U.S. Army Corps of Engineers
Fort Worth District

Final Conceptual Site Model

Bosque and Leon River Watersheds Study

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MWH
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ACROYNMS

AF	Acre-feet
BRA	Brazos River Authority
CCL	Contaminant Candidate List
CDHS	California Department of Health Services
cfs	Cubic feet per second
Cl	Chlorine
ClO_4^-	Perchlorate
CLP	Contract Laboratory Program
cm	Centimeter
COPC	Chemical of Potential Concern
CRQL	Contract Required Quantitation Limit
CSF	Cancer Slope Factor
CSM	Conceptual Site Model
DWEL	Drinking Water Equivalent Level
fbgs	feet below ground surface
FETAX	Frog Embryo Teratogenesis Assay: *Xenopus*
gpd/ft	gallons per day per foot
g/cm^3	gallons per cubic centimeter
$HCLO_4$	Perchloric acid
HEE	Human Equivalent Exposure
IC-50	Inhibitory Concentration in 50% of test subjects
ISM	Interim Stabilization Measures
K	Hydraulic conductivity
K^+	Potassium
LHAAP	Longhorn Army Ammunition Plant
LOAEL	Lowest Observed Adverse Effect Level
MCL	Maximum Contaminant Level
MDL	Method Detection Limit
mg/kg-day	milligrams per kilogram per day
µg/L	micrograms per liter
mm	Millimeter
MRL	Method Reporting Limit
MSDS	Materials Safety Data Sheets
MW	Montgomery Watson
MWH	Montgomery Watson Harza
Na^+	Sodium
NDEP	Nevada Division of Environmental Protection
NH_4^+	Ammonia
NIS	Sodium (Na+)-Iodide (I-) Symporter
NOAEL	No Observed Adverse Effect Level
NWIRP	Navel Weapons Industrial Reserve Plant
O	Oxygen
PBPK	Physiologically-Based Pharmacokinetic

ppb	Parts per billion
PQL	Practical Quantitation Limit
RAGS	Risk Assessment Guidance for Superfund
RCRA	Resource Conservation and Recovery Act
RfD	Reference dose
RRR	Risk Reduction Rule
SAV	Secondary Acute Value
SCV	Secondary Chronic Value
SDWA	Safe Drinking Water Act
SRB	Solid Rocket Boosters
T3	Thyroxine (hormone controlled by the thyroid, pituitary gland and hypothalamus)
T4	Triiodothyronine (hormone controlled by the thyroid, pituitary gland and hypothalamus)
TDS	Total dissolved solids
TIEHH	The Institute of Environmental and Human Health
TNRCC	Texas Natural Resource Conservation Commission
TPDES	Texas Pollution Discharge Elimination System
TPWD	Texas Parks and Wildlife Department
TRRP	Texas Risk Reduction Program
TWDB	Texas Water Development Board
UCMR	Unregulated Contaminants Monitoring Rule
USACE	United States Army Corps of Engineers
USAF	United States Air Force
USEPA	United States Environmental Protection Agency

1.0 INTRODUCTION

Congress has directed the U.S. Army Corps of Engineers Fort Worth District (USACE) to assess the impact of perchlorate releases associated with the former Naval Weapons Industrial Reserve Plant (NWIRP McGregor) at McGregor, Texas. Lake Belton and Lake Waco water quality may be impacted by releases of perchlorate within their watersheds. To address this impact, the USACE is conducting the Bosque and Leon River Watersheds Study. The USACE has assembled an integrated, multi-disciplinary project team to address this issue as part of the Bosque and Leon River Watersheds Study. This conceptual site model (CSM) was prepared for USACE by its environmental contractor, Montgomery Watson Harza, through authorization provided in contract DACW57-97-D-004, Task Order DY01.

1.1 Project History and Overview

Because the primary sources of perchlorate contamination within the Bosque and Leon River watersheds are believed to result from former activities at NWIRP McGregor, a brief historical summary of this facility is presented in Section 1.1.1. The goals and activities of the USACE and its study team in evaluating perchlorate releases to the Bosque and Leon River watersheds are described in Section 1.1.2.

1.1.1 NWIRP McGregor History

Historical use and summaries of the situation at former NWIRP McGregor are also included in the *Perchlorate Monitoring Plan* (MW, 1999) and *Community Relations Plan* (USACE, 2001a).

The property referred to as former NWIRP McGregor was originally established by the U.S. Army Ordnance Corps in 1942 on 18,000 acres as the Bluebonnet Ordnance Plant. During this tenure, it included facilities run by National Gypsum, of Buffalo, New York, to load explosives into bomb bodies during World War II. Production at this facility ceased at the conclusion of the war and the facility was formally closed in 1946.

After World War II, changes in ownership of the property occurred often and included sales to private parties and to Texas A&M University. In 1952, the U.S. Air Force acquired 11,450 acres of the original 18,000 acres and named the area U.S. Air Force Plant 66. Phillips Petroleum Company oversaw the production of jet-assisted take-off boosters during this time period, until the U.S. Air Force expropriated the property to the U.S. Navy in 1966.

After the transfer from the U.S. Air Force, the property was renamed the Naval Weapon Industrial Reserve Plant, McGregor, Texas. In 1972, 70 acres were transferred to the McGregor School District, 33 acres surrounding the wastewater treatment plant were transferred to the City of McGregor, and 1,600 acres were sold to private parties.

Currently, several thousand acres are leased for agriculture. From 1978 to 1995, the Hercules Corporation produced solid propellant rocket motors at NWIRP McGregor for a variety of missiles. Production of these weapons ceased in 1995, when Hercules Corporation was purchased by Alliant Techsystems, Inc.

In 1998, The City of Waco collected 10 samples from selected surface water locations located outside the NWIRP McGregor facility that indicated the presence of perchlorate, presumably related to activities at this facility. This presumption resulted from the fact that a major component of the solid propellant of missiles and rockets manufactured at NWIRP McGregor was ammonium perchlorate. Throughout the remainder of this document “perchlorate” will be used to indicate the perchlorate ion, (ClO_4^-).

More recently, in 1999, the Navy collected additional samples from monitoring wells, springs, and Lake Belton. Perchlorate was detected at a total of 19 sites with concentrations of perchlorate in these samples ranging from approximately 2 to 3300 parts per billion (ppb) (EnSafe Inc., 1999a).

Analytical results on a sample taken on June 10, 1999, at the City of Gatesville’s intake structure on Lake Belton indicate the presence of perchlorate at a reported concentration of 6.0J ppb (subject to validation). However, perchlorate was not detected in subsequent samples taken on June 24, 1999. Perchlorate has also been detected in samples taken from Lake Waco (EnSafe Inc., 1999a).

Investigational and remediation activities are ongoing at the site. As cleanup of NWIRP McGregor proceeds, portions of the property deemed safe for commercial/industrial redevelopment are being transferred to the City of McGregor, Texas, by Congressional order. As of June 2001, approximately 3,500 acres had been transferred to the City of McGregor.

1.1.2 USACE Project Overview

The USACE has assembled an integrated, multi-disciplinary project team consisting of the USACE, Brazos River Authority (BRA), The Institute of Environmental and Human Health at Texas Tech University (TIEHH), Montgomery Watson Harza (MWH), the US Environmental Protection Agency (USEPA), the Texas Natural Resources Conservation Commission (TNRCC), the City of Waco, and the City of Killeen to evaluate potential human and environmental exposure to perchlorate in the Lake Belton and Lake Waco study area. The primary goal of the USACE, and the study team, is to evaluate potential human and environmental exposures to perchlorate in the Lake Waco and Lake Belton study area. To meet this goal, the USACE and its study team are currently engaged in a number of investigations including watershed characterization, modeling, and analysis to determine how perchlorate migrates through the environment; and biological characterization and risk assessment to evaluate potential exposures and risks to public health and the environment. The CSM presented in this report is one component of these investigations.

1.2 Objectives and Scope

This CSM is intended to provide a preliminary conceptual understanding of potential human and environmental exposures to perchlorate in the Lake Belton and Lake Waco study area. Perchlorate, because of its high mobility and persistence in the environment, may pose an impact on local drinking water supplies. The U.S. Navy's environmental contractor has identified various concentrations of perchlorate outside the boundaries of the NWIRP McGregor site in the Lake Waco and Lake Belton watersheds.

This CSM comprehensively incorporates available information on sources of perchlorate contamination and release, the surface hydrology and hydrogeological characteristics of the Bosque and Leon River watersheds, the nature of perchlorate fate and transport, potential pathways of perchlorate migration within the study area, and the human receptors and environmental resources that may receive exposures to perchlorate. This information will be used to identify data gaps in the current understanding of perchlorate migration and exposure within the study area, and to identify additional investigation activities aimed at filling such data gaps.

1.3 Report Organization

The potential for both human and environmental exposure to perchlorate is analyzed in the subsequent sections of the CSM. Complete exposure pathways and effects of exposure are described in detail for potential receptors. The information presented in the CSM is organized as follows:

Section 1.0 Introduction. Describes the purpose and scope of the CSM, and summarizes its organization

Section 2.0 Environmental Setting. Provides a summary of the physical characteristics of the study area.

Section 3.0 Investigation History. Summarizes previous and current investigations of former NWIRP McGregor and the Bosque and Leon River watersheds.

Section 4.0 Perchlorate Fate and Transport. Summarizes the physical, chemical, and biological characteristics of perchlorate that affects its fate and transport within the environment.

Section 5.0 Hydrologic Conceptual Model. Describes the hydrology and water budgets of the rivers and lakes within the Bosque and Leon River watersheds.

Section 6.0 Exposure Assessment. Identifies the human receptors and ecological resources within the study area, and describes potential pathways of exposure to perchlorate.

Section 7.0 Data Gaps. Identifies potential data gaps and associated uncertainties.

Section 8.0 Conclusions and Recommendations. Provides conclusions of the CSM report, and makes recommendations for further activities within the study area.

Section 9.0 References. Lists the sources cited in this report.

2.0 ENVIRONMENTAL SETTING

The following section describes the regional environmental setting of the Bosque and Leon River Watersheds Study areas including the former NWIRP McGregor site.

2.1 Study Area Location and Description

The USACE's perchlorate study area comprises a portion of the two watersheds that supply surface water to Lake Waco and Lake Belton in Central Texas. The location of the USACE perchlorate study area is shown in Figure 2-1. This area includes portions of the Leon River watershed and the Bosque River watershed, as well as groundwater throughout the study area. Lake Waco and Lake Belton serve as the sole-source water supply for approximately 500,000 people in the surrounding communities including Waco, Killeen, Belton, and Temple (U.S. Census Bureau, 2001). Former NWIRP McGregor straddles the watershed boundary between Lake Waco and Lake Belton. Thus, storm water runoff and groundwater flowing from the NWIRP McGregor site is a component of these drinking water supplies.

The city of Temple's in-take structure downstream of the Lake Belton dam defines the southern boundary of the study area. The eastern boundary of the study area extends north from the city of Belton, located to the west of Interstate-35, and continues northeast along the Interstate-35 to the dam at Lake Waco. The dam at Lake Waco defines the northern boundary of the study area. Finally, the western boundary of the study area extends northwest away from Lake Belton along the western edge of the Leon River. In addition to perchlorate contamination originating at NWIRP McGregor, this study will also address potential contamination originating at Fort Hood, which adjoins the western boundary of the study area. The study area does not include environmental investigations within the boundaries of NWIRP McGregor. Other parties are conducting these investigations. Neither is the USACE study area intended to address or serve as environmental investigation within the boundary of Fort Hood.

NWIRP McGregor is located approximately 20 miles to the southwest of Waco, Texas, and encompasses approximately 9,750 acres of generally flat-lying land at the eastern border of the Texas Hill Country. Based on information from the June 7, 2001 Restoration Advisory Board meeting, approximately 3,500 acres have been transferred to the City of McGregor. State Highway 317 runs along the eastern edge of NWIRP McGregor, and FM 2671 runs along much of its southern boundary. The town of McGregor, Texas is located at the northeast corner of NWIRP McGregor.

2.2 Regional Topography

The study area includes portions of McLennan, Coryell and Bell counties and lies in the Washita Prairie, the easternmost part of the Grand Prairie of Texas. The study area is characterized by gently rolling limestone hills and terrain covered by shallow soil and open land vegetation. Creeks and rivers incise this surface, and cliffs and bluffs develop along these waterways (EnSafe Inc., 1999a).

The land surface in the vicinity of NWIRP McGregor consists of sloping, gently rolling hills and plains underlain by the Georgetown Main Street Limestone. Portions of the facility slope toward the drainage tributaries of the South Bosque River, Harris Creek, and Station Creek (EnSafe Inc., 1999a). Other small drainage ditches and various tributaries contribute to these larger streams. Small bluffs rise above some of the creeks and streams, particularly along tributaries of Harris Creek and the South Bosque River. Elevations at the base range from 840 feet above mean sea level in the northwest corner to 630 feet above mean sea level in the southeast corner of the NWIRP McGregor property. The majority of the property slopes to the southeast, except for the southwest corner where it slopes southwest towards Station Creek.

2.3 Regional Geology

The Balcones Fault System, which is a north-northeast trending zone that closely parallels US Interstate 35, is located along the eastern edge of the study area (Hartmann and Scranton, 1992). The system is located at the confluence of two major physiographic systems: the Gulf Coastal Plain and the north Central Plains. Cretaceous rock units dip to the southeast across the Balcones Fault System and into the Gulf Coast Basin. Beds strike northeast to southwest. The Balcones Fault Zone forms a regional boundary that is distinguished by a line of low hills that rise approximately 150 feet above the surrounding plain. However, the line of hills in the study area are erosional and not directly the result of the faulting in the area (Dr. Joe Yelderman, personal communication, August 1999).

Two normal, northeast trending faults of the Balcones Fault System cross the Leon River Valley, both of which are about 2,000 feet downstream from the Lake Belton dam. Displacements on both are about 30 feet and fault blocks are downthrown to the east (USACE, 1998).

Former NWIRP McGregor is situated atop the McGregor High. The McGregor High is a structural feature in the subsurface that caused erosion and nondeposition during the early Cretaceous, but it is questionable whether this has anything to do with the current topographic divide that occurs on the surface in the study area (Dr. Joe Yelderman, personal communication, August 1999).

A thin veneer of soil occurring in two physiographic provinces immediately underlies the study area: Grand Prairie and Blackland Prairie. Soils in the Grand Prairie province form over areas underlain by marl and limestone, whereas soils in the Blackland Prairie province overlie areas underlain by shale, marl, and chalk.

In general, the soil in the study area is not mature and frequently contains fragments of the limestone parent material. Soil Thickness ranges from 0 to 6 feet below ground surface (fbgs) and average a depth of two feet. Vertical hydraulic conductivities range from 0.06 to 0.20 inches per hour, except in the presence of vertical desiccation cracks, which presumably increase vertical hydraulic conductivity. Desiccation cracks are a result of high clay content and form during extended periods of dryness (USACE, 1998).

Beneath the soil lies a transgressive-regressive sequence of early to middle Cretaceous fractured limestone of the Washita and Fredericksburg Divisions. These divisions primarily consist of interbedded shale and limestone. The early Cretaceous Trinity Group, also consisting of interbedded shale and limestone, underlies these units (EnSafe Inc., 1998a). In the vicinity of NWIRP McGregor, the Georgetown Formation of the Washita Division is exposed and consists of the following members from approximate 0-100 fbgs:

- Main Street Limestone;
- Pawpaw Shale;
- Weno Limestone; and
- Denton Marl (EnSafe Inc., 1998a).

The Main Street Limestone is characterized as a fine to medium crystalline nodular limestone that has an average thickness of 35 feet. This unit is highly fractured and contains shallow groundwater as discussed further in Section 2.5. The lower portion of the Main Street Limestone was initially characterized as non-water bearing because it is less weathered and contains fewer fractures and porosity features (EnSafe Inc., 1998a). More recently, new data have been utilized to demonstrate that this zone is a zone of lower conductivity that is correlative across the NWIRP McGregor site (MW, 1999; Clark, 2000).

A sharp contact separates the Main Street Limestone from the underlying Pawpaw Shale, which acts as an aquitard, and consists of light gray shale that grades to silty shale with depth. The Pawpaw Shale is approximately 5-7 feet thick (EnSafe Inc., 1998a).

The Weno Limestone is nodular, bedded limestone with alternating thin marl beds. The unit has a sharp upper contact and gradational lower contact and is approximately 36 feet thick in the McGregor Quadrangle (EnSafe Inc., 1998a).

Finally, the Denton Marl is composed of soft marl with limestone ledges and has an approximate thickness of 7 feet (EnSafe Inc., 1998a).

2.4 Regional Hydrogeology

As discussed above, the Bosque and Leon River watersheds are comprised primarily of limestone and marl. These rocks primarily belong to the Washita Prairie Edwards Aquifer, the most significant water-bearing formation (Cannata and Yelderman, 1987; Cannata, 1988; Myrick, 1989). Depth to water in the unconfined aquifer is typically less than 10 meters and unconfined (Cannata, 1988; Collins, 1989). Recharge to the aquifer occurs in the uplands of the watersheds, where thinner soils and exposed bedrock fractures allow downward water percolation (Myrick, 1989). The primary flow through the aquifer is through fractures and bedding plans and is controlled by topography, with flow originating at the hills, and moving down to the valleys (Cannata, 1988; Collins, 1989, Myrick, 1989). Discharge of water is generally to streams and springs. Water quality typically reflects an increase in TDS with depth.

The hydraulic conductivity of the aquifer has been calculated to range from 10^{-3} m/s to 10^{-10} m/s (Clark, 2000). Aquifer heterogeneity is controlled locally by fractures caused by weathering, and regionally due to changes in lithology and tectonics.

Hydrogeology of the Bosque and Leon River watersheds is described in detail later in this report in Section 5.2, entitled Hydrogeology.

2.5 Regional Hydrology

Regional drainage and surface water in the study area flows toward the Brazos River, then southeast toward the Gulf of Mexico. In fact, The Brazos River Basin drains 15 percent of Texas's land area and eventually empties into the Gulf of Mexico.

In the study area, a number of rivers drain the surrounding watersheds into the Brazos River Basin, including the Bosque, Leon, and Little Rivers. In addition, local creeks and streams contribute to these principal tributaries to the Brazos River.

Former NWIRP McGregor is located on a topographic high near the confluence of four watersheds, two of which occur in the study area:

- Leon River watershed and
- Bosque River watershed.

The headwaters of several tributaries to these two watersheds originate at NWIRP McGregor. Hydrology of the Bosque and Leon River watersheds is described in detail in Section 5.4, entitled Surface Water Attributes.

3.0 INVESTIGATION HISTORY

The following subsections summarize previous and current assessments related to perchlorate contamination within the study area.

3.1 Previous Investigations

Previous investigations have centered primarily on and around the former NWIRP McGregor site (Figure 3-1). These investigations have ranged from basic baseline surveys of media sampling to investigations aimed at determining the nature, extent, fate, and transport of various identified chemicals at the site. Due to potential contamination at the former NWIRP McGregor site, many of the previous owners have conducted environmental assessments there. A summary of the previous investigations is also outlined in the *Groundwater Investigation Report: Risk Assessment – McGregor Texas* (EnSafe Inc., 1999a).

3.1.1 U.S. Navy Assessments

The U.S. Navy conducted an Environmental Baseline Survey of NWIRP McGregor from September to November 1995 after the production of rocket motors ceased. As part of this study, the Resource Conservation and Recovery Act (RCRA) Facilities Assessment identified eight potential sites for RCRA Facilities Investigations. This study and subsequent investigations and activities are discussed in detail in reports published predominantly by EnSafe Inc., the U.S. Navy's environmental contractor. The documents are available for review by the public at the McGinley Memorial Library at 317 S. Main, in McGregor, Texas, the official public repository for the U.S. Navy's work.

In April, 1999, the Waco Tribune-Herald reported that "traces of rocket fuel additive in the watersheds of [Lake Belton and Lake Waco were found] in concentrations as high as 540 ppb (EnSafe Inc., 1999a). The tests also found levels of 8 ppb in the northern end of Lake Belton…" The rocket fuel additive referred to in this article was perchlorate. A long history of the use of perchlorate at NWIRP McGregor is well documented in the U.S. Navy's investigations, and subsequent studies by the U.S. Navy have identified perchlorate contamination in soils, surface water, and groundwater at the site (U.S. Navy, 1996).

EnSafe Inc. also conducted a groundwater investigation on behalf of the U.S. Navy. This study analyzed the nature, extent, fate and transport of the identified chemicals. Results indicated that chemicals have been released from previous site activities. Some chemical contamination has been found migrating beyond the facility boundaries (EnSafe Inc., 1999a). Further results from the groundwater investigation are included in Section 5.5.

In February 1999, the Texas Natural Resource Conservation Commission (TNRCC) required the Navy to implement interim stabilization measures (ISM) to abate potential offsite migration of perchlorate-contaminated surface water originating at the facility (EnSafe Inc., 2001a). The Navy installed collection and cutoff trenches along the southern property boundary, parallel to Tributary M, and in the flow path of a wet-weather spring to collect perchlorate-contaminated groundwater before it issued offsite (EnSafe Inc., 2001a). Original plans called for groundwater collected within the trenches to be pumped to an ex situ biological treatment system, with subsequent discharge to Tributary M in compliance with a Texas Pollution Discharge Elimination System (TPDES) permit. In September 1999, the trenches were modified to serve as a permeable bioreactive barrier, allowing in situ treatment of groundwater before it migrated offsite or issued to the surface. In the winter of 1999, rainfall caused the trench water level to rise, and groundwater seeped to the surface and into Tributary M. To abate this surface discharge, groundwater was pumped from the trenches to a 6.5 million gallon unlined lagoon (Lagoon A) beginning in July 2000. Shortly thereafter, the seep ceased naturally and the trenches resumed passive treatment of perchlorate to below detection levels during the dry season. However, heavy rainfalls in the winter of 2000 again caused surface discharges to occur. Pumping of groundwater from the trenches resumed but pumped water and rainwater exceeded Lagoon A storage capacity. An Emergency Order was issued in March 2001 allowing treated groundwater having perchlorate concentrations below 22 ug/L to be discharged to Tributary M. Subsequently, the TPDES permit was modified to allow for a combination of in situ and ex situ hydraulic and biological controls to prevent *uncontrolled* discharges of groundwater from the trenches to Tributary M, and to allow for the discharge of *treated* water to Tributary M (EnSafe Inc., 2001a).

3.2 Current Investigations

The USACE has now initiated investigations to understand how perchlorate travels from NWIRP McGregor into the groundwater, creeks, streams, and rivers associated with the Bosque and Leon River watersheds, and ultimately into Lakes Belton and Waco. Public Law 106-377 authorized $4 million of funding for the planned $8 million study. Congress supplied an additional $2.5 million of funding in Fiscal Year 2002. Funding beyond this initial $6.5 million are not assured. This CSM is a component of these investigations.

As described in Section 1.1.2, the USACE has assembled an integrated, multi-disciplinary project team consisting of the USACE, BRA, TIEHH, MWH, USEPA, TNRCC, and the Cities of Waco and Killeen to evaluate potential human and environmental exposure to perchlorate in the Lake Belton and Lake Waco study area. The USACE studies include watershed characterization, modeling, and analysis necessary to an understanding of how perchlorate moves through the environment within the Bosque and Leon River watersheds (a process also referred to as “fate and transport”). These fate and transport evaluations will be linked with environmental toxicology investigations studying the effects of perchlorate on fish, amphibians, and mammals in the Lake Belton and Lake Waco watersheds. Together, this work will be utilized to develop a source water protection plan to ensure the safety of the sole-source drinking water supply for the communities surrounding Lake Belton and Lake Waco.

These USACE analyses and investigations are described further in the following subsections.

3.2.1 CSM Development

The CSM is intended to provide a preliminary conceptual understanding of the relationship between contaminant sources, migration pathways, and exposures to human and ecological receptors (USEPA, 1998a). The CSM presented in this report comprehensively incorporates available information on sources of perchlorate contamination and release, surface hydrology and hydrogeological characteristics of the Bosque and Leon River watersheds, the nature of perchlorate fate and transport, potential pathways of perchlorate migration within the study area, and the human receptors and environmental resources that may receive exposures to perchlorate. As such, this CSM combines previous watershed characterization information collected by the Navy (Section 3.1.1) with new watershed characterization information and analyses conducted by the USACE and its study team. This information is used to identify data gaps in the current understanding of perchlorate migration and exposure within the study area (refer to Section 7.0), and to identify additional investigation activities aimed at filling such data gaps (refer to Section 8.0).

3.2.2 Hydrologic Model Development

The Navy previously characterized the hydrologic attributes in the vicinity of the former NWIRP McGregor as part of their environmental investigations (EnSafe Inc., 1999a). Additional investigations of surface and subsurface hydrologic attributes within the Bosque and Leon River watersheds study area will be conducted by MWH. A detailed conceptual hydrogeological model for the study area is critical to understanding the potential fate and transport of perchlorate within the subsurface, as well as the potential for migration of perchlorate between groundwater and surface water systems. Characterization of the volumes of water moving through the surface water and groundwater systems from NWIRP McGregor to Lakes Belton and Waco is being conducted by MWH (refer to Section 5.3). An integrated, groundwater-surface water budget model is being developed to provide a detailed understanding of the quantities of water inflow and outflow within each watershed. These studies are necessary to an understanding of the potential fate and transport of perchlorate in the lakes, and to an evaluation of potential exposures of human and ecological receptors to perchlorate entering these lakes from streams and tributaries. In total, these investigations are intended to result in a comprehensive evaluation of the Lake Belton and Lake Waco watersheds, and an understanding of the interaction between the groundwater, streams, and lakes throughout the watersheds.

3.2.3 Contaminant Characterization

Although the Navy has sampled a variety of media within the Lake Belton and Lake Waco watersheds, these investigations focused on the characterization of perchlorate contamination present at, or originating from, NWIRP McGregor. As described in Section 2.1, there are other potential sources of perchlorate migration to the watersheds (e.g., Fort Hood) that have not been characterized. Further sampling to evaluate other potential sources of perchlorate to the watersheds may be required. In addition to the Navy's investigations, the BRA, TNRCC, and TIEHH have sampled various media for perchlorate (refer to Section 5.5). Based on the results of this CSM, however, it is likely that additional sampling investigations will be required to fully understand the nature and extent of perchlorate contamination within the Lake Belton and Lake Waco watersheds (refer to Sections 7.0 and 8.0). Further characterization of perchlorate contamination within the watersheds will primarily be conducted by MWH and BRA.

3.2.4 Biological Studies

A variety of biological studies are currently being conducted by TIEHH to evaluate the potential impacts of perchlorate contamination on ecological receptors inhabiting or using the watersheds. Studies that are planned or currently being conducted by TIEHH include sampling of biota (i.e., plants and animals), sampling of abiotic media (e.g., soil, water, and sediments) in support of biological characterization, ecotoxicological evaluations, and ecological risk assessment. Biological sampling activities include the collection and analysis of plants, fish, amphibians, small mammals, and birds collected from areas of known or suspected perchlorate contamination. These studies are being conducted to evaluate the spatial distribution of perchlorate exposure in various aquatic and riparian organisms. These studies, and some preliminary results, are further described in Section 6.2.4.

