1F

PREPARED FOR
TINKER AIR FORCE BASE OKLAHOMA CITY OKLAHOMA

PROJ. NO. 799270

FIG. 5-3

UNIQUE NUMBER 799270-B07

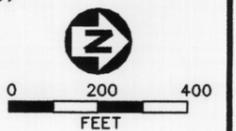


EXPLANATION

- 45B▲ MONITORING WELL LOCATION
- 5+ BWGW 1999 ANALYTICAL DATA (µg/L)
- (5)+ LOWER CONCENTRATION OF NESTED WELLS NOT USED IN CONTOURING
- ND+ ANALYTE NOT DETECTED
- NA CONSTITUENT NOT ANALYZED FOR IN 1999
- NS WELL NOT SAMPLED
- D SAMPLE WAS DILUTED FOR QUANTITATION
- ✓ VALUE IS ESTIMATED
- GROUNDWATER IRP SITE
- ▬ TINKER AIR FORCE BASE PROPERTY LINE

--5-- LINE OF EQUAL CONCENTRATION (µg/L) (DASHED WHERE INFERRED)

1A APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



DRAWN BY: CFB
START DATE: 10/15/01
REVISED BY:
LAST REV: / /
INITIATOR: MG
NET DATE: 10/15/01

TOTAL CHLORINATED HYDROCARBONS ISOPLETH MAP FOR LSZ

CG037 RFI GWMU 1B AND 1F

PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

PROJ. NO. 799270

FIG. 5-5

UNIQUE 799270-B74

6.0 Baseline Risk Assessment

This chapter of the summary RFI report presents the findings of the Baseline Risk Assessment for Tinker AFB CG037 groundwater, inclusive of the portions of both GWMU 1 and GWMU 2 that are associated with CG037, and surface water bodies associated with this area. The complete discussion including methodologies, equations, and supporting calculations for the risk assessment are provided in the RFI report. The Baseline Risk Assessment is presented in two parts: the Human Health Risk Assessment (HHRA) and the Ecological Risk Assessment (ERA). The results of the HHRA for GWMU 1B and 1F are presented in this RFI report. Both the HHRA (Section 6.1) and the ERA (Section 6.2) are intended to reflect appropriate guidance provided by EPA.

The objectives of the human health and ecological risk assessment process are to:

- Provide an analysis of baseline risks and help determine the need for remedial action at the CG037 area
- Provide a basis for determining levels of chemicals that can remain onsite and still be adequately protective of public health and the environment
- Provide a basis for comparing potential health and environmental impacts of various remedial alternatives
- Provide a consistent process for evaluating and documenting public health and environmental threats at the CG037 area.

6.1 Human Health Risk Assessment

The HHRA as defined by EPA (EPA, 1989) includes the exposure assessment, toxicity assessment and risk characterization. This HHRA includes the evaluation of surface water and groundwater. The RFI report provides the risk calculation spreadsheets used in performing the risk assessment; these spreadsheets are not included in this summary report.

6.1.1 Human Health Conceptual Site Model

The CSM for the risk assessment has been developed to provide the basis for identifying and evaluating the potential risks to human health in the baseline risk assessment. The conceptual model facilitates consistent and comprehensive evaluation of risks by creating a framework for identifying the paths by which humans and the environment may be impacted by groundwater and surface water in the CG037 area.

The elements necessary to construct a complete exposure pathway and develop the human health CSM include:

- Constituents of potential concern (COPC) and their sources
- Release mechanisms
- Transport pathways
- Exposure pathway scenarios
- Receptors.

Potential release mechanisms, significant contaminants, potential transport pathways, and possible receptor exposure pathways are shown conceptually in the generalized CSM in Figure 4-7. The exposure setting for the CG037 area can be generally described as light industrial; however, since no deed restriction is in place at this time, the potential exists for future residential use of the property. Operation as a major aircraft, weapons, engine repair depot, and logistics center began in 1942 and continues to the present. Past and current operations have required the use of petroleum products and hazardous materials. Operations particular to this investigation have included the bulk storage and use of petroleum fuels (gasoline and diesel) and the use of chlorinated solvents in Base operations.

Groundwater in the CG037 area, for the purposes of this risk assessment, has been divided into two water-bearing zones: the USZ, and the LSZ. There are approximately eight groundwater supply wells in and around the CG037 area that are screened in the PZ. The geographic location of the PZ wells was considered when formulating the exposure scenarios, and a hypothetical future risk was calculated at those well points even though contamination is currently confined to the USZ and LSZ in this area. The purpose for this was to ensure that the results of the 30 year fate and transport modeling would be considered in calculating future risk. Groundwater flow is, generally, in a west-northwest, or west-southwest direction depending on location within the site. Source areas associated with CG037 groundwater are grouped as GWMU 1 and 2 and are further subdivided into plume areas 1B and 1F of GWMU 1 and 2A, 2B, and 2C of GWMU 2. The GWMU 1B and 1F results are presented in this report. Surface water bodies in the CG037 study area include Crutch Creek, Kuhlman Creek, and a tributary to Kuhlman Creek. Generally, these creeks flow in a northerly direction from the study area interior and exit the Base as they cross SE 29th Street.

The CSM for potential human and environmental exposures to surface water, and groundwater associated with the CG037 area is presented below. Details of ecological receptor exposure scenarios are discussed in Section 6.2. The human health receptor exposure scenarios included in the conceptual model include:

- Onsite Industrial Worker - This exposure scenario is based on the assumption that a worker is present on the property. Occupational exposures include a traditional 8 hour, 250 day/year exposure. Drinking water supplied to this receptor is assumed to originate in the CG037 area. Some workers may have exposures to the surface water bodies as a function of grounds maintenance activities. Exposure routes for this receptor include:
 - Ingestion of groundwater
 - Inhalation of volatiles in groundwater during showering
 - Dermal contact with groundwater during showering
 - Incidental ingestion of surface water
 - Dermal contact with surface water

- Offsite Resident - This exposure scenario is based on the assumption that the receptors, both adults and children, are present near the study area and obtain all household water from private wells near the Base boundary. Exposure routes for this receptor include:
 - Ingestion of groundwater
 - Inhalation of volatiles from groundwater during household use
 - Dermal contact with groundwater during household use
 - Ingestion of fruits and vegetables from home gardens watered or irrigated with groundwater.

- Onsite Trespasser - This exposure scenario is based on the assumption that the receptor (i.e., a young adult) visits an area intermittently. This receptor is not currently exposed to the groundwater. However, this receptor is potentially exposed to surface water. The exposure routes for this receptor include:
 - Incidental ingestion of surface water
 - Dermal contact with surface water.

All receptors are evaluated for the reasonable maximum exposure (RME).

6.1.2 Determination of Constituents of Potential Concern

The objective for selecting COPCs is to identify a set of chemicals that are likely to be site-related and reported concentrations that are of acceptable quality for use in the quantitative risk

assessment (EPA, 1989). In the absence of any background data, all detected constituents in surface water and sediment have been evaluated. The process for selecting COPCs for CG037 groundwater is described below.

6.1.2.1 Data Compilation

The data set for CG037 consists of groundwater data collected during 1999. Wells were selected in the approximate mass center of each plume. Wells were also selected to provide data in both the USZ and LSZ. Data collected from these wells were used to select COPCs for the entire study area. The wells used to provide data for the selection of COPCs for GWMU 1B and 1F are listed below; these wells are also shown with all wells in the study area on Figure 1-3:

Plume	Water Bearing Zone	Well Number
1B	USZ	2-245
1B	USZ	2-195
1B	LSZ	2-251R
1F	USZ	2-269B

6.1.2.2 Comparison of Site-Related Data to Screening Criteria

The initial selection of constituents for evaluation in the risk assessment was based on a risk-based concentration/toxicity screen. The purpose of this screen was to make the baseline risk assessment process more efficient by focusing on the dominant chemicals and routes of exposure at the earliest feasible stage.

The risk-based concentration/toxicity screen is outlined below:

- The maximum concentration is identified for each chemical detected in each groundwater plume area by evaluating monitoring well data near the mass center of the plume.
- The maximum concentration is compared to the risk-based concentration for groundwater exposures. The risk-based concentrations are EPA Region IX PRG (EPA, 1999) for tap water. PRGs are based on a cancer risk of 1×10^{-6} or a noncancer hazard of 1.
- If a specific chemical exceeds the risk-based concentration, the chemical is retained for the risk assessment for all routes of exposure.
- If a specific chemical does not exceed its risk-based concentration for any medium, the chemical is eliminated from the COPC list.

6.1.2.3 Comparison of Site-Related Data to Background Data

Inorganic constituent concentrations were compared with background concentrations of inorganics as defined in *Background Metals Concentrations in Groundwater, Tinker Air Force Base, Oklahoma* (IT, 1999c). Constituent concentrations from wells screened in the USZ were compared with background concentrations from the USZ and constituent concentrations from the LSZ are compared with background concentrations from the LSZ. Barium was present above background in two wells; however, due to significantly elevated turbidity measured at the time of sample collection, this metal was removed from further consideration.

6.1.2.4 Selected Constituents of Potential Concern

The 14 chemicals below are included as COPCs for the CG037 risk assessment:

Volatile Organic Chemicals

Benzene
Carbon Tetrachloride
Chloroform
1,4-Dichlorobenzene
1,2-Dichloroethane
1,1-Dichloroethene
Cis-1,2-Dichloroethene
1,2-Dichloropropane
Tetrachloroethene
Trichloroethylene
1,2,4-Trimethylbenzene
1,3,5-Trimethylbenzene
Vinyl chloride

Semivolatile Organic Chemicals

Naphthalene

6.1.3 Exposure Point Concentrations

The exposure point concentration is the concentration of a contaminant in an exposure medium that will be contacted by an actual or hypothetical receptor. Determination of the exposure point concentration depends on factors such as:

- Availability of data
- Amount of data available to perform statistical analysis
- Location of the potential receptor.

The exposure point concentrations for groundwater are determined on a well-by-well basis. Wells have been selected that represent specific locations of interest for the risk assessment. In addition to those wells that represent the mass center of plumes (see Section 6.1.2.1, above) used in the selection of COPCs, additional wells have been selected that represent potential exposure points in locations down gradient from the plumes. Those potential exposure locations include on-Base supply wells, wells at the Base boundary (representing groundwater concentrations for potential future off-site receptors), and locations near surface water bodies (representing groundwater influences on future surface water concentrations). The well locations chosen for the risk assessment potential exposure locations include:

On-Base Supply Wells

WS-1
WS-2
WS-3
WS-4
WS-5
WS-7
WS-30
WS-31

Well Locations at Base Boundary

40, 40BR, and 40CR
68
69

Well Locations Near Surface Water Bodies

2-263B
2-325A, 2-325B
2-344B
2-347B

Well Locations Off Base

Del City WS-20

The wells listed above include locations downgradient of plumes from both GWMU 1 and GWMU 2 units associated with CG037. This was done to ensure that potential future migration of contaminants from one unit to the other would be accounted for in calculations for future risk. In addition to existing well locations, additional points along the surface water bodies were chosen as theoretical points of exposure to increase the number of sample points. Potential exposure locations are shown on Figure 6-1.

Concentrations of COPCs that represent current conditions are the most recent groundwater monitoring data for each well. Future conditions are described through groundwater modeling. Groundwater modeling (presented in Chapter 7.0 of this report) estimates concentrations in each of the above wells at 30 years; those concentrations are used to estimate risk for each of the above well locations.

Surface water concentrations are selected as maximum concentrations of surface water detected constituents. Modeled concentrations of COPCs in wells near surface water bodies at 30 years are a conservative representation of future surface water concentrations.

6.1.4 Summary of Risk Assessment Methodology

Following establishment of the COPCs and the exposure points, a quantification of the chronic exposures for the various exposure pathways was completed, in order to characterize the RME. This activity included estimation of the intake of chemicals from groundwater and surface water exposures, including water ingestion, inhalation of volatiles released by showering and other household uses, dermal contact while bathing or wading, and ingestion of vegetables and fruits.

Once a quantification of exposure was completed, an assessment of the toxicity of exposure to the COPCs was performed for carcinogenic and noncarcinogenic effects.

Finally, a characterization of the risk was performed to integrate the exposure and toxicity assessments and generate quantitative expressions of risk. Quantitative estimates of carcinogenic risk and noncarcinogenic hazard were calculated for exposures to surface water and groundwater.

6.1.5 Human Health Risk Assessment Results

Generally, cancer risk estimates below 1×10^{-6} are considered negligible. A cancer risk of 1×10^{-6} is considered a point of departure, above which concern rises. EPA (1991), however, states that "EPA uses the general 10^{-4} to 10^{-6} risk range as a *target range* within which the Agency strives to manage risks as part of the Superfund cleanup. Once a decision has been made to take an action, the Agency has expressed a preference for cleanups achieving the more protective end of the range (i.e., 10^{-6}), although waste management strategies achieving reductions in site risks anywhere within the risk range may be deemed acceptable by the EPA risk manager. Furthermore, the upper boundary of the risk range is not a discrete line at 1×10^{-4} , although EPA

generally uses 1×10^{-4} in making risk management decisions. A specific risk estimate around 10^{-4} may be considered acceptable if justified based on site-specific conditions, including any remaining uncertainties on the nature and extent of contamination and associated risks. Therefore, in certain cases EPA may consider risk estimates slightly greater than 1×10^{-4} to be protective.”

A hazard index (HI) below 1.0 is considered acceptable; above 1.0 indicates concern about the occurrence of adverse noncancer effects (EPA, 1989). A complete representation of individual chemical risk for each pathway and receptor is presented in Appendix D of the RFI report.

The following sections present the results of the HHRA for GWMU 1B and GWMU 1F; the results for the subunits of GWMU 2 associated with CG037 are presented in a separate RFI report (IT, 2001).

6.1.5.1 Groundwater

Current Risk and Hazard. Tables 6-1a through 6-1d summarize current cancer risk and noncancer hazard for adult residents and on-site workers exposed to groundwater in the center of each plume. Although risk and hazard have been calculated for the adult resident (Tables 6-1a and 6-1b, respectively), there are currently no residential exposures to groundwater in this area. Current risk and hazard associated with on-site worker exposure are summarized in Tables 6-1c and 6-1d, respectively.

Cancer risk is in excess of 1×10^{-4} in the GWMU-1B plume characterized by well 2-195, where the risk is driven by benzene. Cancer risk at GWMU-1F (well 2-269B) does not exceed 1×10^{-4} in the mass center. No carcinogens were detected in the on-site water supply wells WS-1, 2, 3, or 30, or in the off-site Del City water supply well DC-20 in the vicinity of GWMU-1, in current monitoring well data.

Noncancer hazard associated with on-site worker exposures is summarized in Table 6-1d. Both plumes in GWMU 1B and 1F exhibit current hazard to worker exposures in excess of an HI of 1. Hazard in GWMU 1B (well 2-251R) is driven by benzene and TCE, and in GWMU 1F (well 2-269B) by chloroform and TCE. Noncarcinogens were not detected in on-site water supply wells WS-1, 2, 3, or 30, or in Del City water supply well DC-20 in current monitoring well data.

Future Risk and Hazard. Risk to future receptors is estimated by examining modeled groundwater concentrations at 30 years for on-site water supply wells and in wells at the Base boundary. The groundwater model fate and transport calculations are presented in Chapter 7.0 of this RFI report. Risk and hazard have not been estimated at the mass center of each plume at the 30 year time point; those estimates will not be discussed in the context of future risk as they do not represent true exposure locations.

Future residential risk downgradient from GWMU 1B and 1F in the USZ (Table 6-2a) is 5.7×10^{-6} in well 69, driven by DCE and benzene. Future residential risk downgradient from GWMU 1B and 1F in the LSZ (Table 6-3a) is less than 1×10^{-4} in well 68, driven by DCE. Future residential noncancer hazard downgradient from GWMU 1B and 1F is less than 1 for both the USZ (well 69, Table 6-2b) and the LSZ (well 68, Table 6-3b).

Future risk to on-site workers is summarized in Table 6-2c for the USZ and Table 6-3c for the LSZ. Future risk to on-site workers is evaluated using the on-Base water supply wells as exposure points, and based on future estimated concentrations of COPCs as they are predicted for the USZ and LSZ. The basis for this method was to ensure that conditions are protective of human health in the event the integrity of one or more water supply wells is compromised in the future. None of the water supply wells screened in the PZ exhibits future cancer risk greater than 1×10^{-4} . In addition, future noncancer hazard is found to be below an HI of 1 for all water supply wells for the on-site worker (Tables 6-2d and 6-3d), with the exception of WS-3 (downgradient from GWMU-1B) where the hazard quotient is 3.8, driven by benzene. Again, it should be noted that future risk was based on the estimation of elevated concentrations of COPCs at the location of the water supply wells and does not necessarily indicate that contaminants have been or will be detected in the PZ aquifer where water supply wells are screened. Although contaminants have not been detected in WS-3, due to proximity to the groundwater contamination at the former BX Service Station, WS-3 was shut down as a precaution to prevent contaminated water from entering the water supply system. Because WS-3 is an inactive well, this is not a complete exposure pathway.

6.1.5.2 Surface Water

A summary of cancer and noncancer hazard estimates associated with surface water exposures to the trespasser and maintenance worker are summarized in Table 6-4a and b (for current conditions) and Table 6-5a and b (for future conditions). Cancer risk to both receptors for both

current and future conditions is less than 1×10^{-9} in all water bodies. In addition, noncancer hazard for both receptors for both current and future conditions is less than 1×10^{-4} .

6.1.6 Uncertainties Associated With the Human Health Risk Assessment

Calculated risk estimates are subject to varying degrees of uncertainty from a variety of sources. Areas of uncertainty in a risk assessment can be categorized as: generic or methodological and site-specific. Methodological uncertainties are those that are inherent to the methods or procedures used for risk assessments (i.e., policy decisions made to reflect desire on the part of EPA to err on the side of conservatism). Site-specific areas of uncertainty are those characteristics of the site or the investigation of the site that could result in overestimates or underestimates of risk. The most significant sources of uncertainty in the risk assessment are itemized and evaluated qualitatively for their potential to contribute to either over- or underestimation of risk. Specific areas of uncertainty are discussed in the RFI report.

6.1.7 Human Health Risk Assessment Conclusions

Although cancer risk greater than 1×10^{-4} and noncancer hazard greater than 1 are found in the center of groundwater plumes under current conditions, no exposures are known to occur at this time at these locations. Currently, only the water supply wells on-Base are potentially available for on-site exposures. Current groundwater monitoring data indicate that no carcinogens or non-carcinogens have been detected in these wells.

Future groundwater conditions were evaluated by modeling groundwater concentrations at 30 years to estimate concentrations at the locations of the water supply wells to estimate future on-site exposures and to wells at the Base boundary to evaluate potential future residential exposures.

Future residential risk downgradient from GWMU 1B and 1F in the USZ is 5×10^{-6} in well 69, and in the LSZ is less than 10^{-4} in well 68. Future residential noncancer hazard downgradient from GWMU 1B and 1F is less than 1 for both the USZ (well 69) and the LSZ (well 68).

Future risk to on-site workers and for residential exposures if evaluated for the water supply wells on-Base, and the Del City water supply well (DC-20) off-Base, was calculated. These evaluations were performed using the on-Base and DC-20 water supply wells as exposure points, and based on future estimated concentrations of COPCs as they are predicted for the USZ and the LSZ, although the water supply wells are only screened in the PZ. This method was chosen

to ensure that future water quality would be protective of human health in the event that one or more water supply wells was compromised.

For future residential exposures evaluated for the water supply wells on-Base and DC-20, risk is not found to exceed 1×10^{-4} in the USZ. However, if evaluated for the LSZ, future risk exceeds 1×10^{-4} at the location of WS-3, driven by benzene and DCE. Benzene drives future noncancer hazard in this well also. Because WS-3 is downgradient of the GWMU 1B plume, as a precaution the well was removed from service. This well is currently inactive; therefore, exposure at this location is not possible and this pathway is not complete.

For on-site worker exposures, none of the WS wells evaluated for the USZ or LSZ exhibits future cancer risk greater than 1×10^{-4} . In addition, future noncancer hazard is found to be below a hazard index of 1 for all water supply wells for the on-site worker in the USZ. The only water supply well in the LSZ that exhibits future hazard greater than 1 (for the on-site worker) is WS-3 (downgradient from GWMU 1B) where the hazard quotient is 3.8, driven by benzene. This well is currently inactive; therefore, exposure is not possible and the pathway is incomplete.

6.2 Ecological Risk Assessment

An ecological risk screening assessment was performed for groundwater unit CG037 at Tinker AFB. The purpose of this assessment is to determine whether concentrations of COPCs in groundwater associated with CG037 are at levels that could potentially affect ecological receptors where exposure pathways to these receptors are potentially complete. Of particular interest in this assessment are the potential discharges of water from CG037 to surface drainages on Tinker AFB, especially Crutchko and Kuhlman Creeks and their tributaries.

A habitat assessment was conducted for Crutchko and Kuhlman Creeks in October, 1995, (PES, 1996) to collect information on the physical, hydrological, and biological conditions of these creeks. This assessment included elements of an ecological risk assessment, including comparisons of water and sediment chemistry data to corresponding quality criteria and toxicity benchmarks; performance of toxicity tests using fathead minnows, waterfleas, and amphipods; and comparisons of chemical analysis data for vegetation and fish tissue samples to toxicity benchmarks for wildlife receptors (muskrat and great blue heron, respectively). The assessment concluded that the development of biotic communities along these creeks was principally limited by physical and hydrological conditions (e.g., channel modification and seasonally low and highly variable flows).

