Natural Resource Damage Assessment Plan for the Rocky Mountain Arsenal, Commerce City, Colorado

Prepared by:

Natural Resource Trustees for the
State of Colorado

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October 24, 2007

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Acronyms and Abbreviations

ALAD	aminolevulinic acid dehydratase
Army	U.S. Department of Army
BAS	Rocky Mountain Arsenal Biological Advisory Subcommittee
bcy	bank cubic yards
bw	body weight
CAR	Contamination Assessment Report
CBT	Colorado Big Thompson
CCR	Colorado Code of Regulations
CDPHE	Colorado Department of Public Health and Environment
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CF&I	Colorado Fuel and Iron
CFR	Code of Federal Regulations
cfs	cubic feet per second
ChE	cholinesterase
CMP	Comprehensive Monitoring Program
CRL	certified reporting limit
CRS	Colorado Revised Statutes
CSRG	containment system remediation goal
CWCB	Colorado Water Conservation Board
DBCP	dibromochloropropane (Nemagon)
DCPD	dicyclopentadiene
DDD	dichlorodiphenyldichloroethane
DDE	dichlorodiphenylethane
DDT	dichlorodiphenyltrichloroethane
DIMP	diisopropyl methylphosphonate
DOI	U.S. Department of the Interior
DOW	Colorado Division of Wildlife
DSAY	discounted service-acre year
ECCV	East Cherry Creek Valley
EPA	Environmental Protection Agency

FDA	U.S. Food and Drug Administration
FS	Feasibility Study
GIS	geographic information system
gpm	gallons per minute
HBSF	Hydrazine Blending and Storage Facility
HCBD	hexachlorobutadiene
HEA	habitat equivalency analysis
IEA/RC	Integrated Endangerment Assessment/Risk Characterization
IRA	interim response action
LD_{50}	50% Lethal Dose
MATC	Maximum Acceptable Tissue Concentration
MCL	maximum contaminant level
mg/kg	milligrams per kilogram
mg/m^3	milligrams per cubic meter
MWDA	Metropolitan Water Development Agreement
NCP	National Contingency Plan
NDMA	nitrosodimethylamine
NPL	National Priorities List
NRD	natural resource damage
NRDA	natural resource damage assessment
O&M	operations and maintenance
OU	Operable Unit
PAH	polynuclear aromatic hydrocarbon
PASD	Preassessment Screen Determination
PCE	perchloroethylene
PEC	probable effects concentrations
ppm	parts per million
RCDP	Restoration and Compensation Determination Plan
RCRA	Resource Conservation and Recovery Act
REA	resource equivalency analysis
RI	Remedial Investigation
ROD	Record of Decision
RP	responsible party

SACWSD	South Adams County Water and Sanitation District
SDWA	Safe Drinking Water Act
SEL	severe effect level
SVOC	semivolatile organic compound
TCE	trichloroethylene
TEC	threshold effects concentration
TRER	Terrestrial Residual Ecological Risk
TRV	Toxicity Reference Value
TSP	total suspended particulates
TVE	total value equivalency
μg/g	micrograms per gram
μg/L	micrograms per liter
$\mu g/m^3$	micrograms per cubic meter
UFS	unconfined flow system
USC	United States Code
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VOC	volatile organic compound
WD	water district

Executive Summary

The Rocky Mountain Arsenal (the Arsenal) is a federally-owned facility in Adams County, Colorado, just northeast of the Denver metropolitan area and southwest of Denver International Airport (Figure S.1). In 1942, the U.S. Department of Army (Army) purchased this 27 square-mile property for the manufacture of chemical warfare agents and incendiary munitions. Agents and munitions included rockets and projectiles containing blister agents (e.g., mustard gas), lewisite, phosgene bombs, incendiary bombs, napalm, and later, Sarin nerve agent. The Army also used the Arsenal for “demilitarization” of nerve agents and bombs into the 1980s. Manufacturing byproducts, unexploded munitions, and other wastes were stored on-site.

After World War II, the Army leased portions of the site to private industry, primarily Shell Oil Company (Shell). Shell manufactured pesticides, insecticides, herbicides, and other chemicals at the Arsenal from 1952 to 1982. Wastes from both Shell and Army manufacturing were transported through chemical sewers to on-site trenches and waste disposal basins (Figure S.2). Millions of pounds of chemical weapon and pesticide manufacturing wastes were disposed in these waste areas between 1942 and 1982.

The Environmental Protection Agency (EPA) listed the Arsenal on the Superfund National Priorities List (NPL) in the 1980s, thus recognizing the Arsenal as one of the most contaminated sites in the country and making it a priority for cleanup. The final environmental remediation plans were finalized in 1995 and 1996. At that time, the Army anticipated completion of remediation, excluding ongoing treatment of groundwater, by 2011. That estimate has now been revised to 2010.

The Superfund cleanup program addresses threats to human health and the environment. The same federal law that established this cleanup program also included provisions for recovery of natural resource damages (NRDs). Thus, in addition to those cleanup activities, the Colorado Natural Resource Trustees have initiated a natural resource damage assessment (NRDA) at the Arsenal. The goals of NRDs claims are to restore the environment to the state it would have been in had the pollution not occurred, and to compensate the public for the interim losses of public trust natural resources up to the time that such restoration is complete. Restoration can be accomplished by directly restoring the injured resource, or by rehabilitating, replacing, or acquiring equivalent resources.

The Arsenal Records of Decision (RODs) require continued operation of existing groundwater containment, extraction, and treatment systems, as well as installation of additional extraction systems and upgrades to existing systems. Hazardous substances continue to migrate to groundwater from contaminated subsurface soils, and thus groundwater at the Arsenal will not be clean for the foreseeable future.

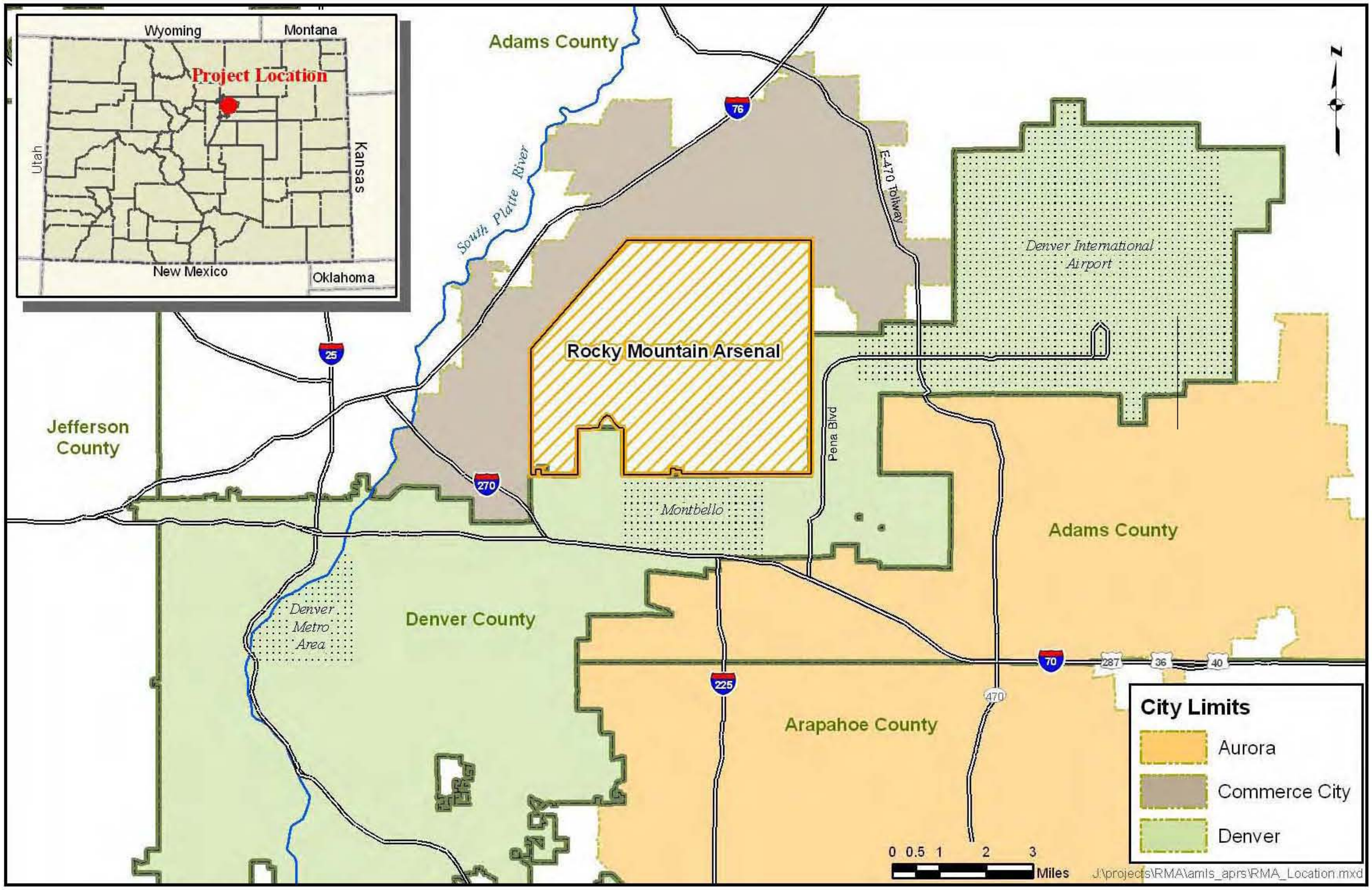

Figure S.1. General location of the Rocky Mountain Arsenal in the Denver area.

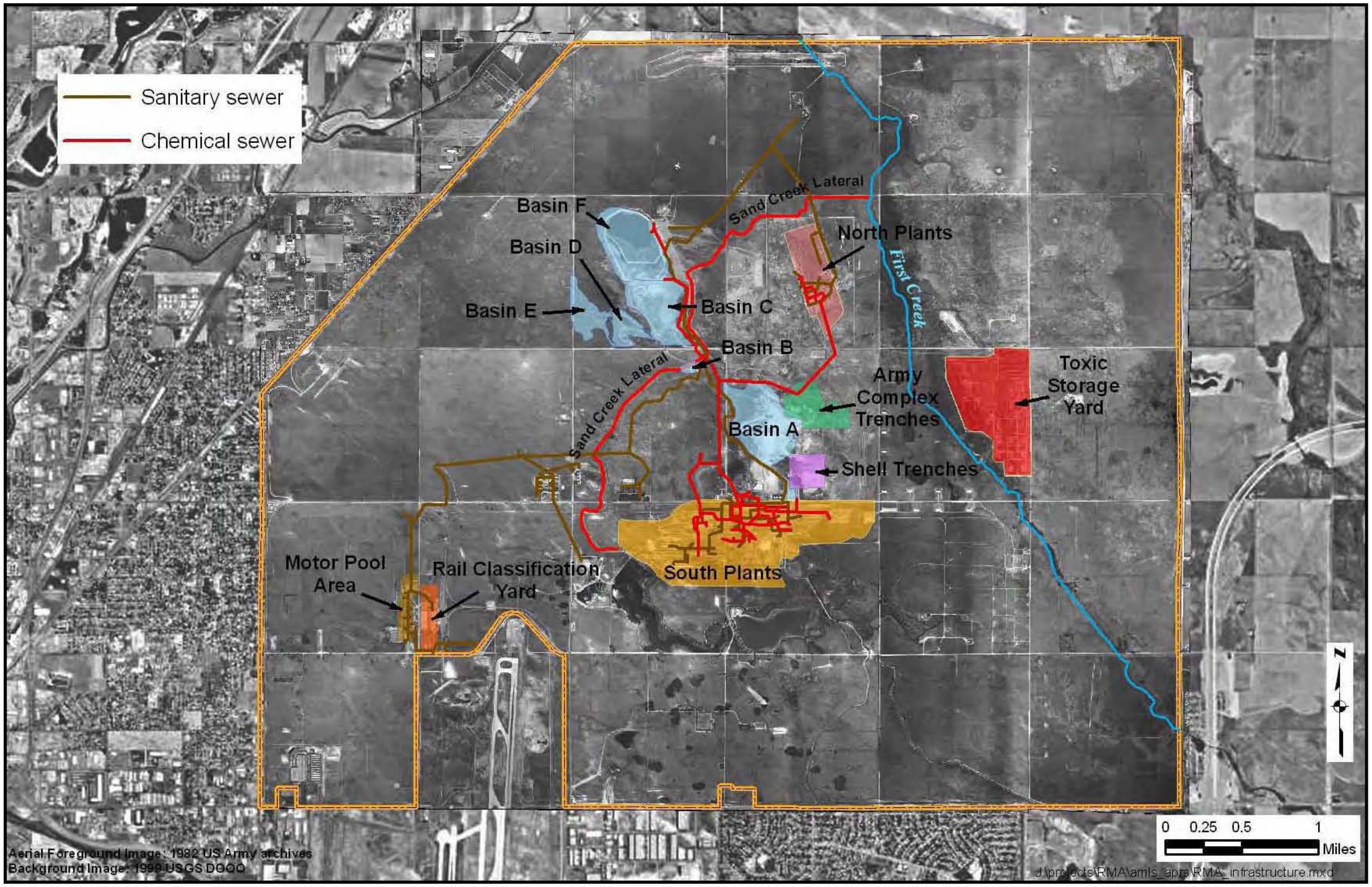

Figure S.2. Manufacturing, storage, waste transit, and waste disposal sites at the Arsenal.

The purpose of this Assessment Plan is to document the State Trustees' basis for conducting a damage assessment, and to set forth the proposed approaches for quantifying harm ("injuries") to natural resources and calculating damages associated with those injuries. The Assessment Plan enables the Trustees to ensure that the NRDA will be completed in a planned and systematic manner and at a reasonable cost. The Plan informs the Army, Shell, and the public of the proposed assessment methods so that stakeholders can participate in the assessment process.