Ecotoxicology studies include the Frog Embryo Teratogenesis Assay: *Xenopus* (FETAX) and a phytoremediation study to examine uptake, distribution, and degradation in experimental systems with rooted cuttings of woody plants, including willow, Eastern Cottonwood and eucalyptus. USEPA has not yet fully reviewed recent data that indicate effects on thyroid function, metamorphosis and sex ratio in developing *Xenopus laevis* (USEPA, 2002; Goleman et al., 2002). FETAX, showed malformations in frog embryos occurring at only slightly lower concentrations than lethality, indicating that perchlorate is probably not a potent developmental toxicant (USEPA, 2002). Analyses of perchlorate levels in different tissues (including the thyroid gland) of organisms collected from the study area are also being performed. The thyroid gland is a primary target organ of perchlorate in higher animals (USEPA, 2002). These studies are intended to evaluate perchlorate exposure levels that are associated with a known or potential ecological impact.

Finally, ecological modeling and risk assessment studies are being planned to predict long-term exposures and impacts in aquatic and terrestrial food chains.

4.0 PERCHLORATE FATE AND TRANSPORT

This section summarizes general knowledge regarding the fate and transport of perchlorate in the environment. This summary is only intended to present some of the key characteristics of perchlorate fate and transport that are likely to affect its migration, occurrence and exposure within the Bosque and Leon River watersheds. For a more detailed description of perchlorate fate and transport, the reader is referred to the following:

- *Fate and Transport of Ammonium Perchlorate in the Subsurface* (Loehr at al., 1998); and
- Perchlorate Environmental Contamination: Toxicological Review and Risk Characterization **–** External Review Draft (USEPA, 2002).

4.1 Nature and Occurrence of Perchlorate

Perchlorate (ClO_4^-) compounds have been used extensively in industrial application, particularly as oxidizing agents in several forms of solid rocket propellant. The former NWIRP McGregor is a known source of perchlorate waste. Ammonium perchlorate is the primary constituent of rocket propellants that were used and disposed at the NWIRP. Because of its short shelf life, perchlorate must be periodically washed out of the United States' missile and rocket inventory to be replaced with a fresh supply. Thus, large volumes have been disposed of at the site over many years. Disposal would often consist of burning the material in open pits or dumping the contaminant and residual waste directly onto soil or into nearby water sources and diluting with water (Loehr at al., 1998).

Ammonium perchlorate is also used in the manufacture of explosives, matches and fireworks. The manufacture and/or use of perchlorate compounds has been documented at facilities in every state with the exception of Alaska, Connecticut, Hawaii, Massachusetts, Maine, Rhode Island, and Vermont (USEPA, 1999a).

Perchlorate salts are highly soluble in water, and the perchlorate anion tends to be persistent and mobile in its aqueous phase. Physiochemical properties limit the reactivity of perchlorate with other constituents commonly found in subsurface soils and groundwater. Due to its stability under typical subsurface conditions, perchlorate may pose a long-term threat to the overall quality of surface water and groundwater (USEPA, 1999a, 2002). As of 1999, fourteen states have reported environmental releases of perchlorate by facilities involved in its manufacture and/or use (USEPA, 1999a). Perchlorate-contaminated water resources have been linked to the production of rocket propellant at facilities located in Arizona, California, Nevada, Utah, and Texas.

The extent of perchlorate migration from NWIRP to the Bosque and Leon River watersheds is unknown. However, factors which may significantly affect the fate and transport of perchlorate include but are not limited to the chemical and physical characteristics of perchlorate, the nature of the medium into which it is released, and potential physical, chemical, and biological interactions occurring in the receiving medium. These factors will vary according to site-specific conditions.

4.2 Chemical and Physical Properties of Perchlorate

Perchlorate (ClO_4^-) is a highly oxidized form of chlorate (ClO_3^-). It is a negatively charged ion that is usually paired with ammonium (NH_4^+), potassium (K^+), or sodium (Na^+) to form solid salts. These salts have been used in diverse industrial applications including, but not limited to, air bag inflators, nuclear reactors, electronic tubes, chemical fertilizer, lubricants, electroplating, rubber manufacture and aluminum refining. However, the abundance of available oxygen atoms in perchlorate compounds has resulted in their predominant use as solid propellants in missiles and rockets (USEPA, 2001). Composite solid propellants, such as those used in the solid rocket boosters (SRB) for the space shuttle, use a crystallized or finely ground perchlorate salt as an oxidizer (often ammonium perchlorate), which constitutes roughly 70% of the mass of the propellant.

The perchlorate ion consists of a single chlorine (Cl) atom in the center of a tetrahedral group of four oxygen (O) atoms. The negative charge on the perchlorate ion is dispersed evenly over the four oxygen atoms instead of being concentrated in one location, which explains its weak ability to form metallic complexes. Therefore, breakdown via chemical reduction is complicated by the fact that a reducing agent can interact only with the outer oxygen atoms rather than with the central Cl atom (Urbansky and Schock, 1999). The perchlorate anion is the most unreactive of all the chlorine oxides. These factors help to explain the relatively high persistence of perchlorate in the environment. Specific properties such as solubility, density and standard potential are described in the following subsections. This information is derived primarily from material safety data sheets (MSDS) available through an online service (MSDS, 2001) and from the report by Loehr et al. (1998).

4.2.1 Solubility

Perchlorate salts and perchloric acid ($HClO_4$) are highly soluble in water, which results in an abundance of perchlorate ions which are not likely to precipitate out of solution. For example, the solubility of ammonium perchlorate is reported as approximately 20g/100g of solution (Greenwood and Earnshaw, 1984). Potassium perchlorate has a solubility of approximately 2g/100g of solution (MSDS, 2001), which indicates that it is more likely to precipitate out of solution than ammonium perchlorate. Perchloric acid is 100% soluble in water. The availability of cations such as potassium in environmental media including soils, surface water, and groundwater may help to remove some of the perchlorate anions via precipitation; however, this process would be limited by the relatively high solubility of the potassium perchlorate compound.

4.2.2 Density

Ammonium, sodium, and potassium perchlorates have a density of 1.95g/cm^3, 2.0 g/cm^3, and 2.52 g/cm^3 respectively. Solid perchlorate salts will sink in water, as will concentrated aqueous brines (Loehr et al., 1998). A concentrated solution of ammonium perchlorate has an estimated density of 1.1 g/cm^3 (Schumacher, 1960). This may result in the sinking of concentrated brines containing perchlorate salts to the bottom of surface water body or groundwater aquifer, thus posing a potential source of long-term contamination.

4.2.3 Standard Potential and Reaction Kinetics

The reduction of perchlorate to chloride (Cl^-) occurs according to the following redox reaction:

$$HClO_4^- + 8e^- + 8H^+ \Longrightarrow Cl^- + 4H_2O \quad E = 1.29\ V$$

The standard electrode potential, which is an indicator of the spontaneity of the reaction, is 1.29 Volts. The positive value indicates that the reaction spontaneously occurs in the direction indicated. This reaction takes place in a number of half-reactions, in which perchlorate is reduced to chlorate (ClO_3^-), chlorite (ClO_2^-), and finally to chloride (Cl^-). The change in the standard potential between these reactions is less than 0, which is thermodynamically favorable. However, perchlorate is also characterized by low kinetic lability. Urbansky and Schock (1999) define the rate-limiting step in perchlorate reduction by the following equation:

$$HClO_4^- + R \Longrightarrow ClO_3^- + RO \text{ (where R is the reducing agent)}$$

The activation energy (E_a) required to reduce perchlorate to chlorate is not easily overcome in natural systems (USEPA, 2002), although subsequent steps require lower activation energies. The kinetic barrier supercedes the thermodynamic favorability ($\Delta E<0$) of the overall reaction and prevents the spontaneous reduction of perchlorate. This process will take place in natural subsurface environments only in the presence of viable catalysts, electron donors, and/or available perchlorate-reducing microorganisms (Herman and Frankenberger, 1999).

There currently is very little information on the potential chemical processes (e.g., chemical oxidation, reduction, hydrolysis or photolysis reactions) that may affect the transport or transformation of perchlorate in the environment. Perchlorate already exists in a stable, highly oxidized state and further oxidation is unlikely. Although chemical reduction in the environment is possible, such a reaction would require a net expenditure of energy for perchlorate (Loehr et al., 1998). Consequently, reduction of perchlorate tends to be mediated by microorganisms (Loehr et al., 1998). In regard to other potential reactions (e.g., hydrolysis or photolysis), it has been reported (Schumacher et al., 1960) that perchlorate (1) does not absorb visible or ultraviolet light, (2) has the smallest tendency of all negative ions in water to associate with other ions or molecules, and (3) is quite inert chemically in dilute solution. Consequently, spontaneous chemical transformation of perchlorate is probably not a significant environmental attenuation mechanism for this chemical.

4.3 Biological Interactions of Perchlorate

Potential microbial processes that may alter perchlorate's disposition in the environment are described in Section 4.3.1, and the uptake and transformation of perchlorate in higher organisms are discussed in Section 4.3.2.

4.3.1 Microbial Processes

The ammonium portion of ammonium perchlorate may undergo microbial degradation as a result of nitrification processes under aerobic conditions. However, there is no evidence that perchlorate itself is subject to microbial degradation under aerobic conditions (Loehr et al., 1998). Therefore, perchlorate in surface soils, and aerobic surface water or groundwater, is not anticipated to undergo attenuation through microbial processes. Bacteria capable of reducing perchlorate may be found in the near-source zone, provided that the oxygen content of the groundwater is sufficiently low (Herman and Frankenberger, 1998). Several genera of microorganisms are capable of using perchlorate as an oxidant for their metabolic activity. These include *Wollinella succinogenes HAP-1* (Wallace et al., 1996), *Vibrio dechloraticans* Cuznesove B-1168 (Korenkov et al., 1976), and a *Proteobacteria*, strain GR-1, described by Rikken et al. (1996). These microbes contain an enzyme that allows them to lower the activation energy required for perchlorate reduction and to make use of this energy for cellular respiration (Wu et al., 2001). The relative abundance of these bacteria in natural systems is affected by the initial concentration of perchlorate in the source area (i.e. high initial concentrations of perchlorate result in more perchlorate-reducing microorganisms). However, the rate of bioreduction is also directly proportional to the concentration. Thus, bioreduction may reduce the concentration of perchlorate in the near-source area to a threshold level, which will allow low concentrations to migrate further downgradient.

4.3.2 Biological Uptake and Transformation

There is a relative lack of information in the literature on the potential uptake of perchlorate in plants and agricultural products through irrigation of food crops (USEPA, 2001). The high aqueous solubility of perchlorate suggests that it would be absorbed by plant roots. Schumacher (1960) reviewed a number of studies demonstrating adverse effects of perchlorates on seed germination and plant growth. However, several of the studies included effects on root morphology and function, and it is possible that observed effects were, at least in part, attributable to decreased root function rather than direct systemic toxicity. None of the studies reviewed by Schumacher (1960) measured uptake of perchlorate into plant tissue. More recent plant uptake and phytotransformation studies reviewed by the USEPA (2002) suggest that perchlorate is uptaken by plants and concentrated in aerial plant parts, especially leaves, from perchlorate-amended soils. For rooted cuttings of woody plants including willow (*salix* spp.), Eastern cottonwood (identified only as "poplar"), and eucalyptus (*Eucalyptus cineria*) grown in sand with perchlorate containing solution added, concentration factors calculated as the ratio of leaf concentration in milligrams per kilogram (mg/kg wet weight) to solution concentration in milligrams per liter (mg/L) ranged from 7.5 to 25 (USEPA, 2002). In seedlings or rooted cuttings of 13 vascular plant species grown in sand and exposed to 0.2, 2.0 or 20 mg/L perchlorate in solution for ten days, concentration factors ranged from 0 – 330 (USEPA, 2002). The USEPA expressed caution in evaluating the results of these studies and in potentially using the derived concentration factors to predict biouptake rates in agricultural or other plants for several reasons, including the fact that these studies were of short-term duration and did not represent steady-state conditions (USEPA, 2002). The USEPA (2002) did, however, suggest that these data support a conservative, screening-level assumption that perchlorate concentrations in leaves can exceed perchlorate concentrations in water by a factor of 100.

Bioaccumulation has also been observed in tobacco plants grown in soils amended with Chilean saltpeter, which contains natural perchlorate. The concentration factor for leaf lamina collected from the 1999 crop was estimated as 43, based on the mean leaf wet weight concentration and soil dry weight concentration (USEPA, 2002). A similarly estimated concentration factor based on the mean leaf dry weight concentration and soil dry weight concentrations is 280.

Smith et al. (2001) documented significant levels of perchlorate uptake in aquatic and terrestrial plant samples collected from the Longhorn Army Ammunition Plant (LHAAP) located in Karnack, Texas. Samples of bullrush collected from a pond containing perchlorate at concentrations up to 31,438 micrograms per kilogram (μg/kg) in surface water and 35,630 ug/kg in sediment contained perchlorate concentrations up to 1,133 μg/kg (dry weight) in roots and 9,487 μg/kg (dry weight) in above-root plant parts. Higher concentrations were detected in terrestrial plants growing in a location with perchlorate levels in soil up to 322 μg/kg. At this location, perchlorate concentrations up to 5,557,000 μg/kg (dry weight) were measured in crabgrass (blades) and up to 1,030,000 μg/kg (dry weight) were measured in goldenrod (leaves). Perchlorate levels were highest in blades (crabgrass) and leaves (goldenrod), and samples of blades, leaves or seeds collected from these plants contained higher levels of perchlorate than were found in stems or roots. It should be noted, however, that these relationships were not statistically evaluated because plant- and tissue-types consisted of only one composite sample each. Furthermore, plant and soil concentrations were measured at different times and the studies were not designed for the purpose of developing concentration factors (USEPA, 2002).

The USEPA (2002) concluded that current plant uptake information is inadequate for more than screening-level risk assessment purposes, and identified additional data needs as follows:

- Data on bioaccumulation in aquatic plants are necessary to assess impacts to primary consumers (i.e., planktonic and benthic invertebrate communities);
- Potential accumulation in terrestrial vascular plants should be investigated further using studies designed to quantify plant concentration factors; and
- Data on the fate of perchlorate in irrigated soils are needed to evaluate the potential for evaporative concentration of this chemical in soil.

Recent investigations (Parsons, 2001; Smith et al., 2001; TIEHH, 2001b,c) also indicate that perchlorate is uptaken by aquatic and terrestrial animals. Mean perchlorate concentrations in water, sediment and organisms inhabiting a pond ecosystem at the LHAAP were water (31,190 µg/L), sediment (25,170 µg/kg), bullrush (below waterline; 4,451 µg/kg), damselfly larvae (1,534 µg/kg), bullfrog tadpoles (1,658 µg/kg), and chorus frog (580 µg/kg) (Smith et al., 2001). These results are in general agreement with earlier data collected by Parsons (2001) that showed perchlorate concentrations in vegetation at levels similar to or greater than surface water or sediment pore water, but concentrations in invertebrates, amphibians, and fish were lower than those in either water or vegetation.

Mean perchlorate concentrations in organisms inhabiting a terrestrial ecosystem at LHAAP were soil (200 µg/kg), crabgrass seeds and blades (3,720,000 µg/kg), goldenrod seeds and leaves (607,000 µg/kg), and harvest mouse livers (1,724 µg/kg) (Smith et al., 2001). Perchlorate concentrations in two composite thyroid samples collected from cotton mice, harvest mice, and cotton rats were 589 µg/kg and 2,170 µg/kg. No data were presented in Smith et al. (2001) on perchlorate concentrations in other tissues or in whole mammals. Parsons (2001) reported that perchlorate concentrations in samples of terrestrial insects, mammals, and birds were not detected, unless soil concentrations exceeded approximately 9,000 µg/kg. Where soil concentrations exceeded this level, detected concentrations in herbivore tissues were less than concentrations in vegetation.

TIEHH (2001b) analyzed fish samples collected from tributaries within the Lake Belton and Lake Waco watersheds that have been be impacted by perchlorate discharges from NWIRP McGregor. Perchlorate concentrations in fish fillets collected in May 2001 ranged from not detected to 1,230 µg/kg (wet weight) (TTIEH, 2001b). Concurrent surface water or pore water samples were not collected for comparison during this sampling event. However, sampling conducted in August-September 2001 included the collection of fish, surface water and sediment pore water samples from the same locations (TTIEH, 2001b). Perchlorate concentrations in individual fillets of green sunfish (*Lepomis cyanellus*), large mouth bass (*Micropterus salmoides*) or channel catfish (*Ictalurus punctatus*) ranged from not detected (detection limit equal to 170 µg/kg wet weight) to 690 µg/kg (wet weight). Perchlorate was not detected (limit of detection equal to 2 µg/L) in sediment pore water samples collected from any of the sampling locations. Surface water concentrations ranged from not detected (limit of detection equal to 2 µg/L) to 36 µg/L at locations coincident with detected concentrations in fish samples. In all cases, detected concentrations in fish samples exceeded detected concentrations or detection limits in surface water samples.

Although the TIEHH (2001b) results suggest that perchlorate may bioconcentrate (i.e., the accumulation of higher concentrations in tissue than in the exposure medium) in aquatic organisms, these data are difficult to interpret. For example, the highest perchlorate concentration measured in fish samples collected during August-September 2001 (690 μg/kg in a large mouth bass fillet) represented the only detection out of a total of 19 fish samples collected at that location. Similar results were observed at other locations, and perchlorate was not detected in the majority of fish samples. Because perchlorate was not detected in most samples, and the detection limits in fish samples were substantially higher than in surface water or pore water samples, it is not possible to statistically evaluate possible trends in bioconcentration using these data.

TIEHH (2001c) conducted an uptake study in catfish exposed to 100 mg/L sodium perchlorate in the laboratory over five days. The mean perchlorate concentration measured in catfish fillets was 7.3 mg/kg (wet weight) and that in heads was 25.5 mg/kg. These data demonstrate preferential uptake in heads versus fillets of fish exposed to high concentrations of perchlorate in the laboratory. These results are potentially significant because the primary target organ in higher animals is the thyroid gland (USEPA, 2002). It should be noted, however, that the exposure concentration used in this study is higher than typical perchlorate concentrations found in surface waters impacted by perchlorate, and the short study duration is not representative of steady-state conditions.

In total, the available wildlife uptake data suggest that perchlorate has the potential to accumulate in animals including fish, amphibians, reptiles, mammals, and birds. There is also evidence to suggest that perchlorate may preferentially distribute to the thyroid gland in wildlife. However, the extent to which this occurs and may adversely affect fecundity in individuals or populations of wildlife is currently unknown. Current data are also inadequate to evaluate the potential for perchlorate to bioconcentrate in aquatic organisms. It is unlikely, however, that perchlorate biomagnifies (i.e., the accumulation of increasing concentrations in successively higher trophic levels) in aquatic and terrestrial ecosystems based on the available data. However, additional data representative of whole animals and higher trophic levels are needed before definitive conclusions can be made regarding these phenomena.

The USEPA (2002) concluded that current animal uptake information is inadequate, and identified additional data needs as follows:

- Data are insufficient to determine whether perchlorate bioconcentrates in aquatic organisms;
- Data on bioaccumulation in aquatic fish and other aquatic organisms are needed to evaluate exposures to organisms that feed on them; and
- Data on bioaccumulation in litter feeding or herbivorous invertebrates are needed to evaluate exposures to mammals or birds that feed on these organisms.

Studies sponsored by the United States Air Force (USAF) and Perchlorate Study Group are currently underway to evaluate the absorption, distribution, metabolism, and elimination of perchlorate in animals and humans (USEPA, 2001). Based on current information, perchlorate is readily absorbed from the intestinal tract and oral uptake is considered to be the major route of exposure (USEPA, 2002). Because of its high charge, perchlorate does not readily pass through the skin. Exposure via the inhalation route is expected to be negligible because the vapor pressure of perchlorate salts and acids is expected to be low at room temperatures (USEPA, 2002). The extent to which perchlorate is metabolized in animals and humans is not well understood. However, perchlorate is not metabolized in the thyroid or peripheral tissues (USEPA, 2002). Schumacher (1960) reported the results of experiments in which potassium perchlorate was recovered unchanged in the urine of animals exposed to the contaminant. Due to the reductive nature of perchlorate metabolism (Loehr et al., 1998) and its high water solubility, it is likely that perchlorate is readily eliminated untransformed in the urine of animals.

4.4 Site-Specific Considerations

In order to accurately predict the fate and transport of perchlorate within the Bosque and Leon River watersheds it is necessary to understand a) how historical handling of ammonium perchlorate composite propellants at former NWIRP McGregor may result in perchlorate soil, surface water, and groundwater contamination, b) how perchlorate disassociates from the composite propellant, c) how perchlorate and the other propellant ingredients migrate through soils, and d) how perchlorate interacts with soil particles as a function of soil and groundwater chemistry (Loehr at al., 1998).

For the case of ammonium perchlorate propellants that have been spilled on the surface and are flushed with water, the extent of dissolution of the ammonium perchlorate in the water will depend on whether the ammonium perchlorate is still associated with the binder and the properties of the binder. If dissolution occurs, water containing the ammonium perchlorate can then percolate through the soil. In addition, rainwater may aid in this process (Loehr at al., 1998).

The contaminant concentration will decrease with distance from the source due to attenuation processes that include physiochemical and biological reactions and hydrodynamic dispersion processes. The aqueous phase concentrations of perchlorate are expected to be relatively dilute and fewer opportunities for chemical and biological reactions are possible as the contaminant migrates from the near sources area to the far source area.

Presumably, propellant waste containing ammonium perchlorate that has been washed from the site has already undergone size reduction so that ammonium perchlorate crystals are exposed. Slow release of the ammonium perchlorate solid from this mixture could represent a long-term source of contamination (Loehr at al., 1998).

The factors and mechanisms included in an evaluation of perchlorate release, migration and fate are summarized in Figure 4-1. For example, the use of perchlorate, its form (solid or liquid), and the disposal method can produce sources of contamination with varying degrees of mobility. Once released, transformation and transport processes in the receiving medium can result in varying degrees of attenuation. This, in turn, affects the potential for ecological receptors or humans to be exposed to perchlorate in high or low concentrations, by pathways such as ingestion of contaminated water or food sources exposed to perchlorate.

The potential for perchlorate release to the subsurface and migration to groundwater is dependent, in large part, on the geology and hydrogeology of the subsurface. These characteristics of the study area are described in detail in Section 5.0 of this report. Due to the low tendency of perchlorate to form metallic complexes in soil or undergo aerobic degradation, and the high solubility of dissociated perchlorate, leaching of perchlorate to groundwater is favored. Once in groundwater, the hydrogeological features of the area will determine the nature and extent of subsurface migration of perchlorate. It is known that shallow groundwater is in communication with surface water within the Bosque and Leon River watersheds, as described further in Section 5.0. Perchlorate that reaches surface waters will distribute according to local surface water attributes and flow characteristics, as described in detail in Sections 5.3 through 5.5 of this report.

Volatilization losses from surface water are anticipated to be insignificant, based on the low vapor pressure of perchlorate. Physical adsorption to suspended particulate matter and chemical reactions, such as photolysis, are also considered to contribute minimally to the perchlorate fate in surface water due to the relatively inert nature of the perchlorate ion. Depending upon the aqueous chemistry and availability of cations such as potassium, some reversible chemical complexation may occur. This phenomenon, and the fact that perchlorate is more dense than water, could potentially contribute to the movement of perchlorate to deeper, anaerobic regions of a surface water body. Once in anaerobic surface water or sediment, there is a potential for anaerobic degradation by perchlorate-reducing microorganisms.

As a result of perchlorate's high water solubility, it is subject to uptake by plants and distribution within the food chain. The potential for significant bioaccumulation and biomagnification within the food chain is generally limited to lipophilic (i.e., fat seeking) chemicals. This would suggest that the hydrophilic (i.e., water seeking) perchlorate ion does not appreciably bioaccumulate in the food chain. However, there is information to indicate that perchlorate is selectively uptaken into the thyroid gland of higher organisms including fish, birds, and mammals (USEPA, 2002). Studies into the uptake, distribution and potential bioaccumulation of perchlorate within ecosystems of the Bosque and Leon River watersheds are currently being conducted by TIEHH (refer to Section 3.2.1).

4.5 Toxicology of Perchlorate

The potential human health effects and ecotoxicology of perchlorate are briefly summarized in the following subsections. For a more detailed understanding of the human health and ecological toxicology of perchlorate, the reader is referred to the USEPA's *Perchlorate Environmental Contamination: Toxicological Review and Risk Characterization – External Review Draft (USEPA, 2002).*

4.5.1 Human Health Effects

Human exposures to perchlorate and associated health effects have been studied extensively due to the medicinal use of perchlorate in the treatment of hyperthyroidism. Hyperthyroidism, also known as Graves' disease, is associated with over-activity of the thyroid gland. Production of thyroid hormone is inhibited by the competitive uptake of perchlorate over iodide. Reduced amounts of thyroid hormone affect the normal metabolic functions as well as the regulation of calcium in the body. Until recently, potassium perchlorate was extensively used to inhibit thyroid hormone production in patients with this condition.

Until recently, toxicity values were unavailable for perchlorate due to an incomplete understanding of the human health risks from this chemical. In 1997, a partnership between the USEPA, Department of Defense (DoD), and an Interagency Perchlorate Steering Committee was formed to identify data gaps in the available toxicity information for perchlorate and to develop a testing strategy to fill data gaps. The human health testing strategy was initiated in 1997 and consisted of eight primary toxicology studies. Follow-up and supplemental studies were included as study results became available and additional issues arose. Results of these studies and their interpretation are described in detail in *Perchlorate Environmental Contamination: Toxicological Review and Risk Characterization – External Review Draft* (USEPA, 2002). Conclusions pertinent to the development of human health toxicity values for use in risk assessment are summarized below.

Perchlorate is known to inhibit the uptake of iodide in the thyroid, thereby causing a reduction in the hormones thyroxine (T3) and triiodothyronine (T4). Control of the circulating concentrations of these hormones is regulated primarily by a negative feedback involving three organs (1) the thyroid, which produces T4 and T3, and (2) the pituitary gland and (3) the hypothalamus, which respond to and help maintain optimal T4 and T3 levels by what is known as the hypothalamic-pituitary-thyroid axis or feedback system. Given its mode of action as an inhibitor of iodide uptake that results in disturbances of the hypothalamic-pituitary-thyroid axis, initial concerns regarding potential neuro-developmental, developmental, reproductive, immunotoxic and carcinogenic effects were identified (USEPA, 2002).