However, based on the toxicity test results for water from the creeks (i.e., waterflea and fathead minnow tests), potential chemical limitations were identified in the middle and upper reaches of Crutch Creek and in the upper reaches of Kuhlman Creek. No toxic responses were observed in amphipods exposed to sediments from these creeks. Comparisons of the analytical data to water and sediment quality criteria and toxicity benchmarks found exceedances for barium, chromium, aluminum, silver, di-n-butylphthalate, and 4-nitrophenol in the middle and lower reaches of Crutch Creek (the sections of the creek potentially in contact with water from CG037) and cadmium, chromium, copper, lead, mercury, silver, zinc, aluminum, iron, polycyclic aromatic hydrocarbons, and di-n-butylphthalate in Kuhlman Creek. These data were from direct water samples from the creek (PES, 1996). These exceedances, however, do not necessarily identify the actual causal factors for the observed toxic responses.

It is not the purpose of the present risk assessment to reevaluate the chemical conditions currently existing in the water and sediments of Crutch and Kuhlman Creeks as was performed in the habitat assessment described above. Instead, the goal of this risk assessment is to evaluate the potential contribution of water discharging to these creeks from groundwater unit CG037 over the next 30-year period to the overall potential for ecological risk along these creeks (and including potential risk to deep-rooted plants that may contact the groundwater of CG037). Although some of the COPCs from CG037 (e.g., TCE, PCE, and 1,2-DCE) were detected in the surface water samples from these creeks in the 1995 evaluation (PES, 1996), discharges from CG037 cannot be identified as the source of these chemicals in the water of the creeks. In order to limit this assessment to the risks from COPCs in CG037, this risk assessment is based strictly on the predicted concentrations of COPCs in groundwater within CG037 that may contact these creeks as based on fate and transport modeling of the groundwater in this unit.

This screening ecological risk assessment follows general guidance obtained from EPA (1997 and 1998), Wentzel et al. (1996), USACE (1996), and EPA Region VI (1995). Although a screening assessment is typically preceded by a scoping assessment in which a determination is made whether ecological exposure pathways exist at the site in question, a separate scoping assessment has not been performed in this risk assessment because the potential existence of complete ecological pathways is assumed. Thus, in this screening-level assessment, the potential ecological risks associated with these pathways are quantified using conservative assumptions of exposure to water from CG037 for selected ecological receptors. The uncertainties associated

with the estimation of risk are evaluated and a final conclusion on the potential for significant ecological risk associated with pathways from CG037 is made.

As recommended by EPA (1992a and 1998), the screening assessment is divided into three main steps: Problem Formulation, Analysis, and Risk Characterization.

6.2.1 Problem Formulation

Problem Formulation is the initial stage of the screening assessment and provides the introduction to the risk evaluation process. Components that are addressed in this section include a description of the ecological setting and resources, the potential exposure pathways linking CG037 to these resources, the identification of constituents of potential ecological concern (COPEC) in the groundwater of CG037, the development of an ecological conceptual site model, and the selection of endpoints for the evaluation of risk.

6.2.1.1 Ecological Setting and Resources

The subunits of groundwater unit CG037 of concern in this evaluation underlie a large portion of the northwest quadrant of Tinker AFB. The surface area overlying these subunits includes urban/industrial, aviation (airdrome), residential, and recreational land uses, as well as open space (pastureland). The water table in most of this area is approximately 8 to 10 feet below ground surface (bgs). The major surface drainages in this part of Tinker AFB are Crutchko and Kuhlman Creeks. Both of these drainages have deep channels with streambeds that contact the water table, resulting in pooling of surface water in most parts of the creeks and a low base flow through the dry seasons (see also discussion on gaining and losing streams in Section 4.5.2 of this report). These drainages also conduct surface water runoff during rainfall events and are part of the storm sewer system of the Base.

On Tinker AFB, Crutchko Creek is divided into two main sections—Upper Crutchko Creek and Main Crutchko Creek (Figure 1-3). Upper Crutchko Creek flows to the northwest, generally paralleling the western boundary of the airdrome and has two minor tributaries that enter it from the south. Main Crutchko Creek enters Tinker AFB from the western base boundary. It also has a minor tributary that enters it from the west, just above its confluence with Upper Crutchko Creek. From this confluence (near Cook Street), the combined flow of the two sections continues north approximately 0.7 mile where it leaves the Base at the northern boundary fence.

Kuhlman Creek originates in the urban/industrial area north of the airdrome and flows west under the northern extension of the runway. As it exits the airdrome, it turns to the north, approximately paralleling Crutcho Creek and leaves the Base at the northern boundary fence, approximately 0.25 mile east of Crutcho Creek. A minor tributary that drains the northwest corner of the industrial area joins Kuhlman Creek from the east approximately 0.25 mile south of the Base boundary fence. Kuhlman Creek flows into Crutcho Creek just north of the Base boundary. From this confluence, Crutcho Creek continues north through Del City and Midwest City before discharging into the North Canadian River, approximately 6 miles north of the Base.

On Tinker AFB, approximately 1.5 miles of Crutcho Creek may be affected by groundwater discharges from the CG037 subunits of concern in this evaluation. This includes Upper Crutcho Creek, from about the location of Landfill 1 to its confluence with Main Crutcho Creek, and continuing downstream to the northern Base boundary fence (Figure 1-3). Essentially all of the channel is open to ecological receptors and only a few short reaches are concrete-lined. The riparian vegetation along the majority of this 1.5-mile segment of creek channel has been modified to maintained lawns and golf course. Natural riparian vegetation is limited to a few places, the most significant of which is the Tinker AFB Urban Greenway, located just downstream of Landfill 1. The Urban Greenway includes approximately 0.3-0.4 mile of the channel and is managed as a natural area. The riparian vegetation here is wooded, dominated by large trees such as cottonwood, elm, and oak. The creek is mostly shaded by overhanging trees and shrubs. Portions of the greenway are designated as jurisdictional wetlands; however, the surface water in these areas is too shallow to be in contact with groundwater.

Crutcho Creek exits the Tinker AFB Urban Greenway at the south end of Mitchell Street, where (just south of Vandenberg Street) about 50 yards of the channel is cement-lined, and has flow control gates (Figure 1-3). From Vandenberg Street to Arnold Street (approximately 0.5 mile), the creek is highly modified, with open, maintained lawns on both sides and few trees planted away from the channel. Between Vandenberg and Cook Streets, the channel has been engineered to be wide, with gentle slopes on each side going down to a flat floodplain. The creek channel going through this floodplain is only a foot or two deep and is about 10 or 12 feet below the surrounding ground surface. Just north of the Cook Street bridge is the confluence with the Main Crutcho Creek branch. This part of the channel is concrete lined for a short distance (approximately 60-100 feet). Below this point to Arnold Street, the channel is still banked by open, maintained lawns. These banks are a simple "V" cut extending down about 10

or 12 feet below the surrounding grade, with a wide, flat streambed at the bottom. The vegetation of the banks is periodically mowed and there is little vegetation along the bottom.

North of the Arnold Street bridge, the channel is approximately 5-8 feet deep, steep (nearly vertical) sided, and about 10 or 12 feet wide. Although the riparian vegetation is more natural, i.e., not landscaped, it is much more limited in lateral extent than that along the greenway. For the first approximately 300-400 feet, the creek goes through a picnic and playground area. A chain-link fence along the east side separates the playground from the channel. Trees of various sizes line the channel forming a fairly dense but narrow ribbon of woody vegetation along the channel. Some of the larger trees (e.g., blackjack oaks) have been left as part of the landscaping of the picnic area. North of the picnic area, the creek flows through the golf course until it exits the Base. In the golf course, most of the woody riparian vegetation has been removed, leaving only scattered trees along the channel.

Kuhlman Creek, from where it exits the airdrome area to where it leaves the Base at the north boundary fence (at the golf course), is approximately 0.75 mile in length. The small tributary of Kuhlman Creek that comes into the golf course from the east is approximately 0.25 mile in length (from Air Depot Blvd to its confluence with Kuhlman Creek). These channels are generally similar in appearance to Crutch Creek, i.e., an incised channel, about 5-8 feet deep, 10-12 feet in width, and steep sided, and both have a perennial base flow with pooled water in most parts of the channels. Kuhlman Creek south of Arnold Street is heavily wooded with natural riparian vegetation. North of Arnold Street, the riparian vegetation has been thinned, leaving some medium or large trees marking the course of the creek. Near the confluence of Kuhlman Creek and the small tributary, the riparian vegetation is more dense. Downstream of the Base, Crutch Creek (now including the flow from Kuhlman Creek) generally remains in a deep channel with heavy, wooded vegetation along its route through the urbanized areas.

The creeks contain small fish and other aquatic organisms. Amphibians (especially various species of frogs) and reptiles, including turtles and some species of snakes, may be closely associated with the creek habitat. Mammals that are also associated with this habitat include beaver, muskrat, raccoons, and opossum. A wide variety of birds, both breeding and migrants, are potentially associated with this habitat. No listed threatened or endangered species occur on Tinker AFB (USAF, 1999). Of the six wildlife species known to occur on Tinker AFB that are either federal species of concern (FSC) or state species of special concern (SSSC), none are expected to be closely associated with the creek habitat; however, the migrant loggerhead shrike,

which is an FSC, and the orchard oriole, which is an SSSC, could potentially nest in the riparian vegetation lining the creeks.

6.2.1.2 Potential Exposure Pathways

Because the upper layer of groundwater is approximately 8 to 10 feet bgs over most of the area of CG037, ecological exposure pathways in the upland parts of Tinker AFB are generally going to be limited to contact by deep-rooted plants, principally trees and shrubs. However, discharges of water from this upper groundwater layer into the incised channels of Crutcho and Kuhlman Creeks provides for additional complete exposure pathways to those receptors that are associated with the creeks, including aquatic and benthic organisms, wetland plants, and wildlife that use the creek for feeding and as a source of drinking water.

6.2.1.3 Determination of Constituents of Potential Ecological Concern

The criteria used in the selection of COPECs are similar to those outlined for COPCs in the Human Health Risk Assessment (Section 6.1); however, only those constituents in the upper layer of CG037 (i.e., either the USZ or the HWBZ) were considered to have potentially complete ecological pathways. All organic analytes detected in 5 percent or more of the samples were considered to be COPECs. Inorganic analytes (metals) were also evaluated for inclusion as COPECs. As described in Section 6.1, most of these were within the screening criteria for groundwater and were therefore not included as COPECs. Two exceptions, however, were arsenic and barium. Arsenic was not included as a COPEC because its concentration in groundwater exceeded the ambient water quality criteria (AWQC) for aquatic life (0.190 milligrams per liter [Buchman, 1999]) in only one sample, and is therefore unlikely to be of significant ecological concern. Although barium was detected at levels exceeding ecological screening values in many of the groundwater samples, it was not considered to be a COPEC because barium is naturally high in the area (PES, 1996) and these concentrations are generally within background ranges (IT, 1999c). In addition, in every case where elevated metals were found, turbidity was also significantly elevated, indicating the presence of suspended particulates in the samples. The identified COPECs for this assessment are listed below:

- Benzene
- Carbon tetrachloride
- Chloroform
- 1,4-Dichlorobenzene
- 1,2-Dichloroethane
- 1,1-Dichloroethene
- 1,2-Dichloroethene

- 1,2-Dichloropropane
- Di-n-butylphthalate
- Naphthalene
- Tetrachloroethylene
- Trichloroethylene
- 1,2,4-Trimethylbenzene
- 1,3,5-Trimethylbenzene
- Vinyl chloride.

6.2.1.4 Ecological Conceptual Site Model

As diagrammed in Figure 6-2, the scenario for the existence of complete exposure pathways from the groundwater in CG037 to ecological receptors is principally based on the assumption that groundwater in this unit is in contact with and is discharging into surface drainages (i.e., Crutch and Kuhlman Creeks), although deep-rooted plants (e.g., riparian trees, such as cottonwoods, elms, and oaks) may contact the groundwater directly through their root systems. Under the scenario of groundwater discharge, groundwater flows through the sediment pore space. Therefore, the groundwater exists at least temporarily as sediment pore water. During the time that the groundwater occupies the sediment pore space, chemicals contained in the groundwater will undergo exchanges between the dissolved and adsorbed fractions in the sediment as regulated by the equilibrium partitioning potentials of the chemicals. Partitioning of organic chemicals in the pore water will be strongly influenced by the fraction of organic matter in the sediment, which will tend to adsorb and retain a larger amount of organic compounds than will the mineral fraction of the sediment.

At the surface of the sediment, the flowing groundwater is released into the stream channel and will mix with the surface water flowing through the channel. The concentrations of chemicals in the groundwater discharging into the stream channel will be diluted by the existing surface water, providing that the concentrations in the surface water are less than those in the discharging groundwater. If that is not the case for some chemicals, however, the concentration in the surface water will either be unaffected by the discharge or will itself be diluted by the discharge. In this risk assessment, it is assumed that the groundwater from CG037 is the sole source of COPECs in the exposure pathways, although inputs into the surface water from other sources may actually exist in these creeks.

Two groups of organisms are potentially exposed to COPECs that are in the sediments of the creeks – rooted plants (e.g., emergents, such as cattails and rushes) and benthic invertebrates (i.e., the “infauna,” or those invertebrates that live within the sediment). Muskrats are potential

consumers of the emergent vegetation along the creeks, thereby becoming potential receptors of COPECs taken up by the plants. Shorebirds, such as killdeer, are potential consumers of benthic invertebrates, thereby also becoming potential receptors to COPECs in the sediment. The muskrats and shorebirds feeding along the creeks may also be exposed to COPECs in the surface water and sediment through drinking and the incidental ingestion of sediment.

In the surface water of the creeks, aquatic plants (e.g., algae), aquatic invertebrates, and fish will be directly exposed to COPECs released to the water column. The invertebrates and fish are also exposed through food ingestion (e.g., plant material and invertebrates). Dabbling waterfowl, such as mallards, may be exposed to COPECs through the consumption of aquatic plants and invertebrates from the water in the creeks. Predators, such as raccoons and herons (e.g., great blue herons) may be exposed to COPECs through the consumption of large invertebrates, such as crayfish, and small vertebrates, such as fish. For the purposes of this risk assessment, the fish consumed by these predators are assumed to be in the third trophic level (consumers of invertebrate prey). Fourth trophic level fish (piscivorous fish) are not expected to occur in the creeks. As with the muskrats and shorebirds described above, the waterfowl, raccoons, and herons feeding along the creeks will also be exposed to COPECs through drinking water and the incidental ingestion of sediment.

6.2.1.5 Assessment and Measurement Endpoints

Endpoints for this screening assessment were selected to be protective of the specific habitats and receptors potentially affected by CG037. Emphasis is therefore placed on the aquatic and riparian resources associated with the sections of Crutcho and Kuhlman Creeks that are potentially affected by CG037. In order to verify whether chemical contaminants in groundwater are within the water quality standards set by the State of Oklahoma and the EPA, modeled concentrations in the groundwater at the margins of the creeks are compared directly against state and federal criteria. In a similar manner, modeled chemical concentrations in sediment are compared against published sediment quality and plant toxicity benchmarks. In addition, potential toxicity to wildlife receptors is assessed through exposure modeling based on water and sediment concentrations and comparisons to toxicity-based benchmark screening values.

6.2.2 Exposure Characterization

The purpose of exposure characterization is to describe the contact or co-occurrence of biota with the COPECs. This effort focuses on specific ecological receptors and addresses the potential for these receptors to be exposed to the COPECs. Ecological receptors are selected to

represent biota associated with the creek habitats at Tinker AFB. The selection process corresponds with the conceptual model. Because the groundwater in CG037 may contact and discharge into the creek channels over extensive sections of the creek, potential exposure concentrations were evaluated at several points adjacent to the creeks that were located to intercept migrating plumes of COPECs. Concentrations of the COPECs in the groundwater at these points were based on the modeling of groundwater fate and transport over a 30-year time period. The points selected for evaluating potential exposure concentrations, and the receptors, exposure models, and associated parameters used to address exposure are discussed below.

6.2.2.1 Exposure Points

Sixteen points along Crutcho and Kuhlman Creeks, and the Kuhlman Creek tributary were selected to evaluate the concentrations in CG037 groundwater over the next 30 years that may contact the creek channels. These points are shown in Figure 6-3. Only water in the HWBZ (primarily GWMU 2) and the USZ (primarily GWMU 1) is expected to be in potential contact with these creeks. Contact with the Hennessey is limited to the reach of Crutcho Creek flowing through the Tinker AFB Urban Greenway and above, and to a short (approximately 500-foot) reach of Kuhlman Creek where it turns to the north after exiting the airdrome area. The locations of the points selected for monitoring the concentrations were based on the directions of flow in the Hennessey and USZ from the current source areas, whichever is the uppermost unit at a location. Of particular interest were points adjacent to the creeks that are in the direct downgradient path of probable plume migration or where groundwater flow from the source areas converge from differing directions.

On Crutcho Creek, the two most upstream points (CR-6 and CR-7) are in the HWBZ and are principally associated with GWMU 2A and 2C of CG037. CR-7 is immediately upstream of the Tinker AFB Urban Greenway, while CR-6 is within the Urban Greenway. Locations CR-2 through CR-5 are distributed along the creek as it parallels Mitchell Street. These points are in the USZ and are associated with GWMU 2B. The final point along Crutcho Creek (CR-1) is at the Base boundary, on the north side of the golf course. Because Kuhlman Creek closely parallels Crutcho Creek across the golf course, the monitoring points along Kuhlman Creek will intercept groundwater plumes from the source units east of these creeks before they reach Crutcho Creek. Therefore, CR-1 is the only monitoring point on Crutcho Creek deemed necessary north of Arnold Street.

On Kuhlman Creek and its small tributary, monitoring points were selected at upstream points (K-7, KT-1, and KT-2; “KT” referring to locations on the small tributary of Kuhlman Creek) in association with the three groundwater units of the industrial area of the Base (GWMU 1A, 1F, and 1B, respectively). The rest of the monitoring points (K-1 through K-6) were located along the northward flowing section of Kuhlman Creek, from near where it exits the airdrome (at K-6) to the Base boundary (at K-1). Three locations (K-4 through K-6) were located south (upstream) of the confluence with the tributary, and three (K-1 through K-3) were located north (downstream) of the confluence. As previously noted, K-6 is the only one of these monitoring points in a reach of Kuhlman Creek that is in the Hennessey; however, the flow modeling indicates that the Hennessey is dry in this area. Therefore, the K-6 location, associated with GWMU 2B, was evaluated for the concentrations in the USZ as well, although it is highly likely that the creek is actually losing water in this reach and is not in direct contact with the USZ.

6.2.2.2 Selection of Ecological Receptors

There are no listed threatened or endangered species known to occur on Tinker AFB (USAF, 1999). The selection of ecological populations of potential concern, therefore, focuses on key species that will serve as indicators of risk to broader classes of wildlife. The species selected as indicators for the analysis of potential ecological risk at Tinker AFB represent various levels of the trophic structure within the riparian and aquatic habitats of Crutcho and Kuhlman Creeks. Because of the large number of plant species found on Tinker AFB and because of the paucity of species-specific toxicological data for plants, evaluations of potential risks to plants were performed for nonspecific perennial vascular plants. Nonspecific aquatic and benthic organisms were also used as potential ecological receptors within the creeks. For exposure modeling to wildlife, a suite of indicator species were selected to represent key components in the food web, including herbivores, insectivores, omnivores, and predators. The wildlife receptor species selected for the creek habitats to represent these trophic guilds were:

- Muskrat (*Ondatra zibethicus*)—mammalian herbivore
- Raccoon (*Procyon lotor*)—mammalian omnivore
- Mallard (*Anas platyrhynchos*)—avian herbivore
- Killdeer (*Charadrius vociferus*)—avian insectivore
- Great blue heron (*Ardea herodias*)—avian predator.

All of these species are known to occur on Tinker AFB. The natural history data for the wildlife receptor species that were used in the determination of risks to mammals and birds on the Base are summarized in the RFI report. Most of the data used as exposure model parameters were

garnered from the published literature. These sources often result in a range of possible values. Single values were selected from these ranges for estimating exposure.

6.2.2.3 Exposure Models

For the purposes of assessing exposure, ecological receptors were separated into two groups: those receptors for which exposure to COPECs is dominated by direct contact with a single, potentially contaminated medium (e.g., plants with roots in direct contact with groundwater and aquatic organisms in direct contact with surface water or sediment) and those with both direct and indirect exposure pathways from the potentially contaminated media. For the first group, risk from exposure to a particular COPEC is evaluated by direct comparison of the medium concentration to a toxicity benchmark concentration for that medium. For the second group (composed of the wildlife receptors), exposure modeling is required for each of the potential pathways, and the sum of these exposures is compared to the toxicity benchmark for the evaluation of potential risk from this exposure.