The State Trustees plan to seek recovery for both the costs of restoring injured resources to baseline conditions (i.e., conditions that would have been present absent the releases of hazardous substances), and for compensatory damages to account for lost services in the past, present, and future until the natural resources have been restored to baseline.

The State's NRD calculations will take into account the benefits of the remedial actions at the Arsenal. For resources where the remedial actions will return or have returned resources to baseline conditions, the State's damage calculations will include the period from the onset of injury (or 1981) until baseline conditions are (or were) achieved.

Response actions

The Army and Shell addressed the contamination at the Arsenal through a series of response actions beginning with the installation of groundwater extraction and treatment systems on the boundaries of the facility in the early 1980s. In the mid-1980s, the Army and Shell implemented interim response actions (IRAs) to address known significant sources of contamination and to protect against immediate threats to human health and the environment. The most extensive IRA was the closure of Basin F (Figure S.2), where the Army removed and incinerated nearly 11 million gallons of liquid chemical waste and transferred over 500,000 cubic yards of contaminated soils and sludge to a temporary waste pile. Noxious odors from the excavation and air-drying of the sludges entered nearby neighborhoods. After approximately six months of failing to control the emissions, the Army abandoned the sludge removal and capped the remaining materials in place.

The selected remedies to address human health and the environment put forth in the On-Post and Off-Post RODs included the construction of a lined hazardous waste landfill and re-construction of Basin A (Figure S.2) as a landfill. The hazardous waste landfill received contaminated soils and sludges posing an unacceptable risk to human health, and Basin A received contaminated soils and sludges that did not exceed human health risk thresholds but did pose a risk to biota. Millions of cubic yards of soils have been transported to these repositories; excavation and transport of Basin F soils and sludges are scheduled for completion in 2008. However, in many locations, only the upper five to ten feet of soils were remediated, leaving large quantities of hazardous substances buried in deeper soils.

After excavation of contaminated soils, hundreds of acres at the Arsenal were capped, covered with clean soil, and revegetated, thereby reducing risks to human health and the environment and benefiting injured natural resources. Once appropriate response actions were completed, portions of the Arsenal were deleted from the NPL. Thus far, over 900 acres were removed from the NPL and sold to Commerce City, and over 12,000 acres were removed from the NPL and transferred to the U.S. Fish and Wildlife Service to be part of the National Wildlife Refuge system. Areas such as waste disposal trenches, landfills, and areas with groundwater treatment systems will remain in the Army's possession.

While response actions address threats to human health and the environment, the State Trustees must calculate the cost of restoring injured resources to baseline conditions, and quantify interim losses up to the time that restoration is complete and baseline conditions are achieved. The State Trustees anticipate using existing data to determine and quantify injuries to groundwater, wildlife and its supporting ecosystems, and air resources.

Groundwater injuries and damages

Hazardous substance releases at the Arsenal have resulted in extensive plumes of contaminated groundwater under the Arsenal property and north of the Arsenal towards the South Platte River (Figure S.3). In addition, the Army placed institutional controls preventing the use of the groundwater as a drinking water source on all groundwater under the Arsenal, and preventing any use of shallow groundwater underlying 350 acres of Shell property north of the Arsenal until that groundwater is clean.

To assess lost groundwater services over time, the State Trustees will:

- Calculate the spatial extent of the groundwater plume containing hazardous substance concentrations in excess of State or federal groundwater standards

- Determine the extent to which hazardous substances have been released to groundwater in deep aquifers underlying the Arsenal, including the Denver, Upper Arapahoe, Lower Arapahoe, and Laramie – Fox Hills Formations

- Determine the volume of groundwater in each of the deep aquifers that is inaccessible for use as a drinking water supply because of institutional controls

- Determine the annual safe yield of shallow alluvial groundwater underlying the Arsenal that is inaccessible as a drinking water supply because of institutional controls, as well as the annual safe yield inaccessible for any purpose because of hazardous substance concentrations.

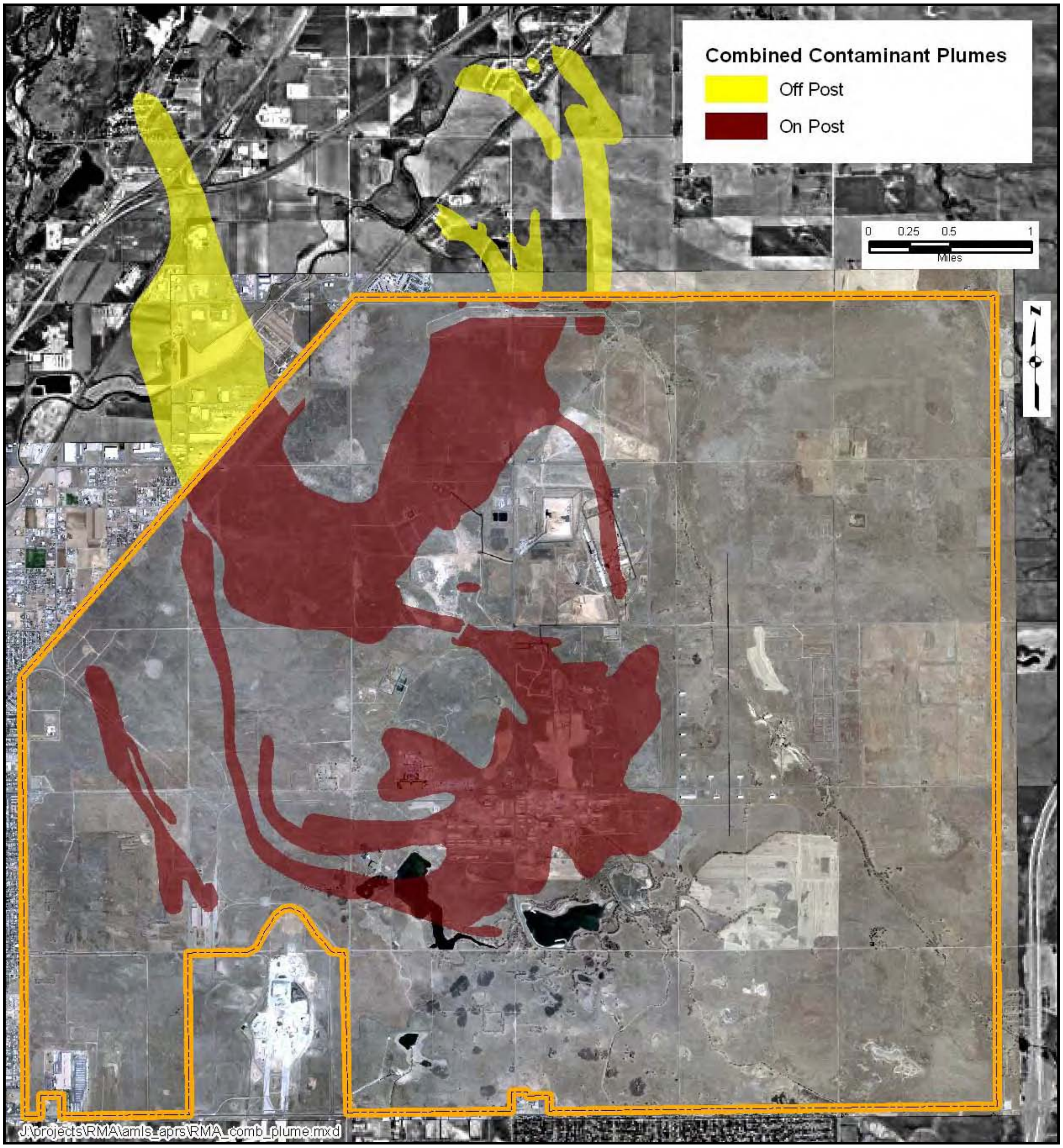

Figure S.3. Estimated extent of a combined contaminant plume (trichloroethylene, benzene, chloroform, dibromochloropropane, and dieldrin) in the shallow alluvial aquifer (1994).

The assessment of groundwater injury will rely primarily on existing data within the Rocky Mountain Arsenal Environmental Database. To determine the spatial extent of groundwater injuries over time, the State Trustees may perform the following additional work as part of the assessment:

- Develop a flow and transport model using MODFLOW/MT3D or MODFLOW-SURFACT to estimate the spatial extent of groundwater injury in the past, present and future
- Develop a hazardous substance plume degradation/decay model to estimate the future spatial extent of groundwater injury
- Evaluate contaminated groundwater in the weathered upper Denver Formation as well as in deeper groundwater formations
- Further identify past and existing uses of groundwater at and downgradient of the Arsenal.

NRDA regulations specify that the highest-and-best use of an injured resource should be used to calculate damages. In the Denver metropolitan area, municipal water supply qualifies as the highest and best use for groundwater. Thus, the State has incurred lost use damages to groundwater both directly, because of the plume of hazardous substances in groundwater, and indirectly, because the hazardous substances resulted in institutional controls preventing the use of the Arsenal groundwater as a municipal water supply.

Many municipal water suppliers in the Denver metropolitan area use shallow alluvial groundwater tributary to the South Platte River as a water source. When easily accessible water supplies such as the shallow South Platte River groundwater are not available, municipalities spend millions of dollars to transport water tens or even hundreds of miles from distant water sources to the end-user. Preliminary evidence thus suggests that clean alluvial groundwater under the Arsenal would be a practical municipal water source.

Shallow groundwater at the Arsenal is tributary to the South Platte River. To access this water (absent hazardous substances and institutional controls), a user would be required to have an approved augmentation plan demonstrating that senior water rights holders in the South Platte River basin would not be harmed as a result of pumping. Most alluvial groundwater pumped in the Arsenal area is either used in households and then released to the South Platte River via wastewater treatment plant effluent, or is used for irrigation, with a portion percolating back to shallow groundwater. Most municipal suppliers use wastewater effluent as well as rights to more polluted water sources such as ditches to provide augmentation when necessary to offset pumping of clean groundwater. Thus, it is likely that, absent the releases of hazardous substances and subsequent enactment of institutional controls, the Arsenal groundwater would have been an attractive and usable municipal water source.

The State Trustees will use a combination of approaches to assess damages to injured groundwater at the Arsenal. These approaches will account for both the cost of restoration and the compensable value of the interim loss. Compensable value is the value of lost direct public use of the services, plus lost non-use values such as existence and bequest values. The State Trustees anticipate using the following approaches for estimating damages:

- Market price methods
- Resource equivalency methods
- Total value/restoration scaling methods.

Water resources, including groundwater, are traded in a reasonably competitive market in the Denver metropolitan area. Initial evaluation of data suggests that sufficient information is available to form an accurate representation of the willingness to pay for water for at least the past 15 years in the Front Range area of Colorado. This can provide a basis on which to value contaminated groundwater damages from the Arsenal.

To develop market prices for groundwater in the Arsenal region, the State Trustees will use observed market data, including associated variables, to establish appropriate market prices for which water would sell in the Front Range region at a given date. The sale price of water will then be used to calculate the annual diminished value of injured resources. If necessary, market prices for any dates after those available in the collected transactions will be based on statistical forecasts using projections of variables that help explain changes in water prices, such as urbanization and development in the region.

The State Trustees also intend to use restoration-based equivalency approaches to assess damages. This includes resource equivalency analysis (REA), in which the State Trustees first quantify injuries in terms of lost groundwater services, then scale restoration projects such that they provide the equivalent amount of groundwater service gain. The State expects to use this "service-to-service" scaling method because restoration alternatives are available that provide similar types and quality of services as those lost. Projects that restore groundwater services may include:

- Water quality protection and improvement programs
- Water reuse programs
- Water conservation programs
- Water recharge programs.

Restoration projects will be scaled to compensate for both interim losses and restoration that is required to return injured resources to baseline conditions. The State will then estimate the cost of the projects based on preliminary project designs – full engineering designs are not feasible or appropriate to develop during the assessment process.

Finally, in addition to service-to-service scaling, the State may use a value-to-value scaling approach to assess the total value equivalency (TVE) of groundwater damages. Using this approach, the State Trustees will conduct a survey with stated-choice questions to determine public preferences for various types of restoration alternatives. This will aid the State Trustees in evaluating the benefits of restoration alternatives and provide additional input into the selection of alternatives. In addition, the study will provide value-based, as opposed to service-based, methods to determine the appropriate scale of potential restoration actions.

Anticipated activities to assess groundwater damages by TVE include:

- Developing restoration options to offset groundwater injuries at the Arsenal
- Conducting qualitative survey research such as focus groups and structured individual interviews to aid in the development of the TVE survey
- Developing the survey instrument, including peer review of the survey and the implementation process
- Administering the survey to a relevant segment of the population
- Analyzing and reporting the data.

Using the TVE approach, groundwater damages will be based on both lost active use values and lost passive use values.

Wildlife injuries and damages

Prior to implementation of the cleanup, much of the wildlife habitat at the Arsenal was contaminated with elevated concentrations of hazardous substances, resulting in widespread wildlife mortality. Contaminants found in soils, surface water, and sediments included the toxic pesticides aldrin, dibenzochloropropane, dieldrin, endrin, and isodrin. Prior to remediation, aldrin and dieldrin were detected in surface soils across much of the Arsenal property (Figure S.4). Most soils in the central processing and disposal areas (see Figure S.2) contained pesticide concentrations exceeding ecological risk thresholds. As a result, approximately 1.5 million cubic yards of contaminated soils were excavated and landfilled as part of the implemented remedy at the Arsenal.