Results of the interagency toxicity testing program confirmed that the thyroid gland is the target tissue for perchlorate toxicity (USEPA, 2002). Perchlorate-related changes included neurodevelopmental deficits, thyroid tumor formation, and indications of immunotoxicity (i.e., dermal contact hypersensitivity). Competitive inhibition of iodide uptake at the sodium (Na+)-iodide (I-) symporter (NIS) is the key event that leads to both neurodevelopmental and neoplastic (i.e., tumor formation) effects. An administered dose of 0.01 milligrams per kilogram per day (mg/kg-day) was identified as the lowest-observed-adverse-effect-level (LOAEL) in laboratory animals. This dose was concluded to be protective of both neurodevelopmental and neoplastic effects. Physiologically-based pharmacokinetic (PBPK) modeling was used to develop a human equivalent exposure (HHE) for perchlorate based on the animal LOAEL. Based on the HHE and a composite uncertainty factor of 300, a human reference dose (RfD) of 0.00003 mg/kg-day was derived. The RfD represents a daily intake of contaminant per kilogram of body weight that is not sufficient to cause the threshold effect of concern for the contaminant. Exposure doses that are above the RfD could potentially cause adverse health effects. The USEPA (2002) described confidence in the principal study upon which the RfD was based, the available toxicity database for perchlorate, and the RfD of 0.00003 mg/kg-day as 'medium'.

It should be noted that conclusions presented in USEPA's *Perchlorate Environmental Contamination: Toxicological Review and Risk Characterization – External Review Draft* (USEPA, 2002), including the revised RfD, are 'draft' and will be subject to peer review. The USEPA has scheduled a peer review workshop that will be open to the public on March 5th and 6th 2002 in Sacramento, California. The USEPA plans to finalize the above document in late summer of 2002.

4.5.2 Ecotoxicology

The interagency toxicity testing program also conducted a battery of ecological screening studies as part of the 1997 testing strategy. Studies were performed in laboratory organisms deemed representative of ecological receptors potentially exposed to perchlorate in water, sediment or soil in order to evaluate dose-response relationships. Laboratory organisms that were evaluated include:

- *Daphnia magna* (water flea) to represent an aquatic invertebrate;
- *Ceriodaphnia magna* (water flea) to represent an aquatic invertebrate;
- *Lactuca sativa* (lettuce) to represent a vascular plant;
- *Pimephales promelas* (flathead minnow) to represent an aquatic vertebrate;
- *Eisenia foetida* (earthworm) to represent a soil invertebrate;
- *Microtus pennsylvanicus* (meadow vole) to represent an herbivore; and
- Frog Embryo Teratogenesis Assay: Xenopus (FETAX).

The results of toxicity studies in aquatic invertebrates (*Daphnia magna* and *Ceriodaphnia magna*) and fish (*Pimephales promelas*) were used by USEPA (2002) to derive screening-level aquatic toxicity benchmarks. A secondary acute value (SAV) of 5 mg/L (as perchlorate) was derived by USEPA to be protective of 95% of aquatic organisms during short-term exposures with 80% confidence. A secondary chronic value (SCV) of 0.6 mg/L (as perchlorate) was derived by USEPA to be protective of 95% of aquatic organisms with 80% confidence. It should be noted that the SAV and SCV are calculated values and take into consideration toxicity test results, in addition to uncertainties related to the database (e.g., the number of test results available and taxonomic groups represented). Since toxicity data for only two taxonomic groups and three species were available, additional toxicity studies across more taxonomic groups and species would reduce the uncertainty in the derived aquatic benchmarks.

A FETAX study of ammonium perchlorate exposures in embryos of the frog, *Xenopus laevis*, was performed by the Department of Zoology, Oklahoma State University in 1998. The USEPA's preliminary review of the data indicate effects on thyroid function, metamorphosis and sex ratio in developing frog embryos (USEPA, 2002). However, USEPA (2002) also observed that results of the assay "…showed malformations in frog embryos occurring at only slightly lower concentrations than lethality, indicating that perchlorate is probably not a potent developmental toxicant." If this preliminary observation is correct it may suggest inter-species variability between perchlorate intakes that produce developmental effects and those producing lethality. This is because results of toxicity studies upon which the human RfD is based indicate that neurodevelopmental effects occur in mammals at intake rates well below those producing mortality. Also unknown is the dose-response relationship for *Xenopus*, and an appropriate toxicity benchmark for the protection of amphibians. Values of the acute 96-hour IC-50 (i.e., inhibitory concentration in 50% of test subjects) for malformations in *Xenopus* larvae exposed to ammonium perchlorate were reported as 420 and 336 mg/L (USEPA, 2002). However, the USEPA has not yet evaluated these results or attempted to derive a screening benchmark for the protection of amphibians. Once a screening benchmark is derived for amphibians, it presumably will be lower than the range of IC-50 values reported in this single FETAX study. A better understanding of the dose-response relationship for *Xenopus* is needed to properly evaluate potential impacts of perchlorate exposures on amphibians, including frogs.

A screening benchmark for terrestrial plants was derived by the USEPA (2002) based on chronic (28-day) test results for lettuce (*Lactuca sativa*). The quartile inhibitory concentration for growth of *Lactuca sativa* in soil and sand were 78 mg/kg (293 mg/L) and 41 mg/kg (160 mg/L), respectively. An uncertainty factor of 10 was applied to account for interspecies variance to obtain a screening benchmark of 4 mg/kg. Toxicity test results across additional taxonomic groups and species would help to reduce the uncertainty in this screening plant benchmark.

The USEPA (2002) derived a screening toxicity benchmark for terrestrial soil invertebrates based upon results of a single 14-day acute lethality study for the earthworm (*Eisenia foetida*). The study was performed in artificial soil irrigated with sodium perchlorate, and the LC-50 (i.e., lethal concentration in 50% of test subjects) was reported as 4,450 mg/kg (wet weight) at both 7 and 14 days. Modification of the LC-50 value by an interspecies uncertainty factor of 242, and an acute-to-chronic ratio of 18, resulted in a screening benchmark for protection of soil invertebrate communities equal to 1 mg/kg. The equivalent aqueous phase benchmark is 2.8 mg/L (USEPA, 2002). Additional acute and/or chronic toxicity studies in soil invertebrates would help to reduce the uncertainty in this soil screening benchmark.

The USEPA (2002) deemed the LOAEL of 0.01 mg/kg-day observed in the multi-generation rat study appropriate to the derivation of a screening toxicity benchmark for the representative herbivore (i.e., meadow vole). A factor of 10 for interspecies variance and to extrapolate the LOAEL to a no-observed-adverse-effect-level (NOAEL) was applied to obtain a screening toxicity benchmark of 0.001 mg/kg-day (USEPA, 2002).

The USEPA (2002) report that estimates of perchlorate exposures for voles at rocket motor manufacturing or testing sites exceed both the LOAEL of 0.01 mg/kg-day and the screening benchmark of 0.001 mg/kg-day. In addition, estimated exposures of voles consuming plants on sites irrigated with contaminated surface water or groundwater also exceed the LOAEL and the screening benchmark. Based on these exposure estimates the USEPA (2002) concluded, "there is a potential hazard to all herbivorous wildlife living in areas that may be irrigated with contaminated water." The USEPA (2002) also estimated a surface water concentration that is equivalent to the screening benchmark for herbivores. Assuming a water ingestion rate of 0.21 grams water per gram body weight per day (g/g-day), an acceptable drinking water concentration for herbivores was estimated as 4.8 ug/L (USEPA, 2002). It should be noted that the above estimates are based on toxicity information derived from laboratory rodents and the application of protective uncertainty factors; thus, these screening-level comparisons may or may not be representative of actual hazards to wildlife. Since it is not uncommon for surface waters impacted by perchlorate to contain levels in excess of 4 ug/L, refinement of the toxicity benchmark for herbivores through additional toxicity testing may be appropriate.

Because only a screening-level tier of toxicity tests has been performed, the USEPA (2002) concluded that there are data gaps in the available ecological toxicity information for perchlorate. These data gaps include the following:

- Effects of perchlorate on algae and aquatic macrophytes are required to estimate risks to aquatic primary producers;
- Toxic effect levels should be determined in non-daphnid invertebrates; and
- Uncertainties related to the use of subchronic fish data in the derivation of the aquatic screening benchmark (i.e., SCV) could be addressed through chronic effects testing.

The USACE and its study team note the following additional data gaps in the available ecological toxicity information for perchlorate:

- A better understanding of the dose-response relationship for *Xenopus* is needed to properly evaluate potential impacts of perchlorate exposures on amphibians, including frogs;
- Effects testing for plants across additional taxonomic groups and species would help to reduce the uncertainty in this screening plant benchmark;
- Additional acute and/or chronic toxicity studies in soil invertebrates would help to reduce the uncertainty in the current soil screening benchmark; and
- Refinement of the screening toxicity benchmark for herbivorous wildlife through additional toxicity testing may be appropriate.

4.6 Regulatory Issues

Perchlorate appears on the USEPA's Contaminant Candidate List (CCL), as a priority contaminant requiring further data gathering and analysis. Perchlorate was also placed on the Unregulated Contaminants Monitoring Rule (UCMR) in March 1999 to gather needed exposure information (USEPA, 2002). Under the UCMR, all large public water systems and a representative sample of small public water systems were required to monitor for perchlorate beginning in January 2001. In early 2000, an analytical method to detect perchlorate in drinking water (USEPA Method 314.0) using ion chromatography was published as a direct final rule. The USEPA Method 314.0 was also approved as a monitoring method for the UCRM. The method detection limit (MDL) for the method is 0.53 ppb and the method reporting limit (MRL) is 4 ppb.

To date, a federal drinking water standard or maximum contaminant level (MCL) for perchlorate have not been established. Currently, states that have discovered sources of perchlorate impacting surface water and groundwater have established preliminary guidance on acceptable levels of perchlorate in drinking water by establishing provisional action levels. The California Department of Health Services (CDHS) previously set its provisional action level at 18 ppb (µg/L) in drinking water, and has closed water supply wells that exceed this concentration. In response to the USEPA's draft revised RfD, the CDHS lowered its action level to 4 ppb. The Arizona Department of Health Services is using 14 ppb as its guidance level, while in Texas the interim action level is set at 4 ppb.

The Texas Risk Reduction Program (TRRP) established a residential groundwater cleanup standard for perchlorate equal to 4 ug/L, and a commercial/industrial groundwater cleanup standard equal to 7 ug/L. The NWIRP McGregor site is regulated under the TRRP, which was promulgated in 1998. Other sites including the LHAAP are regulated under the Risk Reduction Rule (RRR). The RRR residential groundwater cleanup standard for perchlorate is 4 ug/L, and the commercial/ industrial groundwater cleanup standard is 7 ug/L.

As described in Section 4.5.1, the USEPA completed a review of existing toxicological information for perchlorate and is revising the provisional RfD for this chemical in accordance with 1996 SDWA guidelines for unregulated contaminants of potential concern. Based on recently completed toxicological studies, the USEPA has published a draft RfD of 0.00003 mg/kg-day (USEPA, 2002). Hypothetical conversion of the draft RfD to a drinking water equivalent level (DWEL), assuming factors of 70 kilogram (kg) body weight and 2 liter (L) of water consumption per day would be 1 microgram per liter (ug/L) or 1 part per billion (ppb). If the Agency were to make a determination to regulate perchlorate, the RfD along with other considerations including cost and technology would factor into the final value.

5.0 HYDROLOGIC CONCEPTUAL MODEL

- This section describes the hydrologic processes occurring within the study area watersheds of the Bosque and Leon River. Much of this section is derived from the work of Dr. Joe Yelderman of the Department of Geology, Baylor University and Dr. Owen Lind of the Department of Biology, Baylor University.

5.1 Overview

Lake Waco and Lake Belton are part of the Brazos River Basin, one of 23 major river basins in Texas. The Brazos River Basin spans nearly 500 miles, from the Gulf of Mexico west to near Texas' border with New Mexico. Harris Creek and the South Bosque River, which drain NWIRP McGregor and flow into Lake Waco, are contained in the Bosque River Basin. Station Creek is contained in the Leon River Basin, which also drains NWIRP McGregor on its ultimate course to Lake Belton. The Brazos River Basin and its basins of interest are shown in Figure 2-1. The boundaries of these basins are topographic in nature, as regions of higher elevation control the flow of surface water.

NWIRP McGregor straddles the boundary between the Bosque River and Leon River watersheds, which drain into Lake Waco and Lake Belton, respectively. Perchlorate, used in the production of solid rocket motors, has been released into the environment at NWIRP McGregor. Since water from NWIRP McGregor eventually flows downstream into Lakes Belton and Waco, the water quality of these lakes may be impacted by the release of perchlorate within their watersheds

Because of NWIRP McGregor's location atop a watershed divide, surface water originating on the site flows both south to southwest and north to northeast. The southerly flows drain into Lake Belton, six miles away. Major tributaries in this watershed include Station Creek, Stampede Creek, Owl Creek, and Cowhouse Creek. Lake Belton, a reservoir formed by a dam on the Leon River, was constructed in the 1950s. It has a volume of 434,500 AF and a normal pool elevation (water level) of 594.0 feet above mean sea level (TWDB, 1994).

The northerly surface water flows originating from the site drain to Lake Waco via several larger streams, including the South Bosque River, Willow Creek, and Harris Creek. These streams and associated minor tributaries flow east and northeast ten to fifteen miles to join the northward flowing Bosque River at Lake Waco. Lake Waco is formed by a dam on the Bosque River, has a volume of 144,830 AF, and has a normal pool elevation of 455.0 feet above mean sea level (TWDB, 1995). Approximately five miles downstream from Lake Waco, the Bosque River joins the Brazos River.

In addition to surface water systems draining into Lakes Belton and Waco, groundwater is also present. Groundwater is important because it forms approximately 40-60% of the baseflow in area creeks in the upper portions of the Bosque subbasin (Dr. Joe Yelderman, personal communication, August 1999). According to EnSafe (1999a), groundwater in the area is comprised of a shallow and a deep component. Shallow groundwater is stored in voids and lenses of the fractured upper few feet of the fractured bedrock of the Mainstreet member of the Cretaceous (145 to 66 million years ago) Georgetown Limestone Formation. Static water level in shallow wells indicate a high regional static water level, but with some seasonal fluctuations. EnSafe (1999a) also indicates that shallow groundwater is unconfined and flow follows topography, mimicking the patterns of surface water flow. Thus, shallow groundwater basins are generally mirror images of surface water basins, with shallow groundwater flowing to the north of NWIRP McGregor to the Bosque River watershed and south into the Leon River watershed. Some surface water features, such as seeps and springs originate from this shallow groundwater flow along bedding planes, joints, and fractures.

Underlying the Georgetown formation is the Edwards formation, also comprised primarily of limestone, which is limited to less than 40 feet thick and located at a depth of approximately 100 fbgs. Due to the thin nature of this formation, it produces a small quantity of water. The region's shallow and deep aquifers are separated by over 950 feet of limestone and shale beds. Thus, these two systems are not hydraulically connected. The deep aquifer is comprised of the Upper and Lower Trinity sand, a fine- to coarse-sand. Regional groundwater flow in the deep aquifer flows primarily from the northwest to the southwest at a rate of approximately 10 to 40 feet per year.

5.2 Hydrogeology

Most of the information presented in this section is the result of research conducted by Dr. Joe Yelderman within the McGregor area of central Texas (Dr. Joe Yelderman). Results of investigations by EnSafe Inc. are also presented in this section.

The study area is located in the Central Texas area within the Brazos River Basin (Figure 2-1). The watersheds immediately surrounding former NWIRP McGregor are the Bosque and Leon River watersheds. According to Ensafe, the water table within the site is inconsistent and flows are altered seasonally. During the wet season groundwater contributes to stream flow because groundwater heads are higher than the surrounding streams. During drier periods when groundwater heads tend to be lower than stream heads the streams contribute water to the groundwater system. The alternating transitions of water levels from surface water to groundwater and back to surface water allows for changes in contaminant migration directions and velocities (EnSafe Inc., 1999).

According to Dr. Yelderman, there are not many times during the year that the streams are considered losing streams. The upper most reaches of these streams are above the water table and may allow recharge to groundwater when groundwater levels are low. However, in the lower portions of the watershed, the groundwater water levels will grade toward the stream even when streams are dry (Dr. Joe Yelderman, personal communication, February 2002).

Local deep cretaceous-age aquifers consist of the two regionally extensive Trinity Aquifer sands. These sands supply water to local water supply wells including low and high volume domestic, commercial, and municipal wells. Deep groundwater is largely drawn from two formations within the early Cretaceous Trinity Group: the Hensel Aquifer and the Hosston Aquifer. These aquifers are commonly referred to as the Upper Trinity Sand and the Lower Trinity Sand, respectively. Over 900 feet of shales and limestones separate the deep aquifers from the shallow water-bearing zone beneath NWIRP McGregor (EnSafe Inc., 1999a). The documented recharge zone for the deep aquifers is 70 miles to the northwest, and there are no known local faults that would provide conduits for shallow water recharge to the deep aquifers. No perchlorate has been detected in water samples from deep production and private drinking water wells, which suggests there is minimal potential for cross-connection between the shallow water-bearing zone and the deep Trinity aquifers (EnSafe Inc., 1999a).

The Hensel and Hosston aquifers are composed of fine to coarse sand and are separated by limestone and shale associated with the Pearsall and Sligo Formations. The Hensel aquifer is about 40-100 feet thick and located approximately 1,000 feet below the Main Street Limestone (EnSafe Inc., 1998a). Groundwater in the lower aquifer flows from the northwest to the southeast and has a horizontal rate of movement that varies from about 10 to 40 feet per year. Conversely, groundwater in the upper aquifer may travel up to 100 feet per year (Dr. Joe Yelderman, personal communication, February 2002). Average transmissivities in the Hensel and Hosston aquifers are 2,000 gallons per day per foot (gpd/ft) and 7,500 gpd/ft, respectively. Permeability values average 60 gpd/ft and porosity averages 20 to 35% (EnSafe Inc., 1998a).

5.2.1 Groundwater System

The groundwater system of the study areas is comprised of both shallow and deep aquifer systems.

The rocks that comprise the framework for the shallow groundwater system are a continuation of some of the same units that make up the Edwards Aquifer to the south. This northernmost extension has been designated the Washita Prairie Edwards aquifer by several authors (Figure 5-1) (Cannata and Yelderman, 1987; Cannata, 1988; Myrick, 1989). It was given the name Washita because the Georgetown Limestone of the Washita Group occupies the largest outcrop area and is the most significant water-bearing unit in the groundwater system (Figure 5-2). The Georgetown is subdivided in the McGregor area into 7 members (Figure 5-2). The flow is controlled by topography as water flows from higher head on the hills to lower head in the valleys (Cannata, 1988; Myrick, 1989).

Groundwater from the Main Street Limestone is unconfined, and locally supplies water for livestock and irrigation (i.e., residential and commercial landscaping). This limestone is generally described as buff colored, weathered, highly fractured, and jointed. Dissolution features are also present. In this complex matrix, groundwater levels vary dramatically from near surface to 14 fbgs (EnSafe Ind., 1998). Many wells in the shallow limestone only yield water on a seasonal basis. Groundwater follows the corresponding topographic surface expression and discharges into local streams. The fractured nature of the shallow bedrock complicates hydrogeological analysis of the shallow aquifer system (Peter Allen, personal communication, August 1999).

The lower portion of the Main Street Limestone is less weathered and has fewer fractures, thereby causing it to be generally non-water bearing with lower conductivities. This non-water bearing zone is described as gray or blue colored, unoxidized, and of different water quality than the shallow zone. Perchlorate concentrations appear to be higher in this zone (MW, 1999).

5.2.2 Porosity

Even though the groundwater system technically lies west of the Balcones Fault Zone, a dual porosity system exists due to numerous fractures. Although most of the matrix pore spaces are connected, the fractures can be considered the "effective" porosity and the control on permeability when considering groundwater flow rates to streams.

The rock matrix of limestone and marl has porosity and permeability. Howell (1972) determined the matrix porosity of the Edwards to be about 8% and Davis (1969) reports 8.4% for matrix porosity in limestones, generally. Myrick (1989) found the fracture porosity to range from 1%-2%. However, although the matrix porosity is greater than the fracture porosity, the hydraulic conductivity of the matrix is much less than the hydraulic conductivity of the fracture system. Therefor, the fracture porosity can be considered the effective porosity. This effective porosity is low (0.5% to 3%) but the hydraulic conductivity as a result of the fractures can be quite high (10^{-3} m/s). The fractures and bedding plane separations are the result of weathering, neotectonics and release of overburden pressure. Cannata (1988) found the fracture porosity on outcrops to be greater in the Edwards formation than the Georgetown formation due to dissolution (Figure 5-3).

Average transmissivities in the Hensel and Hosston aquifers are 2,000 gallons per day per foot (gpd/ft) and 7,500 gpd/ft, respectively. Permeability values average 60 gpd/ft and porosity averages 20 to 35% (EnSafe Inc., 1998a).

5.2.3 Hydraulic Conductivity

Hydraulic Conductivity is difficult to measure because the representative elementary volume of the aquifer is often larger than cores or wells can sample. Core samples cannot measure fractures and bedding plane separations accurately and even slug tests do not sample a large enough section of the aquifer. Constant-rate pumping tests have been conducted but they are biased by the fractures encountered in the well bore. Spring discharge and baseflow studies are helpful in sampling larger areas of the aquifer and computing hydraulic conductivity (K) values. Values for hydraulic conductivity have been calculated that range from 10^{-3} m/s to 10^{-10} m/s (Table 5-1) (Clark, 2000).

Alternatively, EnSafe calculated values for hydraulic conductivity using slug tests, with results ranging from 10^{-3} m/s to 10^{-7} m/s (EnSafe Inc., 1999b). The hydraulic conductivity is greater near the surface where there is greater fracturing (Figure 5-4) and perhaps greater dissolution due to increased flux. The hydraulic conductivity may also be greater near faults and along streams because of increased fracturing and dissolution (Figures 5-5 and 5-6).

5.2.4 Heterogeneity

The system is heterogeneous as a result of changes in lithology, weathering, and tectonics. Heterogeneity also occurs locally due to variations in fracture density. However, when large sections of the aquifer are concerned it may be considered homogeneous from an areal extent. Fractures are wider and more dissolutioned in the Edwards Limestone than the Georgetown Limestone (Figure 5-3). The fracture apertures measured on outcrops were found to be less than 1mm wide in the Georgetown but between millimeters to centimeters in width in the Edwards (Collins, 1989). Fractures and bedding plane separations also decrease with depth (Edwards, 1991) (Figure 5-4 and 5-5). Just like the more vertically oriented fractures the aperture width and number of bedding plane separations decrease with depth. The decreases with depth are usually gradual but the occurrence of a resistant bed or lithologic change can result in a rather abrupt change in porosity or permeability. Fractures also increase near faulting and predominantly on the downthrown side of normal faults where most of the movement occurred (Figure 5-5).

5.2.5 Anisotrophy

The system is heterogeneous and anisotropic as a result of changes in lithology, weathering and tectonics. The anisotropy is characterized by greater horizontal hydraulic conductivity compared to vertical hydraulic conductivity (Myrick, 1989). This anisotropy increases with depth because many of the fractures associated with weathering and release of overburden or confining pressure are near the surface and along the weakest direction, which is vertical for layered bedrock. Lateral anisotropy is caused by fracture orientation trends but fracture trends do not necessarily determine the overall anisotropy. The width of fracture openings and the length of the fracture can affect the anisotropy. Anisotropic effects in cones of depression measured from pumping tests do not always coincide with local outcrop fracture orientations even when they are within a few tens of yards away. Lateral anisotropy is not as great as the vertical to horizontal anisotropy. Values of lateral anisotropy determined by azimuthal resistivity techniques range from 1:1.1 to 1:1.73 at 10 and 20 feet deep respectively. Similar to the horizontal to vertical anisotropy, the lateral anisotropy also increases with depth (Edwards, 1991). When anisotropic indicators are studied, the faults have a distinctive orientation but fractures measured in the field and lineations from maps have less distinctive and even different trends. The result is the effect of homogeneity over large areas even though local sites may exhibit strong anisotropy (Figure 5-7).

5.2.6 Recharge

Recharge occurs in uplands where soils are often thinner than in valleys and fractured bedrock can be exposed (Myrick, 1989). Stream channels do not contribute significantly to recharge as only in the uppermost basin are the stream channels above the water table and often they are lined with low permeability fine sediment (Nawrocki, 1996; Myrick, 1989). Rapid and significant water level fluctuations indicate the recharge is rapid and the effective porosity is low (Figure 5-8). Recharge tends to affect water chemistry both from events and from seasons. The climate in the McGregor area is humid-subtropical where evaporation exceeds precipitation and most of the rainfall occurs in the fall and spring. Although recharge can occur at any time, most recharge occurs from precipitation events during winter and spring when soil moisture is high.

Alternatively, EnSafe (1999c) characterizes the climate as semi-arid. EnSafe characterizes the surface soils as predominantly clays up to 12 feet thick (with an average thickness of 3 feet), through which rainwater moves quite slowly. However, EnSafe indicates that desiccation cracks and ant mounds assist in percolation. Once downward percolating water meets the soil-bedrock interface, it can move quite quickly and penetrates the underlying weathered bedrock. EnSafe (1999b) comments that the average yearly precipitation in the study area is 36 inches. The heaviest precipitation events are related to thunderstorms, which normally occur between April and August.

5.2.7 Discharge

Discharge from the groundwater system is primarily to streams through springs and seeps resulting in gaining streams (Figure 5-9). In fact, Collins (1989) comments that "during the late spring months, the aquifer is characterized by high amplitude water table fluctuations following high intensity, short duration precipitation events. At this time water-table levels rise to within a few feet of the surface throughout the drainage basins and the aquifer is described as flooded. Aquifer discharge occurs from numerous small episodic overflow springs and seeps in addition to perennial springs.

The upper basins receive more baseflow per basin area because the streams are shallow and the stream dissection is in the most fractured portion of the aquifer material (Figure 5-10 and 5-11). Groundwater is also lost to evapotranspiration, and much of the evapotranspiration occurs along streams. There is not much evapotranspiration during the winter months while the late summer is usually the driest and hottest time of the year.

5.2.8 Flow

The groundwater system in the McGregor area is a shallow (less than 10m) unconfined system that flows primarily through fractures and bedding-plane separations in limestone and marl (Cannata, 1988; Collins, 1989). According to Ensafe, the water table within the site is inconsistent and flows are altered seasonally. During the wet season groundwater contributes to stream flow because groundwater heads are higher than the surrounding streams. During drier periods when groundwater heads tend to be lower than stream heads, the streams contribute water to the groundwater system. The alternating transitions of water levels from surface water to groundwater and back to surface water allows for changes in contaminant migration directions and velocities (EnSafe Inc., 1999a).

According to Dr. Yelderman, there are not many times during the year that the streams are considered losing streams. The upper most reaches of these streams are above the water table and may allow recharge to groundwater when groundwater levels are low. However, in the lower portions of the watershed, the groundwater water levels will grade toward the stream even when streams are dry (Dr. Joe Yelderman, personal communication, February 2002).

Several factors affect groundwater flow at the site. Although lateral anisotropy can occur locally due to strong fracture orientation trends and faulting trends, the fracture density and connectedness is high enough that groundwater flow directions are controlled primarily by topographic relationships under natural gradients. This means that groundwater flow directions are from hill-to-valley, regardless of the fracture orientation. Groundwater in the lower aquifers flows from the northwest to the southeast and has a horizontal rate of movement that varies from about 10 to 40 feet per year. Conversely groundwater flow rate in the upper aquifer may travel up to 100 feet per year (Dr. Joe Yelderman, personal communication, February 2002). However, when gradients are influenced by pumping the flow will be affected by the lateral anisotropy. In other words, contamination will tend to flow toward streams under natural conditions much as that described by Cannata (1988), but if a pump-and-treat cleanup operation is employed, the cones of depression may be skewed heavily due to local anisotropy and fracture orientation trends.