For wildlife receptors, the primary route of exposure is through ingestion of potentially contaminated food (prey organisms), water, and sediment from a site (Sample and Suter, 1994). Therefore, the potential exposure to a COPEC, in milligrams per kilogram receptor body weight per day, is estimated through the modeling of COPEC transfers from groundwater as sediment pore water to surface water and sediment, and then through the food web to the target receptor.

The exposure models used in the risk assessment are based on the food web shown in Figure 6-2. These models were used to estimate the potential daily intake of COPECs by wildlife receptors based on the concentrations of COPECs in the uppermost portions of the groundwater at the 16 locations selected along the creeks. It is assumed that this groundwater is in contact with and is discharging to the creek channels. Because this assessment is for screening purposes, conservatism was incorporated into the exposure modeling to ensure that the estimated exposures are more likely to overestimate the actual exposure rather than to underestimate it. These conservatisms in parameter selection are described in this section. The receptor specific exposure parameter values used in the risk assessment are presented in the RFI report. Exposure parameters were used for COPEC concentrations in food and for exposures in wildlife receptors (limited to the ingestion pathway). Following the exposure characterization, an evaluation of effects of the exposures to COPECs is performed. This is done separately for aquatic and benthic organisms, and for plants and wildlife.

6.2.3 Ecological Risk Characterization

Following exposure characterization and effects evaluation, a quantitative characterization of risk is performed as a comparison of the maximum modeled concentration of a particular COPEC in an exposure medium (i.e., either groundwater at the selected monitoring point or the expected sediment concentration of the COPEC at the point based on groundwater concentration) to toxicity-based benchmark screening values for that medium or as comparisons of the estimated exposure of wildlife receptors as based on those maximum media concentrations to toxicity-based benchmarks for those receptors. Results are presented as hazard quotients (HQ).

6.2.3.1 Hazard Quotient Analysis Results

The HQs that are used in this assessment to initially characterize risk to ecological receptors at Tinker AFB sites are based on the maximum modeled concentrations of the COPECs in CG037 over all monitoring locations and over the 30 years of modeled plume migration. These maximum COPEC concentrations values are shown in the far right-hand column of Table 6-6. Because these are maximum concentrations, the resulting HQs represent the upper limit of risk from the discharges of CG037 groundwater to the creeks in the northwestern section of the Base.

The HQ values for aquatic, benthic, plant, and wildlife receptors based on the maximum groundwater concentrations are presented in Table 6-7. These HQs are specific to a particular receptor for exposure to a particular COPEC. Because of the limited amount of toxicity information available for some of these receptors (especially plants and birds), HQs could not be determined for 55 of the 120 COPEC/receptor combinations; however, all COPECs have HQs for at least two receptors. All of the HQs that were calculated were less than 1.0, with the maximum being 0.248 for TCE exposure in benthic organisms. Among the plant and wildlife receptors, the maximum HQ was 0.0869 for di-n-butylphthalate exposure in the killdeer. Therefore, based on the HQ analysis results, the COPECs in groundwater in CG037 are not expected to contribute significantly to ecological risk along Crutchko and Kuhlman Creeks (and their tributaries) for at least 30 years. For benzene, naphthalene, TCE, and 1,3,5-trimethylbenzene, however, the maximum modeled concentration was at the 30-year time interval, indicating that under the model assumption of a continuous source, risks from these constituents could increase beyond those indicated in this assessment.

6.2.3.2 Uncertainty Analysis

The evaluation of potential ecological risk from chemical exposures requires the use of assumptions about exposure and the potential effects of that exposure in the target receptor(s).

Many assumptions were used in the calculations of the HQs shown in Table 6-7 for CG037. In most cases, these assumptions were made such that the uncertainties associated with the assumptions would generally err on the side of conservatism, i.e., they would lead to an overestimation of the actual risk rather than an underestimation. Some of these conservative assumptions used in this risk assessment are described in the RFI report.

6.2.4 Ecological Risk Assessment Conclusions

The screening-level ERA described in this section was conducted to evaluate the potential contribution of contaminants in groundwater associated with site unit CG037 on Tinker AFB and risks to ecological receptors in the habitats overlying the unit from chemical exposures. The principal habitats of concern in this assessment are the riparian and lotic environments associated with Crutch Creek, Kuhlman Creek, and a small tributary of Kuhlman Creek in the northwestern corner of Tinker AFB. Because of the deeply incised or graded channels of these creeks, it is likely that the creeks are in contact with the upper parts of the CG037 water bearing zones (the USZ in GWMU 1 and the HWBZ in GWMU 2) and are gaining water from CG037 along at least parts of their courses. Further, deep-rooted riparian plants along these creeks may be in direct contact with water in these upper water bearing zones. Based on the assumptions of these contacts, complete ecological pathways may exist between ecological receptors in the riparian and lotic habitats of the creeks and the contaminants in CG037.

Based on existing groundwater monitoring data, 15 COPECs were identified in CG037 for evaluation in this risk assessment, including both volatile and semivolatile organic compounds. Because these contaminants are in the process of migrating as plumes within CG037, the potential for ecological exposure is expected to change with time. Exposures in this assessment were therefore based on current and projected near-surface groundwater concentrations at 16 points adjacent to the creeks as predicted through groundwater transport modeling results for the next 30 years. Because contaminants in these creeks may be present from sources other than CG037 and ecological risks associated with these existing conditions have been more thoroughly assessed in a previous (baseline-level) risk assessment (PES, 1996), risks based on present water and sediment conditions in the creeks were not further evaluated in this assessment. Rather, the goal of this assessment was to determine whether COPEC concentrations in water associated with CG037 have the potential to either be the cause of current risk along the creeks or be a cause of risk to ecological receptors in the foreseeable future.

Receptors selected for evaluation in this risk assessment included aquatic and benthic organisms in the creeks, plants, a muskrat, a raccoon, a mallard, a killdeer, and a great blue heron.

Exposures to these receptors were based on the worst-case scenario, using the maximum modeled COPEC concentrations over all monitoring points and times. Estimated exposures in the receptors assumed 100 percent exposure to these concentrations for all receptors and 100 percent bioavailability of the COPECs. Potential effects were evaluated based on minimum water and sediment quality benchmarks, which included national AWQC and state water quality standards as available. Chronic no-observed-adverse-effect-levels were used as the benchmarks for potential toxicity to the wildlife receptors. HQs were used as the basis for quantitatively assessing potential risk based on these exposures and toxicity benchmarks.

The results of the assessment showed no HQs exceeding 1 for the receptor/chemical combinations for which HQs could be determined. HQs could not be determined for 55 of the 120 receptor/chemical combinations, principally due to the lack of toxicological data for plants and birds. However, because of the conservatism associated with the calculated HQs in this assessment and the low values of the majority of these HQs, (providing a large margin for error), the weight of evidence indicates that it is highly likely that the chemical contaminants in CG037 will have a negligible contribution to the chemical exposures in and subsequent risk to ecological receptors along these creeks over the next 30 years at least, and probably well beyond that time frame.

TABLES

Table 6-1a
Adult Resident Cancer Risk
Center of Plumes, Time Zero (Current)
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Well Number ^a	2-135A	2-20A	2-68A	2-67A	2-328A	2-144B	2-409B	2-20B	2-245	2-195	2-269B	2-251R
VOLATILE ORGANIC CHEMICALS												
Chloroform	6.4E-5	7.9E-8	2.8E-7	0.0E+0	1.4E-6	3.3E-6	8.6E-7	0.0E+0	0.0E+0	0.0E+0	4.3E-7	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.6E-7	0.0E+0	2.4E-6	1.8E-6	1.2E-5	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	0.0E+0											
1,2-Dichloroethane	3.8E-4	1.5E-4	3.1E-6	3.0E-4	2.3E-5	4.3E-3	3.2E-3	0.0E+0	1.4E-4	0.0E+0	0.0E+0	0.0E+0
1,1-Dichloroethene	0.0E+0	0.0E+0	0.0E+0	1.2E-4	0.0E+0	4.2E-5	2.6E-5	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	2.4E-6	0.0E+0	0.0E+0	0.0E+0	0.0E+0	6.2E-6	5.3E-6	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	9.5E-7	0.0E+0	0.0E+0	1.1E-4	0.0E+0	9.5E-7	9.5E-7	1.1E-6	1.6E-6	2.9E-4	0.0E+0	1.4E-2
Carbon tetrachloride	1.3E-3	0.0E+0	4.6E-4	0.0E+0	3.9E-4	8.2E-6	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.9E-5	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	0.0E+0	8.0E-6	0.0E+0	0.0E+0	5.7E-7	2.1E-6	0.0E+0	2.7E-6	0.0E+0	3.9E-5
Trichloroethene	1.3E-5	1.4E-5	7.5E-6	5.4E-6	1.0E-3	2.7E-4	4.6E-5	5.4E-6	3.5E-5	0.0E+0	2.2E-5	5.0E-4
1,2,4-Trimethylbenzene	0.0E+0											
1,3,5-Trimethylbenzene	0.0E+0											
Vinyl chloride	0.0E+0	0.0E+0	0.0E+0	9.2E-4	0.0E+0	1.4E-3	5.5E-4	3.2E-3	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SEMIVOLATILE ORGANIC CHEMICALS												
Naphthalene	0.0E+0											
TOTAL RISK	1.8E-3	1.6E-4	4.7E-4	1.5E-3	1.4E-3	6.0E-3	3.9E-3	3.2E-3	1.8E-4	3.0E-4	4.2E-5	1.4E-2

^a Wells 2-245, 2-195, 2-251R, and 2-269B are associated with GWMU 1. Wells 2-67A, 2-68A, 2-135A, 2-144B, 2-409B, 2-328A, 2-20B, and 2-20A are associated with GWMU 2.

Table 6-1b
Adult Resident Noncancer Hazard
Center of Plumes, Time Zero (Current)
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Well Number ^a	2-135A	2-20A	2-68A	2-67A	2-328A	2-144B	2-409B	2-20B	2-245	2-195	2-269B	2-251R
VOLATILE ORGANIC CHEMICALS												
Chloroform	9.8E+2	1.2E+0	4.2E+0	0.0E+0	2.2E+1	5.0E+1	1.3E+1	0.0E+0	0.0E+0	0.0E+0	6.6E+0	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.5E-3	0.0E+0	2.4E-2	1.8E-2	1.2E-1	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	4.6E-3	2.5E-2	2.6E-3	2.2E-1	2.0E-1	7.8E-1	4.0E-1	1.6E+0	2.6E-2	0.0E+0	2.0E-2	1.7E-1
1,2-Dichloroethane	5.5E+0	2.2E+0	4.5E-2	4.3E+0	3.3E-1	6.2E+1	4.7E+1	0.0E+0	2.1E+0	0.0E+0	0.0E+0	0.0E+0
1,1-Dichloroethene	0.0E+0	0.0E+0	0.0E+0	1.1E-1	0.0E+0	3.9E-2	2.4E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	3.3E-1	0.0E+0	0.0E+0	0.0E+0	0.0E+0	8.5E-1	7.3E-1	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	4.2E-2	0.0E+0	0.0E+0	5.0E+0	0.0E+0	4.2E-2	4.2E-2	5.0E-2	7.1E-2	1.3E+1	0.0E+0	6.1E+2
Carbon tetrachloride	6.1E+1	0.0E+0	2.1E+1	0.0E+0	1.8E+1	3.8E-1	0.0E+0	0.0E+0	0.0E+0	0.0E+0	8.9E-1	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	0.0E+0	3.3E-2	0.0E+0	0.0E+0	2.4E-3	8.5E-3	0.0E+0	1.1E-2	0.0E+0	1.6E-1
Trichloroethene	1.8E+0	2.1E+0	1.1E+0	8.0E-1	1.5E+2	3.9E+1	6.8E+0	8.0E-1	5.2E+0	0.0E+0	3.2E+0	7.4E+1
1,2,4-Trimethylbenzene	0.0E+0	1.5E+1	0.0E+0	0.0E+0	2.2E+0							
1,3,5-Trimethylbenzene	0.0E+0	4.0E-1	0.0E+0	0.0E+0	2.8E-1							
Vinyl chloride	0.0E+0											
SEMIVOLATILE ORGANIC CHEMICALS												
Naphthalene	0.0E+0	1.0E+1	0.0E+0	0.0E+0	0.0E+0							
TOTAL RISK	1.1E+3	5.5E+0	2.6E+1	1.0E+1	1.9E+2	1.5E+2	6.8E+1	2.4E+0	3.3E+1	1.3E+1	1.1E+1	6.9E+2

^a Wells 2-245, 2-195, 2-251R, and 2-269B are associated with GWMU 1. Wells 2-67A, 2-68A, 2-135A, 2-144B, 2-409B, 2-328A, 2-20B, and 2-20A are associated with GWMU 2.

Table 6-1c

**On-Site Worker Cancer Risk
 Center of Plumes, Time Zero (Current)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Well Number ^a	2-135A	2-20A	2-68A	2-67A	2-328A	2-144B	2-409B	2-20B	2-245	2-195	2-269B	2-251R
VOLATILE ORGANIC CHEMICALS												
Chloroform	2.1E-5	2.5E-8	8.9E-8	0.0E+0	4.6E-7	1.1E-6	2.8E-7	0.0E+0	0.0E+0	0.0E+0	1.4E-7	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.1E-7	0.0E+0	1.0E-6	7.7E-7	5.3E-6	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	0.0E+0											
1,2-Dichloroethane	2.0E-4	7.9E-5	1.6E-6	1.6E-4	1.2E-5	2.3E-3	1.7E-3	0.0E+0	7.7E-5	0.0E+0	0.0E+0	0.0E+0
1,1-Dichloroethene	0.0E+0	0.0E+0	0.0E+0	5.4E-5	0.0E+0	1.9E-5	1.2E-5	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	7.8E-7	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.0E-6	1.7E-6	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	5.1E-7	0.0E+0	0.0E+0	6.0E-5	0.0E+0	5.1E-7	5.1E-7	5.9E-7	8.4E-7	1.5E-4	0.0E+0	7.3E-3
Carbon tetrachloride	6.6E-4	0.0E+0	2.2E-4	0.0E+0	1.9E-4	4.0E-6	0.0E+0	0.0E+0	0.0E+0	0.0E+0	9.5E-6	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	0.0E+0	3.5E-6	0.0E+0	0.0E+0	2.5E-7	8.9E-7	0.0E+0	1.2E-6	0.0E+0	1.7E-5
Trichloroethene	6.3E-6	7.1E-6	3.8E-6	2.7E-6	5.0E-4	1.3E-4	2.3E-5	2.7E-6	1.8E-5	0.0E+0	1.1E-5	2.5E-4
1,2,4-Trimethylbenzene	0.0E+0											
1,3,5-Trimethylbenzene	0.0E+0											
Vinyl chloride	0.0E+0	0.0E+0	0.0E+0	3.8E-4	0.0E+0	5.6E-4	2.3E-4	1.3E-3	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SEMIVOLATILE ORGANIC CHEMICALS												
Naphthalene	0.0E+0											
TOTAL RISK	8.9E-4	8.6E-5	2.3E-4	7.4E-4	7.1E-4	3.0E-3	2.0E-3	1.3E-3	9.6E-5	1.6E-4	2.1E-5	7.5E-3

^a Wells 2-245, 2-195, 2-251R, and 2-269B are associated with GWMU 1. Wells 2-67A, 2-68A, 2-135A, 2-144B, 2-409B, 2-328A, 2-20B, and 2-20A are associated with GWMU 2.

Table 6-1d

**On-Site Worker Noncancer Hazard
 Center of Plumes, Time Zero (Current)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Well Number	2-135A	2-20A	2-68A	2-67A	2-328A	2-144B	2-409B	2-20B	2-245	2-195	2-269B	2-251R
VOLATILE ORGANIC CHEMICALS												
Chloroform	7.0E+2	8.5E-1	3.0E+0	0.0E+0	1.5E+1	3.6E+1	9.4E+0	0.0E+0	0.0E+0	0.0E+0	4.7E+0	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.5E-3	0.0E+0	1.4E-2	1.0E-2	7.1E-2	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	1.6E-3	8.8E-3	9.1E-4	7.8E-2	7.2E-2	2.7E-1	1.4E-1	5.4E-1	9.2E-3	0.0E+0	7.2E-3	6.0E-2
1,2-Dichloroethane	3.9E+0	1.5E+0	3.2E-2	3.1E+0	2.3E-1	4.4E+1	3.3E+1	0.0E+0	1.5E+0	0.0E+0	0.0E+0	0.0E+0
1,1-Dichloroethene	0.0E+0	0.0E+0	0.0E+0	6.8E-2	0.0E+0	2.4E-2	1.5E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	2.1E-1	0.0E+0	0.0E+0	0.0E+0	0.0E+0	5.3E-1	4.6E-1	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	2.8E-2	0.0E+0	0.0E+0	3.3E+0	0.0E+0	2.8E-2	2.8E-2	3.3E-2	4.7E-2	8.4E+0	0.0E+0	4.0E+2
Carbon tetrachloride	3.8E+1	0.0E+0	1.3E+1	0.0E+0	1.1E+1	2.3E-1	0.0E+0	0.0E+0	0.0E+0	0.0E+0	5.5E-1	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	0.0E+0	1.0E-2	0.0E+0	0.0E+0	7.1E-4	2.6E-3	0.0E+0	3.4E-3	0.0E+0	4.8E-2
Trichloroethene	1.3E+0	1.5E+0	7.8E-1	5.6E-1	1.0E+2	2.8E+1	4.8E+0	5.6E-1	3.7E+0	0.0E+0	2.3E+0	5.2E+1
1,2,4-Trimethylbenzene	0.0E+0	1.1E+1	0.0E+0	0.0E+0	1.6E+0							
1,3,5-Trimethylbenzene	0.0E+0	1.4E-1	0.0E+0	0.0E+0	9.3E-2							
Vinyl chloride	0.0E+0											
SEMIVOLATILE ORGANIC CHEMICALS												
Naphthalene	0.0E+0	7.1E+0	0.0E+0	0.0E+0	0.0E+0							
TOTAL RISK	7.4E+2	3.9E+0	1.7E+1	7.1E+0	1.3E+2	1.1E+2	4.8E+1	1.2E+0	2.3E+1	8.4E+0	7.5E+0	4.5E+2

^a Wells 2-245, 2-195, 2-251R, and 2-269B are associated with GWMU 1. Wells 2-67A, 2-68A, 2-68A, 2-144B, 2-409B, 2-328A, 2-20B, and 2-20A are associated with GWMU 2.