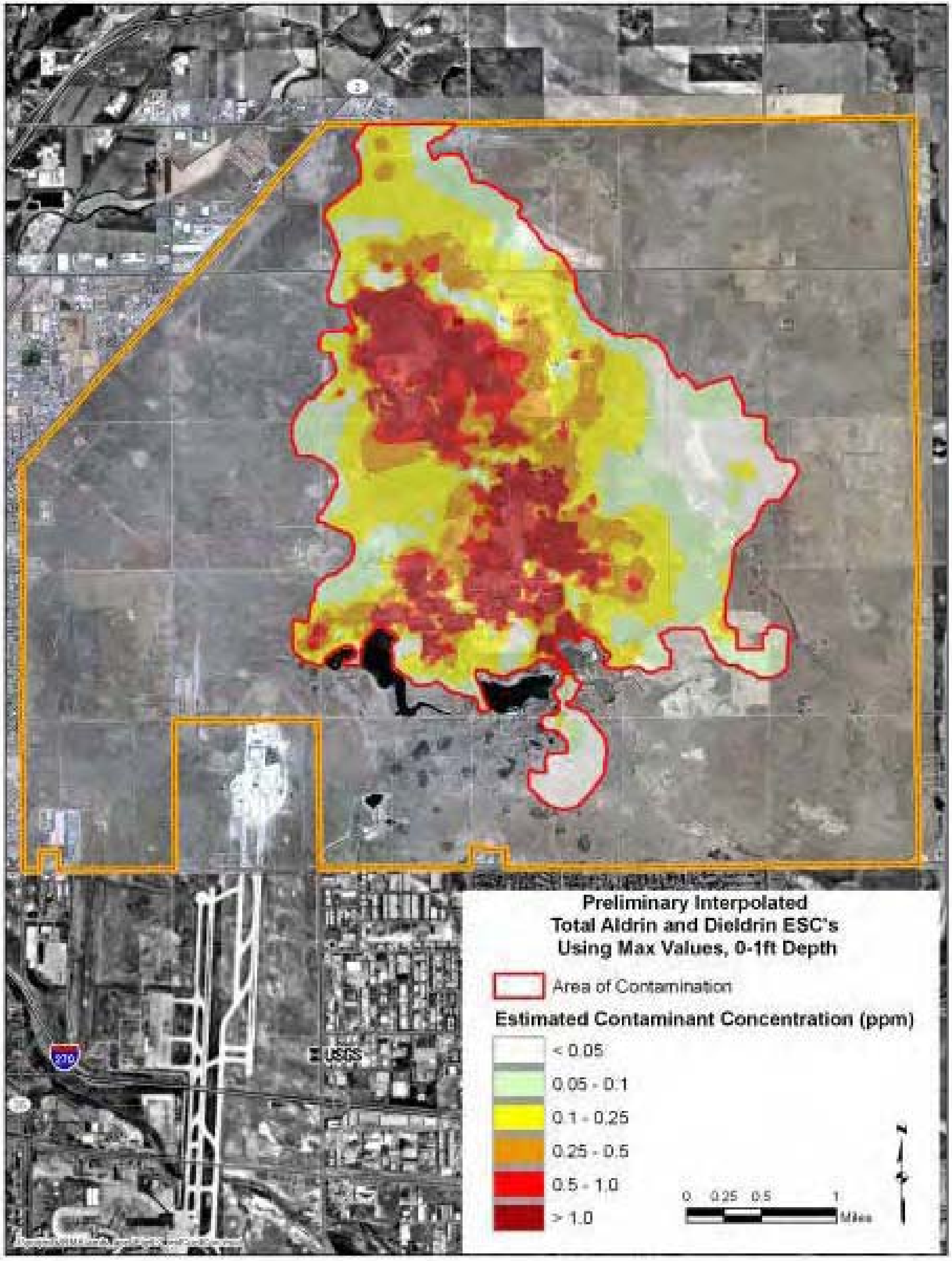

Figure S.4. Organochlorine pesticides such as aldrin and dieldrin were widespread in Arsenal soils before remediation.

To determine and quantify injuries to biota as a result of these hazardous substance releases, the State Trustees will employ multiple methods, including:

- Identifying Food and Drug Administration (FDA) action level exceedences and/or State and federal consumption advisories. Existing data indicate some exceedences of FDA action levels in Arsenal biota. Consumption of fish caught in Arsenal lakes has been banned since 1984. The 1989 Federal Facility Agreement banned consumption of all Arsenal wildlife.

- Compiling evidence of wildlife mortality. Existing documents describe thousands of bird and mammal carcasses found at the Arsenal, including over 1,800 waterfowl carcasses in Basin F alone between 1981 and 1988.

- Developing food web models to estimate injuries to biota. Toxicology studies can be used to determine oral doses of contaminants that cause adverse effects to biota. Food web models will allow estimates of toxic doses of contaminants in wildlife based on contaminant concentrations in soils. Injury thresholds in soils will be developed using these food web models.

- Estimating injuries that have occurred as a result of response actions. Response actions at the site have resulted in harm to wildlife habitat by heavy machinery, intentional eradication of prairie dogs, and reduction in burrowing animal habitat resulting from constructed biota barriers.

As part of this assessment, the State Trustees will compile existing data from Arsenal documents and from the Rocky Mountain Arsenal Environmental Database. Food web models developed during the Superfund remedial investigation will be updated as appropriate to reflect current scientific understanding. The State Trustees may undertake the following additional work to determine and quantify injuries and damages to biological resources:

- Revise and update bioaccumulation and dietary toxicity models

- Address the additive toxicity of organochlorine pesticides such as aldrin and dieldrin

- Assess injuries to biological resources from exposure to metalloids such as arsenic

- Assess injuries to biological resources associated with perennial and intermittent surface water and associated sediments

- Assess injuries to reptiles, amphibians, fish, and bats.

The State Trustees will quantify the spatial and temporal extent of injuries to biological resources and their supporting habitat. Damages will be assessed based on the cost to restore equivalent resources over space and time. The State Trustees will use habitat equivalency analysis or REA to first quantify injuries in terms of lost habitat or lost resource services, then scale restoration projects such that they provide the equivalent amount of habitat or resource service gain.

The State will consider restoration projects from existing regional restoration plans (e.g., from the Northeast Greenway Corridor project) and solicit proposals from State agencies such as the Division of Wildlife, interested nonprofit organizations, and the general public when identifying a list of potential restoration projects. Such projects would benefit the resources that have been injured at the Arsenal. Specific types of restoration projects may include:

- Preservation of existing habitats at risk to development
- Restoration and enhancement of existing degraded habitats
- Preservation of protective buffers for core areas of high wildlife value.

After determining the required size of proposed restoration projects, the State will estimate the cost to implement these projects. Costs will be based on preliminary project designs. Total cost estimates will include project design, implementation, monitoring, continued operation and maintenance, contingencies, Trustee oversight, and adaptive management.

Air injuries and damages

Depending on availability of data, the State Trustees plan to evaluate injuries to air resources incurred during the Basin F IRA in 1988 and 1989. Attempts to excavate and air-dry Basin F sludges released noxious odors to surrounding communities. From the summer of 1988 through the spring of 1989, the Army received 200 odor complaints from nearby citizens. Many people reported adverse effects such as headaches, burning and watering eyes, nausea, and vomiting. Local residents reported that they avoided the outdoors and shut their windows, regardless of the weather. The foul odors and adverse health effects constituted an injury to the State's air resources.

Injuries to air resources will be quantified in terms of lost air services. A REA-type service-to-service scaling approach may be evaluated to quantify damages to air resources. Under this approach, the State would identify air restoration projects that could provide the equivalent of the air resource services lost as a result of the Basin F IRA.

Availability and public comment

The Assessment Plan will be available for public comment for 30 days following publication of a notice of availability in newspapers of statewide circulation. It can be accessed at http://www.cdphe.state.co.us/hm/rma.htm. An extension to the public comment period may be granted if requested and found to be reasonable and appropriate. Questions can be directed to vicky.peters@state.co.us or 303-866-5068; or jeff.edson@state.co.us or 303-692-3388. Comments can also be sent to:

Ms. Vicky Peters
Senior Assistant Attorney General
1525 Sherman Street, 7th Floor
Denver, CO 80203

The Assessment Plan may be modified in the future. If a significant modification is made, the revised Plan will be provided to the public for comment.

1. Introduction

1.1 Statement of Purpose

The Colorado Natural Resource Trustees (the Trustees) are assessing natural resource damages (NRDs) caused by releases of hazardous substances at the Rocky Mountain Arsenal (the Arsenal), located in Adams County, Colorado. Under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA), also known as the Superfund law, parties responsible for releases of hazardous substances are liable for “damages for injury to, destruction of, or loss of natural resources, including the reasonable costs of assessing such injury, destruction, or loss resulting from such a release” [42 USC § 9607(a)]. While the goal of the Superfund cleanup program is to address any threats to human health and the environment, the goal of the NRD provisions is to restore the environment to the state it would have been in had the pollution not occurred, and to compensate the public for the losses of natural resources up to the time that such restoration is complete. Restoration can be accomplished by directly restoring the injured resource, or by rehabilitating, replacing, or acquiring equivalent resources. Restoration as used in this document refers to all four types of activities.

With the publication of this Assessment Plan, the Trustees’ assessment is being formally initiated pursuant to the U.S. Department of the Interior’s (DOI’s) natural resource damage assessment (NRDA) regulations [43 CFR Part 11]. The purpose of the Assessment Plan is to document the Trustees’ basis for conducting a damage assessment, and to set forth the proposed approaches for quantifying natural resource injuries and calculating damages associated with those injuries. The Assessment Plan enables the Trustees to ensure that the NRDA will be completed at a reasonable cost. The Plan informs responsible parties (RPs) and the public of the proposed assessment methods so that stakeholders can participate in the assessment process productively. The RPs at the Arsenal are Shell Oil Company (Shell) and the U.S. Department of Army (Army).

1.2 The Rocky Mountain Arsenal

The Arsenal is a federally-owned facility in Adams County, Colorado, just northeast of the Denver metropolitan area and southwest of Denver International Airport. In 1942, the Army purchased this 27 square-mile property for the manufacture of chemical warfare agents, nerve agents, and incendiary munitions. Agents and munitions included rockets and projectiles containing blister agents (e.g., mustard gas), Sarin nerve agent, lewisite, phosgene bombs, incendiary bombs, and napalm. The Army used the Arsenal for “demilitarization” of nerve agents and bombs into the 1980s. It also stored and transported raw materials, and disposed of manufacturing byproducts, unexploded munitions, and other wastes on-site. These activities resulted in the release of hazardous substances to soil, groundwater, surface water, and air.

After World War II, the Army leased portions of the site to private industry, primarily Shell. Shell manufactured pesticides, insecticides, herbicides, and other chemicals at the Arsenal from 1952 to 1982, and disposed of wastes on-site. These activities also resulted in the release of hazardous substances to soil, groundwater, surface water, and air. Later chapters of this Plan discuss the site's history, manufacturing, and cleanup operations in detail.

The Environmental Protection Agency (EPA) listed most of the Arsenal on the Superfund National Priorities List (NPL)[1] on July 11, 1987.[2] The remainder – the waste disposal impoundment known as Basin F – was included on March 13, 1989.[3] Since 1989, the Army's sole mission at the Arsenal has been cleanup. The final environmental remediation plan was contained in two records of decision (RODs) finalized in 1995 and 1996. At the time, the Army anticipated completion of remediation, excluding the continued treatment of groundwater, by 2011. That estimate has now been revised to 2010.

1.3 The Assessment Plan

This Assessment Plan is divided into nine chapters. The remainder of Chapter 1 describes the State Trustees' authority for conducting an NRDA and the process that the Trustees intend to follow. Chapter 2 provides a general description of the site and the assessment area, includes a history of operations at the Arsenal, and identifies both the sources of contamination and the hazardous substances released. Chapter 3 discusses the remediation activities on- and off-post, and the long-term efficacy of the selected response actions. Chapter 4 discusses the exposure pathways from sources of released hazardous substances to the injured natural resources, and presents data confirming exposure of natural resources to hazardous substances. Chapter 5 describes groundwater resources in the assessment area, provides examples of approaches and illustrative calculations for assessing injury to groundwater, and discusses services lost due to contamination. Chapter 6 describes wildlife resources and outlines the anticipated assessment approaches for quantifying injury to wildlife. Chapter 7 describes air injuries in the assessment area, and identifies the anticipated assessment methodology for that resource. Chapter 8 discusses the approaches to be used for damage determination and restoration planning and

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1. CERCLA mandated the NPL to identify the worst contaminated sites in the country. These sites were to be the priorities for the federal cleanup program [42 USC § 9605(a)(8)(B)].

2. 52 FR 27619.

3. 54 FR 10512.

costing, and Chapter 9 discusses methods specifically intended for calculating groundwater damages, including both lost use and lost passive or non-use values.

1.4 Trusteeship Authority

1.4.1 State Trustees

The Executive Director of the Colorado Department of Public Health and Environment (CDPHE), the Director of the Division of Reclamation, Mining and Safety within the Colorado Department of Natural Resources, and the Attorney General of Colorado are the three natural resource Trustees for the State. The National Contingency Plan (NCP), which constitutes CERCLA's implementing regulations, provides that "[s]tate trustees shall act on behalf of the public as trustees for natural resources, including their supporting ecosystems, within the boundary of a state or belonging to, managed by, controlled by, or appertaining to such state" [40 CFR §300.605]. Natural resources include land, fish, wildlife, biota, air, water, groundwater, and drinking water supplies belonging to, managed by, held in trust by, appertaining to, or otherwise controlled by a government [42 USC § 9601(16)].

1.4.2 Trusteeship

The DOI regulations require Trustees to provide a statement of authority for asserting trusteeship, or co-trusteeship, for those natural resources considered within the Assessment Plan [43 CFR 11.31(a)(2)]. The basis for the State's assertion of trusteeship over each injured resource is explained below.