5.2.9 Chemistry

Groundwater chemistry from shallow zone wells is predominantly calcium-bicarbonate but deeper wells may contain sodium-calcium-bicarbonate water. Total dissolved solids (TDS) increases with depth from the surface and indicates that deeper water has been in contact with the aquifer material longer than the shallower flow systems. Sulfate often occurs in higher concentrations in deeper wells. The higher concentrations of sulfate are interpreted as the result of pyrite oxidation. Pyrite occurs throughout the rock units but the sulfate from oxidation has been leached out or flushed out in the shallower more transmissive zones near the surface and this has not occurred in the deeper less transmissive zones. The major ion concentrations (Ca^+ and $HCO3^-$) remained steady throughout the year in the tributary baseflow but fluctuated in the main stem of the stream (Legg, 1995). The groundwater chemistry is fairly consistent and represents a diffuse flow system. However, ionic concentrations in the aquifer fluctuate slightly in response to seasonal changes in the water table.

There is a shallow weathered zone that has greater hydraulic conductivity than the lower, unweathered zone. The water chemistry in the shallow weathered zone has less total dissolved solids than the deeper unweathered zone and the ionic concentration appears to remain fairly constant throughout the year. The deeper zone ionic concentration fluctuates seasonally.

5.2.10 Data Needs

Although the conceptual model is fairly complete, there are some questions that need to be answered and that require additional data.

- K values used in model calibration runs (Clark, 2000) were obtained from slug tests taken during intermediate water level conditions. As a result, K values for the upper portion of the aquifer were estimated based on these data. Additional slug tests during high water level conditions would be helpful to refine K in the upper portions of the aquifer. These data should be collected with enough values to be used statistically;
- The chemical fluctuations that result from recharge events need to be better understood (Clark, 2000) (Figures 5-12 and 5-13). Chemical data need to be collected during different events at different levels in the aquifer. Tracers could also be used to determine the flow paths of contaminants as a result of recharge events; and
- Groundwater velocities also need to be measured during recharge events and tracers could be used here also.
- Finally, in order to gain a better understanding of year-round groundwater/stream interactions, rainfall-runoff relationships need to be studied during both fall and spring precipitation periods.

5.3 Water Budgets

In order to assess the fate and transport of perchlorate in the study area, the volumes of water moving through the surface water and groundwater system from NWIRP McGregor to the lakes must be better understood. To accomplish this, MWH applied an integrated, groundwater-surface water budget method to describe and quantify these systems.

A water budget quantifies the inflows and outflows in a watershed. A conceptual water budget approach is presented below. This conceptual approach describes water from the standpoint of the lakes as the ultimate receiving body of water. Consequently, the water budget is described from the perspective of the lakes as inflows and outflows. It should be noted, however, that the actual method of calculating water budgets for the Lakes Belton and Waco watersheds by the USACE is slightly different, and will be explained in a later section entitled "Assumptions."

INFLOWS:
Rain (on lakes) + Groundwater Inflow + Treated Effluent Inflow + Stream Inflow

OUTFLOWS:
Municipal Pumping + Dam Releases + Transpiration + Evaporation + Groundwater Outflow

The inflow components of the water budget are rain (on lakes), groundwater inflow, treated effluent inflow, and stream inflow. Rain on lakes is the first component of the water budget. Since rain that flows off the land surface and into streams is accounted for in another component of the water budget, this piece isolates that amount of water that is input to the system by rain falling directly onto Lakes Belton and Waco.

The second inflow component is groundwater inflow. This component of the water budget describes the volume of water that flows from groundwater, out of seeps and springs, and into the streams and lakes. The volume of groundwater flowing into streams and lakes may vary seasonally, depending on the water levels within the shallow groundwater system. It is important to quantify this component because groundwater both on and off NWIRP McGregor has been shown to contain perchlorate. Water from this system may be released from the shallow aquifer system to streams that drain into the two lakes. Groundwater may also be discharged directly into the lakes.

The third component of the water budget is treated effluent inflow into the lakes. This portion of the equation accounts for any discharges of treated effluent to Lakes Belton and Waco, or the streams that drain into these lakes.

The final component of inflow is stream inflow into Lakes Belton and Waco. Major study area streams are shown in Figure 5-14. In addition, if the amount of water originating from each stream flowing into Lakes Belton and Waco is understood, and in particular streams originating at NWIRP McGregor, the mass of perchlorate entering the lakes and the potential dilution that perchlorate is subjected to may be understood better. We note, however, that dilution cannot be determined solely by assessing perchlorate from a mass balance perspective. Rather, complex issues such as lake mixing and preferential stream flow must also be understood. These issues are discussed in Sections 5.3 and 5.4, respectively.

Outflows from Lakes Belton and Waco are municipal pumping, dam releases, transpiration, evaporation, and groundwater outflows. Municipal pumping is the first outflow component of the water budget. It is the amount of water withdrawn from the lakes for drinking water or other uses. Three intake structures draw water directly from Lake Belton and include:

- City of Gatesville Intake: supplies water to the City of Gatesville, North Fort Hood, Coryell, Grove, Flat, Bound, Pancake, Mountain Community, and Fort Gates (City of Gatesville, personal communication, August 1999);

- Bluebonnet Water Supply Corporation Intake: supplies water to the Cities of McGregor, Moody, Bruceville-Eddy, Woodway, Moffat, Pendleton, Elm Creek, and Spring Valley (Bluebonnet Water Supply Corporation, personal communication, August 1999); and
- Bell County WCID #1 Intake: supplies water to the Cities of Belton, Nolanville, Fort Hood, Killeen, Harker Heights, and Copperas Cove (Bell County WCID, personal communication, August 1999).

Downstream of the Lake Belton Dam, the City of Temple operates an intake structure that supplies water to the Cities of Temple, Morgan's Point, Troy, and Little River Academy (Jerry Kean, City of Temple, personal communication, August 1999). However, since this intake is located below the dam, it is not considered in the water budget.

On Lake Waco, one intake structure, operated by the City of Waco, draws water from the lake. The City of Waco intake is located adjacent to the dam and serves the City of Waco and several adjacent communities (Study Area Stakeholders Alliance, 1998).

The second outflow component of the water budget equation is dam releases. Dam releases are a major outflow of the system.

The third outflow from the lakes is due to transpiration by phreatophytes (water-loving plants) that line the periphery of Lakes Belton and Waco. Transpiration levels vary seasonally and daily, with peak transpiration occurring during the summer and during the warmest part of the day. For the purpose of water budget calculations, transpiration is considered to be negligible at both lakes.

Evaporation represents the fourth outflow component of the water budget. Evaporation of water from the lake surfaces represents a major loss from the system.

The last outflow component of the water budget equation is groundwater outflow. Groundwater outflow represents the water that is lost from the lake through the sides and bottom of the lake to groundwater. Groundwater outflow also includes the amount of water that is lost to groundwater by dam seepage or underflow.

5.3.1 Data

Montgomery Watson Harza has collected data from the U.S. Army Corps of Engineers Fort Worth District (USACE, 2001b) quantifying the inflows and outflows of the two lakes. The data include daily lake inflow, reservoir water elevation, gated reservoir outflow, reservoir evaporation, and reservoir pumpage for drinking water use. The time range of inflows and gated outflow for Lake Belton is from January 1, 1972 to December 31, 2000 and for Lake Waco, from January 1, 1965 to December 31, 2000. However, evaporation and pumping records are complete only from June 1993 to present.

5.3.2 Assumptions

As stated previously, the conceptual water budget has been modified by the USACE. Some assumptions were made in the generation of the data provided by the Reservoir Control Branch of the Fort Worth District of the USACE (2001b). For example, since stream gauges are not located at all inflows to the lakes, inflow must be estimated. Thus, inflow is back calculated by observing the change in reservoir storage and subtracting the known outflow volumes. A comparison of the conceptual water budget versus the USACE water budget is shown in Table 5-2.

By this method, streams, treated effluent, rain on the lake, and groundwater, are lumped together as one inflow component. This inflow component is approximated daily by examining the change in storage of the reservoir, which is related to the elevation of the lake by a unique storage-capacity curve. Since gated dam outflows and pumping are quantified, and evaporation occurring on the lake surface and dam underflows may be estimated, total lake outflows are well quantified.

The gated reservoir outflow data supplied by the USACE also include an estimate for groundwater outflow as groundwater leakage beneath the dam, but does not include estimates for reservoir losses to groundwater through the bottom of the reservoir. Thus, total lake inflows are approximated by examining how the lake storage changes in response to known outflows.

5.3.3 Data Presentation and Description

The data utilized for water budget calculation are described in this section.

Lake inflow is the first water budget component calculated by the Reservoir Control Branch of the Fort Worth District of the USACE (2001b) presented. Lake Belton and Lake Waco inflows are graphically depicted in Figure 5-15 and Figure 5-16**,** respectively. Both figures exhibit similar patterns, with higher inflow typically from early spring (March) until mid-summer (July), and lower inflow during the remainder of the year and during droughts. During dry periods, inflow to both lakes may drop to nearly zero. Conversely, during periods of higher-than-normal rainfall, inflow may begin to increase as early as December and continue until around November of the following year. The average inflow is 694 cubic feet per second (cfs) for Lake Belton and 489 cfs for Lake Waco. During 1975, 1977, 1986, 1992, and 1997, central Texas was subject to periods of extended or intense rainfall. During these times, lake inflow was several orders of magnitude higher than average. The maximum inflow during the period of record is 81,348 cfs and 134,403 cfs for Lake Belton and Lake Waco, respectively.

Inflow is a result of streams, groundwater, treated effluent, and precipitation.

Precipitation data collected at the McGregor station, Lake Belton, Lake Stillhouse Hollow, and Lake Waco are presented in Table 5-3.

Historic precipitation records are presented in order to understand the magnitude of this water budget component for the City of McGregor, Lake Stillhouse Hollow, Lake Belton, and Lake Waco. The City of McGregor is located approximately mid way between Lakes Belton and Waco and adjacent to NWIRP McGregor. At this rain gauge, precipitation is above the average forty-three percent of the years. In addition, precipitation is recorded at Stillhouse Hollow, located approximately 5 miles south of Lake Belton (since recording of precipitation was ceased at Lake Belton in 1992). According to Table 5-3, the greatest range in precipitation levels was recorded at McGregor. Lake Waco recorded the wettest average precipitation. The importance of precipitation in the water budget is clear, as patterns in lake inflow volumes (Figures 5-15 and 5-16) mimic those of lake inflow.

Reservoir elevation is important to the overall water budget because it accounts for changes in storage in the system. Reservoir elevation data are presented graphically in Figures 5-17 and 5-18 for Lake Belton and Lake Waco, respectively. Trends in these figures generally mimic those of lake inflows, although changes in reservoir elevation lag behind fluctuations in inflow. Reservoir elevation in both figures centers about the design elevations of each reservoir, which are 594 feet for Lake Belton and 454 feet for Lake Waco. Nevertheless, reservoir elevations fluctuate in response to changes in volumes of inflow. For instance, both reservoirs exhibited elevated lake elevations in response to heavy rains in 1974, 1977, 1990, 1992, and 1997. The maximum recorded lake elevations were 595.25 feet and 488.47 feet for Lake Belton and Lake Waco, respectively. Similarly, Lake Belton water elevation decreased during periods of drought in 1972, 1978, 1984, 1988, and 1996, with a minimum of 592.12 feet. In contrast, Lake Waco maintained more constant lake elevations during droughts, with levels below 450 feet recorded only in 1978, 1984, and 2000.

The second water budget component discussed is gated flow and is presented in Figures 5-19 and 5-20. The peaks of gated flow plots generally mirror those of reservoir elevation; periods of high lake elevation are generally indicative of periods of increased gated flow, with a maximum rate of 9,484 cfs for Lake Belton and 19,957 cfs for Lake Waco. However, periods of depressed lake elevation generally are reflected as times of reduced or curtailed gated flow, with minimum estimated rates of 0 cfs for both lakes. Average gated flow for Lake Belton is 583 cfs and 396 cfs for Lake Waco. Gated outflow data supplied by USACE (2001b) for Lake Belton do not include diversions to the City of Temple’s intake structure, as the City of Temple’s water supply is released through Belton's low flow gates or floodgates. The city of Temple then pumps water released from Lake Belton from their low water dam, which is approximately 1 mile downstream of Belton Dam (USACE, 2001b).

The third component of the water budget is evaporation. Evaporation is directly related to solar radiation and temperature. Thus, evaporation’s annual cycles are easily distinguished in Figures 5-21 and 5-22. For example, evaporation typically peaks in the summer months of June, July, and August and falls to a minimum during the cooler months of November, December, January, February, and March. Evaporation was estimated with maximum daily flows peaking at approximately 450 cfs for Lake Belton and under 400 cfs for Lake Waco.

Pumping for municipal water supplies represents the fourth and last component of the water budget. The annual pattern of pumping tends to mimic that of evaporation very closely, since municipal water demands reach a maximum in the summer months and a minimum need during the winter. Plots of pumping are shown in Figures 5-23 and 5-24. Peak daily values of pumping typically reach a maximum of approximately 170 cfs for Lake Belton and approximately 80 cfs for Lake Waco. Minimum pumping values fall to approximately 30 cfs for Lake Waco and under 20 cfs for Lake Belton. Average pumping flows are approximately 70 cfs for Lake Waco and 30 cfs for Lake Waco.

Groundwater outflow is not estimated by the USACE for either lake. However, the USACE includes an estimate of groundwater seepage under each lake's dam as part of the gated flow outflow values provided. Unfortunately, no attempt is made by the USACE to estimate the volume of water lost annually through the bottom of each reservoir. It is likely that this volume is not significant when compared to other components of the water budget.

Using the data presented, the total outflow of each lake is calculated by summing gated flow, evaporation, and pumping. Because data for evaporation and pumping are available starting in June 1993, Figures 5-25 and 5-26 are truncated, compared to those of gated flow. The plots show that outflow from the two lakes ranges from almost zero to approximately 7,000 cfs in Lake Belton and from almost zero to nearly 15,000 cfs in Lake Waco. Peak outflows generally occur in spring.

Figures 5-27 and 5-28 represent inflow minus total outflow, or change in storage, in each reservoir. In these figures, inflow – total outflow fluctuates a great deal around 0, caused by changes in lake elevation seen in Figures 5-17 and 5-18. However, Figures 5-27 and 5-28 are different than the information presented for lake elevation in Figures 5-17 and 5-18. For example, in Figures 5-17 and 5-18, peaks in lake elevation are evident during the winter and spring after January 1997 and 1998.

5.3.4 Water Budget Calculations

Water budgets were calculated annually from 1994 to 1999, with spreadsheets developed by MWH that utilize data provided by the USACE (2001b). This time period was chosen, since evaporation and pumping data are unavailable before June 1993 and inflow estimates are incomplete in 2000 and 2001. Calculations were converted on a daily basis from cfs to AF and averaged to generate annual results. Evaporation data provided by the USACE (2001b) were multiplied by an evaporation pan coefficient unique to each lake (also provided by the USACE) to produce estimate of evaporation in inches for each lake. The value of evaporation in inches was multiplied by the lake's surface area to produce evaporation in AF for each year. In addition, changes in storage of each lake were calculated by observing the trends in lake elevation. Daily observations of lake elevation were rounded to the nearest tenth of a foot from 1994 to 1999. Values of lake capacity (in AF) from each lake's storage capacity curve were interpolated between each foot of lake elevation. Thus, a value of storage (AF) was calculated for daily lake elevation. Then, the change of storage between two days was calculated for the period of record and summed for each year to estimate the annual change of storage for each lake.

In addition, values for change in storage (column J) were calculated by MWH to gain a better understanding into the origin of the discrepancy between gated flow recorded by the USACE (column F) and the calculated gated flow (column K). Change of storage (in AF) was estimated by examining changes in the daily lake elevations. For each day, elevation was rounded to the nearest tenth of a foot. Then, the storage was calculated using the lake's capacity curve by correlating storage in AF for a given lake elevation. Consequently, the daily change in storage was calculated by subtracting the storage of one day with the storage of the previous day. Finally, annual change in storage was calculated by summing daily change in storage for an entire year.

5.3.5 Results

The results of the calculations described above are presented as minimum, maximum, and average years for Lakes Belton and Waco Table 5-4. Since inflow is the driver for the water budget, the years are ranked based on inflow. For example, 1999 is the year of minimum inflow, and 1997 is the year of maximum inflow.

As indicated in Table 5-4, typical volumes for each component of the water budget are provided for Lakes Belton and Waco during minimum (1999), maximum (1997), and average flow years (the arithmetic mean of 1994 to 1999 has been calculated). For Lake Belton, the minimum inflow was 148,142 AF in 1999. This amount was 66,054 AF less than the total outflows of the lake (evaporation + pumping + gated flow). Similarly, Lake Waco's minimum inflow was 71,683 AF, which is 36,376 AF less than total calculated outflows. However, the differences between inflow and total outflow may be accounted for by changes in lake storage. For instance, Lake Belton experienced a decrease in storage of 65,243 AF, which is very close to the 66,054 AF of net outflow discussed above. Similarly, change in storage calculations for Lake Waco revealed that the reservoir lost 39,679 AF, which is approximately the same as 36,376 AF net outflow. As previously mentioned, the above calculations do not take into account groundwater outflow through the reservoir bottoms, since estimates were not provided by the USACE due to the relatively small volume of this term. However, the preceding calculations suggest that such losses are negligible.

Also for 1999, percent difference values (gated flow – calculated gated flow)/(gated flow) in column L are high. For example a percent difference of 63.98 and 82.75% were calculated for Lakes Belton and Waco, respectively. These percent difference values may be high because water budget calculations do not capture annual changes in storage. For this reason, calculated change in storage (column J) is so high, at –65,243 and –39,679 AF for Lake Belton and Lake Waco, respectively. Similarly, this may explain why percent difference ((inflow – total outflows)/(inflow)) in column I are so great in 1999. If change in storage were zero (lake levels do not change) then column I would be zero. In reality, lake elevations do change and the resulting change of storage must be accounted for in the water budget. Change in storage calculations will be discussed in greater detail later in this section.

Estimates of evaporation and reported values of pumping for Lake Waco are approximately half of those for Lake Belton. For example, pumping for domestic water uses on Lake Belton ranges from 46,896 to 59,482 AF per year. Thus pumping for drinking water represents between 93 and 95 percent of inflow to Lake Belton. On Lake Waco, drinking water pumping remains relatively steady between 26,086 AF and 31,326 AF per year, representing between three percent and 44 percent inflow (a very dry year) of Lake Waco's, depending upon inflow and pumping volumes. Similarly, the average evaporation on Lake Belton was 64,459 AF per year, while the average evaporation on Lake Waco was only 30,423 AF per year.

In addition to 1999, Table 5-4 also shows water budget components for 1997, the year with the largest inflow values. During this year, inflow was estimated by the USACE (2001b) at 1,649,561 AF and 960,999 AF for Lake Belton and Lake Waco, respectively. The inflow rates for 1997 are over 10 times the inflow values measured in 1999. Evaporation values for 1997 are slightly less than in 1999 for each lake, while pumping rates remain approximately the same. In addition to higher rates of inflow, gated flow values are over 10 times the rate recorded in 1997. One discrepancy between 1997 and 1999 is the difference between (inflow – total outflows) and the calculated change in storage. For Lake Belton, the quantity (inflow – total outflows) is 21,687 AF, while the calculated change in storage is 45,161 AF. The cause of the discrepancy between the two numbers is unclear, although both estimates indicate that more water is flowing into the lake than is leaving, resulting in an increase in storage. Similarly, the quantity (inflow – total outflows) for Lake Waco for 1997 is 4,051 AF, while calculated change in storage I –730 AF. The difference between these two values may be within the range of error associated with the water budget calculations. While Table 5-4 shows all the components of the water budget, Table 5-5 shows only the components relative to change in storage. Table 5-5 is presented to explain differences caused by change in storage.

Table 5-5 shows gated flow [C], calculated gated flow [D], and the difference between these two volumes [E]. Gated flow is what was measured to be released from the dam. Calculated gated flow is equal to inflow – (evaporation + pumping). The difference between these values (gated flow – calculated gated flow) [E] should be equal to the calculated change in storage [F]. The percent difference between these two volumes is shown in the final column [G].

For most cases, column E (gated flow – calculated gated flow) and F (calculated change in storage) are similar, in terms of volume for both lakes. It is shown that the percent difference [G] between the gated flow – calculated gated flow and calculated change in storage ranges from –1.24 percent in a minimum inflow year to –304.31 percent in an average year at Lake Belton. For Lake Waco, column G values (percent difference:

((gated flow – calculated gated flow)/(gated flow)) range from 8.32 percent in a minimum inflow year to 654.93 percent in a maximum inflow year. It is understood that a large percent difference exists in maximum inflow years. However, in minimum inflow years, the percent difference is relatively small. MWH believes that the large percent difference in maximum flow years is caused by rapid lake elevation changes due to heaving precipitation events. As lake elevation has been reported at a daily basis, this represents a data gap, since lake elevation measurements at a higher frequency may help refine this calculation. However, MWH feels that this data gap is relatively unimportant. While the percent difference numbers may seem high (particularly during maximum inflow years), it is important that the difference between columns E and F may be insignificant, when compared to the overall inflow volume shown in column C. For example, the difference between –21,687 AF and 45,161 AF (columns E and F for Lake Belton's maximum flow year of 1999) is 23,474 AF. The volume 23,474 AF is only 1.55 percent of the total inflow of 1,510,657 AF. Thus, the water budget calculations presented here appear to be reasonable.

Utilizing the water budget discussed above, residence times (also known as flushing rates) for Lake Belton and Lake Waco may be calculated. Flushing rates for each lake are discussed later in Sections 5.4.1.3 and 5.4.2.3.

In addition to data provided by EnSafe (1999a), the Navy established additional stream gauges in the vicinity of NWIRP McGregor in the year 2000. The stream gauge network as of October 31, 2000 is shown in Figure 5-29. This network consists of five gauges in the Lake Belton watershed, and four gauges in the Lake Waco watershed. The NWIRP stream gauges and periods of record as of October 31, 2000 are summarized in Table 5-6.

The stream gauges record measurements of rainfall, stream stage (or level), velocity, and flow rate every 15 minutes. Unfortunately as shown in the table, the period of record of these stream gauges is at most eight months long. In order to quantify flows on these streams, it is important to analyze a period of record of at least one year. Perhaps, a stream flow analysis may be made upon receipt of lengthier stream gauge records. However, conclusions based upon more limited (although longer periods of record) in the previous section regarding percent of flow from NWIRP McGregor into Lakes Belton and Waco are probably valid.

5.3.6 Water Budget Conclusions

The water budget presented in this section for Lakes Belton and Waco is the most accurate that may be calculated based upon the data available. In 1997, the difference between (inflows – total outflows) on Lakes Belton and Waco is well accounted for in the calculated change of storage. However, in 1997, the difference between (inflows – total outflows) on Lake Belton is not entirely accounted for by the calculated change of storage, perhaps due to discrepancies in calculation methods. Lake Waco does not exhibit this pattern in 1997. Similarly, the average of years 1994 to 1999 for Lake Belton indicates a disparity between (inflows – total outflows) and calculated change of storage.

The cause of this difference may be due to limitations in the method of calculation employed by the USACE. Finally, average values of (inflow – total outflows) versus calculated change of storage for Lake Waco between 1994 and 1999 are very similar, indicating that the actual average water budget may be very similar to that presented in Table 5-4.

The water budget could be more accurately determined if a greater number of streams flowing into Lakes Belton and Waco were gauged. In particular, the contribution of flow from streams originating on NWIRP McGregor may be better understood if permanent stream gauges were established on Harris and Willow Creeks and the South Bosque River in the Lake Waco watershed and on Station Creek in the Lake Belton watershed.

5.4 Surface Water Attributes

This summary of the attributes of Lakes Waco of the Bosque River watershed and Lake Belton of the Leon River watershed is based on published and technical report data and on the personal observations of Dr. Lind. The principal attributes of Lakes Waco and Belton that are relevant to the fate and transport of river-borne materials are discussed in the subsections below.

5.4.1 Bosque River Watershed

Headwaters of several larger streams including the South Bosque, Middle Bosque, and Harris Creek are located within the Bosque River watershed. These streams and associated minor tributaries flow east and northeast 10 to 15 miles to join the northward flowing Bosque River at Lake Waco, a result of damming the Bosque River. Approximately 5 miles downstream from Lake Waco, the Bosque River enters the Brazos River.

5.4.1.1 Lake Waco Attributes

Two very geologically different watersheds supply Lake Waco (Lind, 1976). The Grand Prairie physiographic province encompasses approximately 80% of the reservoir's watershed encompassing the North Bosque River, Middle Bosque River, and Hog Creek. The Grand Prairie is characterized by thin calcareous soils and relatively low erosion (sediment production is approximately 0.5 AF $mile^2$). Traditionally, agriculture was dominated by open range grazing of cattle and goats. Recently, the region has had a great increase in confined animal feeding operations, which is suspected of nutrient, organic matter, and microbial pollution. The other watershed is the Black Prairie physiographic province and encompasses approximately 20% including the South Bosque River. This province has deeper soils and higher erosion (sediment production is approximately 0.9 AF $mile^2$). Traditionally agriculture in this province is dominated by row-crop farming. The study area is primarily comprised of the Grand Prairie physiographic province, however, the Black Parry physiographic province is found in the far eastern portion of the study area. In terms of characteristics of Lake Waco itself, the reservoir has a volume of 144,830 AF and a normal pool elevation of 455.0 feet above mean sea level (TWDB, 1995).

The principal attributes of Lake Waco that are relevant to the fate and transport of river-borne materials include the following: mixing patterns, flushing rate, water transparency, lake morphometry, and trophic state. Each of these attributes is discussed below.

5.4.1.2 Lake Waco Mixing Patterns

Unlike most similar size reservoirs of the region, Lake Waco is polymictic. It does not develop persistent density (thermal) stratification (Kimmel and Lind, 1972). The bottom water temperature is rarely more than 2 or 3 degrees cooler than the surface. For comparison, temperature of the hypolimnion (bottom layer) of stratified Lake Belton in mid summer is typically 15 degrees Celsius (Lind, 1982) while Lake Waco's bottom water is 23 to 27 degrees Celsius. The warm temperature of the bottom of Lake Waco results in high deep-water bacteria metabolism. Assuming traditional temperature-metabolism coefficients, the metabolic rate would approximately double that of Lake Belton's deep bacteria (Atlas and Bartha, 1998). Dissolved oxygen solubility in water is a function of temperature– the higher the temperature, the lower the solubility. At 25 degrees Celsius the maximum oxygen is approximately 8-mg l^{-1} (ppm) whereas at 15 degrees Celsius it is almost 10-mg l^{-1} (Lind, 1985). Because of this low initial concentration and the relatively high content of dissolved organic matter, even with polymixis, dissolved oxygen diminishes with depth. The concentration rarely reaches zero (with attendant redox effects) but does so briefly in scattered depressions (McFarland et al., 2001). Because of the polymixis and wind exposure, we generally assume a regular surface to bottom mixing of dissolved and suspended materials.