Table 6-2a

**Adult Resident Cancer Risk
 USZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Well Number	WS-1	WS-2	WS-3	WS-4	WS-5	WS-7	WS-30	WS-31	DC-20
VOLATILE ORGANIC CHEMICALS									
Chloroform	0.0E+0	0.0E+0	5.5E-10	0.0E+0	1.7E-9	3.0E-10	0.0E+0	6.6E-10	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	1.1E-8	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	0.0E+0								
1,2-Dichloroethane	0.0E+0	0.0E+0	4.1E-7	0.0E+0	6.9E-7	5.3E-9	0.0E+0	0.0E+0	0.0E+0
1,1-Dichloroethene	0.0E+0	6.4E-6	4.1E-6	0.0E+0	3.8E-7	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	0.0E+0								
Benzene	0.0E+0	0.0E+0	1.9E-5	0.0E+0	5.2E-9	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Carbon tetrachloride	0.0E+0	0.0E+0	2.6E-8	0.0E+0	7.8E-8	2.9E-8	0.0E+0	4.8E-8	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	6.1E-8	0.0E+0	1.4E-7	6.8E-7	0.0E+0	0.0E+0	0.0E+0
Trichloroethene	0.0E+0	3.8E-9	1.1E-6	4.5E-9	1.6E-7	1.4E-9	2.0E-9	1.9E-7	0.0E+0
1,2,4-Trimethylbenzene	0.0E+0								
1,3,5-Trimethylbenzene	0.0E+0								
Vinyl chloride	0.0E+0								
SEMIVOLATILE ORGANIC CHEMICALS									
Naphthalene	0.0E+0								
TOTAL RISK	0.0E+0	6.4E-6	2.4E-5	4.5E-9	1.5E-6	7.1E-7	2.0E-9	2.4E-7	0.0E+0

Table 6-2a
Adult Resident Cancer Risk
USZ Aquifer, 30 years (Future)
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Well Number	2-325B	2-263B	69	2-344B	2-347B	40BR
VOLATILE ORGANIC CHEMICALS						
Chloroform	6.4E-10	0.0E+0	5.2E-10	1.3E-10	3.7E-10	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	1.2E-9	0.0E+0	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloroethane	0.0E+0	0.0E+0	4.5E-7	0.0E+0	1.4E-8	0.0E+0
1,1-Dichloroethene	0.0E+0	9.0E-7	1.9E-6	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	0.0E+0	9.7E-9	2.7E-6	0.0E+0	0.0E+0	0.0E+0
Carbon tetrachloride	4.5E-8	0.0E+0	2.3E-7	9.1E-9	1.8E-8	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	2.4E-8	0.0E+0	0.0E+0	0.0E+0
Trichloroethene	1.8E-7	4.8E-9	4.2E-7	2.5E-8	9.9E-8	0.0E+0
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Vinyl chloride	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SEMIVOLATILE ORGANIC CHEMICALS						
Naphthalene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
TOTAL RISK	2.2E-7	9.2E-7	5.7E-6	3.5E-8	1.3E-7	0.0E+0

Table 6-2b

Adult Resident Noncancer Hazard
 USZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma

Well Number	WS-1	WS-2	WS-3	WS-4	WS-5	WS-7	WS-30	WS-31	DC-20
VOLATILE ORGANIC CHEMICALS									
Chloroform	5.1E+2	0.0E+0	8.4E-3	0.0E+0	2.6E-2	4.6E-3	0.0E+0	1.0E-2	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	1.1E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	5.1E-4	1.7E-5	3.9E-4	0.0E+0	0.0E+0	2.9E-6	0.0E+0	2.3E-5	0.0E+0
1,2-Dichloroethane	1.1E+0	0.0E+0	5.9E-3	0.0E+0	1.0E-2	7.7E-5	0.0E+0	0.0E+0	0.0E+0
1,1-Dichloroethene	5.7E-4	5.9E-3	3.8E-3	0.0E+0	3.6E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	3.1E-1	0.0E+0							
Benzene	2.5E-2	0.0E+0	8.3E-1	0.0E+0	2.3E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Carbon tetrachloride	3.8E-1	0.0E+0	1.2E-3	0.0E+0	3.6E-3	1.3E-3	0.0E+0	2.2E-3	0.0E+0
Tetrachloroethene	5.8E-3	0.0E+0	2.5E-4	0.0E+0	6.0E-4	2.8E-3	0.0E+0	0.0E+0	0.0E+0
Trichloroethene	4.7E-3	4.9E-5	1.4E-2	5.9E-5	2.0E-3	1.9E-5	2.6E-5	2.5E-3	0.0E+0
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	2.8E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	4.3E-3	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Vinyl chloride	0.0E+0								
SEMIVOLATILE ORGANIC CHEMICALS									
Naphthalene	0.0E+0	0.0E+0	3.9E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
TOTAL RISK	5.1E+2	6.0E-3	8.7E-1	5.9E-5	4.3E-2	8.8E-3	2.6E-5	1.5E-2	0.0E+0

Table 6-2b

Adult Resident Noncancer Hazard
 USZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma

Well Number	2-325B	2-263B	69	2-344B	2-347B	40BR
VOLATILE ORGANIC CHEMIC						
Chloroform	9.7E-3	0.0E+0	7.9E-3	1.9E-3	5.6E-3	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	1.2E-5	0.0E+0	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	2.6E-5	8.6E-6	2.5E-4	5.5E-6	1.1E-5	0.0E+0
1,2-Dichloroethane	0.0E+0	0.0E+0	6.5E-3	0.0E+0	2.1E-4	0.0E+0
1,1-Dichloroethene	0.0E+0	8.4E-4	1.8E-3	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	0.0E+0	4.3E-4	1.2E-1	0.0E+0	0.0E+0	0.0E+0
Carbon tetrachloride	2.1E-3	0.0E+0	1.0E-2	4.2E-4	8.3E-4	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	9.9E-5	0.0E+0	0.0E+0	0.0E+0
Trichloroethene	2.3E-3	6.3E-5	5.4E-3	3.3E-4	1.3E-3	0.0E+0
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	2.6E-3	0.0E+0	0.0E+0	0.0E+0
Vinyl chloride	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SEMIVOLATILE ORGANIC CH						
Naphthalene	0.0E+0	0.0E+0	8.7E-4	0.0E+0	0.0E+0	0.0E+0
TOTAL RISK	1.4E-2	1.3E-3	1.6E-1	2.7E-3	8.0E-3	0.0E+0

Table 6-2c

**On-Site Worker Cancer Risk
 USZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Well Number	WS-1	WS-2	WS-3	WS-4	WS-5	WS-7	WS-30	WS-31	DC-20
VOLATILE ORGANIC CHEMICALS									
Chloroform	0.0E+0	0.0E+0	1.8E-10	0.0E+0	5.5E-10	9.7E-11	0.0E+0	2.1E-10	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	4.6E-9	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	0.0E+0								
1,2-Dichloroethane	0.0E+0	0.0E+0	2.2E-7	0.0E+0	3.7E-7	2.8E-9	0.0E+0	0.0E+0	0.0E+0
1,1-Dichloroethene	0.0E+0	3.0E-6	1.9E-6	0.0E+0	1.8E-7	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	0.0E+0								
Benzene	0.0E+0	0.0E+0	9.9E-6	0.0E+0	2.8E-9	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Carbon tetrachloride	0.0E+0	0.0E+0	1.3E-8	0.0E+0	3.8E-8	1.4E-8	0.0E+0	2.3E-8	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	2.6E-8	0.0E+0	6.3E-8	3.0E-7	0.0E+0	0.0E+0	0.0E+0
Trichloroethene	0.0E+0	1.9E-9	5.4E-7	2.3E-9	7.9E-8	7.2E-10	1.0E-9	9.5E-8	0.0E+0
1,2,4-Trimethylbenzene	0.0E+0								
1,3,5-Trimethylbenzene	0.0E+0								
Vinyl chloride	0.0E+0								
SEMIVOLATILE ORGANIC CHEMICALS									
Naphthalene	0.0E+0								
TOTAL RISK	0.0E+0	3.0E-6	1.3E-5	2.3E-9	7.3E-7	3.1E-7	1.0E-9	1.2E-7	0.0E+0

Table 6-2c

On-Site Worker Cancer Risk
 USZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma

Well Number	2-325B	2-263B	69	2-344B	2-347B	40BR
VOLATILE ORGANIC CHEMICALS						
Chloroform	2.1E-10	0.0E+0	1.7E-10	4.1E-11	1.2E-10	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	5.1E-10	0.0E+0	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloroethane	0.0E+0	0.0E+0	2.4E-7	0.0E+0	7.7E-9	0.0E+0
1,1-Dichloroethene	0.0E+0	4.2E-7	8.8E-7	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	0.0E+0	5.1E-9	1.4E-6	0.0E+0	0.0E+0	0.0E+0
Carbon tetrachloride	2.2E-8	0.0E+0	1.1E-7	4.5E-9	8.9E-9	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	1.0E-8	0.0E+0	0.0E+0	0.0E+0
Trichloroethene	8.8E-8	2.4E-9	2.1E-7	1.3E-8	5.0E-8	0.0E+0
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Vinyl chloride	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SEMIVOLATILE ORGANIC CHEMICALS						
Naphthalene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
TOTAL RISK	1.1E-7	4.3E-7	2.9E-6	1.7E-8	6.6E-8	0.0E+0

Table 6-2d

**On-Site Worker Noncancer Hazard
 USZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Well Number	WS-1	WS-2	WS-3	WS-4	WS-5	WS-7	WS-30	WS-31	DC-20
VOLATILE ORGANIC CHEMICALS									
Chloroform	0.0E+0	0.0E+0	6.0E-3	0.0E+0	1.8E-2	3.2E-3	0.0E+0	7.2E-3	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	6.2E-5	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	0.0E+0	6.0E-6	1.4E-4	0.0E+0	0.0E+0	1.0E-6	0.0E+0	8.2E-6	0.0E+0
1,2-Dichloroethane	0.0E+0	0.0E+0	4.2E-3	0.0E+0	7.1E-3	5.4E-5	0.0E+0	0.0E+0	0.0E+0
1,1-Dichloroethene	0.0E+0	3.7E-3	2.4E-3	0.0E+0	2.2E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	0.0E+0								
Benzene	0.0E+0	0.0E+0	5.5E-1	0.0E+0	1.5E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Carbon tetrachloride	0.0E+0	0.0E+0	7.3E-4	0.0E+0	2.2E-3	8.1E-4	0.0E+0	1.3E-3	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	7.6E-5	0.0E+0	1.8E-4	8.5E-4	0.0E+0	0.0E+0	0.0E+0
Trichloroethene	0.0E+0	1.6E-5	4.7E-3	2.0E-5	6.9E-4	6.2E-6	8.8E-6	8.3E-4	0.0E+0
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	2.0E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	3.0E-3	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Vinyl chloride	0.0E+0								
SEMIVOLATILE ORGANIC CHEMICALS									
Naphthalene	0.0E+0	0.0E+0	2.8E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
TOTAL RISK	0.0E+0	3.7E-3	5.7E-1	2.0E-5	2.9E-2	5.0E-3	8.8E-6	9.4E-3	0.0E+0

Table 6-2d

On-Site Worker Noncancer Hazard
 USZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma

Well Number	2-325B	2-263B	69	2-344B	2-347B	40BR
VOLATILE ORGANIC CHEMIC						
Chloroform	6.9E-3	0.0E+0	5.6E-3	1.4E-3	4.0E-3	0.0E+0
1,4-Dichlorobenzene	0.0E+0	0.0E+0	6.8E-6	0.0E+0	0.0E+0	0.0E+0
Cis-1,2-Dichloroethene	9.2E-6	3.0E-6	8.9E-5	1.9E-6	3.7E-6	0.0E+0
1,2-Dichloroethane	0.0E+0	0.0E+0	4.6E-3	0.0E+0	1.5E-4	0.0E+0
1,1-Dichloroethene	0.0E+0	5.3E-4	1.1E-3	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloropropane	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	0.0E+0	2.8E-4	7.9E-2	0.0E+0	0.0E+0	0.0E+0
Carbon tetrachloride	1.3E-3	0.0E+0	6.4E-3	2.6E-4	5.1E-4	0.0E+0
Tetrachloroethene	0.0E+0	0.0E+0	3.0E-5	0.0E+0	0.0E+0	0.0E+0
Trichloroethene	7.7E-4	2.1E-5	1.8E-3	1.1E-4	4.3E-4	0.0E+0
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	1.8E-3	0.0E+0	0.0E+0	0.0E+0
Vinyl chloride	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SEMIVOLATILE ORGANIC CH						
Naphthalene	0.0E+0	0.0E+0	6.1E-4	0.0E+0	0.0E+0	0.0E+0
TOTAL RISK	9.0E-3	8.3E-4	1.0E-1	1.7E-3	5.1E-3	0.0E+0

Table 6-3a
Adult Resident Cancer Risk
LSZ Aquifer, 30 years (Future)
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Well Number	WS-1	WS-2	WS-3	WS-4	WS-5	WS-7	WS-30	WS-31	DC-20	2-325A	68
VOLATILE ORGANIC CHEMICALS											
Chloroform	1.0E-10	0.0E+0	7.6E-9	0.0E+0	9.4E-11	2.4E-10	6.4E-10	3.4E-8	0.0E+0	1.7E-9	4.0E-10
1,4-Dichlorobenzene	0.0E+0	0.0E+0	2.2E-7	1.0E-9	0.0E+0						
Cis-1,2-Dichloroethene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloroethane	0.0E+0	0.0E+0	5.8E-6	0.0E+0	8.9E-8	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	3.0E-7
1,1-Dichloroethene	0.0E+0	1.1E-5	2.9E-5	0.0E+0	6.6E-8	0.0E+0	2.9E-8	2.1E-7	0.0E+0	0.0E+0	2.1E-6
1,2-Dichloropropane	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.3E-9	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	0.0E+0	0.0E+0	1.2E-4	4.6E-8	0.0E+0	7.5E-9	6.2E-9	0.0E+0	0.0E+0	0.0E+0	8.7E-7
Carbon tetrachloride	0.0E+0	0.0E+0	5.8E-7	0.0E+0	0.0E+0	4.8E-8	4.2E-8	2.2E-6	0.0E+0	1.2E-7	2.8E-7
Tetrachloroethene	0.0E+0	0.0E+0	4.4E-7	0.0E+0	2.6E-8	8.3E-8	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.9E-8
Trichloroethene	0.0E+0	4.4E-8	8.6E-6	2.1E-9	1.5E-6	2.6E-9	9.6E-8	8.8E-6	0.0E+0	4.3E-7	2.6E-7
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Vinyl chloride	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SEMIVOLATILE ORGANIC CHEMICALS											
Naphthalene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
TOTAL RISK	1.0E-10	1.1E-5	1.6E-4	4.9E-8	1.6E-6	1.4E-7	1.7E-7	1.1E-5	0.0E+0	5.6E-7	3.8E-6

Table 6-3b

Adult Resident Noncancer Hazard
 LSZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma

Well Number	WS-1	WS-2	WS-3	WS-4	WS-5	WS-7	WS-30	WS-31	DC-20	2-325A	68
VOLATILE ORGANIC CHEMICALS											
Chloroform	1.6E-3	0.0E+0	1.2E-1	0.0E+0	1.4E-3	3.6E-3	9.7E-3	5.1E-1	0.0E+0	2.6E-2	6.1E-3
1,4-Dichlorobenzene	0.0E+0	0.0E+0	2.2E-3	1.0E-5	0.0E+0						
Cis-1,2-Dichloroethene	0.0E+0	9.5E-5	3.5E-3	0.0E+0	0.0E+0	0.0E+0	1.7E-5	1.3E-3	0.0E+0	6.8E-5	9.2E-5
1,2-Dichloroethane	0.0E+0	0.0E+0	8.4E-2	0.0E+0	1.3E-3	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	4.3E-3
1,1-Dichloroethene	0.0E+0	1.0E-2	2.7E-2	0.0E+0	6.1E-5	0.0E+0	2.7E-5	2.0E-4	0.0E+0	0.0E+0	1.9E-3
1,2-Dichloropropane	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.8E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	0.0E+0	0.0E+0	5.4E+0	2.1E-3	0.0E+0	3.3E-4	2.8E-4	0.0E+0	0.0E+0	0.0E+0	3.9E-2
Carbon tetrachloride	0.0E+0	0.0E+0	2.6E-2	0.0E+0	0.0E+0	2.2E-3	1.9E-3	1.0E-1	0.0E+0	5.6E-3	1.3E-2
Tetrachloroethene	0.0E+0	0.0E+0	1.8E-3	0.0E+0	1.1E-4	3.4E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	8.0E-5
Trichloroethene	0.0E+0	5.8E-4	1.1E-1	2.7E-5	1.9E-2	3.4E-5	1.2E-3	1.1E-1	0.0E+0	5.6E-3	3.4E-3
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	3.3E-3	0.0E+0							
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	2.9E-2	6.1E-5	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	3.9E-4
Vinyl chloride	0.0E+0										
SEMIVOLATILE ORGANIC CHEMICALS											
Naphthalene	0.0E+0	0.0E+0	3.8E-3	0.0E+0							
TOTAL RISK	1.6E-3	1.1E-2	5.8E+0	2.2E-3	2.2E-2	6.7E-3	1.3E-2	7.3E-1	0.0E+0	3.7E-2	6.8E-2

Table 6-3c

On-Site Worker Cancer Risk
 LSZ Aquifer, 30 year (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma

Well Number	WS-1	WS-2	WS-3	WS-4	WS-5	WS-7	WS-30	WS-31	DC-20	2-325A	68
VOLATILE ORGANIC CHEMICALS											
Chloroform	3.4E-11	0.0E+0	2.5E-9	0.0E+0	3.1E-11	7.6E-11	2.1E-10	1.1E-8	0.0E+0	5.4E-10	1.3E-10
1,4-Dichlorobenzene	0.0E+0	0.0E+0	9.5E-8	4.4E-10	0.0E+0						
Cis-1,2-Dichloroethene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,2-Dichloroethane	0.0E+0	0.0E+0	3.1E-6	0.0E+0	4.8E-8	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.6E-7
1,1-Dichloroethene	0.0E+0	5.1E-6	1.3E-5	0.0E+0	3.0E-8	0.0E+0	1.3E-8	9.8E-8	0.0E+0	0.0E+0	9.7E-7
1,2-Dichloropropane	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	4.3E-10	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	0.0E+0	0.0E+0	6.4E-5	2.4E-8	0.0E+0	4.0E-9	3.3E-9	0.0E+0	0.0E+0	0.0E+0	4.6E-7
Carbon tetrachloride	0.0E+0	0.0E+0	2.8E-7	0.0E+0	0.0E+0	2.3E-8	2.1E-8	1.1E-6	0.0E+0	6.0E-8	1.4E-7
Tetrachloroethene	0.0E+0	0.0E+0	1.9E-7	0.0E+0	1.1E-8	3.6E-8	0.0E+0	0.0E+0	0.0E+0	0.0E+0	8.4E-9
Trichloroethene	0.0E+0	2.2E-8	4.3E-6	1.1E-9	7.4E-7	1.3E-9	4.8E-8	4.4E-6	0.0E+0	2.2E-7	1.3E-7
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Vinyl chloride	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SEMIVOLATILE ORGANIC CHEMICALS											
Naphthalene	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
TOTAL RISK	3.4E-11	5.1E-6	8.5E-5	2.6E-8	8.3E-7	6.5E-8	8.6E-8	5.6E-6	0.0E+0	2.8E-7	1.9E-6

Table 6-3d

On-Site Worker Noncancer Hazard
 LSZ Aquifer, 30 years (Future)
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma

Well Number	WS-1	WS-2	WS-3	WS-4	WS-5	WS-7	WS-30	WS-31	DC-20	2-325A	68
VOLATILE ORGANIC CHEMICALS											
Chloroform	1.1E-3	0.0E+0	8.2E-2	0.0E+0	1.0E-3	2.6E-3	6.9E-3	3.7E-1	0.0E+0	1.8E-2	4.4E-3
1,4-Dichlorobenzene	0.0E+0	0.0E+0	1.3E-3	5.9E-6	0.0E+0						
Cis-1,2-Dichloroethene	0.0E+0	3.3E-5	1.2E-3	0.0E+0	0.0E+0	0.0E+0	5.9E-6	4.6E-4	0.0E+0	2.4E-5	3.2E-5
1,2-Dichloroethane	0.0E+0	0.0E+0	6.0E-2	0.0E+0	9.2E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	3.1E-3
1,1-Dichloroethene	0.0E+0	6.4E-3	1.7E-2	0.0E+0	3.8E-5	0.0E+0	1.7E-5	1.2E-4	0.0E+0	0.0E+0	1.2E-3
1,2-Dichloropropane	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.1E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Benzene	0.0E+0	0.0E+0	3.5E+0	1.3E-3	0.0E+0	2.2E-4	1.8E-4	0.0E+0	0.0E+0	0.0E+0	2.6E-2
Carbon tetrachloride	0.0E+0	0.0E+0	1.6E-2	0.0E+0	0.0E+0	1.3E-3	1.2E-3	6.3E-2	0.0E+0	3.4E-3	7.9E-3
Tetrachloroethene	0.0E+0	0.0E+0	5.6E-4	0.0E+0	3.3E-5	1.0E-4	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.4E-5
Trichloroethene	0.0E+0	1.9E-4	3.7E-2	9.1E-6	6.4E-3	1.2E-5	4.2E-4	3.8E-2	0.0E+0	1.9E-3	1.1E-3
1,2,4-Trimethylbenzene	0.0E+0	0.0E+0	2.3E-3	0.0E+0							
1,3,5-Trimethylbenzene	0.0E+0	0.0E+0	2.0E-2	4.3E-5	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.7E-4
Vinyl chloride	0.0E+0										
SEMI-VOLATILE ORGANIC CHEMICALS											
Naphthalene	0.0E+0	0.0E+0	2.7E-3	0.0E+0							
TOTAL RISK	1.1E-3	6.6E-3	3.8E+0	1.4E-3	8.4E-3	4.3E-3	8.7E-3	4.7E-1	0.0E+0	2.4E-2	4.4E-2

Table 6-4a
Cancer Risk Estimates for Current Concentrations in Surface Water
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Population/Pathway	Crutcho Creek (HWBZ Layer)	Crutcho Creek (USZ Layer)	Kuhlman Creek (USZ Layer)	Tributary to Kuhlman Creek (USZ Layer)
Trespasser				
Ingestion	NTVs ^a	2.8×10^{-11}	2.8×10^{-11}	2.8×10^{-12}
Dermal	NTVs	1.8×10^{-10}	1.8×10^{-10}	1.8×10^{-11}
Total		2.1×10^{-10}	2.1×10^{-10}	2.1×10^{-11}
Maintenance Worker				
Ingestion	NTVs	8.8×10^{-11}	8.9×10^{-11}	8.9×10^{-12}
Dermal	NTVs	6.5×10^{-10}	6.5×10^{-10}	6.6×10^{-11}
Total		7.4×10^{-10}	7.4×10^{-10}	7.4×10^{-11}

^a NTV - No toxicity values available for the COPCs in this pathway.
 HWBZ - Hennessey water bearing zone.
 USZ - Upper saturated zone.

Table 6-4b
Non-cancer Hazard Estimates for Current Concentrations in Surface Water
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Population/Pathway	Crutcho Creek (HWBZ Layer)	Crutcho Creek (USZ Layer)	Kuhlman Creek (USZ Layer)	Tributary to Kuhlman Creek (USZ Layer)
Trespasser				
Ingestion	9.3×10^{-10}	4.9×10^{-6}	4.9×10^{-6}	2.0×10^{-6}
Dermal	4.3×10^{-9}	3.1×10^{-5}	3.2×10^{-5}	5.8×10^{-6}
Total	5.2×10^{-9}	3.6×10^{-5}	3.6×10^{-5}	7.7×10^{-6}
Maintenance Worker				
Ingestion	7.4×10^{-10}	3.9×10^{-6}	3.9×10^{-6}	1.6×10^{-6}
Dermal	3.9×10^{-9}	2.9×10^{-5}	2.9×10^{-5}	5.3×10^{-6}
Total	4.7×10^{-9}	3.3×10^{-5}	3.3×10^{-5}	6.8×10^{-6}

HWBZ - Hennessey water bearing zone.
 USZ - Upper saturated zone.