Water

Colorado's Constitution states that "[t]he water of every natural stream, not heretofore appropriated, within the State of Colorado, is hereby declared to be the property of the public, and the same is dedicated to the use of the people of the State, subject to appropriation as hereinafter provided" [Colo. Const. Art. XVI, §5; CRS § 37-92-102]. This includes water "hydraulically connected to" tributary groundwater if "it can influence the rate or direction of movement of the water in [the] alluvial aquifer or natural stream" [CRS § 37-92-103(11)]. These provisions confirm the State's trust interest in the waters of the State. In addition, pursuant to its sovereign or trust interest, the State exercises management and control over water – and the use of surface and groundwater – whether tributary or not. For example, CRS § 37-82-101 *et seq.* and CRS § 37-92-102 *et seq.* regulate the appropriation of surface water and tributary groundwater, and CRS § 37-90-102 *et seq.* regulates the appropriation of deep groundwater such as the water in the lower aquifers underlying the Arsenal. Further, among other State water quality regulatory authorities, the CDPHE has authority pursuant to CRS § 25-8-101 *et seq.* to enforce promulgated water quality standards [5 CCR 1002-41 (Regulation 41), and 5 CCR 1002-31 (Regulation 31)]. A state's natural resource trusteeship over its waters has been recognized in a number of cases, including a recent Tenth Circuit decision.[4]

Wildlife

All wildlife in Colorado that is not privately owned is the property of the State [CRS § 33-1-101 (2)]. The Colorado Division of Wildlife (DOW) and the Wildlife Commission manage and control wildlife for the benefit of the people, including the taking, possession, and the use of wildlife, pursuant to Articles 1 through 6 of Title 33 of the Colorado Revised Statutes, and the rules and regulations promulgated by the Wildlife Commission [2 CCR § 406 (2006)]. This control extends to federal military installations. For example, 10 USC § 2671 requires all hunting and fishing on a military reservation to "be in accordance with the fish and game laws of the State in which it is located." Thus, ownership, trusteeship, and management and control form the basis of the State's trusteeship over wildlife resources.

Air

As far back as 1907, the Supreme Court recognized the unique trust interest of states in the air breathed by their citizens.[5] Colorado law states that "the prevention, abatement, and control of air pollution in each portion of the state are matters of statewide concern and are affected with a public interest and that the provisions of [Article 25] are enacted in the exercise of the police powers of this state for the purpose of protecting the health, peace, safety, and general welfare of the people of this state" [CRS § 25-7-102 and 5 CCR § 1001-2]. Thus, through its recognized public trust interest, and because of its extensive management and control, the State asserts trusteeship over the air resources adversely affected by Arsenal releases.

Co-trusteeship

The United States claims co-trusteeship for natural resources at the Arsenal through the Army and the U.S. Fish and Wildlife Service (USFWS).

1.5 Restoration and Compensation Determination Plan

The DOI regulations require Trustees to develop a Restoration and Compensation Determination Plan (RCDP). This Plan can be included with the Assessment Plan if existing data are available.

4. *New Mexico v. General Electric*, 467 F.3d 1222, 1243 (10th Cir. 2006).

5. *Georgia v. Tennessee Copper Co.*, 27 S.Ct. 618, 619 (1907).

If sufficient data are not available for the Assessment Plan, the RCDP may be developed at any time before the completion of the Injury Quantification phase, and published separately. The Trustees have determined that separate publication of the RCDP will be necessary at this site.

1.6 Natural Resource Damage Assessment Process

The DOI regulations establish a process for Trustees to follow when assessing NRDs, including pre-assessment, assessment, and post-assessment phases. The use of these regulations is optional, but an NRDA performed in accordance with these regulations has the force and effect of a rebuttable presumption in any administrative or judicial proceeding to recover NRDs [42 USC § 9607(f)(2)(C)]. A rebuttable presumption means that the opposing party has the burden of producing evidence to overcome or rebut the presumption that the Trustees' assessment should form the basis of the damage award.

The assessment process described in the NRDA regulations involves four major components:

1. The Preassessment Screen Determination (PASD)
2. The Assessment Plan
3. The Assessment
4. The Report of Assessment.

1.6.1 Completion of Preassessment Screen Determination

Pursuant to the DOI NRDA regulations, the Trustees conducted a preassessment screen "to provide a rapid review of readily available information" on trust natural resources that may have been injured by releases of hazardous substances [43 CFR § 11.23(b)]. In accordance with the criteria at 43 CFR § 11.23(e), the PASD supported the conclusion that there is a reasonable likelihood that State natural resources have been injured as a result of hazardous substance releases, that sufficient data exist to conduct an assessment, and that response actions will not remedy the injury to natural resources without further actions. Therefore, the Trustees concluded that an NRDA should be undertaken to develop a damage claim under 42 USC § 9607.

1.6.2 The Assessment Plan and Selection of Type B Procedures

The assessment phase begins with the Assessment Plan. This document serves as the work plan for the NRDA. The Assessment Plan is being provided for public review to help the Trustees ensure that the NRDA proceeds efficiently, using data and methodologies appropriate for the site and resources involved. This Assessment Plan was prepared in accordance with the NRDA regulations promulgated by the DOI at 43 CFR § 11.31.

Under DOI's NRDA regulations, the Trustees must elect to perform a Type A or Type B NRDA [43 CFR § 11.33]. Type A assessments use "simplified procedures that require minimal field observation" [43 CFR § 11.33(a)]. Type A procedures are inapplicable in this case because they are designed to address minor releases of short duration resulting from a single event. Further, the DOI has promulgated Type A regulations only for coastal/marine or Great Lakes environments [43 CFR §§ 11.33, 11.34]. Thus, Type A procedures cannot be used at the Arsenal. The Trustees will use the Type B provisions.

1.6.3 Assessment Phase

Under the DOI Type B procedures, three parts comprise the assessment:

1. **Injury Determination Phase.** The first phase of the assessment determines whether injury to the natural resources has occurred and whether the injury has resulted from the release of hazardous substances.

2. **Quantification Phase.** The second phase quantifies the injuries and the reduction of services provided by the natural resources. Services provided by various resources may include such things as habitat for wildlife and drinking water for the public.

3. **Damage Determination Phase.** In the third phase, the monetary compensation for injury is calculated. This phase is based upon the RCDP that, among other things, describes possible alternatives for restoration or replacement of the injured natural resources and their related services. All damages ultimately recovered by RPs must be spent to restore, replace, or acquire equivalent natural resources.

1.6.4 The Report of Assessment

Upon completion of the assessment, the Trustees will prepare a Report of Assessment, which will include the results of analyses performed during assessment. It will also include the Trustees' Restoration Plan. Like this Report, the Assessment Plan will be provided to stakeholders for public comment.

Based on the final Report, the Trustees can make a demand on the RPs for NRDs. If the demand is accepted or some compromise is negotiated, or if the Trustees prevail at trial, any recoveries will be placed in a special account to fund restoration projects, and the Trustees may revise their Restoration Plan to be sure that it can be implemented with the damages recovered. Sometimes RPs choose to conduct appropriate restoration projects themselves instead of paying damages, or a settlement may include both restoration and monetary components. The Trustees can also recover the reasonable costs of performing an NRDA as part of their NRD claim. Examples of reasonable and necessary costs are set forth in 43 CFR § 11.60(d).

1.7 Coordination

1.7.1 Coordination with response agencies and activities

Coordination with response agencies is desirable to avoid duplication, reduce costs, and achieve dual objectives where practical. The Remedial Investigation (RI) for the Arsenal was completed in 1992. The RODs, setting forth the final remedies for the off-post and on-post areas, were finalized in 1995 and 1996, respectively. The completion of remedial actions, excluding the continued treatment of groundwater, is currently anticipated in 2010.

In preparing the PASD, the Trustees relied on existing data from the remedial process and, based upon preliminary review, intend to rely extensively on those data in conducting the NRDA. Extensive field sampling and studies in addition to those already conducted for the Remedial Investigation/Feasibility Study (RI/FS) and other cleanup purposes are currently not envisioned.

While the Trustees intend to use the existing response agency data from the site, an extensive data set from the RI does not preclude the need for injury assessment, and the implemented remedial actions do not preclude the existence of past and ongoing NRDs. Damages have been incurred since the passage of CERCLA, as provided in the DOI regulations [43 CFR § 11.15(a)(1)]. In addition, because the remediation alone will not achieve full restoration of injured natural resources and the services provided by those resources, damages will continue to be incurred after the implemented remedy is complete in 2010.

1.7.2 Coordination with co-Trustees and responsible parties

The State Trustees formally invited the Army and Shell to participate in the State's NRDA. The Trustees sent a Notice of Intent to perform an NRDA to Shell and the Army with the PASD in February 2007. Shell and the Army have indicated a desire to be involved. The Army also indicated that it will conduct its own PASD. The Trustees and the RPs have shared information in the context of settlement negotiations and in anticipation of a formal assessment. The State Trustees will continue to work with the RPs and federal co-trustees in implementing this Assessment Plan.

1.8 Fundamental Terms and Concepts

Individuals familiar with the cleanup process under Superfund and at the Arsenal may not be as conversant with the NRD process. To aid in the public's review of this Assessment Plan, key terms are defined below. In addition, a list of acronyms is provided at the front of this document, and a glossary of uncommon terms is provided at the end. The terms and concepts defined below will recur in subsequent chapters dealing with injury and damage calculations.

Baseline refers to the conditions that would have existed in the assessment area had the release of hazardous substances not occurred [43 CFR § 11.14 (e)]. This is not the same as "pre-release" conditions because disturbances to the assessment area might have decreased resource services without the release of hazardous substances. For example, if a release were to occur in an area with ongoing development, the Trustees should evaluate the probable condition of the resource assuming development occurred.

Damages is the amount of money needed to satisfy a claim in court. In the context of NRDs, that amount includes the cost to perform an NRDA and to restore injured natural resources to baseline conditions. The amount also includes compensation for interim losses. NRDs continue to accrue until restoration and replacement projects result in the complete recovery of resources or services to baseline conditions. "Residual damages" is a term used to describe any damages that remain after remediation is complete.

Injury is a measurable adverse change, either long- or short-term, in the chemical or physical quality or the viability of a natural resource resulting either directly or indirectly from exposure to a release of a hazardous substance, or exposure to a product of reactions resulting from the release of a hazardous substance [43 CFR § 11.14(v)]. Definitions of injuries to specific natural resources are provided in the NRDA regulations at 43 CFR § 11.62, and are included in Chapters 5 to 7 as each injured resource is discussed.

Interim losses refer to injuries (and associated service losses) that accrue until injured resources and the services they provide are returned to baseline conditions. The start date for calculating interim losses is either the time of release or December 1980 (following enactment of CERCLA), whichever comes later.

Response actions refer to activities taken to reduce threats from contaminants to acceptable levels. Short-term actions are generally termed *removals*, and long-term, final response actions are considered *remedial actions* [42 USC § 9601(23) and (24)]. Short-term response actions include initial response actions such as spill containment; long-term actions include permanent treatment or containment of contamination, and revegetation of disturbed areas. Under CERCLA, remedial actions must be protective of human health and the environment.

Restoration refers to actions undertaken to return injured resources and the services they provide to baseline conditions, and additional actions to compensate for interim losses of natural resources and their services. For example, restoration of riparian habitat along a stream might increase the number of birds that use the habitat for food or shelter. Restoration actions can take place off-site, away from the assessment area, or on-site, if the restoration actions improve the condition of the injured resources above levels necessary to satisfy cleanup goals**.** The term *restoration* may refer to direct restoration of injured resources, replacement of injured resources, or acquisition of the equivalent of such resources.

Service flows refer to the services provided by a resource over time. For example, remediation and restoration activities can increase the service flows provided by a resource.

Services are the "physical and biological functions performed by the resource, including the human uses of those functions" [43 CFR § 11.14 (nn)]. Habitat services include, for example, the provision of food and shelter for all kinds of animals, nutrient cycling, contaminant filtering, and aesthetic and recreational services for humans.

1.9 Public Review and Comment

The Assessment Plan will be available for public comment for 30 days following publication of a notice of availability in newspapers of statewide circulation. It can be accessed at http://www.cdphe.state.co.us/hm/rma.htm. An extension to the public comment period may be granted if requested and found to be reasonable and appropriate. Questions can be directed to vicky.peters@state.co.us or 303-866-5068; or jeff.edson@state.co.us or 303-692-3388. Comments can also be sent to:

Ms. Vicky Peters
Senior Assistant Attorney General
1525 Sherman Street, 7th Floor
Denver, CO 80203

The Assessment Plan may be modified in the future. If a significant modification is made, the revised Plan will be provided to the public for comment.

2. Site Description

The Arsenal, a 27 square-mile Army facility located 10 miles northeast of downtown Denver, formerly was used for the production of munitions, chemical warfare agents, nerve agent, industrial and agricultural chemicals, and the blending of rocket fuel. The Arsenal property is adjacent to Commerce City to the north and west, Montbello to the south, and Denver International Airport to the north and east (Figure 2.1) (EPA, 2007a).

Climate

The Arsenal is situated within a temperate grassland region of the High Plains and is part of a broad transition zone between mountain and plains habitats. The land surface slopes from southeast to northwest, with a total change of altitude of 220 ft. Prevailing winds are from the south and southwest. The average annual precipitation is approximately 15 inches, with 50% of that falling between April and July. Snow accounts for about 30% of the average precipitation. Localized summer thunderstorm activity results in large spatial variations in precipitation (Ebasco Services et al., 1989b).

Hydrology

Surface water at the Arsenal follows several small tributaries to the South Platte River, which flows to the northwest approximately 2 miles from the northwest boundary and 3 miles from the north boundary of the Arsenal (Figure 2.2). The drainages within the Arsenal include First Creek in the northeast, and Irondale Gulch in the southwest. A series of ditches, culverts, sewers, retention basins, and constructed lakes have greatly modified surface water flow, particularly in Irondale Gulch.