5.4.1.3 Lake Waco Flushing Rate

The flushing (water exchange) rate of a reservoir is a significant physical feature. Most main stem reservoirs have a high flushing rate and Lake Waco is no exception. Thus the mean water retention time is short. Mean multi-year flushing time is one year. (Kimmel and Lind, 1972; Rendow-Lopen, 1997). But, because of the great climatic variability of the region, water retention time is highly variable among years with a range of approximately 0.1 to 5 years. (McFarland et al., 2001).

MWH has also estimated flushing rates for Lake Waco. Based on the inflow values stated above, and assuming that changes in reservoir storage are zero, reservoir flushing rates may be calculated. Reservoir flushing rates are calculated by dividing lake volume (AF) by inflow (AF/year) using the following formula:

Flushing Rate (years) = (lake volume AF) / (inflow AF/year)

Table 5-7 shows flushing rates for both Lakes Belton and Waco (results for Lake Belton will be presented later in Section 5.4.2.3) for minimum (1999), maximum (1997), and average inflow years. Flushing rates presented in this table are average and do not account for the flushing rate of individual water molecules, which may be much faster or much slower than the average flushing rate. While it is stated above that the mean multi-year flushing rate is 1.0, MWH found that, the mean flushing rate was 0.33 years. MWH also found that Lake Waco's maximum flushing rate (during minimum inflow) was 2.02 years. In addition, Table 5-7 shows that the minimum flushing rate (during maximum inflow) was 0.15 years. All three of these flushing rates are within the range of 0.1 to 5 years presented in McFarland et al (2001). Further investigations that consider the actual flow dynamics of the lakes are required to accurately quantify the possible range of flushing rates on the level of individual water molecules.

The uptake and biogeochemical cycling of nutrients or pollutants is dependent upon flushing. The longer the water retention time the more opportunity of biological uptake, use, and release for reuse. Under high flood-flow conditions the water retention time is less than one week. For many plankton algae, this is less than the species generation time even during warm months (Reynolds, 1997). For lake bacteria it equals two or three generations at summer temperatures. Thus under such high flushing, any material entering the reservoir has much less probability of biological uptake than under normal flushing rates. It is difficult to accurately assign discharge contributions to the South Bosque River, as no gauge exists on the South Bosque.

5.4.1.4 Lake Waco Water Transparency

Water turbidity is primarily caused by inorganic (clay), but periodic algal blooms also contribute. Suspended clay is another major factor in the lake's limnology (Lind, 1986; Lind and Dávalos, 1990). It governs photosynthesis and prevents nutrient loads being fully expressed. Nutrient loading models consistently over-predict primary (algal) production because of the limiting effect of shallow light penetration. Electrically charged clay surfaces bind organic matter, inorganic nutrients, and presumably charged and/or polar molecules of anthropogenic origin (Lind and Dávalos-Lind, 1999). In other lakes, such binding of pollutants has been shown to be both a source and a sink for the pollutant to the biota (Lind et al., 2000). Whether clay sorption functions as a source or sink depends both on ambient water chemistry, the nature of the biota, and the chemical characteristics of the contaminant itself. It is unknown how biologically available is such material in Lake Waco. Sedimentation of clay (and silt) now is minor relative to reservoir capacity loss (Dunbar et al., 1999; TWDB, 1995). Volume loss is less than one-percent per year.

5.4.1.5 Lake Waco Morphometry

Another factor that is closely linked to other factors is the exposure to wind action. Although the lake depth is a factor, it is the exposure that prevents density stratification and maintains high clay turbidity. Two fetches (distances over which the wind acts) are aligned with directions of prevailing winds– WNW to ESE during the winter and SSW to NNE during the summer. The only sheltering surroundings are to the east– an infrequent direction for the wind in central Texas. Strong wave action is common and causes shoreline erosion. This re-suspends clays, contributes to turbidity, and prevents formation of shoreline littoral macrophyte communities. Unlike clearer reservoirs, there is almost no development of rooted or floating plants (Lind, 1979) except the American water willow, which occurs at the shoreline in bays. As noted above, the wind mixing assures both horizontal and vertical mixing of dissolved and suspended materials. Wind-driven water masses (currents) can be especially complex in reservoirs because of interaction with river flows and because of the irregular nature of the shoreline. Current patterns within Lake Waco have never been determined, but because of exposure and shape of reservoir, are probably complex.

In addition to wind-driven mixing, Lake Waco has seasonal vertical mixing near the dam produced by the presence of a "bubbler". Various devices are used in lakes and reservoirs to prevent or reduce deoxygenation of deep water. The "bubbler" in Lake Waco is one of the more frequently used. Simply put, this is an over-sized version of an aquarium air-stone. This was installed in 1970 (Biederman and Fulton 1971). When installed it consisted of a 2.8 m^3 min^{-1} air compressor located on the dam near the outlet tower. The air is fed into a 1000 ft. long galvanized one inch diameter pipe extending to the deepest portion of the reservoir where it terminates in a section of pipe in which small holes are drilled at 6 inch intervals. When operating this stream of bubbles produces a "boil" approximately 60 ft. diameter. The rising bubbles create an upwelling, which brings to the surface materials dissolved and suspended in the bottom water. The surface water near the boil has slightly elevated turbidity and phosphorus concentrations. The impact of this bubbler are very localized and probably have little effect on the lake water quality more than 200 ft. from the "boil" (Roark and Lind 1988).

5.4.1.6 Lake Waco Trophic State

The trophic state describes the reservoir's productivity. Oligotrophic and eutrophic are terms to describe reservoirs with low and high production respectively. Lake Waco is classified as moderately eutrophic (Lind et al., 1993). Its annual primary (photosynthetic) production is moderate at 300 to 400 g C m^{-2} y^{-1} but apparently (no recent measurements) is increasing. Production was high after filling (1960s), declined in the 1970's and 80's when it was classified as mesotrophic, and increased in the 1990's (Kimmel and Lind, 1972; Lind, 1979; Rendon-Lopez, 1997). Undesirable features of eutrophic waters, including Lake Waco, are a high incidence of nuisance algal blooms, the production of taste and odor compounds in the water, and a high content of dissolved organic matter, which may form complexes with other materials. The formation of tri-chloromethane by the coupling of dissolved organic matter with chlorine during drinking water disinfection is an example. Algal biomass in Lake Waco, expressed as chlorophyll, rarely exceeded 15-µg l-1 before 1985 while in the 1990's it rarely was less than that value (Lind, 1979; Rendon-Lopez, 1997; McFarland et al., 2001). Occasional blooms of cyanobacteria (bluegreen algae) occur (Dávalos-Lind and Lind, 1999). Production in Lake Waco is chemically governed by supply of phosphorus (Kimmel and Lind, 1972; Dávalos-Lind and Lind, 1999) and physically by light as described above (Lind, 1986). The algal growth-promoting potential of inflow water was measured monthly for two years and was much greater for South Bosque River water than for any other inflowing water (Dávalos-Lind and Lind, 1999).

A feature, perhaps unique in Texas, is that the reservoir is a re-impoundment. The present reservoir is positioned directly over an older reservoir. The first dam, which created Lake Waco, was constructed in 1929. By the 1950's siltation had rendered it less than adequate to meet the needs of the region (Kimmel and Lind, 1972). The present reservoir was then impounded in 1965-66. The new dam was sited a short distance downstream from the original dam. Under low water conditions, the top of the old dam, though still submerged, can be seen. This feature creates unusually complex lake bottom topography. The thalweg (old river channel) is distorted and there are pocket-like depressions in the plunge pools below the old dam (it is in these that one finds anoxia). Although unmeasured, the presence of the old dam significantly affects current patterns.

5.4.2 Leon River Watershed

Surface water drainages south and west of NWIRP McGregor in the Leon River watershed flow south and southwest, draining into Lake Belton, 6 miles south of the Naval Facility. Major tributaries in this watershed include Station Creek, Stampede Creek, Owl Creek, and Cowhouse Creek. Approximately 40-60% of the base stream flow in these creeks is contributed from groundwater discharge in the upper portions of the watershed (Joe Yelderman, personal communication, August 1999).

5.4.2.1 Lake Belton Attributes

The Leon River is the principal source of water to Lake Belton. Seasonally intermittent Cowhouse Creek supplies minor amounts of water also. Belton Reservoir lies in a long (approximately 21-mi.), narrow and tortuous valley in a generally southerly flowing segment of the Leon River (Lind, 1976). The Cowhouse arm to the west by contrast is a relatively straight valley. The reservoir is at the eastern limit of the Edwards Plateau in the Grand Prairie area. The shoreline is composed of Edwards and other limestone and clay. The soils are shallow and calcareous. Approximately 75% of the watershed is used for grazing. This land is a juniper-oak savanna. Overgrazing has resulted in erosion and loss of considerable native prairie grass cover. Row crop agriculture for maize, corn, cotton and hay occupies the bottomlands. The Leon River flow consists of seasonal rainwater and regulated releases from Proctor Reservoir 62 miles upstream. There are also several minor perennial springs, some of which are subsurface. In terms of the reservoir itself, Lake Belton is formed by a dam of the Leon River constructed in the 1950s. Lake Belton has a volume of 434,500 acre-feet (AF) and a normal pool elevation of 594.0 feet above mean sea level (Texas Water Development Board 'TWDB', 1994).

The principal attributes of Lake Belton that are relevant to the fate and transport of river-borne materials include the following: mixing patterns, flushing rate, water transparency, lake morphometry, and trophic state. Each of these attributes is discussed below.

5.4.2.2 Lake Belton Mixing Patterns

Lake Belton is classified as a warm monomictic reservoir. This is based on the fact that the lake water rarely reaches a winter temperature below 4 degrees Celsius (the temperature of maximum water density) and that it experiences one period of holomixis (top to bottom mixing) and one period of density stratification (epilimnion, metalimnion, hypolimnion) (Hutchinson, 1957). Water temperature at the onset of stratification (typically in late April to early May) is relatively warm (15 to 16 degrees Celsius) producing a warm hypolimnion (Lind, 1998; Rutherford, 1998). The warm temperature of the bottom results in high deep-water bacteria metabolism (Atlas and Bartha, 1998). Dissolved oxygen solubility in water is a function of temperature– the higher the temperature, the lower the solubility. At 15 degrees Celsius, the maximum oxygen is approximately 10-mg l^{-1} (ppm), whereas at 4 degrees Celsius it is almost 13-mg l^{-1}. Because of this lower initial concentration and the relatively high content of organic matter, dissolved oxygen diminishes rapidly with depth (Lind et al. in press). The concentration reaches zero throughout the hypolimnion (with attendant redox effects) by the first part of July and remains so until autumnal mixing, typically during mid November. Oxygen depletion in Lake Belton follows a heterograde pattern (Lind, 1982). This means that oxygen concentration does not decline directly with depth, but has some intermediate depths with greater oxygen demand than at depth. This is usually the consequence of a large community of bacteria located on the surface of some inner density layer. The sharp increase in water density supports the bacteria and retards the sinking of organic matter on which the bacteria feed. Such a pattern creates a complex redox pattern in the water column potentially affecting solubility of various materials.

5.4.2.3 Lake Belton Flushing Rate

The flushing (water exchange) rate of a reservoir is a significant physical feature. Most main stem reservoirs have a high flushing rate and Lake Belton is no exception. Thus, the mean water retention time is short. Mean multi-year water retention time is 1.9 year. But, because of the great climatic variability of the region, water retention time is highly variable among years with a range of approximately 0.46 to 6.3 years. MWH also estimated flushing rates for Lake Belton using the same methodology described in Section 5.4.1.3. Table 5-7 shows that Lake Belton's average flushing rate is 0.64 years, while the minimum flushing rate (during years of maximum inflow) is 0.26 years, and the maximum flushing rate (during years of minimum inflow) is 2.93 years. The minimum flushing rate estimated by MWH of 0.26 years is slightly less than 0.46 years shown above, but this difference may be insignificant. The maximum flushing rate approximated by MWH of 2.93 years is within the range presented above.

Regional hydrology is driven by storm events. The great length of this serpentine reservoir mitigates the impact of storm flows in the lower region (Lind, 1984). The range of mean daily minimum to mean daily maximum discharge is from less than 1 to greater than 49000 cfs. Under even moderately high discharge, it is probable that Leon River water makes up most of the water in the Cowhouse Creek arm.

5.4.2.4 Lake Belton Water Transparency

Water transparency changes along the length of the reservoir. The upper riverine portion of the reservoir is high in nutrients and suspended clay. These factors reduce the water transparency in this portion of the reservoir. The lower portion of the reservoir has unusually high transparency for the region. The photic depth (1% surface illumination) in this portion of the reservoir is typically 8 to 10 m (Lind, 1982). . Clay has been lost via sedimentation and because of the narrow and torturous valley, wind action is not significant in resuspension (except for the Cowhouse Creek arm). Biogenic turbidity (algae and bacteria) in the lower portions is present only for a short time in the spring. Subsequent depletion of nutrients through sedimentation of the dead biota produces a prolonged "clear water phase."

5.4.2.5 Lake Belton Morphometry

The reservoir's morphometry and alignment to the prevailing winds enable the long period of stratification (Lind, 1982). The down-reservoir deeper portion is aligned perpendicular to the prevailing westerly winds. It is situated in a relatively deep valley that provides shelter. The maximum fetch to northwesterly winds is only about 3 mi. It is rare that wind-warnings have prevented use of boats on the lake. The top of the hypolimnion for much of the stratification period is approximately 18-m. The lower 8 to 10 miles of reservoir are of sufficient depth to stratify. Significant portions of the lake of lesser depth are not stratified (Cowhouse arm and upper Leon River arm).

The 21-mile length of the Leon River arm is a significant feature of this reservoir. This length is responsible for the transparency and trophic state of the down-reservoir portion (Lind, 1982). River-borne materials such as suspended clay and dissolved nutrients are deposited as sediment and/or biologically processed before the river water reaches the main body (lacustrine region) of the reservoir. By contrast, the upper riverine portion of the reservoir is high in nutrients. The planktonic biota changes along the course of the reservoir (Lind, 1984). For five regions between headwater and dam, a similarity index was applied to the phytoplankton. None of the five sites were taxonomically similar to one another.

5.4.2.6 Lake Belton Trophic State

The trophic state describes the reservoir's productivity. Oligotrophic and eutrophic are terms to describe reservoirs with low and high production respectively. Lake Belton may be classified variously because of its length. Its annual primary (photosynthetic) production has not been measured. However, it is possible to indirectly estimate production from the rate of hypolimnetic oxygen depletion; i.e., the reduction of carbon in the epilimnion is approximately equal to the oxidation of organic carbon in the hypolimnion. Hypolimnetic oxygen deficit measurements in the lacustrine region placed this region as mesotrophic (Rutherford, 1998). These data are consistent with measures of algal biomass (as chlorophyll). The annual mean epilimnetic chlorophyll *a* concentration was less than 10-µg l^{-1}. In the riverine region the annual mean was a very eutrophic 69-µg l^{-1}. In the lacustrine region late in the stratification period, chlorophyll was below detection limits. In the riverine region, concentrations > 200 µg l^{-1} occurred (Lind, 1982, 1984).

Undesirable features of eutrophic waters, including Lake Belton, are a high incidence of nuisance algal blooms, the production of taste and odor compounds in the water, and a high content of dissolved organic matter, which may form complexes with other materials. Occasional blooms of cyanobacteria (bluegreen algae) occur seasonally throughout Lake Belton (Lind, 1984). The algal growth-limiting nutrient has not been determined for this lake. One can speculate that the occurrence of cyanobacteria (some nitrogen fixing) is evidence that other taxa are excluded by the shortage of nitrogen. By September, cyanobacteria make up greater than 75% of the phytoplankton community for all reservoir regions.

There is evidence of unusual properties of the hypolimnion anaerobic bacterial community of Lake Belton (Rutherford, 1998; Lind et al. in press; Christian et al., in press). For most lakes, the abundance and individual cell volumes of bacteria are inversely correlated with oxygen; i.e., anoxia results in more and larger bacteria. For Lake Belton, this is not so. For the hypolimnion near the dam, there was no correlation of either abundance or volume with oxygen concentration. For the hypolimnion near the upper reservoir limits of stratification, the correlation was strongly direct. It has been postulated that this may be the result of different types of organic matter to promote bacterial production. The hypolimnion in this region is only the thalweg (old river channel) which may be transporting organic materials of river origin rather than of lake origin. Based on water temperature (density), such underflows can occur transporting river-borne materials great distances without mixing with the mass of reservoir water. We are presently conducting research into this phenomenon.

5.5 Migration Pathway Analysis

This section integrates information on the available nature and extent of perchlorate contamination within the study area, the hydrological conceptual model, and perchlorate fate and transport characteristics to assess potential migration pathways between perchlorate sources and receptor points. Included is a discussion of potential data gaps in the existing sampling information, and recommendations for future sampling activities to better understand the extent of perchlorate contamination within the Bosque and Leon River watersheds.

5.5.1 Nature and Extent of Contamination

Available information regarding the nature and extent of perchlorate contamination within the study area was obtained from Navy investigations (EnSafe, 2001b), TNRCC, and TIEHH. Sampling locations and ranges of concentrations detected in media for which validated data are available (i.e., soil, storm water, groundwater, surface water, and sediment) are presented in Figures 5-30 through 5-46. It should be noted that these figures are intended to facilitate a general understanding of the available nature and extent of perchlorate contamination within the study area, and are not a detailed presentation of the data. For a detailed graphical presentation of all validated sampling results collected to date, the reader is referred to a compiled GIS database prepared by MWH (in progress). In addition, sampling location ID's, or sample ID's, for each media are presented in Figures 5-30 through 5-46 and the perchlorate results corresponding to each are presented in Appendix B.

The Navy conducted soil sampling investigations within, and in the vicinity of, NWIRP McGregor between 1999 and 2001 (EnSafe, 2001b). Soil sampling locations and sample ID's are identified in Figure 5-30. In 1999, perchlorate concentrations in soil samples ranged from not detected to 1800 mg/kg upgradient of Tributary M, which discharges to Station Creek (Figure 5-31). Perchlorate concentrations in soil samples collected at various locations upgradient of Harris Creek and the South Bosque River in 1999 were less than 1 mg/kg. Perchlorate concentrations in soil samples collected upgradient of Tributary M in 2000 and 2001 were generally consistent with the range of detections observed in 1999 (Figures 5-32 and 5-33). However, samples collected from the north central portion of NWIRP McGregor in 2000 and 2001 contained up to 140 mg/kg perchlorate. To put these concentration in perspective, the USEPA has derived screening-level benchmarks for perchlorate for the protection of plants and soil invertebrates equal to 4 mg/kg and 1 mg/kg, respectively (refer to Section 4.5.2).

The Navy conducted storm water sampling at the perimeter of NWIRP McGregor in 2000 and 2001 (EnSafe, 2001b). Detections of perchlorate in storm water samples collected at Tributary M in 2000 (January 9 to November 29) ranged from 4 to 500 ug/L (Figure 5-34). Detections of perchlorate in storm water samples collected upgradient of Harris Creek in 2000 ranged from 5.9 to 34 ug/L, and those collected upgradient of the South Bosque River ranged from 12 to 160 ug/L. In 2001, detections of perchlorate in Tributary M ranged from 40 to 5200 ug/L (Figure 5-35). It should be noted that heavy rainfalls in the winter of 2000/2001 caused surface discharges of contaminated groundwater to Tributary M to occur. Later in 2001 hydraulic and biological controls were implemented to reduce perchlorate discharges to Tributary M (refer to Section 3.1.1). A TNRCC Emergency Order issued in March 2001 allowed groundwater having perchlorate concentrations below 22 ug/L to be discharged to Tributary M (EnSafe, Inc., 2001). Detections of perchlorate in storm water samples collected upgradient of Harris Creek in 2001 ranged from 2.9 to 92 ug/L, and those collected upgradient of the South Bosque River ranged from 2.9 to 25 ug/L (Figure 5-35). To put these discharge levels in perspective, the current Texas 'interim action level' for perchlorate is equal to 4 ug/L (refer to Section 4.6).

The Navy conducted groundwater sampling investigations within, and in the vicinity of, NWIRP McGregor between 1998 and 2001 (EnSafe, 2001b). Groundwater sampling locations and sample ID's are identified in Figure 5-36. In 1998, perchlorate concentrations in groundwater samples collected near perchlorate sources ranged from 4.5 to 840 ug/L upgradient of Tributary M, which discharges to Station Creek (Figure 5-37). Perchlorate concentrations in groundwater samples collected at various locations upgradient of Harris Creek in 1998 ranged from not detected to 2200 ug/L. Perchlorate concentrations in groundwater samples collected upgradient of the South Bosque River in 1998 ranged from 520 to 8600 ug/L. In 1999, additional locations were sampled downgradient of perchlorate source areas (Figure 5-38). As would be anticipated, perchlorate concentrations generally decreased with increasing distance from source areas. However, perchlorate concentrations in groundwater samples collected from monitoring wells and dug wells along Tributary M, upgradient of Station Creek, were routinely greater than 1,000 ug/L (Figure 5-38). Detected concentrations of perchlorate in samples collected from monitoring wells and a spring located upgradient of Harris Creek ranged from 5.2 to 15,000 ug/L. Detected concentrations in samples collected from monitoring wells and a spring located upgradient of the South Bosque River exceeded 100 ug/L. Groundwater sampling results for 2000 were generally similar to, or slightly lower than, those observed in 1999 (Figure 5-39). In 2001, onsite groundwater concentrations appear to have decreased slightly in comparison to 1999 sampling results (Figure 5-40). It should be noted, however, that elevated reporting limits were observed for a number of groundwater samples collected in 1998 and 1999. Reporting limits for groundwater samples collected in 1999 were in the range of 20 ug/L, and as high as 31,000 ug/L. Thus comparisons between 1998 or 1999 sampling results and more recent data are difficult to make. Sampling of dug wells in 2001 revealed perchlorate concentrations in offsite groundwater adjacent to Tributary M and Tributary S in excess of 100 ug/L, and upgradient of Harris Creek in excess of 30 ug/L. To put the above groundwater concentrations in perspective, the current Texas 'interim action level' for perchlorate is equal to 4 ug/L, as described above. In addition, the TRRP residential groundwater cleanup standard is equal to 4 ug/L, and the TRRP commercial/industrial groundwater cleanup standard is 7 ug/L (refer to Section 4.6).

Surface water sampling for perchlorate was conducted by the Navy, Texas Tech, and TNRCC between 1998 and 2001. Locations of surface water sample collection are shown in Figure 5-41. In 1998 and 1999, detections of perchlorate in surface water samples collected from Tributary M, upgradient of Station Creek, exceeded 1,000 ug/L (Figure 5-42). A maximum concentration of 570 ug/L was detected in Station Creek (SWWS-9) approximately 1.5 miles downgradient of NWIRP McGregor, and a maximum concentration of 210 ug/L was detected in Lake Belton (SWBL-1) approximately four miles downgradient of the facility. These data suggest that discharges of perchlorate from NWIRP McGregor have reached Lake Belton at concentrations above the 'interim action level' of 4 ug/L. Perchlorate concentrations above 4 ug/L were detected in Harris Creek, north of NWIRP McGregor, in Tributary P, Tributary S, and the South Bosque River approximately six miles downgradient of the facility (SBSR-7). Reporting limits for surface water and stock pond grab samples collected in 1998 and 1999 were often in excess of 4 ug/L, and ranged as high as 400 ug/L. In 2000 and 2001 (Figures 5-43 and 5-44), perchlorate concentrations above 10 ug/L were detected in Tributary M and Station Creek, and in Lake Belton south of the point of discharge of Station Creek to the lake. Perchlorate concentrations above 10 ug/L were also detected in Harris Creek north of NWIRP McGregor, and concentrations above 4 ug/L were detected in Harris Creek and the South Bosque River at locations further down stream than in 1998 and 1999 (Figures 5-43 and 5-44). A single perchlorate detection of 17 ug/L was detected in Lake Waco in 2000 (Figure 5-43). Reporting limits for surface water data collected in 2000 and 2001 were generally in the range of 4 ug/L (Appendix B).

Perchlorate at concentrations above 4 ug/L were detected in surface water samples collected from the southern portion of Lake Belton (INBL-1) in 1999 and (BEL-071) in 2000. A perchlorate concentration above 4 ug/L was also detected downgradient of Lake Belton (INLR-2) in 2000. These detections suggest another potential source of perchlorate to the Lake Belton watershed. A possible alternate source of perchlorate discharge to this watershed is Fort Hood, which is located west of Lake Belton. Future sampling activities should include the collection of surface water samples from Lake Belton tributaries originating on or near this facility.

Sediment sampling for perchlorate was conducted by the Navy in 2000 within NWIRP McGregor, in tributaries adjacent to the facility, and in Lakes Belton and Waco. Locations of sediment sample collection are shown in Figure 5-45. Concentrations of perchlorate below 1 mg/kg were detected in one sediment sample collected from Tributary M and in two sediment samples collected from the South Bosque River (Figure 5-46). Perchlorate was not detected in any sediment samples collected from Lake Waco, while it was detected at concentrations below 1 mg/kg in three sediment samples collected from Lake Belton. Reporting limits were below 0.25 mg/kg in the majority of sediment samples collected within the streams or lakes (Appendix B). It is worth noting that perchlorate detections in Lake Belton were only observed within the southern portion of the lake. As was described for surface water, these detections may be indicative of an alternate source of perchlorate discharge such as Fort Hood. It should also be noted that the Navy collected and analyzed bulk sediment samples, as opposed to sediment pore water samples. Although the collection of bulk sediment samples is valid, pore water concentrations are generally more sensitive for highly water-soluble chemicals (USEPA, 1999b). Sediment criteria or screening benchmarks are not currently available for perchlorate. However, the USEPA (2002) has derived screening-level benchmarks for soil for the protection of terrestrial plants and soil invertebrates equal to 4 mg/kg and 1 mg/kg, respectively (refer to Section 4.5.2).

5.5.2 Primary Migration Pathways

Because NWIRP McGregor is located on a ridge separating the Bosque and Leon River watersheds, releases of perchlorate from the facility disperse in two main directions, primarily in surface water and groundwater. Harris Creek and the South Bosque River transfer water northeast to Lake Waco. Station Creek transports water south to Lake Belton. The major inflow source of water to the watersheds is precipitation. Perchlorate transport from soil sources to surface water likely occurs in brief pulses tied to local weather and recharge events.

Groundwater flow systems contribute to over 50 percent of the total stream flow in the Washita Prairie (Cannata, 1988, Myrick 1989). Perchlorate migrates from the water bearing zone to surface water through upward or horizontal movement during recharge events that discharge contaminated groundwater through seeps and springs to surface water.