Table 6-5a

**Cancer Risk Estimates for Future Concentrations in Surface Water
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Population/Pathway	Crutcho Creek (HWBZ Layer)	Crutcho Creek (USZ Layer)	Kuhlman Creek (USZ Layer)	Tributary to Kuhlman Creek (USZ Layer)
<i>Trespasser</i>				
Ingestion	8.1x10 ⁻¹¹	1.4x10 ⁻¹¹	2.4x10 ⁻¹¹	1.2x10 ⁻¹⁰
Dermal	4.0x10 ⁻¹⁰	6.3x10 ⁻¹¹	1.4x10 ⁻¹⁰	6.5x10 ⁻¹⁰
Total	4.8x10 ⁻¹⁰	7.7x10 ⁻¹¹	1.7x10 ⁻¹⁰	7.7x10 ⁻¹⁰
<i>Maintenance Worker</i>				
Ingestion	2.6x10 ⁻¹⁰	4.5x10 ⁻¹¹	7.6x10 ⁻¹¹	3.9x10 ⁻¹⁰
Dermal	1.5x10 ⁻⁹	2.3x10 ⁻¹⁰	5.2x10 ⁻¹⁰	2.4x10 ⁻⁹
Total	1.7x10 ⁻⁹	2.7x10 ⁻¹⁰	5.9x10 ⁻¹⁰	2.8x10 ⁻⁹

HWBZ - Hennessey water bearing zone.
 USZ - Upper saturated zone.

Table 6-5b

**Non-cancer Hazard Estimates for Future Concentrations in Surface Water
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Population/Pathway	Crutcho Creek (HWBZ Layer)	Crutcho Creek (USZ Layer)	Kuhlman Creek (USZ Layer)	Tributary to Kuhlman Creek (USZ Layer)
<i>Trespasser</i>				
Ingestion	9.5x10 ⁻⁶	5.4x10 ⁻⁷	1.8x10 ⁻⁶	3.0x10 ⁻⁷
Dermal	5.9x10 ⁻⁵	3.6x10 ⁻⁶	1.2x10 ⁻⁵	1.7x10 ⁻⁶
Total	6.9x10 ⁻⁵	4.1x10 ⁻⁶	1.3x10 ⁻⁵	2.0x10 ⁻⁶
<i>Maintenance Worker</i>				
Ingestion	7.6x10 ⁻⁶	4.3x10 ⁻⁷	1.4x10 ⁻⁶	2.4x10 ⁻⁷
Dermal	5.4x10 ⁻⁵	3.3x10 ⁻⁶	1.1x10 ⁻⁵	1.5x10 ⁻⁶
Total	6.2x10 ⁻⁵	3.7x10 ⁻⁶	1.2x10 ⁻⁵	1.8x10 ⁻⁶

HWBZ - Hennessey water bearing zone.
 USZ - Upper saturated zone.

Table 6-6

**Maximum Concentrations^a of Constituents of Potential Ecological Concern
 Based on Groundwater Migration Modeling at CG037
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Constituent	Initial (0)	Time (years)					Maximum
		1	5	10	20	30	
Benzene	0.00E+00 (NA) ^b	1.03E-04 (CR-6/HWBZ)	7.88E-03 (KT-1/USZ)	5.29E-03 (CR-6/HWBZ)	2.82E-01 (K-4/USZ)	1.26E+00 (K-4/USZ)	1.26E+00 (K-4/USZ)
Carbon tetrachloride	2.35E-04 (K-6/USZ)	6.59E-02 (K-6/USZ)	1.80E+00 (CR-6/HWBZ)	1.29E+00 (CR-6/HWBZ)	1.17E-01 (CR-6/HWBZ)	4.23E-02 (CR-6/HWBZ)	1.80E+00 (CR-6/HWBZ)
Chloroform	3.40E-04 (K-6/USZ)	8.90E-02 (CR-6/HWBZ)	7.12E+00 (CR-6/HWBZ)	2.06E+00 (CR-6/HWBZ)	1.32E+00 (CR-6/HWBZ)	1.28E+00 (CR-6/HWBZ)	7.12E+00 (CR-6/HWBZ)
1,4-Dichlorobenzene	1.54E-05 (CR-7/HWBZ)	6.62E-02 (CR-7/HWBZ)	4.53E-02 (CR-7/HWBZ)	1.13E-02 (CR-7/HWBZ)	1.77E-03 (CR-7/HWBZ)	4.74E-03 (K-4/USZ)	6.62E-02 (CR-7/HWBZ)
1,2-Dichloroethane	0.00E+00 (NA)	7.94E-05 (CR-6/HWBZ)	8.54E-01 (CR-6/HWBZ)	1.01E+00 (CR-6/HWBZ)	1.34E+00 (CR-6/HWBZ)	1.14E+00 (CR-6/HWBZ)	1.34E+00 (CR-6/HWBZ)
1,1-Dichloroethene	0.00E+00 (NA)	2.12E-04 (K-6/USZ)	3.32E-03 (KT-1/USZ)	6.75E-01 (KT-1/USZ)	8.17E-01 (KT-1/USZ)	8.14E-01 (KT-1/USZ)	8.17E-01 (KT-1/USZ)
cis-1,2-Dichloroethene	4.98E+00 (KT-1/USZ)	3.76E+00 (CR-7/HWBZ)	2.49E+00 (CR-7/HWBZ)	1.41E+00 (CR-6/HWBZ)	1.13E+00 (CR-6/HWBZ)	1.02E+00 (CR-6/HWBZ)	4.98E+00 (KT-1/USZ)
1,2-Dichloropropane	0.00E+00 (NA)	2.41E-06 (CR-6/HWBZ)	9.84E-02 (CR-6/HWBZ)	2.25E-02 (CR-6/HWBZ)	1.02E-02 (CR-6/HWBZ)	4.99E-03 (CR-6/HWBZ)	9.84E-02 (CR-6/HWBZ)
Di-n-butyl phthalate	0.00E+00 (NA)	1.42E-02 (K-7/USZ)	6.90E-03 (K-7/USZ)	1.70E-03 (K-7/USZ)	1.16E-03 (CR-6/HWBZ)	4.87E-04 (CR-6/HWBZ)	1.42E-02 (K-7/USZ)
Naphthalene	0.00E+00 (NA)	7.02E-13 (KT-1/USZ)	5.88E-06 (KT-2/USZ)	2.17E-05 (KT-2/USZ)	1.03E-03 (K-3/USZ)	4.37E-03 (K-1/USZ)	4.37E-03 (K-1/USZ)
Tetrachloroethylene	1.04E-05 (CR-7/HWBZ)	2.95E-02 (CR-7/HWBZ)	5.65E-02 (CR-6/HWBZ)	5.30E-02 (CR-6/HWBZ)	5.70E-02 (CR-6/HWBZ)	4.60E-02 (CR-6/HWBZ)	5.70E-02 (CR-6/HWBZ)
Trichloroethylene	1.00E+01 (K-7/USZ)	6.05E+00 (K-7/USZ)	1.32E+01 (K-7/USZ)	7.58E+00 (CR-6/HWBZ)	1.70E+01 (CR-6/HWBZ)	1.75E+01 (CR-6/HWBZ)	1.75E+01 (CR-6/HWBZ)
1,2,4-Trimethylbenzene	1.93E-03 (CR-7/HWBZ)	2.56E+00 (CR-7/HWBZ)	8.58E-01 (CR-7/HWBZ)	1.78E-01 (CR-7/HWBZ)	2.53E-02 (CR-7/HWBZ)	5.25E-03 (CR-7/HWBZ)	2.56E+00 (CR-7/HWBZ)
1,3,5-Trimethylbenzene	0.00E+00 (NA)	1.44E-11 (K-2/USZ)	5.09E-05 (K-2/USZ)	2.11E-04 (K-2/USZ)	7.75E-03 (K-1/USZ)	2.53E-02 (K-1/USZ)	2.53E-02 (K-1/USZ)
Vinyl chloride	2.81E-04 (CR-6/HWBZ)	6.46E-01 (CR-7/HWBZ)	3.80E-01 (CR-7/HWBZ)	8.73E-02 (CR-7/HWBZ)	1.26E-02 (CR-7/HWBZ)	5.25E-03 (CR-6/HWBZ)	6.46E-01 (CR-7/HWBZ)

^aConcentrations are in micrograms per liter (µg/L).

^bLocation/zone of maximum concentration shown in parentheses: USZ is the Upper Saturated Zone and HWBZ is the Hennessey Water-Bearing Zone. NA - not applicable.

Table 6-7

**Maximum Hazard Quotients for Constituents of Potential Ecological Concern for CG037
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

Constituent	Aquatic Organisms ^a	Benthic Organisms ^b	Plants ^c	Wildlife ^d				
				Muskrat	Raccoon	Mallard	Killdeer	Great Blue Heron
Benzene	2.73E-02	1.80E-02	---	8.45E-06	2.24E-05	---	---	---
Carbon tetrachloride	7.51E-03	1.25E-01	---	3.05E-05	1.31E-04	7.02E-05	9.27E-03	4.83E-04
Chloroform	2.46E-02	1.69E-02	---	6.11E-05	1.40E-04	---	---	---
1,4-Dichlorobenzene	5.91E-03	3.05E-03	---	2.89E-07	2.76E-06	---	---	---
1,2-Dichloroethane	6.72E-04	1.02E-03	---	2.72E-06	5.88E-06	5.85E-06	3.72E-04	2.15E-05
1,1-Dichloroethene	2.70E-03	2.15E-02	---	4.17E-06	1.32E-05	---	---	---
1,2-Dichloroethene	2.04E-01	5.67E-03	---	1.57E-05	3.86E-05	---	---	---
1,2-Dichloropropane	1.87E-04	---	---	1.32E-07	3.97E-07	---	---	---
Di-n-butyl phthalate	4.73E-03	2.98E-04	1.64E-05	9.02E-08	1.66E-06	4.00E-04	8.69E-02	6.13E-03
Naphthalene	1.82E-04	2.48E-04	4.37E-07	5.48E-07	3.72E-06	---	---	---
Tetrachloroethylene	6.78E-04	3.97E-04	5.70E-06	1.22E-05	5.93E-05	---	---	---
Trichloroethylene	4.99E-02	2.48E-01	---	8.18E-03	3.45E-02	---	---	---
1,2,4-Trimethylbenzene	---	---	---	8.77E-06	1.61E-04	---	---	---
1,3,5-Trimethylbenzene	---	---	---	4.36E-08	6.16E-07	---	---	---
Vinyl chloride	---	---	---	3.45E-04	6.25E-04	---	---	---

^aHazard quotient for aquatic organisms is the ratio of the maximum modeled water concentration to the water quality benchmark.

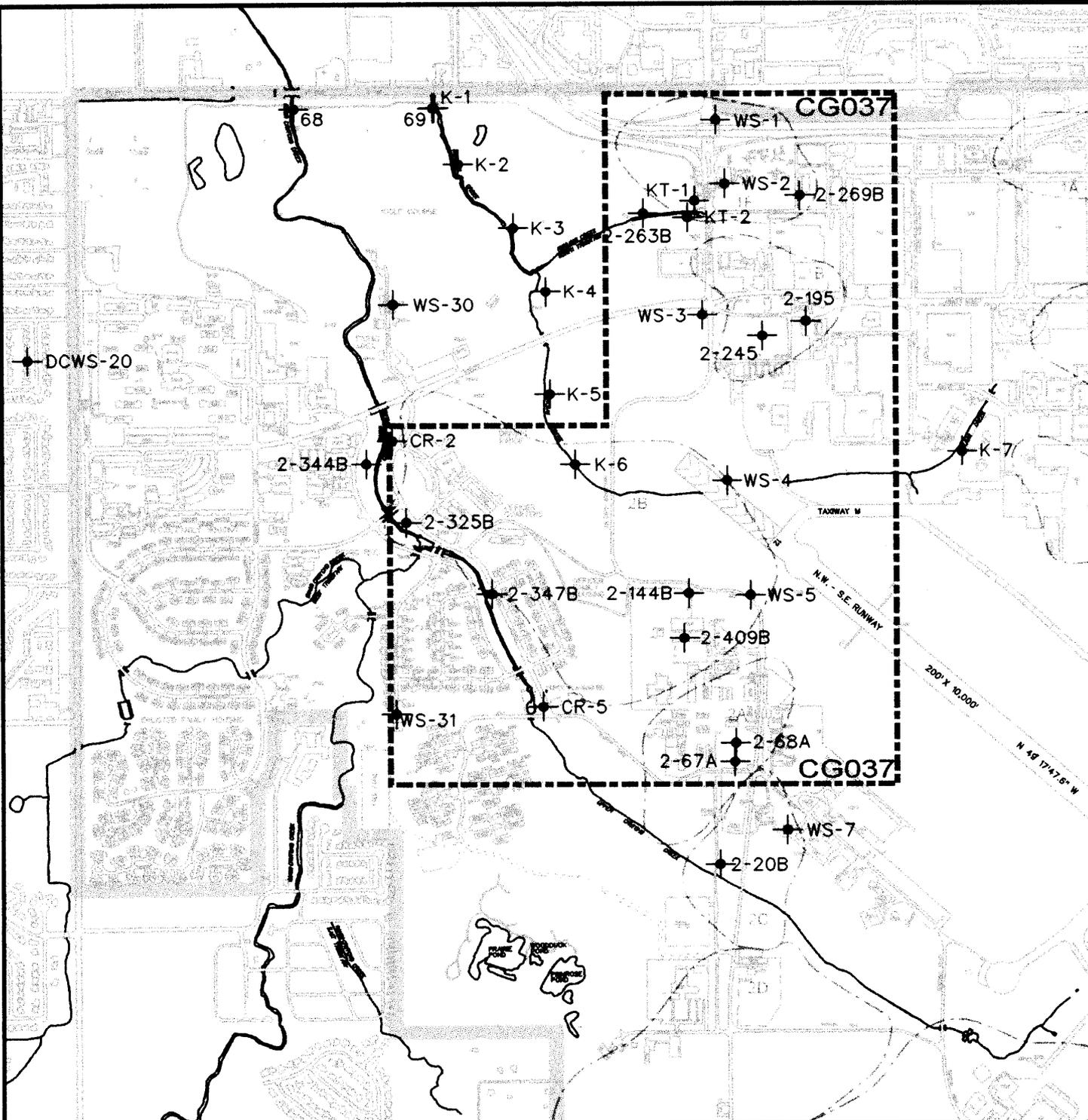
^bHazard quotient for benthic organisms is the ratio of the maximum modeled sediment concentration to the sediment quality benchmark.

^cHazard quotient for plants is the ratio of the maximum modeled water or sediment concentration to the corresponding plant toxicity benchmark.

^dHazard quotient for the wildlife receptors is the ratio of the modeled exposure to the constituent of ecological concern based on the maximum modeled water concentration to the toxicity benchmark for that species.

"---" = No toxicity benchmark available.

FIGURES



EXPLANATION

- ◆ POTENTIAL EXPOSURE LOCATION
- K - KUHLMAN CREEK
- KT - UNNAMED TRIBUTARY TO KUHLMAN CREEK
- CR - CRUTCHO CREEK
- WS - WATER SUPPLY WELL
- DCWS - DEL CITY WATER SUPPLY WELL

- GROUNDWATER IRP SITE
- ▨ TINKER AIR FORCE BASE PROPERTY LINE



0 600 1200
FEET

1A APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER

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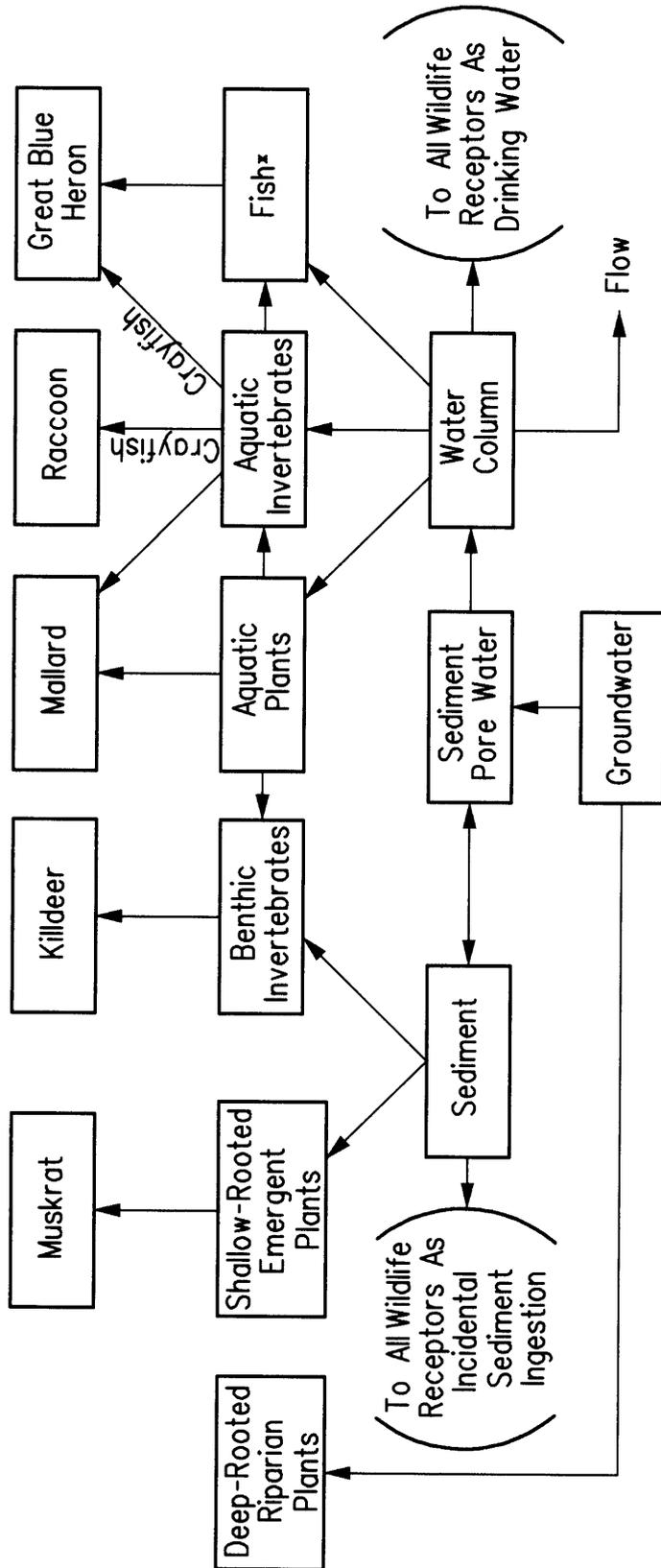
DRAWN BY: CFB
START DATE: 12/01/00
REVISED BY: CFB
LAST REV: 10/01/01
INITIATOR: MG
INT. DATE: 12/01/00

POTENTIAL EXPOSURE AND SOURCE CHARACTERIZATION LOCATIONS USED IN THE HUMAN HEALTH RISK ASSESSMENT
CG037 RFI GWMU 1B AND 1F
 PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

PROJ. NO. 799270

FIG. 6-1

UNIQUE NUMBER 799270-A04



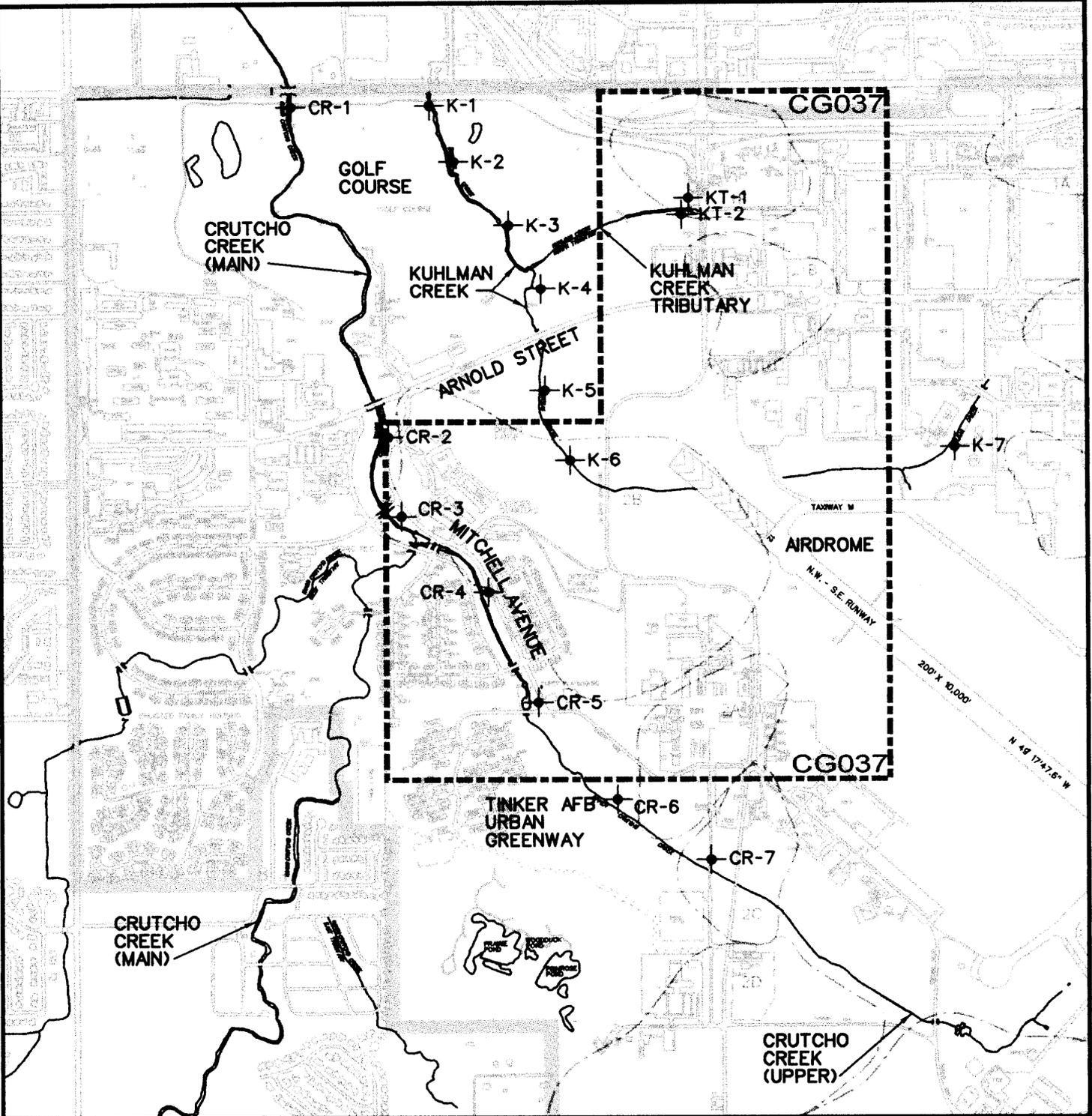
* Fish Assumed To Be In Tropical Level 3