First Creek is a natural intermittent stream with few diversions. The Creek generally loses water as it crosses the Arsenal. In the mid-1980s, the average flow entering the Arsenal was 1.36 cubic feet per second (cfs), and the average flow leaving was 1.15 cfs (Ebasco Services et al., 1989b). Extended periods with little or no flow are common. First Creek discharges to O’Brian Canal approximately 0.5 miles north of the Arsenal boundary.

Irondale Gulch is a poorly defined topographic feature on the western side of the Arsenal and in the Irondale community northwest of the site (Figure 2.2). Surface water in Irondale Gulch does not follow a defined stream channel. Various lakes, ditches, and retention basins capture the surface water, which subsequently enters shallow groundwater or evaporates. Located in the southern section of the Arsenal, Lower Derby Lake and Lake Ladora were irrigation reservoirs prior to the construction of the Arsenal and were subsequently enlarged by the Army. The Army constructed Upper Derby Lake as an additional water storage area, and constructed Lake Mary for recreational fishing (Ebasco Services et al., 1989b).

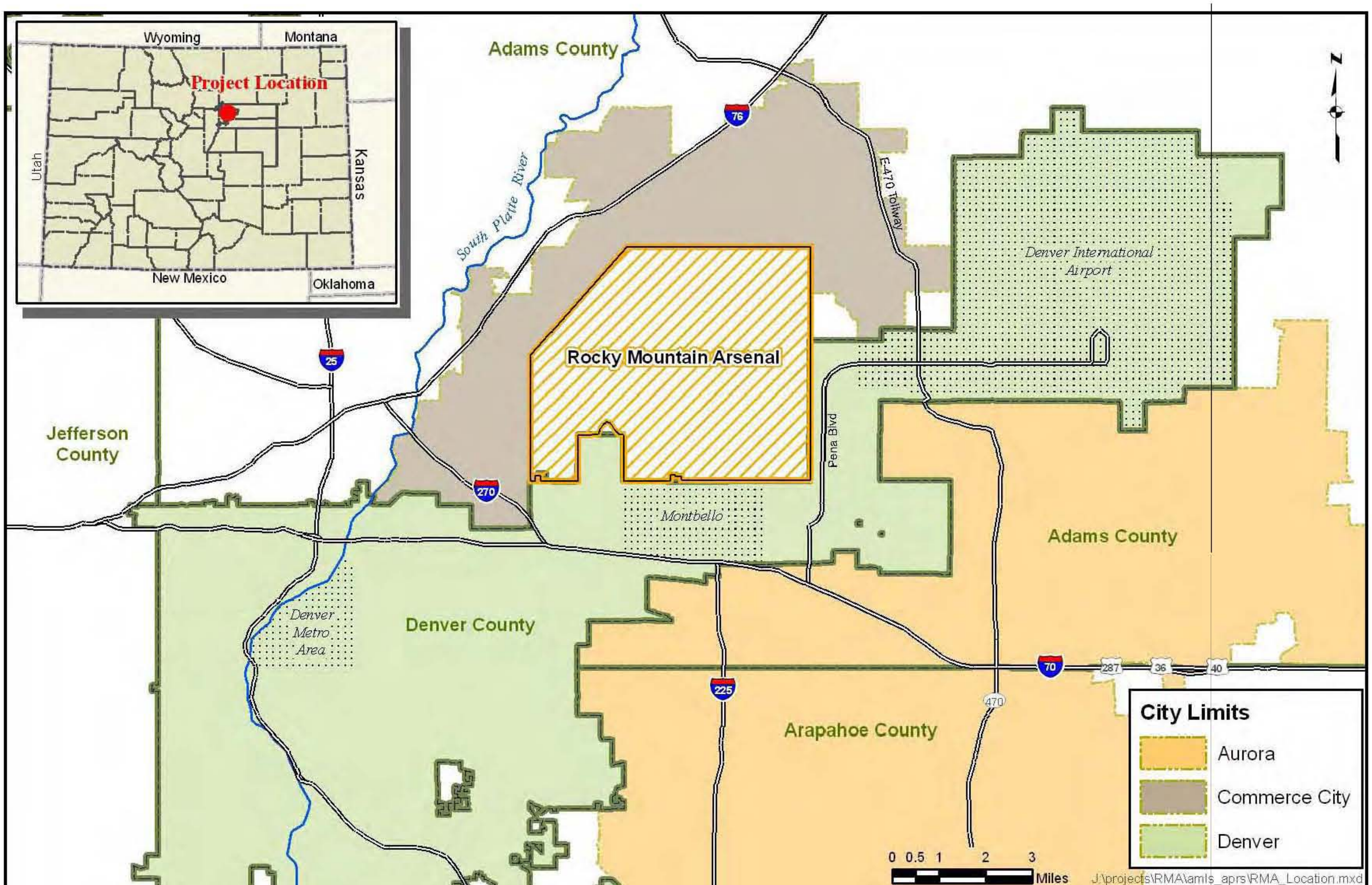

Figure 2.1. General location of the Rocky Mountain Arsenal in the Denver area.

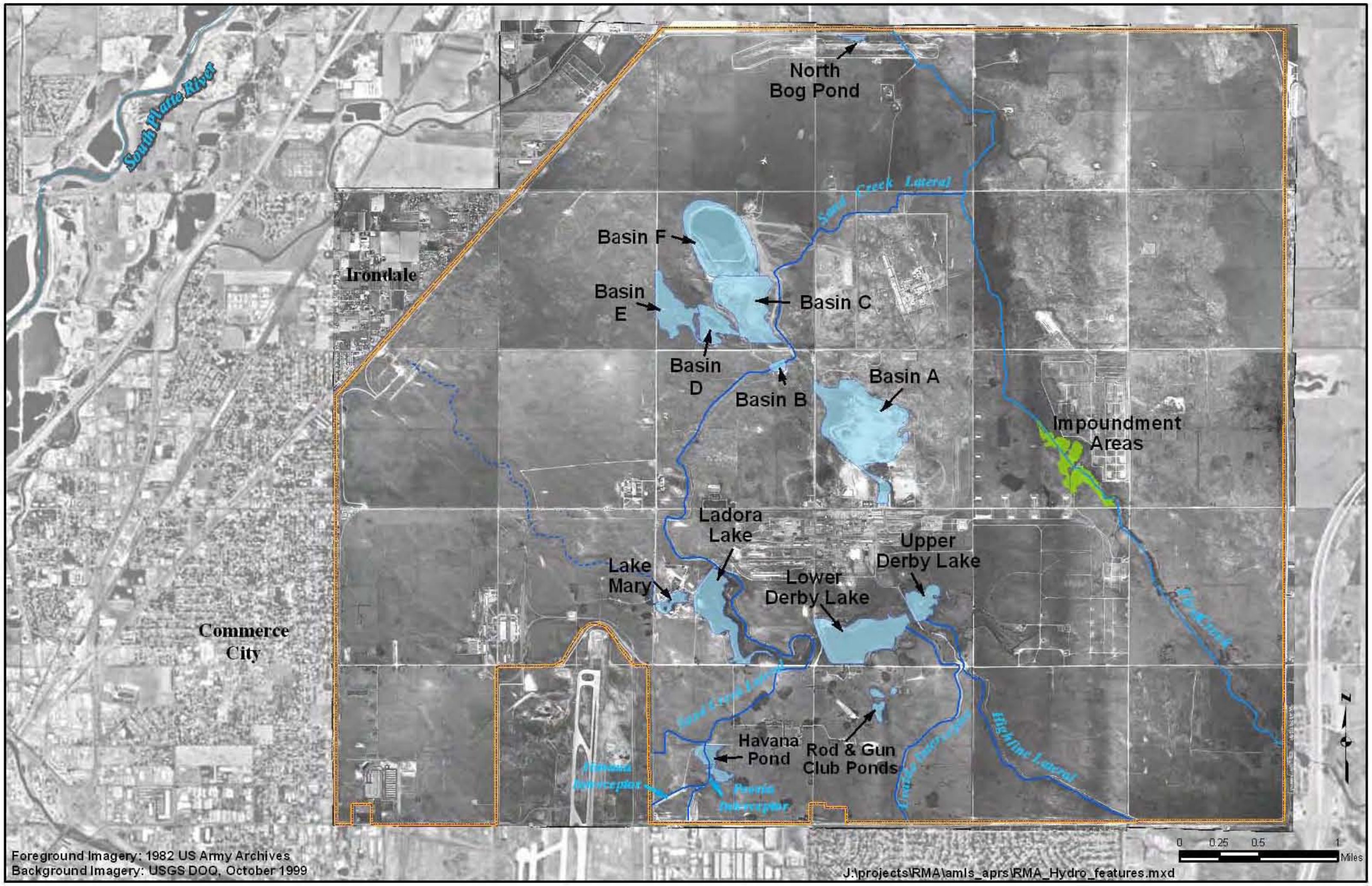

Figure 2.2. Past and present hydrologic features at the Arsenal. Most of the ditches and basins no longer hold surface water.

The Army also maintained six basins, Basin A through Basin F, for retention of stormwater, process water, and process waste (Figure 2.2). Basins A through E were unlined natural depressions, modified with berms and connecting overflow ditches. Basin F was constructed by the Army Corps of Engineers and lined with 3/8-inch thick asphalt (Environmental Science & Engineering and Harding Lawson Associates, 1988d). Liquids in these basins either evaporated or percolated to groundwater. Groundwater was often in direct contact with the bottom of Basin A (Ebasco Services et al., 1989b). The basins are no longer used for water retention and no longer contain surface water.

Groundwater

The groundwater at the Arsenal is part of the regional Denver Basin. Bedrock below the Arsenal is part of the Denver Formation. Sandy deposits known as alluvium overlie the bedrock, with thick deposits ranging from 50 to 130 ft found in ancient channels, and thinner deposits of approximately 20 ft found outside of these channels.

Shallow groundwater tends to follow these ancient alluvial channels, flowing to the north and northwest. The depth to groundwater and the thickness of the alluvial aquifer vary considerably across the site. From the 1950s through the 1980s, the groundwater levels near the manufacturing plants and the Basin A waste disposal basin were close to the surface (Ebasco Services et al., 1989b). Groundwater levels have dropped since manufacturing ended at the site (Foster Wheeler, 2000a).

Chapter 5 discusses the groundwater underlying the Arsenal in more detail.

Biota

Native vegetation at the Arsenal consists primarily of open semiarid grasslands, with some areas of shrubland, patches of yucca, riparian woodlands, cattail marshes and other wetland types, locust and wild plum thickets, upland groves of deciduous trees, and ornamental plantings. Parts of the Arsenal were planted with crested wheatgrass in the 1930s and 1940s to stabilize land susceptible to erosion. Societal changes in the region have altered the landscape to a mosaic of agricultural, developed (industrial and residential), and native habitats (Ebasco Services et al., 1994).

When ecological surveys were conducted in the 1970s and 1980s, 26 species of mammals were found at the Arsenal, including all of the common mammals that inhabit the prairie grasslands of the Colorado Front Range, as well as 176 species of birds and at least 17 species of reptiles and amphibians. The species richness of birds at the Arsenal was found to be high. Ground-nesting songbirds and other birds preferring open habitat are common in the primary Arsenal habitats of open grassland and weedy plains (Ebasco Services et al., 1994).

Ebasco Services et al. (1994) state that the larger lakes at the Arsenal (Figure 2.2) support viable aquatic communities, but benthic invertebrates are largely absent. Fish in the lakes are stocked.

Chapter 6 describes the biota at the Arsenal in more detail.

The remainder of this chapter describes the industrial activities and the waste disposal practices that occurred at the Arsenal. Section 2.1 provides a brief operational history of the Arsenal. Section 2.2 describes some of the manufacturing and disposal sites that became sources of hazardous substance releases to natural resources, followed by references cited in the text. Chapter 3 discusses the investigation and remediation of these releases.

2.1 Site History

Prior to World War II, the land where the Arsenal sits was shortgrass prairie that had been converted to agriculture. In May 1942, the Army purchased over 17,000 acres for manufacturing chemical and incendiary weapons (Army, 2004). After World War II, the Arsenal was placed on standby status, but with the start of the Korean conflict in 1950, the Army resumed operations. Production continued through 1957 as Cold War tensions heightened (Army, 2004). In the late 1950s into the 1960s, Army activities at the Arsenal included the manufacturing of nerve agent and weapons, demilitarization of chemical weapons, and the blending of rocket fuel for the Air Force (Army, 2004). In the 1970s, the Army used the Arsenal primarily for the demilitarization of chemical weapons. These activities ceased in the early 1980s (Army, 2004).

In addition to Army activities, private industries used the Arsenal for manufacturing. Julius Hyman and Company (Hyman) began producing pesticides at the Arsenal in 1946, followed by Colorado Fuel and Iron (CF&I) in 1947. In 1952, Shell acquired Hyman and continued to produce agricultural pesticides on-site until 1982 (EPA, 2007a).

Since the early 1980s, site investigation and remediation have been the primary activities at the Arsenal (Army, 2004; EPA, 2007a). The remainder of this section describes the industrial facilities and the products manufactured at the site. Chapter 3 then discusses cleanup activities in more detail.

2.1.1 Army manufacturing

Chemical agents, nerve agents, and munitions

The majority of the manufacturing at the Arsenal occurred at the South Plants Complex (Figure 2.3), which covered approximately 500 acres with buildings, roads, parking lots, railroad tracks, sewer lines, culverts, steam pipes, manholes, water mains, and some open space (Ebasco Services et al., 1989c). Chemical agents produced within the complex included mustard, lewisite, and phosgene (Table 2.1). Incendiary munitions were mainly napalm, white phosphorous, and a mixture of potassium chlorate, red phosphorous and glass known as “button bombs” and “sandwich button bombs” (DOJ, 1986; Ebasco Services et al., 1988b).