Available soil and storm water sampling results suggest that Station Creek should be the most impacted of the three primary surface water streams. Comparison of surface water sampling results between Tributary M and tributaries draining to Harris Creek and the South Bosque River bear this out. However, substantial concentrations of perchlorate were detected in samples collected from groundwater monitoring wells, dug wells, and springs in the vicinity of tributaries to Harris Creek and the South Bosque River. Furthermore, perchlorate concentrations above 4 ug/L were measured in the South Bosque River approximately nine miles downgradient from NWIRP and one detection at 17 ug/L was observed in Lake Waco. The influence of groundwater contamination on surface water concentrations in these watersheds is a major uncertainty and warrants further evaluation.

The hydrologic model and preliminary water budget results suggest that significant dilution should occur once perchlorate contamination reaches the lakes. With the exception of a single surface water detection in Lake Waco and several surface water detections in Lake Belton, the Navy's sampling results generally support this supposition. Additional investigation and refinements to the water budget models should help to better understand the potential for impacts to these lakes and the receptors using them.

As described in Section 5.5.1, perchlorate was measured at concentrations above 10 ug/L downgradient of the point of discharge of Station Creek to Lake Belton, and at concentration above 4 ug/L in the southern portion of Lake Belton. A perchlorate concentration above 4 ug/L was also detected in INLR-2 downgradient of Lake Belton. These detections suggest another potential source of perchlorate to the Lake Belton watershed such as Fort Hood. As recommended in Section 5.5.1, future sampling activities should include the collection of surface water samples from Lake Belton tributaries originating on or near this facility.

5.5.3 Data Gaps

Data gaps in the available information regarding the nature and extent of perchlorate contamination, and in the migration pathway analysis for the Bosque and Leon River watersheds, include the following.

- Portions of the study area with measured or potential concentrations in surface water or groundwater exceeding the 'interim action level' of 4 ug/L should be better characterized to evaluate potential impacts to human health and the environment.
- Portions of the study area with measured or potential concentrations in soil or sediment exceeding the screening benchmark of 1 mg/kg perchlorate should be further characterized in order to evaluate potential impacts to human health and the environment.
- Dug wells, private groundwater wells, and springs that occur in areas likely to contain greater than the 'interim action level' of 4 ug/L perchlorate should be characterized to evaluate potential impacts to human health and the environment.
- The significance of elevated reporting limits during the 1998 and 1999 groundwater sampling events should be further evaluated to determine if re-sampling of groundwater is required at specific locations.
- The significance of elevated reporting limits during collection of the 1998 and 1999 surface water and stock pond grab samples should be further evaluated to determine if re-sampling of surface water is required at specific locations.
- Tributaries originating on, or in the vicinity of, Fort Hood should be characterized to evaluate potential discharges of perchlorate from this facility to the Lake Belton Watershed.

5.6 Generalized Watershed Model

A generalized watershed model was prepared for the study area to provide a conceptual understanding of the potential factors affecting the migration and fate of perchlorate within the watersheds. This model describes the attributes of each watershed compartment that may affect perchlorate migration and fate, as well as the inter-relationships between the various compartments. This conceptual watershed model is presented in Figure 5-47.

TABLE 5-1

HYDRAULIC CONDUCTIVITY AND POROSITY VALUES FOUND BY OTHER STUDIES IN FRACTURED CABONATES

Author	Hydraulic Conductivity (m/s)	Porosity (%)
Barquest (1989)	3.5×10^{-10} --- 1.7×10^{-4}	0.21 --- 0.55
Bernhardt (1991)		0.51
Cannata (1988)	1.62×10^{-4}	0.51 --- 1.0
Dahl (1990)	1.06×10^{-7} --- 1.26×10^{-5}	0.41 --- 2.89
Dutton (1994)	2.28×10^{7} --- 2.33×10^{-5}	
Gerhart (1984)	3.53×10^{-7} --- 6.13×10^{-4}	0.035 --- 35.0
Gburek (1999)	1.17×10^{-5} --- 1.16×10^{-4}	0.01 --- 1.0
Moore (1992)	5.78×10^{-6} --- 1.06×10^{-4}	0.23 --- 3.2
Myrick (1989)	2.12×10^{-5} --- 2.85×10^{-3}	

TABLE 5-2
COMPARISON OF CONCEPTUAL AND USACE WATER BUDGETS

Water Budget Type	Inflows	Outflows
Conceptual	Rain (on lakes) + Groundwater Inflow + Treated Effluent Inflow + Stream Inflow	Municipal Pumping + Dam Releases + Transpiration + Evaporation + Groundwater Outflow
USACE	Inflows Unknown. Inflow is estimated as the volume necessary to produce an observed Change in Lake Storage based upon known Outflows.	Gated Reservoir Outflow + Reservoir Evaporation + Reservoir Pumpage

TABLE 5-3
PRECIPITATION DATA (INCHES)

Precipitation Station	Period of Record (in)	Average Annual Precipitation (in)	Average Minimum Annual Precipitation (in)	Average Maximum Annual Precipitation (in)
McGregor	1910 to 1999	32.41	3.62	55.41
Lake Stillhouse Hollow	1964 to 2000	34.16	13.39	51.94
Lake Belton	1954 to 1992	33.83	13.75	50.82
Lake Waco	1965 to 2000	35.77	22.25	48.43

TABLE 5-4
WATER BUDGET RESULTS FOR LAKES BELTON AND WACO (AF/YEAR)

A Lake	B Year	C Inflow	D Evapo-ration	E Pumping	F Gated Flow	G Total Outflows	H (Inflow – Total Outflows)	I Percent Difference: (Inflow – Total Outflows) / (Inflow)	J Calculated Change in Storage	K Calculated Gated Flow: Inflow – (Evaporation + Pumping)	L Percent Difference: (Gated Flow – Calculated Gated Flow) / (Gated Flow)
Belton	Minimum (1999)	148,142	64,062	46,896	103,238	214,196	-66,054	-44.59	-65,243	37,184	63.98
Belton	Maximum (1997)	1,649,561	57,735	59,482	1,510,657	1,627,874	21,687	1.31	45,161	1,532,344	-1.44
Belton	Average	678,114	64,459	57,493	596,747	718,699	-40,585	-12.66	-10,038	556,162	16.81
Waco	Minimum (1999)	71,683	32,773	31,326	43,960	108,058	-36,376	-50.75	-39,679	7,584	82.75
Waco	Maximum (1997)	960,999	28,895	26,086	901,967	956,948	4,051	0.42	-730	906,018	-0.45
Waco	Average	436,675	30,423	27,102	376,980	434,505	2,170	-5.60	-5,413	379,150	9.79

TABLE 5-5
WATER BUDGET, CHANGE IN STORAGE CALCULATIONS (AF/YEAR)

A	B	C	D	E	F	G
Lake	**Year**	**Gated Flow**	**Calculated Gated Flow:** **Inflow – (Evaporation + Pumping)**	**Gated Flow – Calculated Gated Flow**	**Calculated Change in Storage**	**Percent Difference:** **(Gated Flow – Calculated Gated Flow) / (Gated Flow)**
Belton	Minimum (1999)	103,238	37,184	66,054	-65,243	**-1.24**
Belton	Maximum (1997)	1,510,657	1,532,344	-21,687	45,161	**-148.02**
Belton	Average	596,747	556,162	40,585	-10,038	**-304.31**
Waco	Minimum (1999)	43,960	7,584	36,376	-39,679	**8.32**
Waco	Maximum (1997)	901,967	906,018	-4,051	-730	**654.93**
Waco	Average	376,980	379,150	-2,170	-5,413	**140.09**

TABLE 5-6
NWIRP MCGREGOR STREAM GAUGES AS OF OCTOBER, 2000

Watershed	Stream Gauge Name	Period of Record	
		Start	Finish
Lake Belton	Station Creek	2/25/00	5/13/00
Lake Belton	Tributary M 0	3/11/00	5/16/00
Lake Belton	Tributary M 2	2/22/00	9/14/00
Lake Belton	Tributary M 4	5/19/00	9/14/00
Lake Belton	Tributary M 6	5/20/00	7/10/00
Lake Waco	Harris Creek	2/22/00	9/27/00
Lake Waco	Tributary F	3/2/00	10/11/00
Lake Waco	Tributary P	2/28/00	10/31/00
Lake Waco	Tributary S	4/2/00	7/21/00

TABLE 5-7
FLUSHING RATE FOR LAKES BELTON AND WACO

Lake	**Year**	**Lake Volume (AF)**	**Inflow (AF)**	**Flushing Rate (Years)** (Lake Volume / Inflow)
Belton	Minimum (1999)	434,500	148,142	2.93
Belton	Maximum (1997)	434,500	1,649,561	0.26
Belton	Average	434,500	678,114	0.64
Waco	Minimum (1999)	144,830	71,683	2.02
Waco	Maximum (1997)	144,830	960,999	0.15
Waco	Average	144,830	436,675	0.33

6.0 EXPOSURE ASSESSMENT

Exposure assessment is an analysis of the potential exposure pathways between the source of a chemical or physical contaminant and human or ecological receptors. Previous sections of this CSM report have described the current understanding of the potential for perchlorate releases from former NWIRP McGregor or other sources to impact various environmental media (i.e., surface water, groundwater, soil, sediment, or biota) within the Bosque and Leon River watersheds. The preliminary exposure analyses presented in this section describe potential exposures of human or ecological receptors to perchlorate at the point of contact with these known or potentially impacted media. As described in Section 7.0, further work may be required to expand our understanding of potential exposures to human and ecological receptors within the Bosque and Leon River watersheds.

A human health exposure analysis is presented in Section 6.1, and an analysis of potential exposure pathways for ecological receptors is presented in Section 6.2.

6.1 Human Health Exposure Analysis

The human health exposure analysis considers current and future land uses, human activities and receptors consistent with these land uses, and exposure pathways between human receptors and contaminated media.

6.1.1 Land Uses

Current land use indicates urban, pasture, range/forest, crops, and dairy waste fields (EnSafe Inc., 1999a). Land and properties surrounding NWIRP McGregor are primarily 'agricultural'. It should be noted, however, that the Washita Prairie west of the South Bosque River contains calciferous soils, and little-to-no farming occurs there. East of the South Bosque River are fertile, black soils that support non-irrigated row-crop farming. The City of McGregor, which adjoins the facility at the northeast corner, has a population of approximately 4,700. Land bordering the east side of NWIRP McGregor is zoned residential and land near the southern boundary supports commercial and light manufacturing operations and a university research center. Just south of the residential area is the McGregor High School (EnSafe Inc., 1999a). The remainder is sparsely populated open farming and grazing land (EnSafe Inc., 1999a). Approximately 3,500 acres of former NWIRP McGregor have been transferred to the city of McGregor, and 1,600 acres have been sold to private parties.

The study area includes portions of three counties (i.e., Bell, Coryell, and McClennan counties) and there are rural or developed communities within each of these counties. The Lake Waco and Lake Belton watersheds provide drinking water for nearly 500,000 citizens (Brazos River Authority, 2001b). Seeps, dug wells and private wells supply additional sources of drinking water and/or water for stock ponds.

Lake Waco and Lake Belton support a variety of recreational activities including boating, swimming, and fishing. The Bosque River also supports a significant recreational fishery.

6.1.2 Human Receptors

Based on the land uses described above, the following potential human receptors were identified:

- Residential Users;
- Commercial/Industrial Workers;
- NWIRP Site Workers;
- Agricultural Workers; and
- Recreational Users.

6.1.3 Exposure Pathways

In order for chemical contamination from a site to pose a potential threat to human health, a complete exposure pathway between the source of the contamination and an individual must exist. A complete exposure pathways as defined by Risk Assessment Guidance for Superfund (RAGS) (USEPA, 1998a) consists of four essential elements as follows:

- A source of contamination and a mechanism of release;
- A receiving or transport medium (soil, sediment, groundwater, surface water, air or food). Once released from the matrix or the soil, transformations may occur that can change the chemical;
- A point of potential human contact with the contaminant or one of its products (exposure point); and
- An exposure route, such as eating and drinking (ingestion), skin (dermal) contact, and breathing (inhalation).

An exposure pathway is incomplete if one of more of the above elements is absent.

The potential exposure media and exposure routes are described in the following subsections and depicted in Figure 6-1, Simplified Human Health Exposure Model, and Figure 6-2, Human Health Conceptual Site Model Diagram.

6.1.3.1 Surface Water Pathways

Perchlorate may be transported to surface water via erosion and runoff from former NWIRP McGregor soils that are contaminated with perchlorate, or from direct deposition of perchlorate containing wastes to surface water. Within the Lake Waco and Lake Belton watersheds, surface water has direct communication with groundwater (EnSafe Inc., 1999a). Therefore surface water may serve as a migration pathway for groundwater. Please see Section 6.1.3.2, below.

Surface water is currently used for human consumption in the form of springs at a few residential locations and some dug wells have been historical sources of drinking water (EnSafe Inc., 1999a). Public water supply in the study area is a mix of surface water from Lakes Waco and Belton as well as limited local groundwater from city wells (Study Area Stakeholders Alliance, 1998). The City of Waco operates the Lake Waco in-take structure located adjacent to the dam and serves the City of Waco and several adjacent communities (Study Area Stakeholders Alliance, 1998).

Three in-take structures draw water from Lake Belton and these are:

- City of Gatesville In-Take – supplying water to the City of Gatesville, North Fort Hood, Coryell, Grove, Flat, Bound, Pancake, Mountain Community, and Fort Gates (City of Gatesville, personal communication, August 1999);.
- Blue Bonnet Water Supply Corporation – supplying water to the Cities of McGregor, Moody, Bruceville-Eddy, Woodway, Moffat, Pendleton, Elm Creek, and Spring Valley (Bluebonnet Water Supply Corporation, personal communication, August 1999); and
- Bell County WCID #1 – supplying water to the Cities of Belton, Nolanville, Fort Hood, Killeen, Harker Heights, and Copperas Cove (Bell County WCID, personal communication, August 1999).

Downstream of the Lake Belton Dam, the City of Temple operates a diversion and accompanying in-take structure that supplies water to the Cities of Temple, Morgan’s Point, Troy, and Little-River Academy (Jerry Kean, City of Temple, personal communication, August 1999).

Therefore, direct human consumption is a potentially complete pathway for all human receptors listed in Section 6.1.2, above.

It should be noted that, the water supply for the Cities of Ogelsby and Robinson is obtained from city wells screened in the Trinity Aquifer (Study Area Stakeholders Alliance, 1998). These water supply sources are not anticipated to be contaminated due to the hydrogeological considerations described previously (refer to Section 5.2).

Recreational users of Lake Waco and Lake Belton are susceptible to incidental ingestion while swimming in the lakes.

Dermal contact with surface water is considered an insignificant pathway. Due to the high charge associated with the perchlorate ion, it does not readily pass through the skin (USEPA, 2002).

Inhalation during bathing is considered to be an insignificant exposure route because exposure to droplet size contaminated water during showering likely would preclude inhalation of perchlorate contaminated water as an aerosol (USEPA, 2002).

6.1.3.2 Groundwater Pathways

Perchlorate can enter the groundwater through migration from surface and subsurface soils or through direct deposition of wastes into water-bearing soils. Seeps, some dug wells and surface water have been used for domestic purposes (EnSafe Inc., 1999a; MW, 1999). In addition there is communication between shallow groundwater and surface water within the Lake Waco and Lake Belton watersheds. These watersheds provide the sole source water supply nearly 500,000 citizens (Brazos River Authority, 2001b). Therefore, exposures to perchlorate in groundwater through ingestion is a potentially complete exposure pathway for human receptors. Perchlorate is readily absorbed from the intestinal tract and oral uptake is considered to be the major route of exposure (USEPA, 2002).

Dermal contact with groundwater water is considered an insignificant pathway. Due to the high charge of perchlorate it does not readily pass through the skin (USEPA, 2002).

Inhalation during bathing is considered to be an insignificant exposure route because exposure to droplet size contaminated water during showering would likely preclude inhalation of perchlorate contaminated water as an aerosol (USEPA, 2002).

6.1.3.3 Sediment Pathways

Individuals who work, play, or conduct other outdoor activities (e.g., hunting and fishing) may be exposed to perchlorate that has been deposited onto sediment or has diffused into sediment. Any outdoor activities that involve digging into or contacting sediment may result in potential incidental ingestion and inhalation of particulates. The incidental ingestion pathway is considered complete for NWIRP site workers, and recreational users. Inhalation of particulates is considered complete for NWIRP site workers and recreational users, only.

Dermal exposure scenarios are also thought to be insignificant. Due to the high charge on the perchlorate ion, it does not readily pass through the skin (USEPA, 2002).

Inhalation of volatilized perchlorate in outdoor air is not considered to be a significant exposure route due to the fact that the vapor pressure of perchlorate salts and acids is low (USEPA, 2002).

6.1.3.4 Soil Pathways

Perchlorate may be dispersed to soil through disposal of perchlorate at the former NWIRP McGregor source areas where perchlorate was released. Irrigation of commercial and residential lawns with perchlorate-contaminated water may also transport perchlorate contamination to soil. As described in Section 6.1.1, no significant irrigated farming occurs within the study area. Agricultural pathways are limited to exposures associated with livestock grazing. Incidental ingestion and inhalation of soil particulates are potentially complete pathways for NWIRP site workers, agricultural workers, recreational users and residential users. In addition uptake by wildlife may result in potential contamination transfer to recreational users.

Dermal exposure scenarios are also thought to be insignificant. Due to the high charge on the perchlorate ion, it does not readily pass through the skin (USEPA, 2002).

Inhalation of volatilized perchlorate in outdoor air is not considered to be a significant exposure route due to the fact that the vapor pressure of perchlorate salts and acids is low (USEPA, 2002).

6.1.3.5 Food Chain Pathways

Surface water from springs and dug wells is used for stock pond watering and cattle consumption. These surface water uses can transfer perchlorate to human receptors via ingestion of livestock products in the form of beef or milk consumption.

Perchlorate may accumulate in aquatic and terrestrial wildlife species and present an exposure pathway for recreational or subsistence users that harvest them. Recent studies indicate that perchlorate may be uptaken by plants and concentrated in aerial plant parts, especially leaves and seeds (Smith et al., 2001; USEPA, 2002). Subsequent transfers to herbivorous species that consume contaminated plants or ingest contaminated surface water may occur (Smith et al., 2001; USEPA, 2002). Uptake and accumulation of perchlorate in aquatic species (e.g., fish and amphibians) also has been demonstrated to occur (Smith et al., 2001; TIEHH, 2001b,c; USEPA, 2002). Studies currently being conducted by TIEHH are directed at determining the significance of perchlorate transfer and accumulation within the food chain. Human receptors may be exposed to perchlorate indirectly via consumption of aquatic or terrestrial species that have taken up this contaminant through contact with surface water, sediment or soil, or via food consumption. Fishers and hunters who eat their game are particularly susceptible to this pathway, and are included under the recreational users category.

6.2 Ecological Exposure Analysis

The ecological exposure analysis includes an assessment of the biological resources within the study area, and an evaluation of potential exposure pathways between these resources and contaminated media.

6.2.1 Biological Resources

This section describes the biological resources present at the former NWIRP McGregor site and the surrounding areas.

Biological resources consist of vegetation and wildlife in addition to ecological processes and significant ecological features of the area.

The Bosque and Leon River watersheds do contain one ecologically significant stream segment, as defined by Texas Parks and Wildlife Department (TPWD) (2001). Neils Creek from the confluence with the Bosque River 6.5 miles southeast of Clifton in Bosque County upstream to the union of the Middle forks on Neils Creek in the southern extremity of Bosque County is noted as ecologically significant due to the presence of unique or critical habitats and exceptional benthic macroinvertebrate uses dependent on or associated with high water quality and dissolved oxygen there.

In addition, five segments from the Bosque River watershed and three segments from the Leon River watershed are on the State's 303(d) List from August 31, 2000. The 303(d) list is a compilation of water bodies within Texas State that have been identified as threatened or impaired (Brazos River Authority, 2001b).

6.2.1.1 Vegetation

The Bosque and Leon River watersheds are within the Washita Prairie, the easternmost part of the Grand Pair of Texas. The study area is characterized by gently rolling limestone hills and terrain covered by shallow soil with open-land vegetation (EnSafe Inc., 1999a). Plant species identified as occurring or potentially occurring within the Bosque River watershed are listed in Table 6-1.

6.2.1.2 Wildlife

Terrestrial and aquatic species inhabit the area associated with the Bosque and Leon River watersheds. Terrestrial species of mammals, birds, invertebrates and some reptiles occur near the watersheds and often consume aquatic species from the watersheds. Aquatic species of fish, mollusks, invertebrates, amphibians, reptiles, and birds occur within the vicinity of the watersheds. Resident and seasonal wildlife inhabiting the study area are described in the subsections below.

6.2.1.2.1 Fish

The rivers and streams within close proximity to the site support a variety of native and introduced fishes (Table 6-2). According to a study conducted by Texas Parks and Wildlife Department, *Evaluation of Selected Natural Resources in Part of the Central Texas (Waco) Area* (TPWD, 1999), it was concluded that the water quality and habitat in the Bosque River drainage were adequate to support a diverse and healthy fish community. Upstream reaches of the river had lower species richness and index of biotic integrity ratings, probably due to depressed water quality during low flow periods. The Bosque River supports a significant recreational fishery. Spawning runs of white bass occur in the North Bosque River upstream of Waco.

Fish species present or potentially occurring in the Bosque River watershed are listed in Table 6-2

6.2.1.2.2 Other Aquatic Species

Several springs exist in the counties surrounding the former NWIRP McGregor. Flowing springs emphasize the fact that ground and surface water are interconnected. Therefore, potential contamination at NWIRP could result in contamination in springs down gradient of the site through the hydrology of the surrounding areas. Several species of crustaceans have been found living in caves and associated springs in Bell County. As these species can live nowhere else, they are of ecological significance (TPWD, 1999).

6.2.1.2.3 Amphibians/Reptiles

Many amphibian and reptile species occur in the watersheds associated with the study area. Snakes, frogs, salamanders, and turtles are commonly identified within the area.

Amphibian and reptile species occurring or potentially occurring within the Bosque River watershed are listed in Table 6-3.

6.2.1.2.4 Birds

Many avian species occur within the study area. Some are migrants that are only present for a portion of the year or come to the region to breed, others are present year-round.

Both aquatic and terrestrial species occur within the vicinity of the watersheds and are significant to ecological food web interactions of the area.

Avian species present or potentially occurring in the Bosque River watershed are listed in Table 6-4.

6.2.1.2.5 Mammals

Domestic and nondomestic animals occur within the study area. Small mammal species including squirrels and rabbits are common along with larger mammalian species of coyote, deer, and nearby domestic cattle. Mammalian species are mostly terrestrial, but food web interactions present the potential for contamination transfer from aquatic and riparian habitats to both human and other ecological receptors. In addition, terrestrial mammals drink water or have contact with other contaminated media within aquatic or riparian areas. In order to have a complete evaluation of the ecological impacts of perchlorate in the watersheds, it is important to evaluate all potential ecological interactions, including those of terrestrial mammals.

Mammals that occur or potentially occur in the study area are listed in Table 6-5.

6.2.1.3 Threatened and Endangered Species

Within the site, there potentially exists species listed as state and/or federally endangered, threatened, candidate, sensitive, species of concern, proposed threatened, proposed endangered, and priority for conservation and management. In addition, some species are identified as rare within the specified county without specific listing status. Table 6-6 identifies Texas' special species that occur within the counties of Bell, Coryell, Falls, and/or McLennan. Closer examination of these species' life history characteristics shows that none of the threatened/endangered species are likely to occur within the NWIRP McGregor site, but could potentially occur within the study area. Appendix A gives species characteristics and criteria for listing.

6.2.1.4 Simplified Food Web

A simplified food web was developed to help identify specific receptors that might be directly or indirectly exposed to perchlorate while breeding or foraging within the study area (Figure 6-3). This figure depicts potential food chain transfer between the major feeding guilds and trophic levels present at the site and the relationships between interconnecting patterns of consumption. The food web depicts how energy or a contaminant such as perchlorate may be transferred within an ecosystem.

6.2.2 Ecological Receptors

The potential for perchlorate exposure however remote, exists for all species outlined in Figure 6-3: Food Web for Riparian/Freshwater Habitat, and listed in Tables 6-1, 6-2, 6-3, 6-4, and 6-5. However, actual exposures will vary significantly between feeding guilds and individual species depending upon the manner in which they interact with individual components of the watersheds. Therefore, it is more appropriate to describe the potentially complete and incomplete exposure pathways for ecological receptors. Descriptions of potential exposure pathways are presented in Section 6.2.3.

6.2.3 Exposure Pathways

As described under the human health exposure analysis (Section 6.1), a potentially complete exposure pathway consists of the following:

- A source of contamination and a mechanism of release.
- A receiving or transport medium (soil, sediment, groundwater, surface water, air or food). Once released from the matrix or the soil, transformations may occur that can change the chemical.
- A point of potential human contact with the contaminant or one of its products (exposure point).
- An exposure route, such as eating and drinking (ingestion), skin (dermal) contact, and breathing (inhalation).

An exposure pathway is incomplete if one of more of the above elements is absent.

Potentially complete and incomplete exposure pathways for ecological receptors are described in Subsections 6.2.3.1 through 6.2.3.5. In general, potentially complete exposure pathways include incidental ingestion of contaminated soil, sediment, surface water, and food chain exposure. Dermal exposure is deemed insignificant due to the high charge on perchlorate inhibiting transfer through the skin. Inhalation of particulate contaminants in ambient air is thought to result in minor exposure for ecological receptors. The inhalation pathway for gaseous forms of perchlorate is also incomplete due to the low vapor pressure of perchlorate salts and acids.

Complete ecological exposure pathways are depicted in Figure 6-4, Simplified Ecological Exposure Model, and Figure 6-5, Ecological Conceptual site Model Diagram.

6.2.3.1 Groundwater Pathways

Perchlorate can potentially enter the groundwater through migration from surface and subsurface soils, surface water or through direct deposition of wastes into water-bearing soils as previously described. Direct exposure of ecological species to groundwater is incomplete because wildlife do not directly consume groundwater. However, because groundwater is in communication with surface water, and there are numerous springs, dug wells and seeps within the study area, perchlorate in groundwater may be transferred to surface water including stockponds where wildlife drink and aquatic organisms live. Potential exposure to surface water pathways are described in the following subsection.

6.2.3.2 Surface Water Pathways

Perchlorate may be transported to surface water via erosion and runoff from watershed soils that contain perchlorate or from direct deposition of perchlorate containing wastes to surface water. Communication between surface water and groundwater also creates the potential of exposure through seeps, dug wells, and springs in the study area. The potential exists for many mammal and bird species to directly consume surface water as the water runs through the Leon and Bosque River watersheds. The USEPA (2002) has identified this as a potentially significant pathway in perchlorate contaminated areas (refer to Section 4.5.2). Uptake of perchlorate by aquatic producers (e.g., phytoplankton and algae) is anticipated, as is absorption across the gill membranes of fish. Once absorbed by such receptors, there is a potential for transfer of perchlorate to higher trophic level organisms through the food chain, as described further in Section 6.2.3.5.