DRAWN BY:	CFB
START DATE:	10/05/00
REVISED BY:	CFB
LAST REV:	03/27/01
INITIATOR:	MG
INT. DATE:	10/05/00

CONCEPTUAL MODEL OF EXPOSURE PATHWAYS FOR ECOLOGICAL RECEPTORS AT CRUTCHO AND KUHLMAN CREEKS CG037 RFI GWMU 1B AND 1F

PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

PROJ. NO.	799270
FIG. 6-2	
UNIQUE NUMBER	799270-A02



EXPLANATION

- POTENTIAL EXPOSURE LOCATION
- K** - KUHLMAN CREEK
- KT** - UNNAMED TRIBUTARY TO KUHLMAN CREEK
- CR** - CRUTCHO CREEK

GROUNDWATER IRP SITE

TINKER AIR FORCE BASE PROPERTY LINE

APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



DRAWN BY: CFB
START DATE: 10/05/00
REVISED BY: CFB
LAST REV: 10/01/01
INITIATOR: MG
INT. DATE: 10/05/00

LOCATIONS OF THE GROUNDWATER MODELING POINTS USED IN THE ECOLOGICAL RISK ASSESSMENT

CG037 RFI GWMU 1B AND 1F

PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

PROJ. NO. 799270

FIG. 6-3

UNIQUE NUMBER 799270-A01

7.0 Contaminant Fate and Transport

This chapter discusses numerical modeling of groundwater flow and contaminant migration that was performed in support of the risk assessment. The groundwater flow modeling is the first part of a two-step groundwater-modeling program for CG037; the second step includes contaminant transport modeling of those COPCs present in GWMU 1.

The overall objectives of the modeling effort were to:

- Integrate geologic, hydrologic, and chemical data collected within CG037.
- Provide a predictive tool for evaluating groundwater flow and contaminant migration.
- Provide input data for estimation of future risk, i.e., to predict contaminant concentrations at specific locations approximately 30 years from the present.
- Provide a predictive tool for groundwater remedy selection and design.

7.1 Groundwater Flow Modeling

The objectives of the groundwater model were to provide a tool for evaluation of flow patterns and to generate simulated hydraulic head distributions to be used as input for the contaminant transport model. In meeting these objectives, the numerical flow model Modflow (McDonald and Harbaugh, 1988) was used to provide hydraulic heads and fluxes across cell interfaces which were then used as input to a fate and transport model.

Design and implementation of the model was aided by the use of Groundwater Vistas (Environmental Simulations, Inc., 1998), a graphical user interface to Modflow. Groundwater Vistas displays the entire model design in both plan and cross-sectional views. Model results, hydraulic parameters, and boundary conditions are shown in shaded color zones and contours. Groundwater Vistas operates in a Windows® environment and allows the user to build the model, perform model runs, and evaluate results without exiting the program. Groundwater Vistas also supports a large number of input and output file formats.

7.1.1 Model Grid Discretization

The model includes all of CG037 and portions of surrounding areas, and covers an area of approximately 3.5 square miles. The x-axis is 9,000 feet in length while the y-axis is 11,000 feet. There are 180 finite-difference nodes in the x-direction and 220 nodes in the y-direction for

a total of 39,600 nodes per model layer. The model contains five layers as described below; thus, there are a total 198,000 nodes in the model. Of those, 187,818 are active nodes (see below for a discussion of inactive nodes in the HWBZ). For location purposes, the center of the grid cell was used to represent the cell.

Vertically, the model is divided into five layers. Layer one represents the HWBZ, layer two is the USZ, layer three is the USZ-LSZ aquitard, layer four is the LSZ. The LSZ was further broken down into a fifth layer corresponding to the lower portion of the LSZ. For the purposes of the fate and transport model, this fifth layer is referred to as the LLSZ. The thickness of each layer is variable in order to account for geologic changes in each layer. All layers generally dip westward. The elevation data for each layer were used to construct variograms and contour maps using Surfer (Golden Software, 1999); the contoured Surfer file was imported directly into the model using Groundwater Vistas. This technique allows for more accurate numerical representation of the change in thickness and dip for each geologic layer. In the case of the HWBZ, it has been replaced by the USZ in the northeast part of the model and along parts of Crutch and Kuhlman Creeks. To account for that in the model, the portion of the layer that was nonexistent was simulated with inactive cells and the layer thickness was reduced to one foot. Surface recharge was applied to the layer directly below (i.e., the USZ) and the one-foot thickness was deemed minimal enough to avoid a hydraulic impact in the model.

The grid was aligned directly along compass points. It is usually best to align a model grid with the primary direction of groundwater flow. However, flow in the HWBZ and USZ is generally to the northwest while flow in the LSZ and the lower portion of the LSZ is more to the west and southwest. Keeping the grid aligned due north was deemed the best compromise in this case.

7.1.2 Boundary Conditions and Hydraulic Parameters

Model boundaries were designated as constant hydraulic head, no flow, surface recharge, or river (surface water) boundaries. Pumping wells are also important boundary conditions; however, water supply wells were not incorporated into the model as pumping wells because virtually all these wells are screened in the PZ and this model does not include that aquifer. The RFI report describes in detail how these boundaries were designated.

The vertical and lateral geometries of the five major hydrogeologic units (i.e., the HWBZ, USZ, USZ-LSZ aquitard, LSZ, and LLSZ) were incorporated into the model. Stratigraphic contacts between the units were delineated from evaluation of downhole gamma log data and core

descriptions collected during installation of monitoring wells and piezometers across Tinker AFB. The elevation above mean sea level of each contact at each well location was correlated with the x-y survey coordinates for each well to create a set of points in three-dimensional space correlating to each contact. From these points, surfaces illustrating the stratigraphic contacts between the units were contoured and used for three-dimensional hydrologic modeling.

Hydrologic and hydraulic data used as input to the model were derived from a number of sources. The bulk of the hydraulic conductivity data were taken from IT (1996), which provided a summary of specific aquifer and slug tests performed in the HWBZ, the USZ, and the LSZ. Other data were found in IT (1997), and in Parkhurst et al. (1993).

Hydraulic head data from IT (1997) helped provide a regional understanding of hydraulic heads and flow directions. Water level data used specifically for model calibration were measured in October 1999. Water levels from October 1999 were chosen because they were the most recent, complete data set when the project began, and they correspond to the chemical analytical data set collected in December 1999.

7.1.3 Flow Model Calibration

Calibration can be defined as "finding a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field-measured values within a pre-established range of error" (Anderson and Woessner, 1992). Hence, the flow model calibration objective was to match the observed water table with the simulated groundwater elevations. The approach involved adjusting hydraulic conductivity zones, recharge, and/or river conductance for a large number of model runs until an acceptable match in water levels at specified target locations was obtained. There were a total of 212 target wells used in the calibration. By layer, the HWBZ contained 7 targets, the USZ contained 109, the LSZ contained 85, and the LLSZ contained 11 target wells. There were no target wells in the USZ-LSZ aquitard.

Calibration was performed using the trial-and-error method, supported by the auto-calibration routine in Groundwater Vistas. Calibration statistics and the methodology used were chosen using guidance from Anderson and Woessner (1992) and ASTM (1994). The auto-calibration procedure in Groundwater Vistas proved to be a significant aid on this project. It uses Marquardt's modification to the Gauss-Newton nonlinear least-squares parameter estimation technique (Hill, 1998). The auto-calibration procedure allows several parameters to be varied at once and completion of a number of model runs with different combinations. A log file is

written upon completion to allow review of the calibration statistics and determination of which combination or modification produced the best results. For this project, alternating between the trial-and-error method and the use of the Groundwater Vistas automatic routine proved to be an efficient approach to achieving successful calibration.

Data reported in the literature from other parts of Tinker AFB and vicinity list Ks that range from a low of approximately 0.2 foot (ft)/day to a high of approximately 120 ft/day. All studies discussed were outside the GWMU 1 model domain. The 244 ft/day zone, in the absence of field data for this specific region of the Base, was derived through the calibration process. That is, K and other hydraulic parameters were varied (both in value and the extent of the zone) until the model-predicted heads closely matched the field-measured heads from October 1999. In the LSZ, there were 85 wells within the model domain and all were used as calibration targets. In order to lower the model-predicted head in some wells, thus making them consistent with the field-measured values, the horizontal and vertical conductivities were increased. In addition, the K in the overlying aquitard was decreased to limit leakage from the USZ into the LSZ. At the end of calibration, 244 ft/day was the optimal value needed in the LSZ to allow the hydraulic heads to match the observed values based on field measurements within acceptable limits. This high value, and the relatively high vertical K of 30 ft/day, allowed water to flow horizontally (northward) and vertically, into the lower portion of the LSZ (the LLSZ model layer).

Three statistical parameters were used to evaluate calibration: the average residual (AR), the average absolute residual (AAR), and the residual standard deviation.

Because calibration is a site-specific process, there are no specific guidelines published on what constitutes an acceptable or reasonable calibration (ASTM, 1994); however, the goal clearly is to minimize the residuals. A general rule of thumb is that the residual standard deviation should be less than 10 percent of the range of hydraulic heads measured across the entire model domain. For the CG037 area, hydraulic heads ranged from a maximum elevation of about 1,226 feet at well 2-371B to a minimum elevation of about 1,182 feet at well 40A. This is a difference of about 43 feet; hence, an acceptable target for the residual standard deviation would be on the order of 4 feet or less (for the model as a whole). This is a relatively high residual, even for a model of this scale; therefore, a goal of 1 foot or less was set as a target residual standard deviation for the entire model. In addition, an AAR of 1 foot or less was set as a second, overall calibration goal.

Approximately 700 Modflow runs were performed to achieve adequate calibration. For the model as a whole, the AR was 0.06 feet, the AAR was 0.91 feet, and the residual standard deviation was 1.22 feet. Overall, the model accurately reflects area groundwater trends and the complex vertical and horizontal hydrogeology above the PZ in CG037.

A summary of all inflows and outflows to a model domain represents the volumetric water budget for that model. Modflow calculates a water budget for the overall model as a check on the acceptability of the solution. Thus the total simulated inflows and outflows in a model can be used to check the error in the solution; a water balance error of less than 1 percent is considered acceptable (Anderson and Woessner, 1992). The calibrated model for this project has a more than acceptable water balance error of 0.01 percent.

7.2 Contaminant Transport Modeling

This section presents the model setup, parameters, and results of modeling the fates and transport of COPCs present in GWMU 1. Those COPCs are:

- Benzene
- Carbon Tetrachloride
- Chloroform
- 1,4-Dichlorobenzene
- 1,2-Dichloroethane
- cis-1,2-Dichloroethene
- Di-n-butylphthalate
- Naphthalene
- Tetrachloroethene
- Trichloroethylene
- 1,2,4-Trimethylbenzene
- 1,3,5-Trimethylbenzene

The COPCs cited above include those constituents identified in the HHRA (Section 6.1) specific to GWMU 1, as well as COPECs from the ERA (Section 6.2). The primary purpose of the transport model was to predict the concentration of COPCs 30 years from the present and to use those data in the assessment of human health and ecological risk. Figures 6-1 and 6-3 show points of compliance identified for the assessment. MT3D-predicted concentrations after 30 years were determined for the COPCs in GWMU 1 at each of those locations.

The GWMU 1 transport model was developed using MT3D, a modular three-dimensional code for simulation of advection, dispersion, and chemical reaction of a dissolved contaminant in groundwater.

7.2.1 Assumptions

The model was used in conjunction with the calibrated flow model by extracting the velocity field, hydraulic heads, and sink/source information from Modflow. The flow model and the GWMU 1 transport model have the same domain that is divided vertically into five layers, with the same horizontal discretization of active areas in each layer. The transport model included the following additional assumptions:

- The conceptual model is correct in that groundwater flow in the CG037 area (and specifically, GWMU 1) is hydraulically at steady state
- The calibrated flow model is an accurate representation of the rate and direction of groundwater flow in CG037 and GWMU 1
- Both dispersivity and porosity are constants
- Both advective and dispersive transport occurs
- COPCs are subject to natural decay or degradation, as appropriate
- Changes in the concentration field do not affect the flow field
- Diffusion is negligible
- Degradation is described by a first-order, irreversible rate reaction
- Adsorption is negligible (a conservative assumption for the risk assessment)
- Contaminant sources are either continuous (to represent the presence of a DNAPL) or instantaneous (to represent an aqueous phase-only COPC).

The assumptions described above are consistent with the objectives of this model. However, these assumptions may limit the application of the model and should be considered carefully prior to using the model for other purposes or to achieve other objectives.

7.2.2 Transport Processes

There are a number of important physical and chemical processes that affect the fate and transport of contaminants in groundwater, including advection, dispersion, degradation or decay, and retardation. The RFI report presents brief discussions of each of these processes and the ramification of the assumptions that are applied to each process.

7.2.3 Initial Conditions

Groundwater samples taken in October 1999 were deemed to be initial conditions (or “time zero”) for this phase of the modeling. Most of the data were contoured by hand initially, then with Surfer for import to Modflow. The compounds Naphthalene and Di-n-butylphthalate were detected in only one or two wells and contouring was not feasible. For those, specific nodes in Modflow were designated with the measured concentration but no structured plume was contoured. Isopleth maps for the significant COPCs are presented in Chapter 5.0 of this report. Table 7-1 lists the maximum October 1999 concentration that was used as an initial condition and the layer in which it was detected.

For the purposes of the groundwater transport calculations, certain compounds were treated as a constant source as described below, in cases where the absence of DNAPL could not be fully proved. Table 7-1 lists the specific density of all the COPCs in GWMU 1. For those compounds with a density greater than that of water (1.0) and that could form DNAPL, the source was described in the following manner:

1. The approximate source area of the plume was identified using historical data such as aerial photographs from as far back as the 1940s.
2. The selected source area was located on the model grid and a constant concentration boundary node was placed one grid block (50 feet) upgradient. This assumption allows for some latitude in any downgradient migration of the source that may have occurred since the original discharge. The location of the source cell on the grid is shown on the 30-year plume maps discussed below in Section 7.2.4.
3. The concentration at the constant source node was specified as twice the highest concentration measured in October 1999. Therefore, this cell was held at a constant concentration throughout the 30-year simulation. In this manner, a DNAPL source that could be slowly releasing soluble contaminant to groundwater was simulated.

It should be noted that Step 3 contains a significant assumption in that the constant source was set to twice the highest concentration measured in October 1999. It is virtually impossible to

know for sure the actual concentration of a COPC that exists as a DNAPL. Evidence in the literature suggests that DNAPL may or may not exist as a “pool” in the aquifer, or may be present as residual, disseminated blebs in pore spaces, and that it can be very hard to detect even when one drills within a few feet of it (e.g., Chrysikopoulos et al., 2000; EPA, 1994; Kueper and McWhorter, 1991). In cases such as this, the EPA (1992b) suggests that one percent of the solubility limit of a particular COPC is a good approximation of a DNAPL source. Results from some well-controlled experiments performed by Chrysikopoulos et al. (2000) suggest that approximately four percent of the solubility limit may be a better approximation. Table 7-1 lists the solubility limit for each COPC and the corresponding value when one percent and four percent of that value is derived. As can be seen, the numbers are enormous and are hundreds, and in some case thousands, of times greater than the maximum concentration seen in October 1999. These values were extraordinarily high compared with current concentrations and could result in a grossly overly-conservative risk assessment. Therefore, the determination was made to use twice the highest concentration seen in October 1999 as the constant source value.

7.2.4 Discussion of Results

Table 7-2 lists the MT3D-predicted concentrations of COPCs at the risk assessment monitoring points after a 30 year simulation. The monitoring points are shown on Figures 6-1 and 6-3. All COPCs present in GWMU 1 are listed, although many did not show significant quantities of contaminant present in the groundwater after 30 years. In those simulations where the COPC was represented with a constant source, monitoring points just downgradient may remain high, even after 30 years. For example, well 2-251R is approximately 50 feet downgradient of the constant source cell for TCE and the model-predicted concentration at that well effectively mimics that constant source.

For those COPCs with no constant source, advection and dispersion act to spread and dilute the plumes over time. For example, Benzene had an initial maximum concentration of approximately 8,600 µg/L in October 1999. After 30 years with no constant source, decay, or retardation, the maximum concentration predicted by the model was 4,623 µg/L. This is still a high value, but significantly lower than initial concentrations. In some cases (e.g., 1,2,4-Trimethylbenzene), the model-predicted concentration was well below the MCL after 30 years, and construction of an isopleth map was not possible.

For those COPCs which were “risk drivers” (see Chapter 6.0) and for which there was enough mass remaining after 30 years, contour plots were constructed. Figures 7-1 through 7-6 show the

30-year concentration in the USZ and/or LSZ for benzene, 1,2-DCA, PCE, TCE, and chloroform. These figures show a pattern of advection and dispersion that is consistent with the particle tracking flow paths. Generally, sources in GWMU 1 move northwestward, roughly parallel to Crutch Creek. There is clearly a west and southwest component to flow; however, it does not impact COPCs in GWMU 1. It should be noted that the shape, direction, and concentration of contaminants on the 30-year plume maps is greatly influenced by the Kh values used in the model, and in many cases mimic the shape of the zone of 244 ft/day for the LSZ.

With one exception, there were no COPCs present in the lower portions of the LSZ in concentrations above the MCL. For PCE, the model predicted a small zone of approximately 55 µg/L in the LLSZ near well 2-251R (the MCL is 5 µg/L).

7.3 Contaminant Fate and Transport Conclusions

A three-dimensional model of flow in and around GWMU 1 was developed and numerically implemented with Modflow. The model domain covered approximately 3.5 square miles horizontally and extended vertically-downward approximately 400 feet. The model included 5 primary hydrogeologic layers: the HWBZ, the USZ, the USZ-LSZ aquitard, the LSZ, and the LLSZ. The model was calibrated to water levels from 211 monitoring wells measured in October 1999; final calibration statistics showed an average hydraulic head residual of -0.06 feet, an average absolute residual of 0.90 feet, and a residual standard deviation of 1.22 feet. While the hydrologic and geologic complexities of the site presented some numerical challenges, overall the model accurately represents groundwater flow patterns and provides a good basis for continuing with contaminant transport simulations.

Output from the calibrated flow model was used with the contaminant transport code MT3D to predict the fate of 12 COPCs in GWMU 1. The purpose of the transport model was to predict the fate of those COPCs 30 years from the present and to use those data to assess the potential risk to human health and the environment. Results from the MT3D simulations indicate that 1,2-DCA, benzene, TCE, PCE, and chloroform had concentrations above their particular MCL in the USZ and/or LSZ. The predicted concentrations at pre-determined receptor points presented previously in this chapter were provided for the human health and ecological risk assessment for further analysis as presented in Chapter 6.0 of this report.