From 1942 to 1943, over 3.5 million tons of mustard were produced. Of this, over 334 tons were determined to be off-specification and ultimately treated and disposed of on-site (DOJ, 1986). In total, the Army produced about 1.6 million nerve gas munitions, including cluster bombs, shells, bomblets, rockets, and warheads at the Arsenal (Goldstein, 2001).

Napalm was produced from 1943 to 1945, with a total output of over 2.6 million bombs (Environmental Science & Engineering et al., 1988d). White phosphorous-filled munitions, including white phosphorous cups, igniters, grenades, and 105 mm shells, followed from 1945 until 1970 (DOJ, 1986). By the end of World War II, the Arsenal had created more than 100,000 tons of incendiary munitions (Army, 2004). By 1968, over 1.7 million button bombs and 7 million sandwich button bombs had been manufactured at the Arsenal (DOJ, 1986). White phosphorous and burned incendiary device casings were disposed of in the Army Section 36 Complex Disposal Trenches (Foster Wheeler, 2001) (Figure 2.3).

The Army constructed the 90-acre North Plants Complex (Figure 2.3) from 1950 to 1952. From 1952 to 1957, the Army used the North Plants Complex to manufacture Sarin nerve agent (Table 2.1), fill munitions with Sarin, and assemble cluster bombs, as well as to store Sarin, feedstock chemicals, and munitions. The facility was later used for the demilitarization of chemical warfare agents. The Army stored Sarin in one-ton containers and in underground tanks (DOJ, 1986; RVO, 2004).

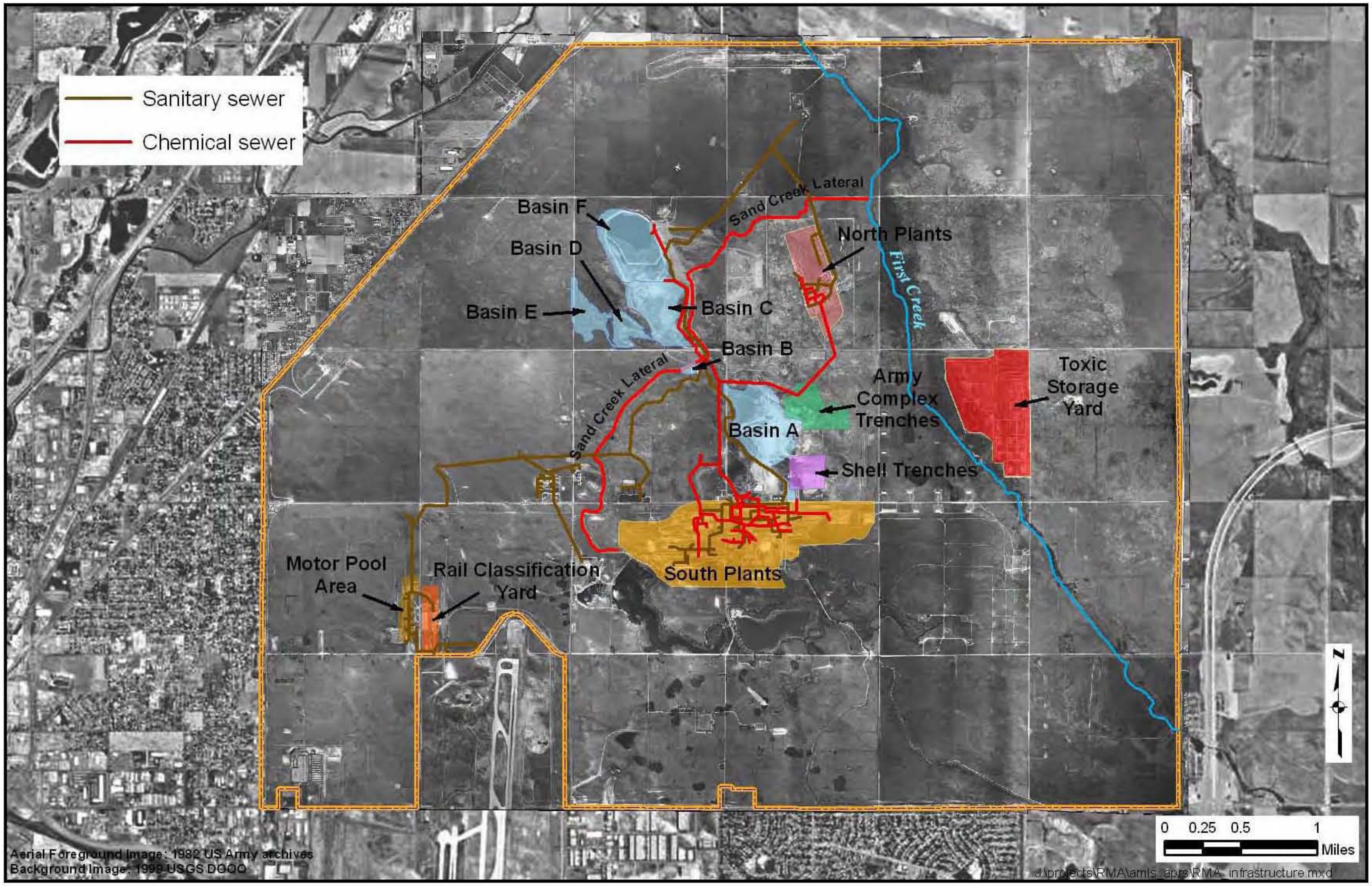

Figure 2.3. Manufacturing, storage, waste transit, and waste disposal sites at the Arsenal. Background image from 1982.

Table 2.1. Chemical agents and munitions manufactured or handled at the Arsenal

Product	Description	Sources
Mustard [bis (2-chloroethyl) sulfide; H; HS; Levinstein mustard]	Mustard is a vesicant, or blistering agent. Raw materials used in the production of mustard were ethyl alcohol, Freon 114, sulfur monochloride, calcium chloride, bleaching powder, coke, kerosene, fuel oil, caustic soda, and hexamine. Mustard and mustard-filled munitions were manufactured at the Arsenal in 1943 and from 1950 to 1957. Between 1945 and 1946, the Army reprocessed mustard into distilled mustard.	Ebasco Services et al., 1988b
Lewisite [2-chlorovinyl dichloro arsine]	Lewisite is a vesicant, sometimes used in combination with mustard. Raw materials associated with lewisite production included acetylene, arsenic trichloride, thionyl chloride, hydrochloric acid and mercuric chloride, many of which were manufactured at the Arsenal. The Army produced lewisite from April through November 1943.	Kuznear and Trautmann, 1980
Phosgene [carbonyl chloride]	Phosgene is a choking agent. The phosgene bomb-filling plant at the Arsenal operated from January 1944 to December 1944.	Kuznear and Trautmann, 1980; Army, 2004
Napalm	Napalm is a powdered thickening agent added to gasoline to produce the incendiary mixture called NP gel. This thickened fuel was used in incendiary bombs and flamethrowers. The incendiary oil plant, which mixed the napalm thickener and gasoline, operated from April 1943 to August 1945.	Ebasco Services et al., 1988b
White and red phosphorus	White phosphorus was used for production of incendiary bombs. Red phosphorus was used as a chemical constituent in button bombs and sandwich button bombs. The phosphorus plant operated in 1944–1945, 1952, 1953, and 1958–1960.	Ebasco Services et al., 1988b
Sarin [GB; isopropyl methylphosphono-fluoridate]	Sarin is an extremely toxic nerve agent. Raw materials included methylphosphonic dichloride, hydrofluoric acid, isopropyl, tributylamine, methanol, carbon tetrachloride, ethyl ether, methylene chloride, and calcium chloride. Sarin was manufactured at the North Plants from July 1952 through March 1957.	Ebasco Services et al., 1988b
VX [O-ethyl-S-(2-diisopropylaminoethyl) methylphosphonothiolate]	VX is an extremely toxic nerve agent. VX was not manufactured at the Arsenal, but VX bombs were decommissioned along with Sarin bombs at the site in the 1960s, and byproducts of the process were disposed of at the site.	Ebasco Services et al., 1988b

Demilitarization of munitions

Figure 2.4. Technician deactivating fuses in cluster bombs at the Arsenal.

Source: Army (2004).

After manufacturing these chemical agents and munitions, the Army subsequently demilitarized many of the same munitions at the facility (Figure 2.4). Beginning in 1947, obsolete and deteriorating mustard-filled munitions were disassembled at the Arsenal. The mustard was incinerated in a furnace located in the South Plants, and the casings were decontaminated in an acid bath and/or burned (DOJ, 1986). Other mustard demilitarization activities at the site included:

- *1958 to 1959*: 30,000 mustard-filled munitions
- *1964 to 1969*: more than 58,000 mustard-filled munitions
- *1973 to 1976*: 3,407 mustard-filled one-ton containers incinerated (DOJ, 1986).

Demilitarization of Sarin munitions began in the 1950s, primarily on munitions that were off-specification. From 1955 to 1970, over 204,000 Sarin-filled munitions were demilitarized. In 1969, the Army initiated "Project Eagle" to demilitarize excess stocks of toxic agent at the Arsenal. From 1973 to 1976, over 21,000 stored M34 cluster bombs, each containing 76 bomblets filled with 2.6 pounds of Sarin, were demilitarized. The Army drained the bomblets, mixed the Sarin with caustic in a reactor chamber, and spray-dried the brine. Approximately 450,000 gallons of Sarin from over 21,000 munitions were deactivated as part of Project Eagle, resulting in almost 6.25 million pounds of contaminated spray-dried salt. The salt was stored in more than 18,000 steel and fiberboard drums in the Toxic Storage Yard (Army, 1978; DOJ, 1986).

In 1968, the Army began the demilitarization of the nerve agent VX, which was "the deadliest nerve agent ever created" (Council on Foreign Relations, 2006). VX was not produced at the Arsenal, but from 1964 to 1969, 2.3 million pounds were transported to the site and stored in steel containers, spray tanks, rockets, and mines. Approximately 3,600 pounds of VX munitions were neutralized at the Arsenal (DOJ, 1986).

Demilitarization of chemical weapons halted in 1984, essentially ending industrial operations at the site (Ebasco Services et al., 1988g).

Rocket fuel

In 1959, in coordination with the Air Force, the Army constructed the Hydrazine Blending and Storage Facility (HBSF) to blend anhydrous hydrazine with unsymmetrical dimethylhydrazine to produce Aerozine 50 (Ebasco Services et al., 1988c). Aerozine 50 is a hypergolic fuel (ignites spontaneously) when used with nitrogen oxidizers. It was primarily used in the Titan and Delta missile programs (NASA KSC, 2005). Blending of Aerozine 50 began in 1961 and continued through 1982 (Ebasco Services et al., 1988c).

2.1.2 Other chemical manufacturing

CF&I manufactured dichlorodiphenyltrichloroethane (DDT) in the South Plants area in 1947 and 1948 (Ebasco Services et al., 1988d). CF&I also produced monochlorobenzene, a precursor of DDT, at a benzene plant in the South Plants complex in 1947 (Army, 2001). During the 1950s, CF&I manufactured chlorobenzene, DDT, naphthalene, and chlorine (Ebasco Services et al., 1988a).

Hyman developed the pesticides aldrin, dieldrin, and chlordane, and produced those pesticides as well as endrin at the Arsenal between 1947 and 1952 (Army, 2004). In 1950, Hyman took over caustic soda and chlorine production facilities formerly operated by CF&I. In 1948, Shell merged with Hyman, and in 1952, Shell assumed Hyman’s leases at the Arsenal.

Shell manufactured a wide variety of pesticides, insecticides, and herbicides at South Plants (Table 2.2), producing aldrin and dieldrin until 1974 and other pesticides until the 1980s (Ebasco Services et al., 1988b; Army, 2001, 2004). Hazardous substance waste streams associated with the production of aldrin/dieldrin included: acetic acid, benzene, cyclopentadiene, dicyclopentadiene (DCPD), hexachlorocyclopentadiene, hydrogen, toluene, and xylene (Ebasco Services et al., 1988b).

Table 2.2. Herbicides and pesticides produced by Shell at the Arsenal

Substance	Years produced	Description
Aldrin/dieldrin	1947–1974	An organochlorine pesticide used on cotton and corn, among others. Use now banned or severely restricted.
Chlordane	1947–1952	A pesticide used on corn and citrus crops and on home lawns and gardens. Use now banned or severely restricted.
Endrin	1952–1965	A chlorinated hydrocarbon pesticide used to control insects, rodents, and birds. Use now banned or severely restricted.
Isodrin	1952–1965	A process intermediate of endrin with insecticidal properties similar to those of aldrin.
Methyl parathion	1957–1967	An insecticide for farm crops, especially cotton. Use now banned or severely restricted.
Ethyl parathion	1964–1966	An organophosphate insecticide used primarily on row crops and fruit.
Vapona	1960–1982	An insecticide used in Shell "No Pest Strips."
Supona	1963–1969	A pesticide used to kill parasites in sheep and cattle. No longer used in the United States.
Bidrin	1962–1979	A pesticide used to control aphids, mites, thrips, fleahoppers, grasshoppers, boll weevils, and other insects on cotton, ornamental trees, and fruit crops.
Dibrom	1962–1970	An organophosphate pesticide used for, among other things, mosquito control.
Ciodrin	1962–1976	An organophosphate insecticide.
Azodrin	1965–1977	An insecticide used to control a broad spectrum of pests. Use now banned or severely restricted.
Atrazine	1977–1987	An agricultural herbicide.
Gardona	1967–1968	An insecticide used to control flies.
Akton	1952–1974	An organophosphate insecticide.
Landrin	1969–?	An insecticide.
Nudrin	1973–1977	An insecticide included on EPA's Superfund Extremely Hazardous Substances list.
Nemagon[a]	1955–1977	A soil fumigant used to control soil-inhabiting nematodes. Use now banned or severely restricted.
Bladex	1970–1971, 1974–1975	A restricted use herbicide used to control weeds and invasive grasses.
Planavin	1966–1975	A herbicide used to control weeds and grass.
Nemafere	Unknown	A nemacide used to control nematodes.
Phosdrin	1956–1973	An insecticide used on vegetables, alfalfa, fruits, and nuts. Use now banned or severely restricted.

a. Nemagon is the trade name for dibromochloropropane (DBCP).