6.2.3.3 Soil Pathways

Perchlorate may be released to soil through discharge of perchlorate at former NWIRP McGregor source areas where perchlorate containing wastes were disposed of. Irrigation of commercial and residential lawns, and stock ponds, with perchlorate-contaminated water may also transport perchlorate to soil. Incidental ingestion of soil particulates is a potentially complete pathway for terrestrial ecological receptors. Inhalation of gaseous forms of perchlorate in air is incomplete due to the low vapor pressure of perchlorate salts and acids (USEPA, 2002). Dermal exposure scenarios are also thought to be insignificant. Due to the high charge of perchlorate it does not readily pass through the skin (USEPA, 2002). Root uptake by plants may lead to transfer of perchlorate to higher trophic levels through the food chain, as described in Section 6.2.3.5.

6.2.3.4 Sediment Pathways

Perchlorate may be transported to sediment via erosion and runoff from watershed soils that contain this contaminant or from direct deposition of perchlorate containing wastes to the surface water bodies of which they are a part. Sediment may be directly ingested by benthic invertebrates or species that forage on benthic invertebrates of fish. Benthic flora may accumulate perchlorate through root uptake and transfer contamination to consumer species.

6.2.3.5 Food Chain Exposure Pathways

As previously described in the above Sections 6.2.3.1-3, food chain transfer may result in contamination of higher trophic level species within the ecosystem by consumption of contaminated flora or prey. This process is depicted in Figure 6-3.

Uptake of perchlorate by aquatic producers (e.g., phytoplankton and algae), submergent macrophytes, and emergent vegetation through foliar transport and/or root uptake is likely to occur within surface water bodies of the Bosque and Leon River watersheds (Figure 6-4). Once absorbed by producer level receptors, there is a potential for transfer of perchlorate to consumer level receptors including aquatic invertebrates, planktivorous fish and herbivorous aquatic birds. These species in turn provide a means of perchlorate transfer to higher trophic level receptors including omnivorous or carnivorous fish, amphibians, reptiles, mammals and birds that may prey on them (Figure 6-4).

The magnitude of potential food chain exposures will be a function of 1) the degree of uptake and accumulation of perchlorate in specific food items; 2) a receptor's dietary relationship to the aquatic component of the watersheds; 3) their proximity to sources of perchlorate contamination, and 4) their foraging range. The available information indicates that perchlorate has the potential to accumulate in aquatic and terrestrial plants and animals (Smith et al, 2001; TIEHH, 2001b,c,; USEPA, 2002). Aquatic species such as aquatic plants invertebrates, fish, amphibians, reptiles and birds are generally anticipated to have the highest potential exposures to this contaminant. In addition, seasonally inundated or irrigated areas may accumulate significant levels of perchlorate in soil and vegetation (Smith et al, 2001; USEPA, 2002). Riparian species such as raccoon, deer mouse, and yellow-headed blackbird that are dependent upon surface water bodies or riparian areas for all or a portion of their dietary needs are anticipated to have the next highest exposures to perchlorate. Terrestrial species including jack rabbit, deer, and coyote use surface waters within the study area primarily as a source of drinking water and are generally anticipated to have the lowest exposures to perchlorate. However, USEPA (2002) has indicated that even drinking water may be a significant source of exposure for terrestrial organisms where perchlorate concentrations in surface water exceed approximately 4.8 ug/L (refer to Section 4.5.2).

For all three of these primary groups of receptors, those that are located nearest to areas impacted by perchlorate are anticipated to have the highest exposure to perchlorate. For receptors that are located closest to an area of perchlorate contamination, those species with small foraging ranges (e.g., bullhead minnow, yellow mud turtle, red-winged blackbird) are anticipated to have higher exposures to perchlorate than those species with large foraging areas (e.g., white bass, armadillo, great blue heron) because the latter tend to forage over areas of varying degrees of contamination.

A significant data gap in the existing knowledge concerning perchlorate is the extent to which this chemical may accumulate and transfer within the food chain. Bioconcentration and biomagnification phenomena are generally limited to lipophilic (i.e., fat seeking) chemicals. Perchlorate, which is hydrophilic (i.e., water seeking), is not expected to appreciably bioconcentrate or biomagnify. Although limited information is available to indicate that perchlorate may have the potential to bioconcentrate in fish (TIEHH, 2001b,c), this phenomenon warrants further evaluation (refer to Section 4.3.2). However, information is available to indicate that perchlorate is selectively uptaken into the thyroid gland of higher organisms including fish, birds, and mammals (Smith et al., 2001; TIEHH, 2001c; USEPA, 2002). Additional information regarding perchlorate uptake, accumulation, and transfer within the food chain are needed before the relative exposure relationships described in general terms above can be properly evaluated.

6.2.4 Biological Sampling Results

Biological sampling within the study area is currently being conducted by TIEHH (2002, 2001a). Preliminary studies conducted by TIEHH (2001b, c) suggest that perchlorate is uptaken by aquatic organisms. Fish tissue samples collected from the Lake Waco and Lake Belton Watersheds contained perchlorate at concentrations ranging from non-detect (nd) to 1,230 nanograms/gram (ng/g) wet weight (TIEHH, 2001b). Laboratory studies on the uptake and distribution of perchlorate in catfish demonstrated uptake of perchlorate in fish tissues, with preferential distribution into the heads versus fillets (TIEHH, 2001c). Additional studies by TIEHH on plants, amphibians, and small mammals are ongoing (TIEHH, 2001a). Preliminary results from body burden studies indicate that perchlorate is not detectable in the fish tissue collected from Station Creek or Little Bosque (TIEHH, 2002). Liver samples from fish tissue collected in September, 2001, are currently being processed. An electroshocking boat was assembled for further fish collection from the open water in Lakes Belton and Waco in late January, early February, 2002. Perchlorate analysis on frog samples collected from Lake Waco and NWIRP McGregor will be completed after further breeding enough tadpoles to perform the analysis. Elm and smart weed samples were collected and analyzed for perchlorate. Plant samples had detectable concentrations of perchlorate in all cases where perchlorate was found in the sediment pore water. No perchlorate was detected in plant samples where the bulk water contained perchlorate but not the sediment pore water. Previous small mammal collection attempts only resulted in the collection of 3 least shrews (*Cryptotis parva*). Further small mammal and avian trapping took place in January 2002. Several deer mice, cotton rats, house mice, and harvest mice were collected using live traps and snap traps. Avian species collected were northern cardinal, mockingbird, eastern phoebe, Lincoln sparrow, song sparrow, and white-crowned sparrow. Birds were collected using a mist net. Analysis of these specimens was not complete at the time of preparation of this report.

TABLE 6-1

PLANT SPECIES PRESENT OR POTENTIALLY OCCURRING IN THE BOSQUE AND LEON RIVER WATERSHEDS WACO, TEXAS

Common Name	Scientific Name	State Status	Federal Status	Sources
Trees				a
American Elm	*Ulmus americana*	N	N	a
Ash	*Fraxinus*	N	N	b
Black Willow	*Salix nigra*	N	N	a
Box Elder	*Acer negundo*	N	N	b
Dogwood	*Cornus drummondii*	N	N	a
Eastern Cottonwood	*Populus deltoides*	N	N	a
Eastern Red Cedar	*Juniperus virginiana*	N	N	a
Eastern Sycamore	*Platanus occidentalis*	N	N	a
Honey Mesquite	*Prosopis glandulosa*	N	N	a
Pecan	*Carya illinoinensis*	N	N	b
Red Mulberry	*Morus rubra*	N	N	a
Slippery Elm	*Ulmus rubra*	N	N	a
Sugar Hackberry	*Celtis laevigata*	N	N	a
Virginia Live Oak	*Quercus virginiana*	N	N	a
				a
Flowering Plants				a
Antelope Horns	*Asclepias asperula*	N	N	a
Blackberry	*Rubus allegheniensis*	N	N	a
Blue Gilia	*Gilia rigidula*	N	N	a
Blue-Eyed Grass	*Sisyrinchium spp.*	N	N	a
Cattail	*Typha latifolia*	N	N	a
Dartgrass spp.		N	N	a
Dog's Ears	*Coldenia canescens*	N	N	a
Englemann Daisy	*Engelmannia pinnatifida*	N	N	a
Firewheel	*Gaillardia pulchella*	N	N	a
Fleabane spp.	*Erigeron*	N	N	a
Fluttermill	*Oenothera macrocarpa*	N	N	a
Goat's Beard	*Tragopogon dubius*	N	N	a
Golden Flax	*Linum rigidum var. Berlandier*	N	N	a
Gray Vervain	*Verbena canescens*	N	N	a
Green Milkweed	*Asclepias asperula*	N	N	a
Honeysuckle	*Lonicera albiflora*	N	N	a
Limestone Gaura	*Gaura calcicola*	N	N	a
Mesquite	*Prosopis*	N	N	b
Musk Thistle	*Carduus nutans*	N	N	a
Mustang Grape	*Vitis mustangensis*	N	N	a

TABLE 6-1

PLANT SPECIES PRESENT OR POTENTIALLY OCCURRING IN THE BOSQUE AND LEON RIVER WATERSHEDS WACO, TEXAS

Common Name	Scientific Name	State Status	Federal Status	Sources
Praire Primrose	*Oenothera speciosa*	N	N	a
Praire Vervain	*Castilleja purpurea*	N	N	a
Prairie Verbena	*Glandularia bipinnatifida*	N	N	a
Prickly-Pear Cactus	*Opuntia lindheimeri*	N	N	a,b
Rushes spp.	*Juncaceae*	N	N	a
Sour Clover	*Meliliotus indicus*	N	N	a
Spanish Dagger	*Yucca baccata var. brevifolia*	N	N	a
Sumac spp.	*Rhus*	N	N	a
Tall Goldenrod	*Solidago altissima*	N	N	a
Texas Bluebonnets	*Lupinus texensis*	N	N	a
Texas Dandelion	*Pyrrhopappusmulticaulis*	N	N	a
Texas Paintbrush	*Castilleja indivisa*	N	N	a
Texas Star	*Lindheimera Texana*	N	N	a
Texas Thistle	*Cirsium texanum*	N	N	a
Texas Vervain	*Verbena canescens*	N	N	a
Two-Leaved Senna	*Senna roemeriana*	N	N	a
Western Horse-Nettle	*Solanum dimidiatum*	N	N	a
Western Spiderwort	*Tradescantia occidentalis*	N	N	a
White prickly Poppy	*Argemone albifora*	N	N	a
Wild Onion	*Allium canadense var. canadense*	N	N	a
Wine Cup	*Callirhoe leiocarpa*	N	N	a
Yucca Twisted Leaf	*Yucca rupicola*	N	N	a

Notes:
N – Not listed as state or federal endangered, threatened or rare.

Source information:
[a] Groundwater Investigation Report Risk Assessment (EnSafe Inc., 1999a
[b] Perchlorate Monitoring Plan (MW, 1999)

TABLE 6-2

**FISH SPECIES PRESENT OR POTENTIALLY OCCURRING IN THE BOSQUE AND LEON RIVER WATERSHEDS
WACO, TEXAS**

Common Name	**Scientific Name**	**State Status**	**Federal Status**	**Sources**
Alligator gar	Lepisosteus spatula	N	N	a
Bigscale logperch	Percina macrolepida	N	N	a
Black crappie	*Pomoxis nigromaculatus*	N	N	b
Black bullhead	*Ameiurus melas*	N	N	a
Blackstripe topminnow	*Fundalus notatus*	N	N	a
Blacktail shiner	*Cyprinella venusta*	N	N	a
Blue catfish	*Ictalurus furcatus*	N	N	b
Bluegill	*Lepomis macrochirus*	N	N	a, b, c
Bullhead minnow	*Pimephales vigilax*	N	N	a
Carp	*Cyprinidae*	N	N	d
Channel catfish	*Ictalurus punctatus*	N	N	a, b
Common stoneroller	*Campostoma anomalum*	N	N	a
Flathead catfish	*Pylodictis olivaris*	N	N	a, b, d
Flathead minnow	*Pimephales promelas*	N	N	a
Gizzard shad	*Dorosoma cepedianum*	N	N	a
Golden shiner	*Notemigonus crysoleucas*	N	N	a
Gray redhorse	*Moxostoma congestum*	N	N	a
Green sunfish	*Lepomis cyanellus*	N	N	a, d
Inland silverside	*Menidia beryllina*	N	N	a
Largemouth bass	*Micropterus salmoides*	N	N	a, b
Longear sunfish	*Lepomis megalotis*	N	N	a
Longnose gar	*Lepisosteus osseus*	N	N	a
Mimic shiner	*Notropis volucellus*	N	N	a
Minnow	*Notropis spp.*	N	N	c
Orangethroat darter	*Etheostoma spectabile*	N	N	a
Pugnose minnow	*Opsopoeodus emiliae*	N	N	a
Red shiner	*Cyprinella lutrensis*	N	N	a
River carpsucker	*Carpiodes carpio*	N	N	a
Smallmouth bass	*Micropterus dolomieu*	N	N	b
Striped bass	*Morone lineatus*	N	N	b
Sucker	*Catostomidae*	N	N	d
Yellow bullhead	*Ameiurus natalis*	N	N	a
Western mosquitofish	*Gambusia affinis*	N	N	a, c
White bass	*Morone chrysops*	N	N	a, b, d
White crappie	*Pomoxis annularis*	N	N	b

Notes:
N – Not listed as state or federal endangered, threatened or rare.

Source information:
[a] Evaluation of Selected Natural Resources in Part of the Central Texas (Waco) Area (TPWD, 1999).
[b] Fianl Draft Report - Lake Water Quality Assessment NWIRP McGregor – Volume I (EnSafe Inc., 2000).
[c] Groundwater Investigation Report Risk Assessment (EnSafe Inc., 1999a).
[d] Waco Perchlorate Project, November Progress Report (TIEHH, 2001a).

TABLE 6-3

AMPHIBIAN AND REPTILE SPECIES PRESENT OR POTENTIALLY OCCURRING IN THE BOSQUE AND LEON RIVER WATERSHEDS WACO, TEXAS

Common Name	Scientific Name	State Status [a]	Federal Status [a]	Sources
Amphibians				
Bullfrog	*Rana catesbeiana*			b
Couch's spadefoot	*Scaphiopus couchii*			b
Eastern newt	*Notophthalmus viridescens*			b
Eastern spadefoot	*Scaphiopus holbrookii*			b
Frogs				c
Great Plains narrowmouth toad	*Gastrophryne olivacea*			b
Green frog	*Rana clamitans*			b
Gulf Coast toad	*Bufo valliceps*			b
Lesser siren	*Siren intermedia*			b
New Mexico spadefoot	*Spea multiplicata*			b
Northern cricket frog	*Acris crepitans*			b
Plains leopard frog	*Rana blairi*			b
Red-spotted toad	*Bufo punctatus*			b
Rio Grande leopard frog	*Rana berlandieri*			b
Salado Springs salamander	*Eurycea spp. 2*	rare	rare	b
Smallmouth salamander	*Ambystoma texanum*			b
Southern dusky salamander	*Desmognathus auriculatus*			b
Southern leopard frog	*Rana sphenocephala*			b
Spotted chorus frog	*Pseudacris clarkii*			b
Strecher's chorus frog	*Pseudacris strecheri*			b
Striped chorus frog	*Pseudacris triseriata*			b
Texas toad	*Bufo speciosus*			b
Tiger salamander	*Ambystoma tigrinum*			b
Woodhouse's toad	*Bufo woodhousii*			b
Reptiles				
Brozos water snake	*Nerodia herteri*	rare	T	b
Checkered garter snake	*Thamnophis marcianus*			b
Chicken turtle	*Deirochelys reticularia*			b
Common garter snake	*Thamnophis sirtalis*			b
Common musk turtle	*Sternotherus odoratus*			b
Copperhead	*Aghistrodon contortrix*			b
Cottonmouth	*Aghistodon piscivorus*			b
Eastern mud turtle	*Kinosternon subrubrum*			b
Graham's crayfish snake	*Regina grahamii*			b

TABLE 6-3

AMPHIBIAN AND REPTILE SPECIES PRESENT OR POTENTIALLY OCCURRING IN THE BOSQUE AND LEON RIVER WATERSHEDS WACO, TEXAS

Common Name	Scientific Name	State Status [a]	Federal Status [a]	Sources
Plainbelly water snake	*Nerodia erythrogaster*			b
Razorback musk turtle	*Sternotherus carinatus*			b
Smooth softshell	*Trionyx muticus*			b
Snapping turtle	*Chelydra serpentina*			b
Southern water snake	*Nerodia fasciata*			b
Spiny softshell	*Trionyx spiniferus*			b
Texas garter snake	*Thamnophis sirtalisannectens*	rare	rare	b
Texas river cooter	*Pseudemys texana*			b
Western ribbon snake	*Thamnophis proximus*			b
Yellow mud turtle	*Kinosternon flavescens*			b

Notes:
N – Not listed as state or federal endangered, threatened or rare.
rare - Rare, but with no regulatory listing status.
T - State Threatened.

Source Information:
[a] Texas Parks and Wildlife, Wildlife Diversity Branch. County Lists of Texas' Special Species. (TXBCD, 2001; 2000; 1999a; 1999b).
The Salado Springs salamander occurs in Bell County and the Texas garter snake occurs in Bell, Coryell, Falls and McLennan Counties. The Brazos Water snake is not listed as occurring in Bell, Coryell, Falls or McLennan Counties.
[b] Evaluation of Selected Natural Resources in Part of the Central Texas (Waco) Area (TPWD, 1999).
These species are noted as occurring within the proposed Priority Groundwater Management Area of central Texas (Waco) which encompasses 17 counties.
[c] Groundwater Investigation Report Risk Assessment (EnSafe Inc., 1999a).

TABLE 6-4

AVIAN SPECIES PRESENT OR POTENTIALLY OCCURRING IN THE BOSQUE AND LEON RIVER WATERSHEDS WACO, TEXAS

Common Name	Scientific Name	State Status	Federal Status	Sources
American coot	*Fulica americana*	N	N	a,b
American crow	*Corvus brachyrhynchos*	N	N	a,b
American Kestral	*Falco sparverius*	N	N	b
American robin	*Turdus migratorius*	N	N	b
Bachman's sparrow	*Aimophila aestiualis*	N	N	b
Barn swallows	*Hirundo rustica*	N	N	b
Black vulture	*Coragyps atratus*	N	N	b
Blue-winged teal	*Anas discors*	N	N	a,b
Boat-tailed grebe	*Quiscalus major*	N	N	b
Bobwhite quail	*Colinus virginianus*	N	N	a,b
Brown-headed cowbird	*Molothrus ater*	N	N	b
Cattle egret	*Bubulcus ibis*	N	N	b
Common loon	*Gavia immer*	N	N	a
Common merganser	*Mergus merganser*	N	N	a
Common nighthawk	*Chordriles minor*	N	N	b
Common tern	*Sterna hirundo*	N	N	a
Crested caracara	*Caracara cheriway*	N	N	b
Dickcissel	*Spiza americana*	N	N	b
Double-crested cormorant	*Phalacrocorax auritus*	N	N	a,b
Eared Grebe	*Podiceps nigricollis*	N	N	b
Eastern Phoebe	*Sayornis phoebe*	N	N	c
European starling	*Sturnus vulgaris*	N	N	b
Field sparrow	*Spizella pusilla*	N	N	b
Great blue herron	*Ardea herodias*	N	N	b
Great horned owl	*Bubo virginianus*	N	N	b
Greater roadrunner	*Geococcyx californianus*	N	N	b
House finch	*Carpodacus mexicanus*	N	N	b
House sparrow	*Passer domesticus*	N	N	b
House wren	*Troglodytes aedon*	N	N	a
Killdeer	*Charadrius vociferus*	N	N	b
Lark sparrow	*Pchondestes grammacus*	N	N	b
Lesser scaup	*Aythya marila*	N	N	b
Lincoln Sparrow	*Melospiza lincolnii*	N	N	c
Loggerhead shrike	*Lanius ludovicianus*	N	N	b
Mallard	*Anas platyrhynchos*	N	N	a
Mourning dove	*Zenaida macroura*	N	N	a,b

TABLE 6-4

AVIAN SPECIES PRESENT OR POTENTIALLY OCCURRING IN THE BOSQUE AND LEON RIVER WATERSHEDS WACO, TEXAS

Common Name	Scientific Name	State Status	Federal Status	Sources
Northern cardinal	*Cardinalis cardinalis*	N	N	b, c
Northern harrier	*Circus cyaneus*	N	N	b
Northern mockingbird	*Mimus polyglottos*	N	N	b, c
Red-bellied woodpecker	*Melanerpes carolinus*	N	N	b
Red-shouldered hawk	*Buteo lineatus*	N	N	b
Red-tailed hawk	*Buteo jamaicensis*	N	N	a,b
Red-winged blackbird	*Agelaius phoeniceus*	N	N	b
Rock dove	*Columba livia*	N	N	b
Savannah sparrow	*Passerculus sanwichensis*	N	N	b
Scissor-tailed flycatcher	*Muscivora forficata*	N	N	b
Song Sparrow	*Melospiza melodia*	N	N	c
Spotted sandpiper	*Actitis macularia*	N	N	b
Turkey vulture	*Cathartes aura*	N	N	b
Upland sandpiper	*Bartramia longicauda*	N	N	b
Waterfowl	*Anseriformes*	N	N	a
Western Meadowlark	*Sturnella neglecta*	N	N	b
White pelican	*Pelecanus*	N	N	a
White-crowned sparrow	*Zonotrichia leucophrys*	N	N	b, c
Yellow-headed blackbird	*Xanthocephalus xanthocephalus*	N	N	b

Notes:
N – Not listed as state or federal endangered, threatened or rare.

Source information:
[a] Fianl Draft Report - Lake Water Quality Assessment NWIRP McGregor - Volume I (EnSafe Inc., 2000).
[b] Groundwater Investigation Report Risk Assessment (EnSafe Inc., 1999a).
[c] Waco Perchlorate Project, January 2002 Progress Report (TIEHH, 2002).

TABLE 6-5

MAMMAL SPECIES PRESENT OR POTENTIALLY OCCURING IN THE BOSQUE AND LEON RIVER WATERSHEDS WACO, TEXAS

Common Name	**Scientific Name**	**State Status**	**Federal Status**	**Sources**
Armadillo	*Dasypus novemcinctus*	N	N	a,b
Blacktail jackrabbit	*Lepus californianus*	N	N	b
Cotton rat	*Sigmodon*	N	N	c
Coyote	*Canis latrans*	N	N	b
Deer	*Cervus*	N	N	a
Deer mouse	*Peromyscus maniculatus*	N	N	d
Eastern cottontail	*Sylvilagus floridanus*	N	N	b
Fox Squirrel	*Sciurus niger*	N	N	b
Gray Squirrel	*Sciurus carolinensis*	N	N	b
Harvest mouse	*Reithrodontomys megalotis*	N	N	
House mouse	*Mus musculus*	N	N	
Least Shrew	*Cryptotis parva*	N	N	e
Opossum	*Didelphidae*	N	N	a
Raccoon	*Procyon lotor*	N	N	b
Skunk	*Mephitidae*	N	N	a
Squirrel	*Sciuridae*	N	N	a
Striped skunk	*Mephitis mephitis*	N	N	b
Swamp rabbit	*Sylvilagus aquaticus*	N	N	a, f

Notes:
N – Not listed as state or federal endangered, threatened or rare.

Source information:
[a] Fianl Draft Report - Lake Water Quality Assessment NWIRP McGregor - Volume I (EnSafe Inc., 2000).
[b] Groundwater Investigation Report Risk Assessment (EnSafe, 1999).
[c] Waco Perchlorate Project, January 2002 Progress Report (TIEHH, 2002).
[d] Waco Perchlorate Project, November Progress Report (TIEHH, 2001a).
[e] Waco Perchlorate Project - November Progress Report (TIEHH, 2001a).
[f] Evaluation of Selected Natural Resources in Part of the Central Texas (Waco) Area (TPWD, 1999).

TABLE 6-6
THREATENED AND ENDANGERED SPECIES, AND SPECIES OF CONCERN, FOR BELL, CORYELL AND MCLENNAN COUNTIES

Common Name	Scientific Name	County [a]	Federal [b]	State [b]	Source
Amphibians					
Salado Springs Salamander	*Eurycea spp. 2*	B	rare	rare	c
Birds					
Arctic peregrine Falcon	*Falco peregrinus tundrius*	B,C,F,M	DL	T	c
Bald Eagle	*Haliaeetus leucocephalus*	B,C,F,M	LT-PDL	T	c
Black-Capped Vireo	*Vireo atricapillus*	B,C	LE	E	c
Golden-Cheeked Warbler	*Dendroica chrysoparia*	B,C,M	LE	E	c
Henslow's Sparrow	*Ammodramus henslowii*	B,C,F,M	rare	rare	c
Interior Least Tern	*Sterna antillarum athalassos*	B,C,F,M	LE	E	c
Migrant Loggerhead Shrike	*Lanius ludovicianus migrans*	B,C,F,M	rare	rare	c
Western Burrowing Owl	*Athene cunicularia hypugaea*	B,C,F,M	rare	rare	c
Whte-Faced Ibis	*Plegadis chihi*	F,M	rare	T	c
Whooping Crane	*Grus americana*	B,C,F,M	LE	E	c
Fishes					
Guadalupe Bass	*Micropterus treculi*	B,C,M	rare	rare	c
Smalleye Shiner	*Notopis buccala*	B,C,F,M	rare	rare	c
Insects					
Leon River Winter Stonefly	*Taeniopteryx starki*	C	rare	rare	c
Mammals					
Cave Myotis Bat	*Myotis velifer*	B,C,F,M	rare	rare	c
Plains Spotted Skunk	*Spilogale putorius interrupta*	B,C,F,M	rare	rare	c
Reptiles					
Texas Garter Snake	*Thamnophis sirtalis annectans*	B,C,F,M	rare	rare	c
Texas Horned Lizard	*Phrynosoma cornum*	B,C,F,M	rare	T	c
Timber/Canebrake Rattlesnake	*Crotalus horridus*	B,C,F,M	rare	T	c
Vascular Plants					
Texabama croton	*Croton alabamensis var. texensis*	B,C	rare	rare	c

Notes:
[a] Counties include:
B - Bell
C - Coryell County
F - Falls
M - McLennan County

[b] Key:

LE, LT - Federally Listed Endangered/Threatened
PE, PT - Federally Proposed Endangered/Threatened
DL, PDL - Federally Delisted/Proposed Delisted
E, T - State Endangered/Threatened
rare - Rare, but with no regulatory listing status

[c] Texas Parks and Wildlife, Wildlife Diversity Branch. County Lists of Texas' Special Species. (TXBCD,1999a, 1999b, 2000, 2001).

7.0 DATA GAPS

During preparation of this draft CSM, a number of data gaps were identified in the current knowledge regarding perchlorate contamination, migration, and fate within the Bosque and Leon River watersheds. Further investigations to resolve or reduce these data gaps will be necessary to conduct an accurate assessment of perchlorate exposures and risks to human health and the environment. Additionally, these investigations will be critical to the development of remedial decisions and strategies that may be necessary to mitigate potential risks to acceptable levels.

Data gaps as identified in this draft CSM are described in the following subsections.

7.1 Fate and Transport of Perchlorate

Chemical-specific characteristics that potentially affect the fate and transport of perchlorate were described in Section 4.0. Data gaps in the current understanding of perchlorate fate and transport include the following.