TABLES

Table 7-1
Chemical Data for Constituents of Potential Concern in GWMU 1
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma

Constituent of Potential Concern	Maximum Contaminant Level (µg/L)	Specific Density ^{b,c}	Solubility Limit (25 C) (µg/L) ^{b,c}	0.01 x Solubility Limit (µg/L) ^d	0.04 x Solubility Limit (µg/L) ^e	Maximum Concentration Detected, October 1999 (USZ; LSZ) (µg/L)	Half-life (yr) ^f	Concentration Used in Model for Constant Source (USZ; LSZ) (µg/L)
Benzene	5	0.87	1800000	18000	72000	310; 8600	2.0	NA
Carbon Tetrachloride	5	1.59	1160000	11600	46400	450; 310	1.0	900; 620
Chloroform	100	1.48	9300000	93000	372000	890; 820	5.0	1780; 1640
1,4 Dichlorobenzene	75	1.25	79000	790	3160	24	1.0	50
1,2-Dichloroethane	5	1.24	8300000	83000	332000	840; 800	1.0	1680; 1600
cis-1,2-Dichloroethene	70	1.2	5000000	50000	200000	540; 71	0.4	1080; 142
Di-n-butylphthalate	3700	1.04	28000	280	1120	8.7; 7.8	0.1	NA
Napthalene	6.2(1)	0.96	31000	310	1240	83	0.7	NA
Tetrachloroethene	5	1.62	400000	4000	16000	96; 34	2.0	192; 68
Trichloroethene	5	1.46	1100000	11000	44000	1200; 2400	4.5	2400; 4800
1,2,4-Trimethylbenzene	12(1)	0.87	57000	570	2280	69	0.2	NA
1,3,5-Trimethylbenzene	1.2(1)	0.86	50000	500	2000	74; 51	0.2	NA

^aPreliminary Remediation Goal as defined by EPA, 2000.

^bMontgomery and Welkom, 1989.

^cMontgomery, 1991.

^dEPA, 1991.

^eChryskopoulos et al., 2000.

^fHoward et al., 1991.

EPA = U.S. Environmental Protection Agency.

LSZ = Lower Saturated Zone.

µg/L = Microgram(s) per liter.

USZ = Upper Saturated Zone.

yr = Year.

Table 7-2

**Model-Predicted Concentrations of COPC after 30 Years at Risk Assessment Monitoring Points
CG037 RFI, GWMU 1B and 1F
Tinker AFB, Oklahoma**

(All results in micrograms per liter)

Well ID	Benzene	Carbon Tetrachloride	Chloroform	1,4-dichlorobenzene	1,2-dichloroethane	cis-1,2-dichloroethene	di-n-butylphthalate	Napthalene	Tetrachloroethylene	Trichloroethene	1,2,4 Trimethylbenzene	1,3,5 Trimethylbenzene
1-144B(2)	0	0.03		0	824.65	0.81	0	0	0.27	33.42	0	0
2-135A(4)	0.11	1.16	29.12	0	282.86	0.13	0	0	0.3	8.39	0	0
2-195B(2)	0.34	0	0	24	0.01	0	0	0	0	0.04	0	0
2-20A(4)	0.02	0.29	0.95	0.01	1.17	9.56	0	0	0.31	0.35	0.15	0
2-20B(2)	0.01	0.12	0.37	0.01	0.38	13.47	0	0	0.24	0.21	0.1	0
2-245(2)	32.57	0.03	0.01	0.11	0.08	0.28	0	0	0.09	5.86	0.06	0.1
2-251R(4)	4623	0.94	0.01	0.02	0.01	46.4	0	0	31.31	2400	46	46.32
2-263B(2)	0.01	0	0	0	0	0	0	0	0	0.01	0	0
2-269B(2)	0	0.01	0	0	0	0.02	0	0	0	0.06	0	0
2-325A(4)	0	0.03	0.02	0	0	0.02	0	0	0	1.04	0	0
2-325B(2)	0	0.01	0.01	0	0	0.01	0	0	0	0.42	0	0
2-344B(2)	0	0	0	0	0	0	0	0	0	0.06	0	0
2-347B(2)	0	0	0	0	0	0	0	0	0	0.24	0	0
2-409B(2)	0	0.09	0.21	0	8.54	1.66	0	0	0.21	27.84	0	0
2-67A(2)	2.33	0.82	8.01	0	2.95	1.17	0	0	0.81	0.6	0	0
2-68A(2)	0.35	1.93	423.87	0	14.97	0.18	0	0	1.23	0.86	0	0.01
3-328A(4)	0.02	0	0	0	0.13	11.71	0	0	0.01	11.83	0	0.04
40A(5)	0	0	0	0	0	0	0	0	0	0	0	0
40BR(2)	0	0	0	0	0	0	0	0	0	0	0	0
40CR(4)	0	0	0	0	0	0	0	0	0	0	0	0
68A(4)	0.55	0.06	0.01	0	0.06	0.03	0	0	0.02	0.62	0	0
69(2)	1.71	0.05	0.01	0	0.09	0.09	0	0.01	0.02	1.01	0	0
CR-1(2)	0.13	0.02	0	0	0.01	0.01	0	0	0	0.16	0	0
CR-2(2)	0	0	0	0	0	0	0	0	0	0.15	0	0
CR-5(2)	0	0.01	0.02	0	0.18	0.04	0	0	0	0.57	0	0
CR-6(1)	0	0.04	1.28	0	1.14	1.02	0	0	0.05	17.47	0.01	0
CR-7(1)	0	0	0.06	0	0.07	0.52	0	0	0.02	0.03	0.01	0
DC-20(1)	0	0	0	0	0	0	0	0	0	0	0	0
DC-20(2)	0	0	0	0	0	0	0	0	0	0	0	0
DC-20(3)	0	0	0	0	0	0	0	0	0	0	0	0
DC-20(4)	0	0	0	0	0	0	0	0	0	0	0	0
DC-20(5)	0	0	0	0	0	0	0	0	0	0	0	0
K-1(2)	0.99	0.03	0	0	0.05	0.05	0	0	0.01	0.55	0	0.03
K-2(2)	0.43	0.01	0	0	0.02	0.02	0	0	0.01	0.25	0	0.01
K-3(2)	0.93	0.02	0	0	0.03	0.03	0	0	0.01	0.37	0	0.01
K-4(2)	1.26	0.03	0	0	0.04	0.03	0	0	0.01	0.44	0	0.01
K-5(2)	0.24	0.01	0	0	0.01	0.01	0	0	0	0.09	0	0
K-6(1)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
K-6(2)	0	0	0	0	0	0	0	0	0	0.01	0	0
K-7(2)	0	0	0	0	0	0	0	0	0	0.72	0	0
KT-1(2)	0	0	0	0	0	0.01	0	0	0	0.04	0	0
KT-2(2)	0	0	0	0	0	0.01	0	0	0	0.04	0	0
WS-1(1)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
WS-1(2)	0	0	0	0	0	0	0	0	0	0	0	0
WS-1(3)	0	0	0	0	0	0	0	0	0	0	0	0
WS-1(4)	0	0	0	0	0	0	0	0	0	0	0	0
WS-1(5)	0	0	0	0	0	0	0	0	0	0	0	0

Table 7-2

**Model-Predicted Concentrations of COPC after 30 Years at Risk Assessment Monitoring Points
 CG037 RFI, GWMU 1B and 1F
 Tinker AFB, Oklahoma**

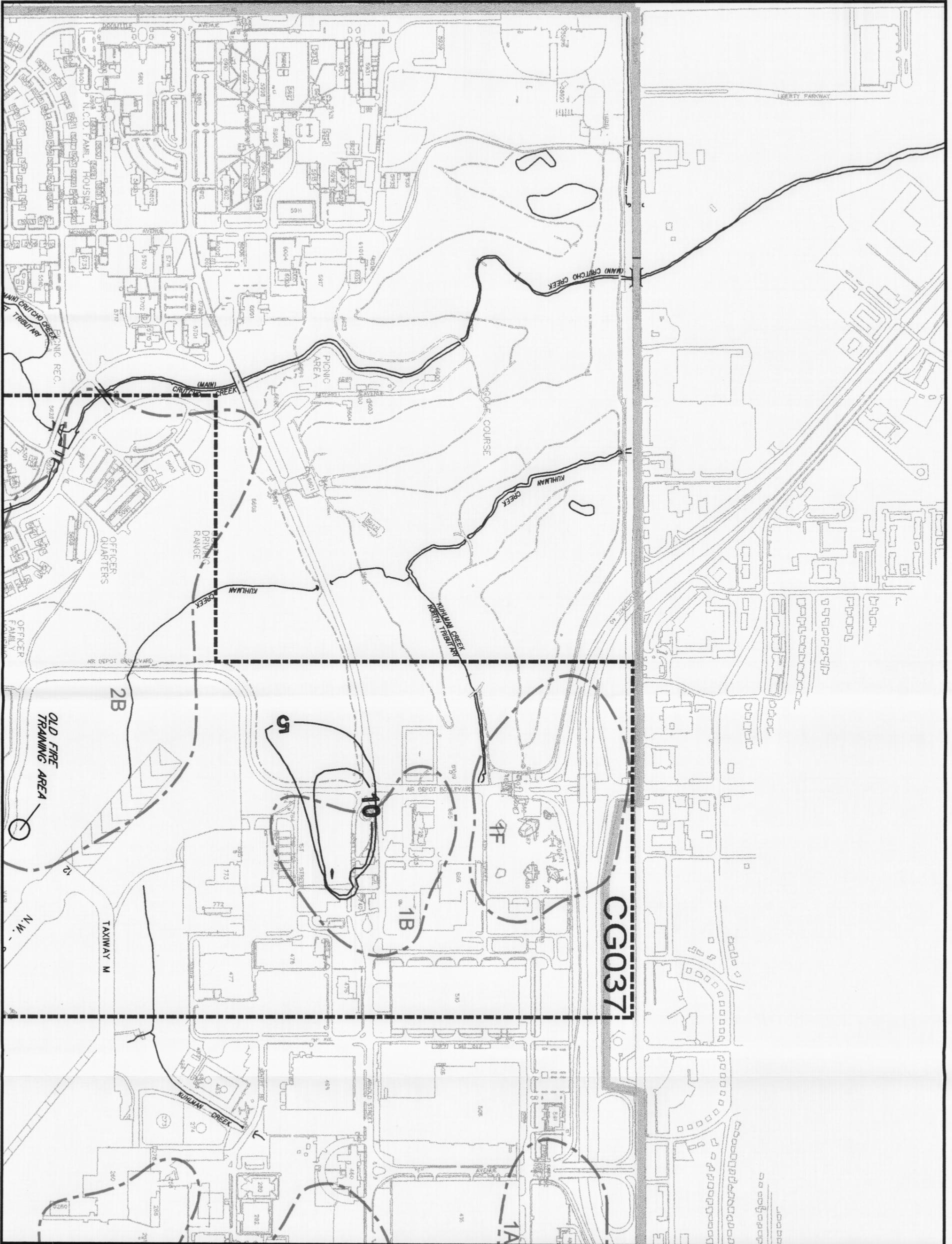
(All results in micrograms per liter)

Well ID	Benzene	Carbon Tetrachloride	Chloroform	1,4-dichlorobenzene	1,2-dichloroethane	cis-1,2-dichloroethene	di-n-butylphthalate	Napthalene	Tetrachloroethylene	Trichloroethene	1,2,4 Trimethylbenzene	1,3,5 Trimethylbenzene
WS-2(1)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
WS-2(2)	0	0	0	0	0	0.01	0	0	0	0.01	0	0
WS-2(3)	0	0	0	0	0	0.01	0	0	0	0.02	0	0
WS-2(4)	0	0.01	0.01	0	0	0.03	0	0	0	0.11	0	0
WS-2(5)	0	0	0	0	0	0.01	0.01	0	0	0.03	0	0
WS-3(1)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
WS-3(2)	11.75	0.01	0.01	0.02	0.08	0.14	0	0	0.05	2.57	0	0.07
WS-3(3)	23.27	0.03	0.02	0.08	0.26	0.32	0	0.01	0.11	5.64	0.01	0.15
WS-3(4)	75.83	0.13	0.1	0.43	1.13	1.21	0	0.03	0.39	20.47	0.05	0.47
WS-3(5)	35.77	0.08	0.04	0.06	0.31	0.57	0.01	0.02	0.19	9.26	0.05	0.25
WS-30(1)	0	0	0	0	0	0	0	0	0	0	0	0
WS-30(2)	0	0	0	0	0	0	0	0	0	0	0	0
WS-30(3)	0	0	0	0	0	0	0	0	0	0.05	0	0
WS-30(4)	0	0.01	0.01	0	0	0.01	0	0	0	0.22	0	0
WS-30(5)	0	0	0	0	0	0	0	0	0	0.1	0	0
WS-31(1)	0	0	0	0	0	0	0	0	0	0.18	0	0
WS-31(2)	0	0.01	0.01	0	0	0.01	0	0	0	0.45	0	0
WS-31(3)	0	0.08	0.07	0	0	0.07	0	0	0	3.37	0	0
WS-31(4)	0	0.52	0.43	0	0	0.45	0	0	0	20.97	0	0
WS-31(5)	0	0.24	0.21	0	0	0.21	0	0	0	10.31	0	0
WS-4(1)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
WS-4(2)	0	0	0	0	0	0	0	0	0	0.01	0	0
WS-4(3)	0	0	0	0	0	0	0	0	0	0.04	0	0
WS-4(4)	0.03	0	0	0	0	0	0	0	0	0	0	0
WS-4(5)	0.01	0	0	0	0	0	0	0	0	0.08	0	0
WS-5(1)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
WS-5(2)	0	0.02	0.02	0	0.14	0	0	0	0.13	0.38	0	0
WS-5(3)	0	0.01	0.02	0	0.16	0	0	0	0.24	0.92	0	0
WS-5(4)	0	0	0	0	0.02	0	0	0	0.02	3.51	0	0
WS-5(5)	0	0	0	0	0	0	0	0	0	1.37	0	0
WS-7(1)	0	0	0	0	0	0	0	0	0.33	0	0	0
WS-7(2)	0	0.01	0	0	0	0	0	0	0.6	0	0	0
WS-7(3)	0	0.01	0	0	0	0	0	0	0.57	0	0	0
WS-7(4)	0	0.01	0	0	0	0	0	0	0.07	0.01	0	0
WS-7(5)	0	0	0	0	0	0	0	0	0.01	0	0	0

Note: Water supply (WS) wells are screened only in the producing zone. Their locations as they pass through the other zones are listed for risk assessment purposes only.

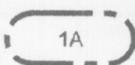
- (1) Hennessey Water Bearing Zone.
- (2) Upper Saturated Zone.
- (3) Upper Saturated Zone-Lower Saturated Zone Aquitard.
- (4) Lower Saturated Zone.
- (5) Lower Lower Saturated Zone.
- 1 = Dry Cell.

FIGURES



EXPLANATION

- LINE OF EQUAL CONCENTRATION ($\mu\text{g/L}$)
- GROUNDWATER IRP SITE
- TINKER AIR FORCE BASE PROPERTY LINE



APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



DRAWN BY:	CFB
START DATE:	10/15/01
REVISED BY:	
LAST REV:	/ /
INITIATOR:	MG

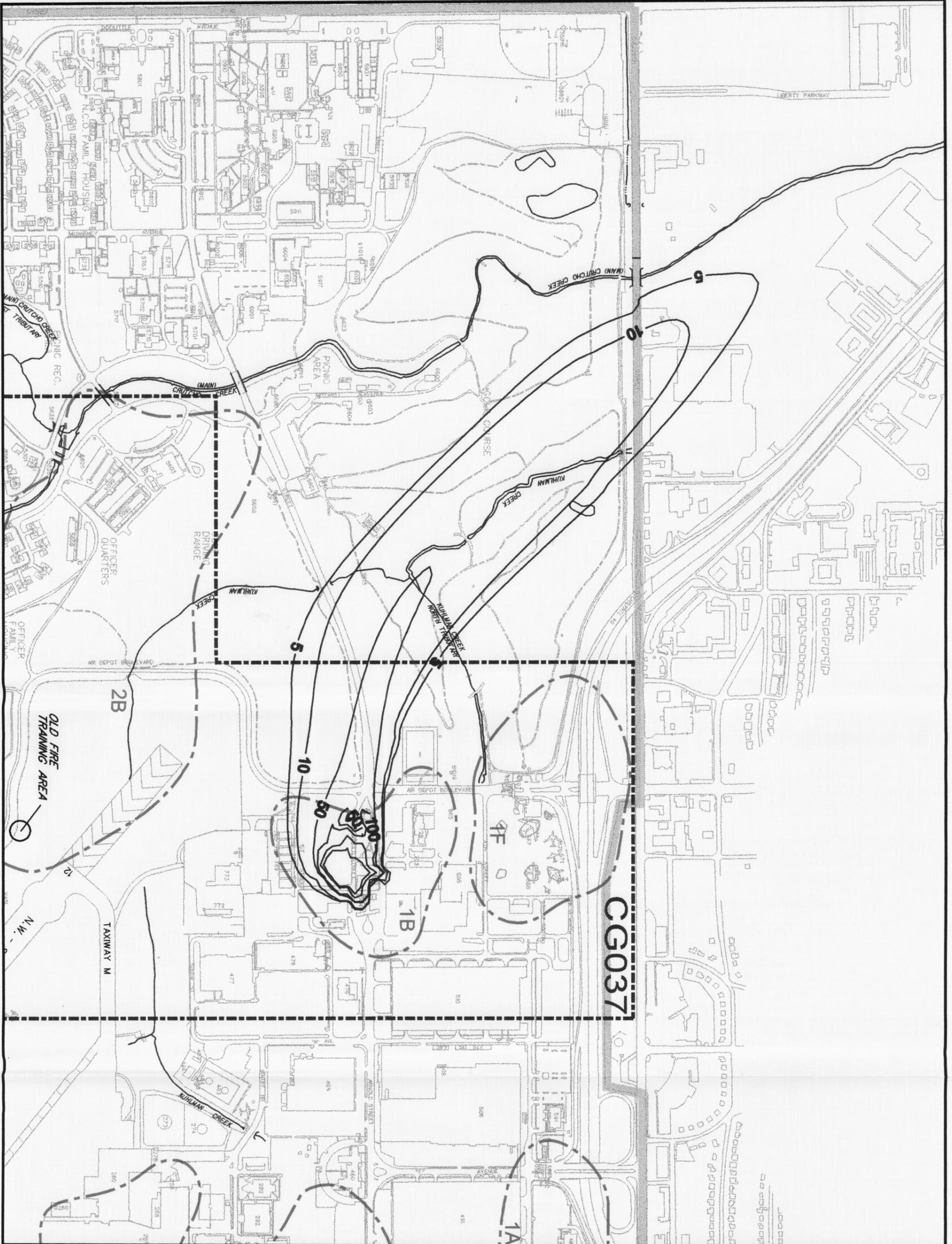
RESULTS OF 30-YEAR CONTAMINANT TRANSPORT MODEL FOR BENZENE IN THE USZ CG037 RFI GWMU 1B AND 1F

PROJ. NO. 799270

FIG. 7-1

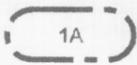
PREPARED FOR

UNIQUE 799270-B75

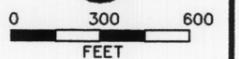


EXPLANATION

- 5—** LINE OF EQUAL CONCENTRATION ($\mu\text{g/L}$)
- GROUNDWATER IRP SITE
- ▬** TINKER AIR FORCE BASE PROPERTY LINE



APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



DRAWN BY: CFB
START DATE: 10/15/01
REVISED BY:
LAST REV: / /
INITIATOR: MG

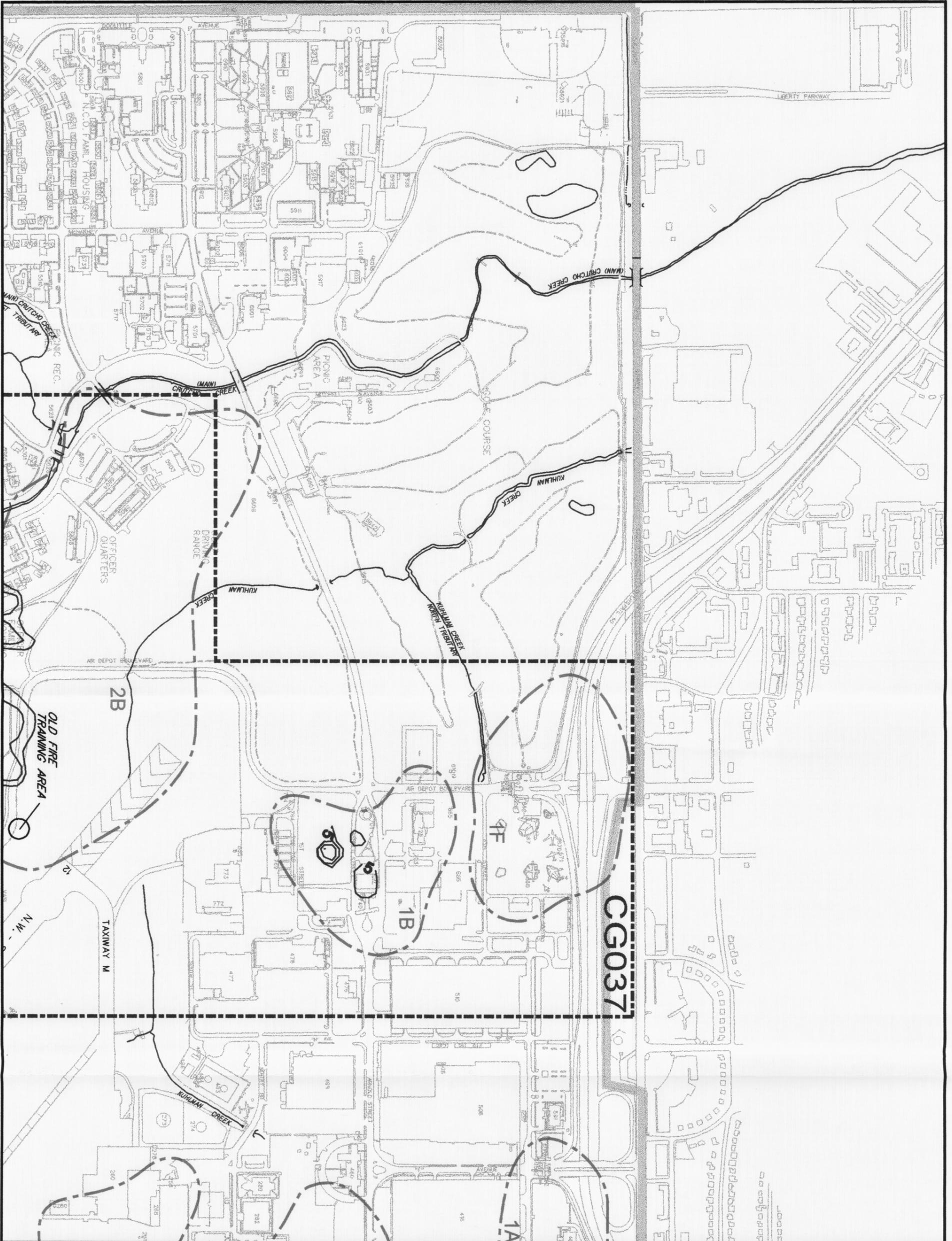
RESULTS OF 30-YEAR CONTAMINANT TRANSPORT MODEL FOR BENZENE IN THE LSZ CG037 RFI GWMU 1B AND 1F