Sources: DOJ, 1986; Ebasco Services et al., 1988b; MK-Environmental Services, 1993; ATSDR, 2003; EPA, 2007b; Scorecard.org, 2007.

2.2 Sources of Hazardous Substances

In 1984, the Army developed a map that identified over 100 potentially contaminated sites. These included 15 basins and lagoons; 14 ditches, lakes, and ponds; 13 contaminated sewers; 38 solid waste burial sites; and 8 ordnance testing and disposal sites (Ebasco Services, 1985). Each of these sites may have released hazardous substances into the environment. A detailed assessment of each of the sources of hazardous substances is beyond the scope of this report. The Trustees instead provide a list of contaminants that are known to have been released at the Arsenal (Table 2.3), and then describe some of the primary manufacturing, waste transport, and waste disposal sites that are, or were, sources of hazardous substances and other contaminants (Figure 2.3). Table 2.3 is a partial list of contaminants released at the Arsenal; a complete compendium is beyond the scope of this document.

Table 2.3 lists over 160 contaminants, including over 100 hazardous substances, released at the Arsenal (DOJ, 1986; Ebasco Services et al., 1988b). Shell released an estimated 150,112 tons of contaminants into the environment, and the Army an estimated 26,405 tons (DOJ, 1986).

Table 2.3. Documented contaminants released at the Arsenal

Contaminant	Use	Contaminant	Use
Acetic acid	Used in the production of dieldrin, endrin, and bidrin	Ammonium nitrate	Waste product from Shell manufacturing
Acetone	Used in the production of azodrin and planavin	Ammonium nitrite	Waste product from Shell manufacturing
Acetonitrile	Waste product from Shell manufacturing	Ammonium sulfite	Waste product from Shell manufacturing
Acetophenone	Breakdown product of ciodrin	Antimony	Used in the production of lewisite
Acetylene tetrachloride	Used in laundry and clothing operations	Antimony compounds	Antimony chloride was used in the production of lewisite
Aldrin	Shell product manufactured at the Arsenal	Antimony hydroxide	Used in the production of lewisite
Allyl alcohol	Used in the production of Nemagon	Arsenic	Used in the production of lewisite
Allyl chloride	Used in the production of Nemagon	Arsenic trichloride	Used in the production of lewisite
Aminoisobutyronitrile	Process intermediate in the production of Bladex	Arsenic trioxide	Used in the production of lewisite
Ammonia	Used in the production of azodrin, bladex, and planavin	Asbestos	Insulation of pipes and buildings
Ammonium chloride	Fire retardant	Benzene	Used in the production of aldrin, dieldrin, and endrin

Table 2.3. Documented contaminants released at the Arsenal (cont.)

Contaminant	Use	Contaminant	Use
Bidrin	Shell product manufactured at the Arsenal	Copper	Used in pesticide manufacture
Cacodylic acid	Possibly used in the production of lewisite or as an herbicide	Copper compounds	Used in the production of azodrin and white phosphorous cups
Cadmium	Purpose of use not documented	Cyanide	Purpose of use not documented
Calcium arsenide	Used in the production of lewisite	Cyanogen chloride	Used in the production of phosgene
Calcium arsenite	Used in the production of lewisite	Cyclohexane	Purpose of use not documented
Calcium carbide	Used in the production of aldrin, dieldrin, and acetylene	Cyclohexanone	Purpose of use not documented
Carbon tetrachloride	Used in the production of Dibrom and as a cleaning solvent	Cyclopentadiene	Used in the production of aldrin, dieldrin, and heptachlor
Chlordane	Used in the production of heptachlor	DBCP	Shell product manufactured at the Arsenal
Chlorinated phenols	Use not documented	D-D soil fumigant	Shell product manufactured at the Arsenal
Chlorine	Used in the production of lewisite, azodrin, bidrin, heptachlor, and nudrin	DDT	Product manufactured at the Arsenal
Chloroacetic acid	Purpose of use not documented	Dibromoethane	Purpose of use not documented
Chlorobenzene	Used in the production of lewisite	Dichlorobenzene	Used in the production of akton
Chloroethylbenzene	Shell process intermediate	Dichlorodiphenylethane (DDE)	Decomposition product of DDE
Chloroform	Used in the production of azodrin and bidrin	1,1 dichloroethane	Used in the production of acetylene
Chlorophenylmethyl sulfide	Process intermediate in the production of Planavin	1,2 dichloroethane	Purpose of use not documented
Chlorophenylmethyl sulfone	Process intermediate in the production of Planavin	1,1-dichloroethylene	Purpose of use not documented
Chlorothiophenol	Purpose of use not documented	Dichloromethane	Used in the production of dichlor
Chromic acid	Used in the production of acetylene	Dichloropropane	Used in the production of D-D soil fumigant for nematodes
Chromium	Purpose of use not documented	Dichloropropene	Used in the production of D D soil fumigant for nematodes

Table 2.3. Documented contaminants released at the Arsenal (cont.)

Contaminant	Use	Contaminant	Use
Dichlorotrichlorophenyl urea	Used in laundry and clothing operation	Hexachlorocyclopenta-diene	Used in the production of aldrin, dieldrin, and endrin
Dichlorvos	Shell product manufactured at the Arsenal; also used in the production of bidrin	Hexane	Used in the production of ciodrin and nudrin
Dicyclopentadiene	Used in the production of aldrin and endrin	Hydrazine	Used in the production of Aerozine 50
Dieldrin	Shell product manufactured at the Arsenal	Hydrochloric acid	Used in the production of lewisite, phosgene, and landrin
Diketene	Used in the production of azodrin and ciodrin	Hydrofluoric acid	Used in the production of Sarin
Dimethylamine	Used in the production of bidrin	Hydrogen cyanide	Used in the production of Bladex
Dimethylhydrazine	Used in the production of Aerozine 50	Hydrogen peroxide	Used in the production of dieldrin, endrin, and planavin
Dipropylamine	Used in the production of Planavin	Hydrogen sulfide	Decomposition product of akton, parathion, and nudrin
Endrin	Shell product manufactured at the Arsenal	Isodrin	Process intermediate in the production of endrin
Ethylbenzene	Purpose of use not documented	Isopropanol	Used in the production of Sarin, endrin, and planavin
Ferric chloride	Purpose of use not documented	Lead	Purpose of use not documented
Fluoroacetic acid	Purpose of use not documented	Malathion	Used in military training
Freon	Used in the production of button and sandwich button bombs	Mercuric compounds	Mercuric chloride was used in the production of lewisite
Heptachlor	Julius Hyman product manufactured at the Arsenal	Mercury	Purpose of use not documented
Heptachlor epoxide	Degradation product of heptachlor	Methanethiol	Process intermediate associated with the production of nudrin
Heptachlorobicyclohep-tadiene	Process intermediate in the production of endrin	Methanol	Used in the manufacture of Sarin and akton
Heptane	Purpose of use not documented	Methomyl	Shell product manufactured at the Arsenal
Hexachlorobenzene	Purpose of use not documented	Methyl disulfide	Used in the production of nudrin
Hexachlorobicyclopent-adiene	Metabolite of heptachlor	Methyl isobutyl ketone	Used in the production of nudrin

Table 2.3. Documented contaminants released at the Arsenal (cont.)

Contaminant	Use	Contaminant	Use
Methyl isocyanate	Used in the production of landrin and nudrin	Phenol	Purpose of use not documented
Methyl mercaptan	Used in the production of nudrin	Phosdrin	Shell product manufactured at the Arsenal
Methyl parathion	Shell product manufactured at the Arsenal	Phosgene	A choking agent used in bombs at the Arsenal; a decomposition product of dibrom
Methylhydrazine	Used in the production of Aerozine 50	Phosphoric acid	A decomposition product of azodrin, bidrin, ciodrin, and gardona
Methylthioacetaldoxime	Used in the production of nudrin	Phosphorous (red)	Used in the production of button and sandwich button bombs
Mixed oleum and nitric acid	Used in the production of mustard	Phosphorus (white)	Used in the production of white phosphorous cups
Mustard	Army product manufactured at the Arsenal	Potassium chlorate	Used in the production of button and sandwich button bombs
Naled	Shell product manufactured at the Arsenal	Pyrene	Purpose of use not documented
Nitric acid	Used in the production of planavin and mustard demilitarization	Sarin	Army product at the Arsenal
Nitro sodium phenolate	Hydrolysis product of methyl and ethyl parathion	Sodium	Byproduct and decomposition product of Sarin
4-nitrophenol	Product of parathion hydrolysis	Sodium chlorate	Used in the production of Sarin and chlorine
N-nitrosodimethylamine (NDMA)	Impurity of dimethyl hydrazine; used in the production of Aerozine 50	Sodium fluoride	Byproduct of production; filling and demilitarization of Sarin munitions
Octachlorocyclopenta-diene	Purpose of use not documented	Sodium hydroxide	Used in the manufacture of caustic, chlorine, Sarin scrubber effluent, akton, and nudrin
Parathion	Shell product manufactured at the Arsenal	Sodium hypochlorite	Used to decontaminate equipment and work areas
Pentachlorobenzene	Purpose of use not documented	Sodium methylate	Used in the production of akton
Phenanthrene	Purpose of use not documented	Sodium nitrate	Used in M-74 incendiary munitions

Table 2.3. Documented contaminants released at the Arsenal (cont.)

Contaminant	Use	Contaminant	Use
Sodium nitrite	Used in M-74 incendiary munitions and a Shell waste	Trichlorobenzene	Used in the manufacture of gardona
Sulfur monochloride	Used in the production of mustard	1,1,1 trichloroethane	Solvent used by Shell
Sulfuric acid	Used in the production of nudrin and planavin; used in chlorine production and mustard distillation	1,1,2 trichloroethane	Purpose of use not documented
Sulfuryl chloride	Used in the production of ciodrin, heptachlor, and phosdrin	Trichloroethylene (TCE)	Used in laundry and M-74 bomb filling
Tetrachloroethane	Purpose of use not documented	Trimethyl phosphite	Used in the production of azodrin, bidrin, ciodrin, phosdrin, and vapona
Tetrachloroethylene (or perchloroethylene, PCE)	Used in laundry and clothing operations	TX	Army biological agent processed at the Arsenal
Tetrahydrofuran	Solvent used by Shell for unreported purposes	Vinyl chloride	Used in the manufacture of endrin
Thiodiglycol	Used in the production of mustard	Xylene	Used in the production of dieldrin, endrin, and gardona
Toluene	Used in the production of aldrin dieldrin and endrin	Zinc	Purpose of use not documented
Trichloroacetaldhyde	Used in the production of dibrom and dichlorovos	Zinc oxide	Used in laundry and clothing operations

Sources: DOJ, 1986; Ebasco Services et al., 1988b.

2.2.1 South Plants Complex

The South Plants Complex (Figure 2.3) was the site of the first manufacturing operations at the Arsenal and ultimately contained between 165 and 197 structures (Ebasco Services et al., 1988d). The Army initially used South Plants for the production, filling, and storage of bombs containing mustard, lewisite, phosgene, white phosphorus, chlorine, incendiary mixtures, and explosives (Ebasco Services et al., 1988d). Beginning in 1957 and continuing into the 1980s, the Army also demilitarized chemical weapons in the South Plants area. Demilitarization included emptying, burning, neutralizing, and disposing of nerve agents, nerve agent munitions, and nerve agent-contaminated items (Environmental Science & Engineering et al., 1988b). As discussed above, a succession of companies, primarily Shell, manufactured pesticides, insecticides, and herbicides at South Plants beginning in 1946 and continuing until 1982.

The South Plants Complex released hazardous substances to the environment through direct disposal of wastes into, among other locations, Basins A through F, Lime Settling Basins, Army Complex Trenches, Shell Trenches, sewers, ditches, and lakes (Figure 2.3). In addition, numerous spills associated with Army and Shell activities were reported. From the late 1940s to the end of manufacturing activities in the early 1980s, over 87,000 gallons of solvents, pesticides, metals, and other process intermediates leaked or spilled in the South Plants manufacturing area (DOJ, 1986; Ebasco Services et al., 1988b, 1988d).

In 1966, Shell constructed an incinerator in South Plants to decontaminate and dispose of their wastes. The incinerator was shut down in 1970 due to high particulate emission levels (Ebasco Services et al., 1992).

Numerous small waste pits and lagoons were located in and around the South Plants Complex, including the Liquid Storage Pool, Hex Pits, M1 Pits, South Plants Lime Pits, South Plants Lagoon, the Test Site, and the Insecticide/Pesticide Pits. Each of these has been identified as a source of hazardous substances (Ebasco Services et al., 1989c). A description of each is beyond the scope of this document, but all of these sites are within or adjacent to the South Plants and therefore the entire complex should be considered a source of hazardous substances.

South Plants Tank Farm

The South Plants Tank Farm was another source of hazardous substances located within the South Plants Complex. The Army, CF&I, Hyman, and Shell used the tanks for liquid storage (Ebasco Services et al., 1987). The tanks were constructed of dismantled salvage material, and they contained fuel, alcohol, benzene, bicycloheptadiene bottoms, DCPD, water, D-D soil fumigant, DBCP, and sulfuric acid (Ebasco Services et al., 1987). The overall capacity of the tanks was 2.3 million gallons (Ebasco Services et al., 1987). As reported in Ebasco Services et al. (1987), some of the numerous releases to the environment via spills and tank leakage included:

- 100,000 gallons of benzene in 1947
- 17,000 gallons of DCPD in 1963
- 1,548 gallons of DCPD and oil in 1976
- 58,864 gallons of DCPD in 1978.