- Perchlorate is denser than water but little information is available regarding the potential for perchlorate to sink in groundwater, or undergo differential stratification in surface waters. Simple bench-top testing, or stratified water column testing in the field, would help to better understand the vertical transport of perchlorate in groundwater and surface water bodies within the watersheds.
- Information regarding the potential for perchlorate to undergo cation exchange with minerals in soil or sediment is not well documented. Such interactions may affect the fate of perchlorate in soil and sediment compartments, and could be useful in the development of strategies to mitigate perchlorate transport. Simple bench-top testing, or field evaluation of cation exchange capacity in watershed soils or sediments, would help to better understand the fate of perchlorate within these media.
- The potential for perchlorate to accumulate in soils following sequential irrigation and evaporation is currently unknown. Laboratory experiments, or sampling investigations in agricultural areas of the watersheds, would help to better evaluate the potential for accumulation of perchlorate in irrigated soils.
- Microbial degradation of perchlorate is an anaerobic process. Assessment of the anaerobic capacity of the watersheds would be helpful in evaluating the potential for perchlorate degradation to less toxic constituents.

7.2 Biological Uptake and Transformation

A summary of the biological uptake and transformation processes for perchlorate was presented in Section 4.3.2. Data gaps in the current understanding of perchlorate uptake and transformation include the following.

- Potential accumulation in terrestrial vascular plants, including home-grown produce, should be investigated further using studies designed to quantify plant concentration factors. This data will aid in determining exposure to human and ecological receptors through the food chain pathway.

- Data on accumulation in fish and other aquatic organisms are insufficient to evaluate exposures to organisms that feed on them. Laboratory or field assessments using methods designed to quantify aquatic organism concentration factors should be conducted.
- Data on accumulation in litter feeding or herbivorous invertebrates are insufficient to evaluate exposures to mammals or birds that feed on these organisms. Laboratory or field assessments using methods designed to quantify litter feeding or herbivorous invertebrate concentration factors would help to better evaluate potential exposures to these receptors.

7.3 Toxicology of Perchlorate

The available toxicological information for perchlorate was briefly described in Section 4.5. A thorough understanding of perchlorate-related risks requires knowledge of toxicity to all potential ecological receptors. Significant data gaps in the toxicological information for perchlorate include the following.

- Effects of perchlorate on algae and aquatic macrophytes are required to estimate risks to aquatic primary producers. Laboratory or field studies should be conducted to quantify effect levels for algae and aquatic macrophytes.
- Toxic effect levels in aquatic invertebrates are limited to daphnids. Laboratory toxicity studies or field assessments across several taxonomic groups wold help to reduce the uncertainty in this limited database.
- USEPA's aquatic screening benchmark is based on subchronic fish data and only two taxonomic groups. Uncertainties related to the use of subchronic fish data in the derivation of the aquatic screening benchmark (i.e., SCV) could be addressed through chronic effects testing. Chronic laboratory studies or field assessments should be conducted across several taxonomic groups.
- Data regarding the dose-response relationship for *Xenopus* are insufficient to properly evaluate potential impacts of perchlorate exposures on amphibians, including frogs. Additional FETAX studies would help to better evaluate the dose-response relationship for amphibians.
- Toxicity data for terrestrial plants is limited to a single study in lettuce. Effects testing for terrestrial plants across additional taxonomic groups and species would help to reduce the uncertainty in this value.
- Toxicity data for soil invertebrates is limited to a single study in the earthworm. Additional acute and/or chronic toxicity studies in soil invertebrates would help to reduce the uncertainty in USEPA's current soil screening benchmark.
- The USEPA's screening toxicity benchmark for herbivorous wildlife is based on laboratory rodent data. Laboratory or field assessments to evaluate the relevance of the rodent study and toxicity endpoints to herbivorous mammals would help to reduce the uncertainty in the current toxicity benchmark for herbivorous wildlife.

- Toxicity data are currently unavailable to evaluate potential impacts of perchlorate on aquatic or terrestrial birds. Laboratory toxicity studies or field assessments should be conducted in at least two species of birds.

7.4 Hydrologic Conceptual Model

Data gaps in the hydrologic conceptual model for the Bosque and Leon River watersheds include uncertainties in the hydrogeologic features of the watersheds, modeled water budgets, and surface water attributes of Lake Waco and Lake Belton. These data gaps are described in the following subsections.

7.4.1 Hydrogeology

A detailed, hydrologic conceptual model for the watersheds was developed, as described in Section 5.0. However, additional data are necessary to adequately refine this model, as follows.

- The only values of hydraulic conductivity (K) for high water levels are estimations used in model calibration runs. Direct measurements of K would be helpful in refining the actual variations. These data should be collected with enough measurements to permit statistical evaluation.
- The chemical fluctuations that result from recharge events need to be better understood. Chemical data should be collected during different recharge events, and at different levels within the aquifer. Tracers could be used to determine the flow paths of contaminants as a result of recharge events.
- Groundwater velocities also need to be measured during recharge events; tracers could be used for these measurements as well.
- Finally, groundwater-stream interactions need to be investigated during recharge events and during different times of the year.

7.4.2 Water Budget Modeling

An integrated, groundwater-surface water budget model was used to assess the potential migration of perchlorate within the Bosque and Leon River watersheds (Section 5.3). Several data gaps in the information currently available were found to limit the predictive ability of these models, as follows.

- Stream gauges at various locations record measurements of rainfall, stream stage (or level), velocity, and flow rate every 15 minutes. Unfortunately, the duration of recorded measurements from these stream gauges is at most eight months long. In order to quantify flows on these streams, it will be necessary to collect measurements for at least one year.
- Installation of stream gauges and collection of data from additional streams flowing into Lake Waco and Lake Belton would more accurately determine the water budgets

for these watersheds. In particular, the contribution of flow from streams originating on NWIRP McGregor may be better understood if permanent stream gauges were established on Harris and Willow Creeks and the South Bosque River in the Lake Waco watershed, and on Station Creek in the Lake Belton watershed.

- Collection of surface flow measurements in conjunction with perchlorate sampling of surface water would allow for correlations between concentrations and flows. At a minimum, such co-located flow and concentration sampling should be conducted at the confluence of tributaries.
- Longitudinal sampling along main tributaries and streams should be conducted to validate results of surface modeling. Comparison of actual concentrations with modeled concentrations can help to identify the relative contributions of groundwater contamination to surface water concentrations of perchlorate.
- Lake elevation measurements are collected once per day and represent a data gap in storage calculations. Collection of more frequent elevation measurements would help to refine the water budget.

7.4.3 Surface Water Attributes

Principal surface water attributes that may affect the fate and transport of perchlorate within Lake Waco and Lake Belton were characterized (Sections 5.4.1 and 5.4.2). Data gaps in our current understanding of these features were identified that limit an accurate assessment of potential fate and transport processes for perchlorate within these watersheds. These data gaps include the following.

- Clay and silt particles are generally charged and are often capable of sorbing charged and/or polar molecules of anthropogenic origin to their surfaces. Such binding may serve as either a sink or a source of pollutants to biota. Although perchlorate has been measured in surface water samples collected from Lake Waco, the *bioavailability* of perchlorate within this surface water body is currently unknown.
- Lake Waco is classified as moderately eutrophic and, as such, supports seasonal algal blooms. The extent to which these conditions may affect the bioavailability of perchlorate and either hinder or promote transfer to biota is unknown. The potential effects of the diffuser system operated within Lake Waco on the lake’s trophic state, flow patterns, or other attributes is also unknown.
- Lake Belton is characterized as a warm monomictic reservoir, and the warm temperature of the bottom is believed to result in high deep-water bacteria metabolism. This phenomenon contributes to oxygen depletion that generally follows a heterograde pattern. As a result, the water column supports a complex redox pattern, potentially affecting both the solubility and metabolism of contaminants. The extent to which these attributes may affect perchlorate solubility and/or metabolism is currently unknown.
- Linear differences in sedimentation, stratification, turbidity and trophic state along the 21-mile length of Lake Belton result in taxonomic differences, as assessed by phytoplankton types. The extent to which such differences may affect surface water

concentrations and bioavailability of perchlorate within different portions of this watershed are unknown.

- Evaluation of the bacteria-oxygen relationship of the hypolimnion suggests that the thalweg (old river channel) within the upper portion of Lake Belton may be transporting organic materials of river origin rather than lake origin. Based on water temperature (density), such underflows can transport river-borne materials great distances without mixing with the mass of reservoir water. More research into this phenomenon is necessary in order to evaluate potential impacts on water budgets and potential downstream exposures.

7.5 Nature and Extent of Perchlorate Contamination

Data gaps in the available information regarding the nature and extent of perchlorate contamination, and in the migration pathway analysis for the Bosque and Leon River watersheds, include the following.

- Portions of the study area with measured or potential concentrations in surface water or groundwater exceeding the 'interim action level' of 4 ug/L should be better characterized to evaluate potential impacts to human health and the environment.
- Portions of the study area with measured or potential concentrations in soil or sediment exceeding the screening benchmark of 1 mg/kg perchlorate should be further characterized in order to evaluate potential impacts to human health and the environment.
- Dug wells, private groundwater wells, and springs that occur in areas likely to contain greater than the 'interim action level' of 4 ug/L perchlorate should be characterized to evaluate potential impacts to human health and the environment.
- The significance of elevated reporting limits during the 1998 and 1999 groundwater sampling events should be further evaluated to determine if re-sampling of groundwater is required at specific locations.
- The significance of elevated reporting limits during collection of the 1998 and 1999 surface water and stock pond grab samples should be further evaluated to determine if re-sampling of surface water is required at specific locations.
- Tributaries originating on, or in the vicinity of, Fort Hood should be characterized to evaluate potential discharges of perchlorate from this facility to the Lake Belton Watershed.

7.6 Exposure Assessment

Existing information regarding the potential for perchlorate releases from former NWIRP McGregor, or other sources, to impact media within the Bosque and Leon River watersheds was used to evaluate potential exposures of human or ecological receptors that may come in contact with these media. The uncertainties and data gaps in the information needed to complete more detailed assessments of exposure and risk to human and ecological receptors are described in the following subsections.

7.6.1 Human Health Exposure Analysis

Data gaps related to the human exposure assessment include the following.

- Drinking water intake structures located within Lake Belton, downstream of Lake Belton, and within Lake Waco provide the sole-source drinking water supply for nearly 500,000 people in the surrounding communities. Measured or modeled concentrations of perchlorate at these in-take structures are needed to conduct quantitative evaluations of exposure and risk to users of public water supplies. Knowledge regarding potential mixing of water sources to achieve contaminant compliance goals, or specific perchlorate monitoring data collected by the utilities, would allow for a refined assessment of public health risks.
- Surface water obtained from springs and some dug wells is also used for human consumption in areas not connected to public water supplies. The extent to which supplies with known or potential contamination are used for potable purposes should be addressed.
- Humans may potentially consume home-grown produce or livestock products that are irrigated with contaminated water. Sources of water for irrigation or stock ponds and their relationship to contaminated areas of the watersheds need to be further evaluated.
- Recreational users of the Lake Waco and Lake Belton watersheds are susceptible to perchlorate exposures while swimming, fishing, or hunting in contaminated areas. Additional characterization data are necessary to evaluate such exposures. Data currently being collected by TIEHH should be helpful to an evaluation of recreational exposures through consumption of wildlife.

7.6.2 Ecological Exposure Analysis

Identified data gaps in the ecological exposure assessment are as follows.

- The ecological exposure analysis included an assessment of the biological resources within the study area. This evaluation resulted in the identification of several protected or special status species. Additional biological assessment including field surveys may be appropriate to identify the co-occurrence of special status species with areas of elevated perchlorate contamination.
- Uptake of perchlorate by aquatic producers (e.g., phytoplankton and algae), submergent macrophytes, and emergent vegetation through foliar transport and/or root uptake is likely to occur within surface water bodies of the Bosque and Leon River watersheds. In addition, benthic invertebrates and omnivorous and carnivorous fish are exposed to these media. Additional characterization data are necessary to evaluate such exposures in areas that have not been sampled.
- Little information is available regarding the uptake of perchlorate into phytoplankton and algae. It is possible that serial blooms of such organisms within Lakes Belton and Waco may serve to transfer perchlorate from the water column to planktivorous

fish or waterfowl. Measurements of perchlorate uptake by phytoplankton and/or algae would help to identify whether or not this is a potentially significant fate process for perchlorate within these watersheds.

- Once absorbed by producer level receptors (e.g., plants), there is a potential for transfer of perchlorate to consumer level receptors and to higher trophic level receptors through the ecological food chain. The potential for transfer of perchlorate through the ecological food chain is relatively unknown. Studies into the uptake, distribution and potential transfer of perchlorate within multiple trophic levels inhabiting the Bosque and Leon River watersheds are currently being conducted by TIEHH. This information should be useful to an evaluation of ecological exposures through food chain transfer. Once this data is collected and analyzed, it can be evaluated to determine whether or not additional biological sampling may be required.

8.0 CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusions and recommendation of the Final CSM for the Bosque and Leon River Watersheds Study. A Draft CSM (February, 2002) was prepared prior to a meeting between technical members of the USACE and its study team that was held on February 21, 2002. The primary goal of the Draft CSM was to provide a preliminary conceptual understanding of potential human and environmental exposures to perchlorate in the Lake Belton and Lake Waco study area. Based on the Draft CSM, it was concluded that a significant potential exists for human and ecological receptors inhabiting or using the study area to receive exposures to perchlorate through a variety of pathways. It was also concluded that substantial data gaps exist in the available information regarding the occurrence, migration, and fate of perchlorate within the Bosque and Leon River watersheds. The results of the February 21, 2002 technical meeting confirmed that a significant potential exists for human and environmental exposures to perchlorate in the Lake Belton and Lake Waco study area. The technical meeting also resulted in the prioritization of data gaps regarding available information on the occurrence, migration, and fate of perchlorate within the Bosque and Leon River Watersheds.

Data gaps identified as ‘high’ priority and warranting further investigation include, but are not limited to, the following:

- Acquiring a better understanding of fluctuations in stream perchlorate concentrations due to recharge events.
- Supplementation of existing stream gauges to reduce uncertainties in the modeled water budgets for the Bosque and Leon River watersheds.
- Confirmation of perchlorate concentrations potentially reaching the lakes through focused sampling in the Lake Waco and Lake Belton deltas.
- Evaluation of a potential additional source of perchlorate to the Lake Belton (e.g., Fort Hood).

Table 8-1 provides a comprehensive list of all data gaps identified during the preparation of this Final CSM, general recommendations for resolving each data gap, and a consensus ranking of the importance of resolving each data gap, consistent with the outcome of the February 21, 2002 technical meeting.

TABLE 8-1

SUMMARY OF DATA GAPS AND RECOMMENDATIONS FOR RESOLUTION

Data Gap	Recommendation for Data Gap Resolution	Resolution Priority
Fate and Transport of Perchlorate		
Perchlorate is denser than water but little information is available regarding the potential for perchlorate to sink in groundwater, or undergo differential stratification in surface waters.	Conduct simple bench-top testing, or stratified water column testing in the field to better understand the vertical transport of perchlorate in groundwater and surface water bodies.	Medium
Information regarding the potential for perchlorate to undergo cation exchange with minerals in soil or sediment is not well documented.	Conduct bench-top testing or field evaluation of cation exchange capacity in watershed soils or sediments to better understand the fate of perchlorate within these media.	Low
The potential for perchlorate to accumulate in soils following sequential irrigation and evaporation is currently unknown.	Conduct laboratory experiments, or sampling investigations in agricultural areas of the watersheds to evaluate the potential for accumulation of perchlorate in irrigated soils.	High
The extent of areas of sediment scour and deposition in streams and lakes is poorly understood.	Sediment deposits behind the old Lake Waco dam may be investigated for potential sediment pore water sampling.	Medium
The extent to which conditions favorable to anaerobic degradation of perchlorate within portions of the watersheds associated with elevated perchlorate concentrations is currently unknown.	Conduct field assessments of current watershed conditions in areas with elevated perchlorate concentrations.	Medium
Hydrologic Conceptual Model		
Direct measurements of hydraulic conductivity K would be helpful in refining the actual variations of hydraulic conductivity (K) for high water levels.	Collect hydraulic conductivity data with enough measurements to permit statistical evaluation.	Medium

TABLE 8-1

SUMMARY OF DATA GAPS AND RECOMMENDATIONS FOR RESOLUTION

Data Gap	Recommendation for Data Gap Resolution	Resolution Priority
The chemical fluctuations that result from recharge events need to be better understood.	Chemical data should be collected during different recharge events, and at different levels within the aquifer. Tracers could be used to determine the flow paths of contaminants as a result of recharge events.	High
Groundwater velocities during recharge events need to be better understood.	Groundwater velocity data should be collected during different recharge events, and at different levels within the aquifer. Tracers could be used to determine the groundwater velocities as a result of recharge events	Medium
Groundwater-stream interactions during recharge events and during different times of the year needs to be better understood.	Seasonal measurements of groundwater and stream characteristics should be taken concurrently during known recharge events.	Medium
Water Budget Modeling		
The absence of continual measurements of lake elevation for Lake Belton and Lake Waco creates data gaps in the water budget.	More frequent measurements could help refine the water budget model.	Low
The duration of recorded measurements of rainfall, stream stage (or level), velocity, and flow rate is insufficient to quantify flows on the streams.	Collect measurements of rainfall, stream stage (or level), velocity, and flow rate every 15 minutes for at least one year from stream gauges at various locations.	Medium
Water budgets for the watersheds are inaccurate due to absence of stream gauges and collection of data from certain streams flowing into Lake Waco and Lake Belton originating on NWIRP McGregor.	Permanent stream gauges should be established on Harris and Willow Creeks and the South Bosque River in the Lake Waco watershed, and on Station Creek in the Lake Belton watershed.	High
A correlation between concentrations and flows is impossible due to the absence of co-located data for surface flow and perchlorate concentrations.	Conduct co-located flow and concentration sampling at the confluence of tributaries.	Medium

TABLE 8-1

SUMMARY OF DATA GAPS AND RECOMMENDATIONS FOR RESOLUTION

Data Gap	Recommendation for Data Gap Resolution	Resolution Priority
It is not currently possible to evaluate the contribution of groundwater contamination to surface water concentrations based on current surface modeling results.	Longitudinal sampling along main tributaries and streams should be conducted to validate results of surface modeling. Compare measured concentrations with modeled concentrations.	Medium
Surface Water Attributes		
The bioavailability of perchlorate within the surface water bodies of Lake Waco and Lake Belton watersheds is currently unknown.	Further studies on the bioavailability of perchlorate in the watersheds are necessary.	Medium
The extent to which seasonal algal blooms may affect the bioavailability of perchlorate and either hinder or promote transfer to biota is unknown.	Studies of biota uptake should be conducted to compare uptake rates during and between agal blooms.	Medium
The potential effects of the diffuser system operated within Lake Waco on the lake's trophic state, flow patterns, or other attributes is currently unknown.	Compare measurements of Lake Waco's trophic state, flow patterns, and other attributes from before the installation of the diffuser system to measurements taken since the installation.	Medium
The extent to which high deep-water bacteria metabolism in Lake Belton may affect perchlorate solubility and/or metabolism is currently unknown.	Laboratory tests must be conducted simulating the attributes present in Lake Belton to determine the expected affect on perchlorate.	Low
The extent to which taxonomic differences along the 21-mile length of Lake Belton may affect surface water concentrations and bioavailability of perchlorate within different portions of this watershed are unknown.	Sampling of surface water concentrations and bioavailability in conjunction with measurements of taxonomic differences should be able to help correlate these characteristics within the watershed.	Low
Transportation of organic materials of river origin rather than lake origin without mixing with the mass of Lake Belton is not well understood.	Movement of river borne organic materials through the reservoir should be tracked with tracers to determine impacts on water budgets and downstream exposures.	High

TABLE 8-1

SUMMARY OF DATA GAPS AND RECOMMENDATIONS FOR RESOLUTION

Data Gap	Recommendation for Data Gap Resolution	Resolution Priority
Migration Pathway Analysis		
Characterization of perchlorate in surface water and groundwater is insufficient.	Portions of the study area with measured or potential concentrations in surface water or groundwater exceeding the ‘interim action level’ of 4 ug/L should be further characterized.	High
Characterization of perchlorate in soil and sediment is insufficient.	Portions of the study area with measured or potential concentrations in soil or sediment exceeding the screening benchmark of 1 mg/kg perchlorate should be further characterized.	High
Dug wells, private groundwater wells, and springs may be insufficiently characterized.	Dug wells, private groundwater wells, and springs that occur in areas likely to contain greater than the ‘interim action level’ of 4 ug/L perchlorate should be further characterized.	Medium
Elevated reporting limits during the 1998 and 1999 groundwater sampling events create uncertainty.	The significance of elevated reporting limits should be further evaluated to determine if re-sampling of groundwater is required at specific locations.	Medium
Elevated reporting limits during collection of 1998 and 1999 surface water and stock pond grab samples create uncertainty.	The significance of elevated reporting limits should be further evaluated to determine if re-sampling of surface water is required at specific locations.	Medium
The flow patterns of streams running into Lake Belton and Lake Waco are poorly understood.	The flow patterns of streams impacted by perchlorate may be better understood by utilizing dye tracers and other related studies.	Medium
The mixing of streams impacted by perchlorate with non-impacted streams may be better understood.	Sampling of streams (across the stream’s cross section and at a variety of depths) downstreams of stream confluence may increase understanding of mixing.	Medium
Perchlorate detections in the southern portion of Lake Belton suggest potential contamination from another source.	Tributaries in the vicinity of Fort Hood should be characterized to evaluate potential discharges of perchlorate from this facility to Lake Belton.	High

TABLE 8-1

SUMMARY OF DATA GAPS AND RECOMMENDATIONS FOR RESOLUTION

Data Gap	Recommendation for Data Gap Resolution	Resolution Priority
Exposure Assessment		
Further knowledge regarding potential mixing of water sources to achieve contaminant compliance goals or specific perchlorate monitoring data collected by the utilities is necessary for assessment of public health risks.	Measured or modeled concentrations of perchlorate at the Lake Belton and Lake Waco in-take structures will be needed to conduct quantitative evaluations of exposure and risk to users of public water supplies.	High
In order to evaluate exposures and risks for users of springs and some dug wells for human consumption further measurements are needed from these water sources.	Measured or modeled concentrations of perchlorate in these water sources should also be obtained in order to evaluate exposures and risks for such users.	Medium
The potential uptake of perchlorate in plants and agricultural products through irrigation of food crops needs to be better understood.	Conduct laboratory or field assessments using methods designed to quantify perchlorate uptake in agricultural products.	High
Exposure of humans to perchlorate in surface water, sediment and biota associated with recreational uses of the Lake Waco and Lake Belton watersheds is incomplete.	Additional characterization data are needed to in areas that have not been sampled. Data currently being collected by TIEHH should be useful to an evaluation of exposures through consumption of wildlife.	Medium
Locations of protected or special status species in relation to areas of high perchlorate contamination are unknown.	Biological field surveys may be appropriate to identify the co-occurrence of special status species with areas of elevated perchlorate contamination.	Medium
Measurements of perchlorate uptake by aquatic producers (e.g., phytoplankton and algae), submergent macrophytes, emergent vegetation, benthic invertebrates and omnivorous and carnivorous fish are limited.	Studies of this phenomenon are currently being conducted by TIEHH. This information should be useful to an evaluation of ecological exposures through food chain transfer. Additional biological sampling may be required.	High
The extent to which phytoplankton and algae may serve to transfer perchlorate from the water column to planktivorous fish or waterfowl is currently unknown.	Measurements of perchlorate uptake by phytoplankton and/or algae would help to identify whether or not this is a potentially significant fate process for perchlorate within these watersheds.	Medium

TABLE 8-1

SUMMARY OF DATA GAPS AND RECOMMENDATIONS FOR RESOLUTION

Data Gap	Recommendation for Data Gap Resolution	Resolution Priority
Biological Uptake and Transformation		
Data on perchlorate accumulation in aquatic plants are insufficient to assess exposures to primary consumers (i.e., planktonic and benthic invertebrate communities).	Conduct laboratory or field uptake and accumulation studies using methods designed to quantify aquatic plant concentration factors.	Medium/High
Data are insufficient to determine whether perchlorate bioconcentrates in aquatic organisms.	Conduct laboratory or field assessments using methods designed to quantify aquatic organism concentration factors under steady state conditions.	Medium/High
Data on accumulation in fish and other aquatic organisms are insufficient to evaluate exposures to organisms that feed on them.	Conduct laboratory or field uptake and accumulation studies using methods designed to quantify aquatic plant concentration factors across multiple trophic levels.	Medium/High
Data on perchlorate accumulation in terrestrial vascular plants are insufficient to evaluate potential exposures to terrestrial herbivores.	Conduct laboratory or field assessments using methods designed to quantify terrestrial herbivore concentration factors.	Medium/High
Data on the fate of perchlorate in irrigated soils and plants are insufficient to evaluate potential exposures to humans through agricultural products.	Conduct laboratory or field assessments to determine effects of perchlorate in irrigated soils and concentration factors in terrestrial plants.	Medium/High
Data on accumulation in litter feeding or herbivorous invertebrates are insufficient to evaluate exposures to mammals or birds that feed on these organisms.	Conduct laboratory or field assessments using methods designed to quantify litter feeding or herbivorous invertebrate concentration factors.	Medium/High
Ecotoxicology		
Effects of perchlorate on algae and aquatic macrophytes are insufficient to estimate impacts to aquatic primary producers.	Conduct laboratory or field assessments to quantify effects of perchlorate on algae and aquatic macrophytes.	Medium
Toxic effect levels in aquatic invertebrates are limited to daphnids.	Conduct laboratory toxicity studies or field assessments in at least two species of aquatic invertebrates.	Medium
USEPA's aquatic screening benchmark is based on subchronic fish data and only two taxonomic groups.	Conduct chronic laboratory toxicity studies or field assessments across several taxonomic groups.	Medium

TABLE 8-1

SUMMARY OF DATA GAPS AND RECOMMENDATIONS FOR RESOLUTION

Data Gap	Recommendation for Data Gap Resolution	Resolution Priority
Data regarding the dose-response relationship for *Xenopus* are insufficient to properly evaluate potential impacts of perchlorate exposures on amphibians, including frogs.	Conduct additional FETAX studies to better evaluate the dose-response relationship for amphibians.	Medium
Toxicity data for terrestrial plants is limited to a single study in lettuce.	Conduct laboratory or field assessments in additional terrestrial plant species.	Medium
Toxicity data for soil invertebrates is limited to a single study in the earthworm.	Conduct laboratory or field assessments in additional terrestrial invertebrate species.	Medium
The USEPA's screening toxicity benchmark for herbivorous wildlife is based on laboratory rodent data.	Conduct laboratory or field assessments to evaluate the relevance of the rodent study and toxicity endpoints to herbivorous mammals.	Medium
Toxicity data are currently unavailable to evaluate potential impacts of perchlorate on aquatic or terrestrial birds.	Conduct laboratory toxicity studies or field assessments in at least two species of birds.	High

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