PROJ. NO. 799270

FIG. 7-2

PREPARED FOR

UNIQUE 799270-B76

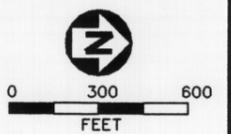


EXPLANATION

- LINE OF EQUAL CONCENTRATION (µg/L)
- GROUNDWATER IRP SITE
- TINKER AIR FORCE BASE PROPERTY LINE



APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



DRAWN BY: CFB
START DATE: 10/15/01
REVISED BY:
LAST REV: / /
INITIATOR: MG
INT. DATE: 10/15/01

RESULTS OF 30-YEAR CONTAMINANT TRANSPORT MODEL FOR 1,2-DICHLOROETHANE IN THE LSZ CG037 RFI GWMU 1B AND 1F

PREPARED FOR TINKER AIR FORCE BASE OKLAHOMA CITY OKLAHOMA

PROJ. NO. 799270

FIG. 7-3

UNIQUE 799270-B77



EXPLANATION

- LINE OF EQUAL CONCENTRATION ($\mu\text{g/L}$)
- - - -** GROUNDWATER IRP SITE
- ▬** TINKER AIR FORCE BASE PROPERTY LINE
- APPROXIMATE LOCATION OF 50 FOOT SQUARE CONSTANT SOURCE CELL IN THE HYDROGEOLOGIC MODEL

- 1A** APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER

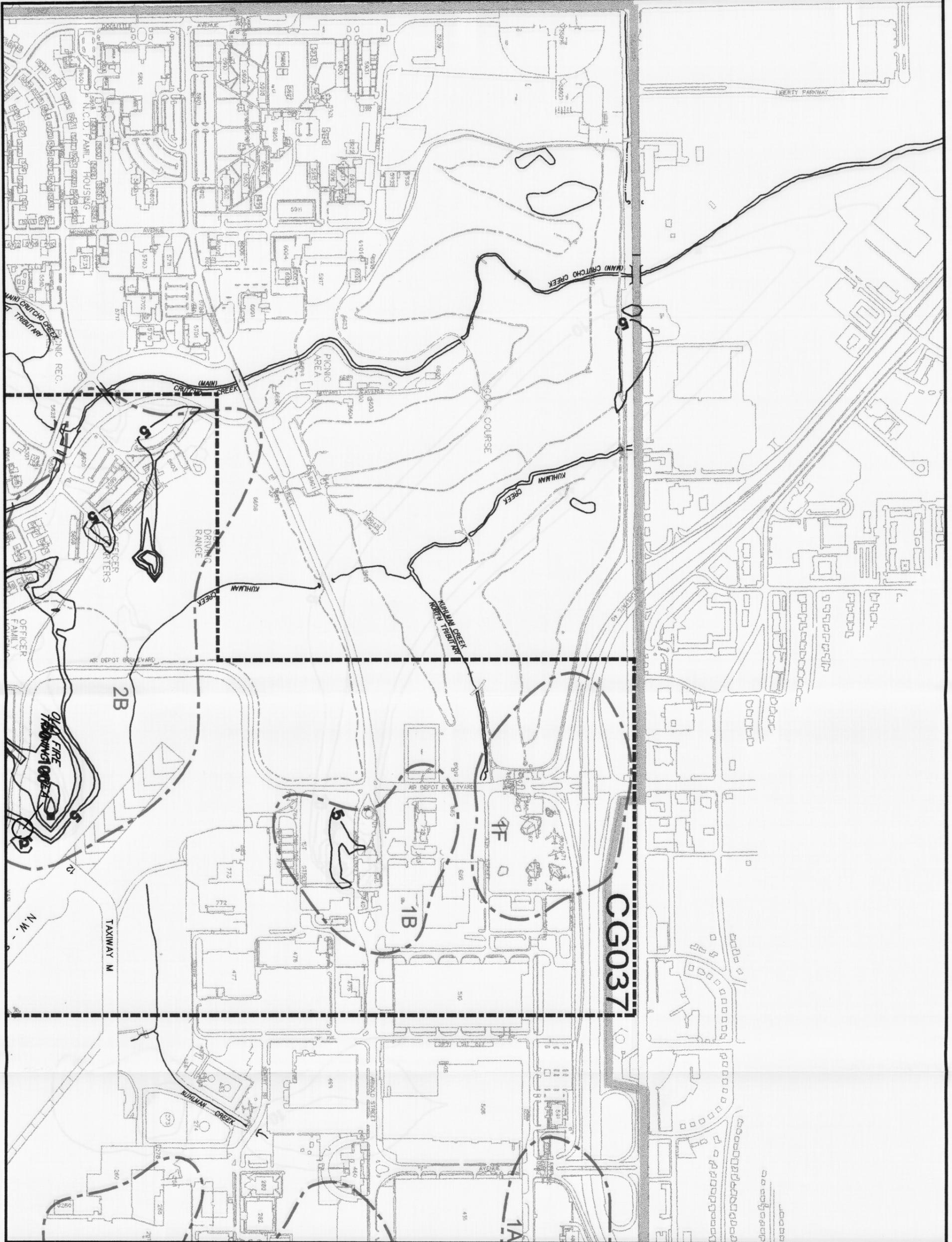


DRAWN BY: CFB
START DATE: 10/15/01
REVISED BY:
LAST REV: / /

RESULTS OF 30-YEAR CONTAMINANT TRANSPORT MODEL FOR TETRACHLOROETHENE IN THE LSZ CG037 RFI GWMU 1B AND 1F

PROJ. NO. 799270

FIG. 7-4



EXPLANATION

- LINE OF EQUAL CONCENTRATION ($\mu\text{g/L}$)
- GROUNDWATER IRP SITE
- TINKER AIR FORCE BASE PROPERTY LINE
- APPROXIMATE LOCATION OF 50 FOOT SQUARE CONSTANT SOURCE CELL IN THE HYDROGEOLOGIC MODEL

- APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



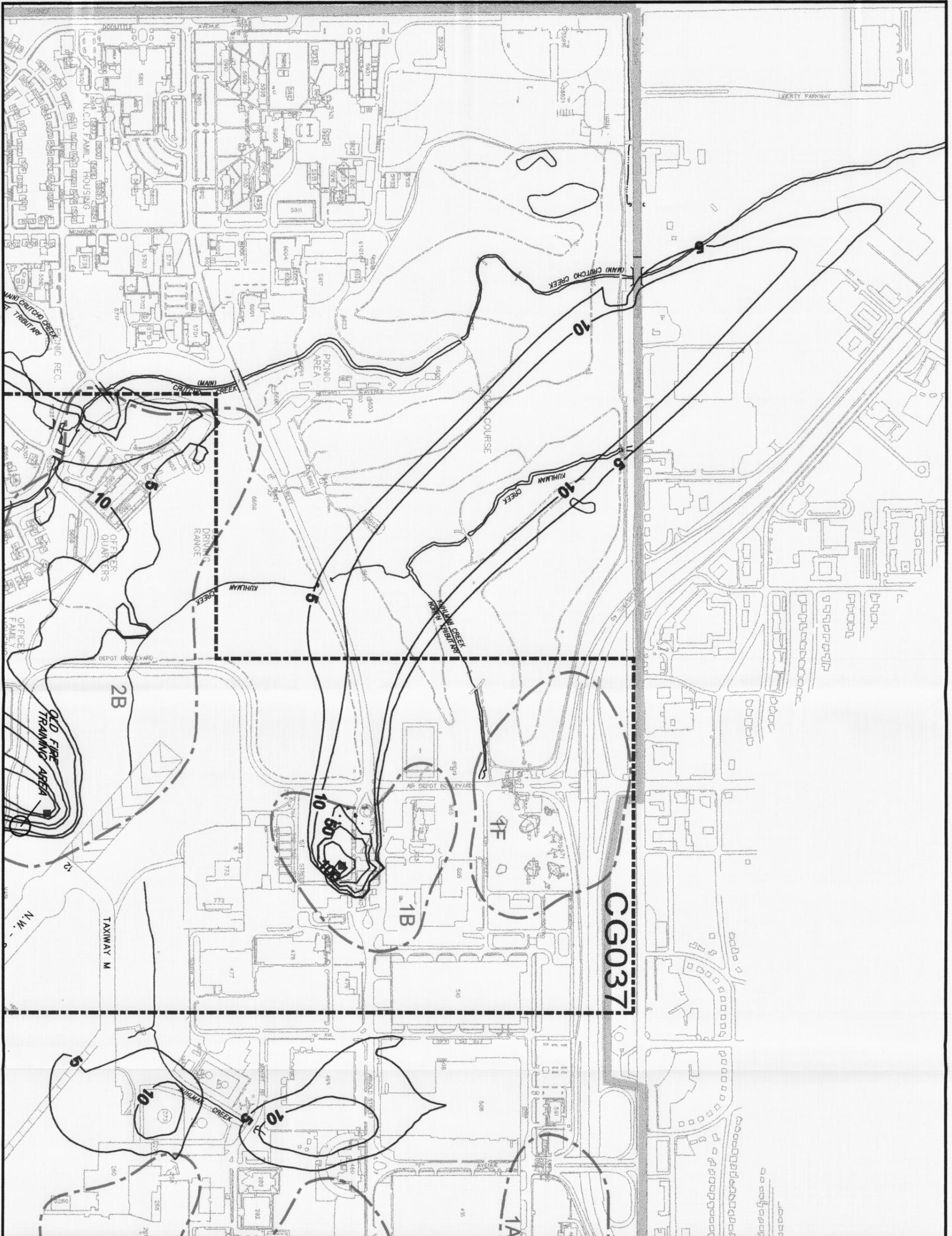
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START DATE: 10/15/01
REVISED BY:
LAST REV: / /
INITIATOR: MG

RESULTS OF 30-YEAR CONTAMINANT TRANSPORT MODEL FOR TRICHLOROETHENE IN THE USZ CG037 RFI GWMU 1B AND 1F

PROJ. NO. 799270

FIG. 7-5

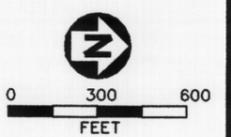
PREPARED FOR



EXPLANATION

- LINE OF EQUAL CONCENTRATION (µg/L)
- GROUNDWATER IRP SITE
- TINKER AIR FORCE BASE PROPERTY LINE
- APPROXIMATE LOCATION OF 50 FOOT SQUARE CONSTANT SOURCE CELL IN THE HYDROGEOLOGIC MODEL

- APPROXIMATE BOUNDARY OF GROUNDWATER MANAGEMENT SUB-UNIT LOCATION AND SUB-UNIT IDENTIFICATION NUMBER



DRAWN BY:	CFB
START DATE:	10/15/01
REVISED BY:	
LAST REV:	/ /
INITIATOR:	MG
INT. DATE:	10/15/01

RESULTS OF 30-YEAR CONTAMINANT TRANSPORT MODEL FOR TRICHLOROETHENE IN THE LSZ CG037 RFI GWMU 1B AND 1F

PREPARED FOR
TINKER AIR FORCE BASE, OKLAHOMA CITY, OKLAHOMA

PROJ. NO.	799270
FIG.	7-6
UNIQUE NUMBER	799270-B80

8.0 Summary and Conclusions

The following sections summarize the conclusions and recommendations provided in previous chapters of this report.

8.1 Characterization

Based on the analysis of data and observations made in the nature and extent of contamination, the following conclusions are made:

- The nature and extent of contamination of CG037 associated with GWMU 1 has been defined, particularly the lateral extent. The vertical extent of VOC contamination is less well-characterized; however, there is no evidence that contamination has moved significantly into the lower portion of the LSZ at this time.
- Concentrations of major COPCs, especially fuel-related compounds and TCH, are generally higher in the LSZ than in the USZ in the area around GWMU 1B. This phenomenon is explained by the presence of a zone of increased vertical hydraulic conductivity in the vicinity of the BX Service Station in the USZ-LSZ aquitard. A vacuum enhanced pumping remediation system is currently in place in this vicinity, and was expanded in 1998 and 1999 to include additional extraction wells in the LSZ.
- Temporal trend analysis indicates that although reductive dechlorination is an ongoing process at most locations, little to no CAH mass loss is observed. This constant, or at some locations increasing, total CAH mass suggests that there may be a continuing source that is contributing solvents to the groundwater concurrently with degradation. Three potential sources include desorption of solvents from saturated sediments, a continuing source of solvents in overlying sediments, or the presence of a DNAPL within the plume.

At GWMU 1, there is little evidence that DNAPL is present, other than the limited degree of reduction of chlorinated solvents and the slight increase in total chlorinated hydrocarbons mass. As discussed above, there is a zone of increased vertical hydraulic conductivity in the area around GWMU 1B in the USZ-LSZ aquitard that would serve as a conduit for the downward migration of dissolved constituents. However, a DNAPL or the presence of a continuing source of hydrocarbon contamination from the overlying soils cannot be ruled out based on the existing data.

- Concentrations of TCH are significantly lower in GWMU 1F than in -1B, and are generally confined to the USZ. Fuel-related compounds were not detected above MCLs in groundwater at GWMU 1F.

- Groundwater at GWMU 1B and 1F contains slightly elevated concentrations of some metals. However, in every case where elevated metals were observed, significantly elevated turbidity of the sample was also observed. It has been shown that there is a strong correlation between increased concentrations of metals in samples with high turbidity, caused by the tendency of some metals to adsorb to clay and iron oxide particles entrained in the water sample (IT, 1999c). In addition, it has been shown that elevated concentrations of nickel and chromium are related to issues associated with corrosion of steel well screens, and are not indicative of Base activities that contributed to contamination (IT, 1999d). There is no known activity at the Base or suspected source for elevated concentrations of the other metals, such as barium and arsenic.

8.2 **Baseline Risk Assessment**

Based on the data and analysis presented in the baseline risk assessment, both for potential human health and ecological receptors, the following conclusions are made:

- **Current Risk and Hazard.** Cancer risk, based on the conservative estimates described in Section 6.1 of this report, is in excess of 10^{-4} in the GWMU 1B plume, driven by benzene. The GWMU 1F plume does not exceed cancer risk of 10^{-4} . Carcinogens were not detected in any water supply well within the study area.

Noncancer hazard exceeds 1.0 in both GWMU 1B and 1F. Hazard in GWMU 1B is driven by benzene and TCE; hazard in GWMU 1F is driven by chloroform and TCE. Noncarcinogens were not detected in any water supply well within the study area. Although calculations show that risk and hazard exceed established values, there is no current exposure pathway for on-site workers or offsite residents.

- **Future Risk and Hazard.** Future risk at compliance points was estimated by examining modeled groundwater concentrations at 30 years for the locations of on-site water supply wells, and in wells at the Base boundary. As discussed in Chapter 7.0 of this report, conservative assumptions made during the modeling process resulted in a conservative estimate of risk. Residential risk downgradient from GWMU 1 in the vicinity of CG037 is significantly below 10^{-4} at well 69 (USZ well adjacent to Kuhlman Creek at the Base boundary), and slightly below 10^{-4} at well 68 (LSZ well adjacent to Crutch Creek at the Base boundary). Future risk to residents from LSZ groundwater at the Base boundary is less than 10^{-4} , and no constituents of concern are predicted in Base boundary wells in units below the LSZ. In addition, no residential wells are known to be screened in the USZ in the immediate vicinity of Tinker AFB. Future risk to on-site workers indicates that no potential exposure wells (i.e., water supply wells) exhibit cancer risk greater than 10^{-4} in the 30 year time period modeled.

Future hazard to residents downgradient from GWMU 1 from USZ groundwater is less than 1.0. Hazard is less than 1.0 in LSZ wells downgradient of GWMU 1 in the

vicinity of CG037, and no constituents of concern are predicted in Base boundary wells in units below the LSZ. In addition, no off-site water supply wells are known to be screened in the USZ in the vicinity of Tinker AFB. Future hazard to on-site workers is below 1.0 for all potential exposure points with the exception of water from water supply well WS-3 (HI = 3.8). However, WS-3 is an inactive well; therefore, the potential exposure pathway is not complete.

- Cancer risk to the trespasser and maintenance worker for surface water in the vicinity of CG037 associated with GWMU 1 were estimated. Cancer risk to both receptors is less than 10^{-8} ; noncancer hazard is less than 10^{-4} .
- The results of the ecological risk assessment showed no HQs exceeding 1 for the receptor/chemical combinations for which HQs could be determined. HQs could not be determined for 55 of the 120 receptor/chemical combinations, principally due to the lack of toxicological data for plants and birds. However, because of the conservatism associated with the calculated HQs in the assessment and the low values of the majority of these HQs, the weight of evidence indicates that it is highly likely that the chemical contaminants in CG037 will have a negligible contribution to the chemical exposures in and subsequent risk to ecological receptors along these creeks over the next 30 years at least, and probably well beyond that time frame.

8.3 Contaminant Fate and Transport

A groundwater hydrologic model was prepared and used to estimate contaminant fate and transport for the CG037 site. The following conclusions from the contaminant fate and transport model are made:

- Low levels of contamination from GWMU 1B are predicted to reach USZ (well 69) and LSZ (well 68) receptor points at the Base boundary within the 30 year time frame calculated by the model. The primary contaminants that will reach the Base boundary include benzene and daughter products of TCE. These predictions assume that no active effort is made during the 30-year time frame to halt or reduce the migration.
- Contamination from GWMU 1B and 1F are predicted to move in a west-northwest direction, initially towards Crutcho and Kuhlman Creeks, then northwest roughly parallel to Crutcho Creek towards the boundary of the Base, primarily in the LSZ. These predictions assume that no active effort is made during the 30-year time frame to halt or reduce the migration.
- Particle tracking calculations performed during the modeling exercise indicate a preferred downward vertical migration pathway from the LSZ toward the PZ over time, followed by migration to the northwest coincident with Crutcho Creek. It should be noted that particles could not continue to move vertically into the LSZ-PZ aquitard due to the absence of that unit in the hydrologic model.

8.4 Recommendations

The following recommendations are made for the portions of the RFI at IRP site CG037 within GWMU 1B and GWMU 1F:

- Continue monitoring groundwater wells in the vicinity of water supply wells in GWMU 1, particularly the LSZ wells to ensure that the quality of water remains acceptable above the water supply well screened intervals in the PZ.
- Analyze samples collected from within GWMU 1B for the full Target Analyte List to enable more accurate determinations of metals background issues, to provide additional data to support the conclusion that metals concentrations in samples are associated with turbidity and suspended solids, and continued monitoring of well-screen degradation issues associated with chromium and nickel.
- Due to elevated risk and hazard in the mass centers of plumes at GWMU 1B and GWMU 1F, and the potential for contamination to migrate vertically toward the PZ, source control is recommended for consideration in a corrective measures study.
- Contaminants have not been detected at the receptor monitoring wells downgradient from GWMU 1B and 1F; therefore, there is no current risk or hazard from exposure to groundwater at these points. Future risk and hazard at the downgradient receptor wells near the Base boundary are also within acceptable levels; therefore, remediation techniques focused on capture of the leading edge of the plume may not be warranted.
- It is recommended that the inactive water supply well WS-3 be properly plugged and abandoned to preclude it serving as a possible conduit for contaminant migration from the USZ and LSZ to the PZ.

9.0 References

American Society for Testing and Materials (ASTM), 1994, "Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information," *Standard Guide D5490-93*, prepared by Subcommittee D18.21 on Groundwater and Vadose Zone Investigations, ASTM, West Conshohocken, Pennsylvania.

Anderson, M.P., and W.W. Woessner, 1992, *Applied Groundwater Modeling, Simulation of Flow and Advective Transport*, Academic Press, San Diego, California.

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