In addition, sediments and DCPD bottoms were routinely removed from the tanks during cleaning and buried at unreported locations, possibly in pits adjacent to the tanks (Ebasco Services et al., 1987).

South Plants Chemical Sewers

The South Plants sewer system carried chemical wastewaters from production units to Basin A, the M-1 Pits, the Lime Settling Basins, the Sand Creek Lateral (via the storm sewer), ditches, and Basin F (Ebasco Services et al., 1988a). The sewers were originally constructed to dispose of wastewater generated at the South Plants Complex (Ebasco Services et al., 1988a). These sewers released hazardous substances, including acetic acid, aldrin, caustic soda, dieldrin, endrin, xylene, acids, and tetrachloroethylene, to South Plants groundwater (Ebasco Services et al., 1988a).

Sand Creek Lateral

Farmers originally constructed the Sand Creek Lateral (Figures 2.2 and 2.3) in the early 1900s for flood irrigation (Foster Wheeler, 2000b). As part of Arsenal operations, it served as a chemical sewer conveying wastes from the South Plants. The Sand Creek Lateral originally discharged liquid waste from the chlorine plants and South Plants stormwater runoff directly into First Creek. When sodium chloride concentrations in the waste reached 20,000 parts per million (ppm), flows from the Lateral were redirected to Basins D and E (Tetra Tech EC, 2005).

In 1951, the waste from the White Phosphorus Plant and the M-74 Bomb Filling Operations were redirected from Basin A to the Sand Creek Lateral (Tetra Tech EC, 2005). In 1953, the Sand Creek Lateral was incorporated into the liquid waste disposal system to convey overflow wastes from Basins A and B downstream to Basin C and subsequently into Basins D and E (Tetra Tech EC, 2005). The Sand Creek Lateral was used until the Basin F chemical sewer system was brought online in late 1956 (Tetra Tech FW, 2004; Tetra Tech EC, 2005).

The use of the Sand Creek Lateral for storm water runoff and discharge from the South Plants resulted in releases of hazardous substances, including aldrin, copper, dieldrin, TCE, trichloroethane arsenic, mercury, lead, sulfate, white phosphorous, various salts, caustics, and acids, to groundwater, surface water, and sediments (Tetra Tech FW, 2004; Tetra Tech EC, 2005).

North Plants Complex

The Army constructed the North Plants Complex (Figures 2.3 and 2.5) in the early 1950s to produce Sarin nerve gas, create the Sarin delivery systems (bombs), and subsequently to demilitarize Sarin bombs and other chemical warfare and incendiary munitions (Ebasco Services et al., 1989a; RVO, 2004). The manufacturing process resulted in the release of hazardous substances into, among other locations, Basins A and F, Army Complex Trenches, the Toxic Storage Yard, sewers, trenches, pits, and ditches, as well as directly to the ground from leakage and overflow of underground tanks and sumps within the North Plants (Ebasco Services et al., 1989a).

Figure 2.5. North Plants Complex.

Source: Army archives.

Floor drains from 18 buildings in the North Plants were connected to the Building 1727 Sump, an 80,000-gallon wastewater repository (Ebasco Services et al., 1989a). Wastes in the sump were neutralized with caustic, then pumped into Basin A or Basin F (Ebasco Services et al., 1989a).

Between 1953 and 1982, waste liquids from sump overflow migrated through ditches into First Creek. Leakage from the sump, in addition to spills and leakage from other areas of the North Plants, resulted in the release of benzene, 1,1 dichloroethane, 1,2 dichloroethane, carbon tetrachloride, 1,1,1 trichloroethane, TCE, chloroform, methylisobutyl ketone, arsenic, mercury, cadmium, chromium, copper, lead, zinc, pyrene, chloroacetic acid, aldrin, and dieldrin (Ebasco Services et al., 1989a). Soil samples taken adjacent to the North Plant sewers showed releases of dieldrin, arsenic, cadmium, chromium, and lead (Ebasco Services et al., 1989a).

2.2.2 Basins

Lime Settling Basins

The Lime Settling Basins (Figure 2.3) comprised three, one-acre unlined basins originally used during World War II to precipitate arsenic and metals from lewisite production wastewater (Environmental Science & Engineering et al., 1987e). All South Plants wastewater, including pesticide waste and byproducts, was reportedly channeled through the Lime Settling Basins to Basin A and, later, Basin B (Environmental Science & Engineering et al., 1987e). In addition, over 150 drums of mustard may have been disposed in these basins from 1959 to 1960 (Environmental Science & Engineering et al., 1987e). When their use was discontinued, the Army estimated that 80,000 cubic yards of sludge were contained in the Lime Settling Basins, with an additional 26,000 cubic yards located adjacent to them (Ebasco Services et al., 1990). Discharge of liquids into the Lime Settling Basins resulted in the release of numerous hazardous substances, including aldrin, dieldrin, endrin, isodrin, DDT, DDE, chlorophenylmethyl sulfide, arsenic, mercury, lead, cadmium, and chromium (Ebasco Services et al., 1990).

Basin A

Basin A was an unlined natural depression and the primary disposal area for liquid chemical waste from the South Plants from the time production of mustard was initiated in the early 1940s until the mid-1950s when the construction of Basin F was completed. Liquids were discharged to Basin A primarily through the chemical sewers. At maximum capacity, Basin A covered 125 acres (Environmental Science & Engineering, 1987; Figure 2.6).

In 1943, approximately 10% of the mustard produced was determined to be off-specification (DOJ, 1986). Each batch of off-specification mustard was neutralized with caustic and discharged through a toxic waste sewer into Basin A (Ebasco Services et al., 1988d). The treatment of mustard with caustic was not always successful, and high levels of mustard were often found in the water of Basin A near the sewer outlet (Kuznear and Trautmann, 1980). Mustard neutralization also produced 514,000 pounds of the hazardous substance thiodiglycol, which was also disposed of in Basin A (DOJ, 1986).

In addition, the Army flushed the mustard storage tanks with a mixture of carbon tetrachloride and fuel oil, and then a 10% solution of caustic and chlorinated water. Other parts of the mustard complex were rinsed using approximately 20,000 gallons of 98% sulfuric acid. All rinsate was discharged through the sewer into Basin A (DOJ, 1986).

During munitions filling operations, approximately 500 gallons of distilled mustard leaked from a corroded storage tank and was discharged untreated into Basin A (DOJ, 1986).

Figure 2.6. Basin A in June 1950.

Source: Army archives.

White phosphorous was shipped to the Arsenal in specialized railroad cars. The phosphorous was covered with water to avoid auto-ignition. The “phossy water,” as it was called, was discharged to Basin A via the chemical sewers until 1951 (DOJ, 1986).

Documented disposal of hazardous substances to Basin A from pesticide and herbicide manufacturing include (Ebasco Services et al., 1988b):

- > 170,000 pounds of aldrin mixtures
- 11,000 pounds of endrin manufacturing wastes
- 17,000 pounds of isodrin manufacturing wastes
- 406 pounds of nemafere manufacturing wastes.

Basin B

Basin B was a two-acre, unlined natural depression that was used until 1956 as an intermediate containment reservoir for excess Basin A liquids directed to Basin C (Figure 2.3) (Environmental Science & Engineering et al., 1987d). Disposal of waste liquids into Basin B resulted in the release of numerous hazardous substances, including dieldrin, arsenic, mercury, lead, cadmium, and chromium (Environmental Science & Engineering et al., 1987d; Environmental Science & Engineering and Harding Lawson Associates, 1988e).

Basin C

Basin C was a 77-acre unlined natural depression (Figure 2.3) that the Army reportedly first used in the early 1950s as a repository for an unknown amount of white phosphorous waste considered to be incompatible with Basin A fluid (Environmental Science & Engineering et al., 1987a). The Army constructed dikes in 1953 to create a waste repository with an estimated capacity of 190 million gallons (Environmental Science & Engineering et al., 1987a). All waste liquids flowing into the basin were derived from two sources: (1) overflow from Basins A and B, and (2) surface drainage ditches in the South Plants that led into the Sand Creek Lateral (see Figure 2.2). Basin C was hydraulically connected to groundwater and thus served as a direct source of hazardous substance to groundwater (Environmental Science & Engineering et al., 1987a). Disposal of liquids into Basin C resulted in the release of numerous hazardous substances, including xylene, aldrin, dieldrin, DDE, chlorophenylmethyl sulfide, arsenic, mercury, copper, lead, cadmium, and chromium (Environmental Science & Engineering et al., 1987a; Environmental Science & Engineering and Harding Lawson Associates, 1988a).

Basin D

Basin D was a 21-acre unlined natural depression (Figure 2.3) that originally received Army waste from the chlorine plant and white phosphorous filling operations in the South Plants Complex via the Sand Creek Lateral prior to 1946 (Environmental Science & Engineering et al., 1987b). In 1952, the Army opened a spillway from Basin A, allowing 113 million gallons of Shell and Army waste to flow to Basin D over a three-month period (Environmental Science & Engineering et al., 1987b). From 1953 to 1956, all aqueous wastes entering Basin D were Basin A overflows from Shell manufacturing in the South Plants and the Army's Sarin manufacturing in the North Plants (Environmental Science & Engineering et al., 1987b). Disposal of liquids into Basin D resulted in the release of numerous hazardous substances, including aldrin, dieldrin, chlorophenylmethyl sulfide, arsenic, mercury, copper, lead, cadmium, and chromium (Environmental Science & Engineering et al., 1987b; Environmental Science & Engineering and Harding Lawson Associates, 1988b).

Basin E

Basin E was a 29-acre unlined natural depression (Figure 2.3) that, like Basin D, was a disposal site for wastewater overflow from Basin A (Environmental Science & Engineering et al., 1987c). Basin E began receiving overflow from Basin A and discharge from the chlorine plant in the South Plants in 1953 and continued to be used as additional storage capacity for overflow from Basin A until 1956 (Environmental Science & Engineering et al., 1987c). Disposal of liquids into Basin E resulted in the release of numerous hazardous substances, including aldrin, dieldrin, arsenic, mercury, lead, and chromium (Environmental Science & Engineering et al., 1987c; Environmental Science & Engineering and Harding Lawson Associates, 1988c).

Basin F

Basin F was a 93-acre, asphalt-lined evaporative disposal basin with a capacity of 240,000,000 gallons constructed in 1956 (Figure 2.3). By December 1956, the majority of contaminated liquid waste streams at the Arsenal were discharged into Basin F. On three occasions, Basin F filled to capacity: in 1962, 1965, and between 1975 and 1976. Shell disposed of liquid wastes in Basin F until 1978, and the Army until 1981. In 1981, the Army installed an aeration system that sprayed Basin F liquids into the air. While this accelerated evaporation of Basin F liquids, it also resulted in considerable contamination to surface soils around the exterior of the basin (Tetra Tech EC, 2005).

Repairs and modifications to Basin F’s liner and dikes occurred several times during its use. The asphalt liner in Basin F did not prevent the release of hazardous substances to underlying soils and groundwater. Discharge of liquid wastes into Basin F resulted in the release of numerous hazardous substances, including aldrin, dieldrin, endrin, isodrin, toluene, trichloroethane, TCE, DBCP, ethyl benzene, xylene, DDE, arsenic, mercury, lead, and chromium (Environmental Science & Engineering et al., 1988a).

Specific documented disposal of hazardous substances from Shell’s pesticide and herbicide manufacturing to Basin F includes (DOJ, 1986; Ebasco Services et al., 1988b):

- 44,000 pounds of endrin manufacturing wastes
- 50,000 pounds of isodrin manufacturing wastes
- 60,000 pounds per year (~10 years) of methyl parathion salts
- 140,000 pounds of methyl parathion manufacturing wastes
- 120,000 pounds of ethyl parathion manufacturing wastes
- 150,000 pounds of bidrim manufacturing wastes
- 12,000 pounds of dibrom manufacturing wastes
- 28,000 pounds of ciodrin manufacturing wastes
- 2,000 pounds of azodrin manufacturing wastes

- 8,600 pounds of nudrin manufacturing wastes
- 238,400 pounds of DBCP manufacturing wastes
- 9,300 pounds of bladex manufacturing wastes
- 1,360,000 pounds of planavin manufacturing wastes
- 1,300 pounds of phosdrin manufacturing wastes.

2.2.3 Trenches

Army Complex Trenches

The Army Complex Trenches (Figure 2.3) was a solid waste disposal site covering over 100 acres. The Army used the trenches from the 1940s to the early 1970s to dispose of wastes that included potentially contaminated tools, equipment, unwanted containers, rejected incendiaries, vehicles, empty munitions casings, chemical warfare agent, and chemical agent-filled unexploded ordnance (Foster Wheeler, 2001). Because of the lack of disposal records, and the Army's fear that an intrusive investigation could result in exposure to unexploded ordnance and chemical agent, the nature of waste disposed in discrete portions of the site is undetermined. Hazardous substances identified in some trench contents or trench soils include aldrin, dieldrin, endrin, chlordane, DDT, DBCP, fluoroacetic acid, arsenic, mercury, cadmium, chromium, and lead (Harding Lawson Associates, 1993). Additional hazardous substances identified in groundwater downgradient of the trenches include chlorobenzene, dichloroethane, dichloroethene, tetrachloroethane, TCE, trichloroethane, xylene, and cyanide (Harding Lawson Associates, 1993).

Shell Section 36 Trenches

The Shell Section 36 Trenches (Figure 2.3), also known as the Shell Trenches, covered an eight-acre area that Shell used from 1952 to 1965 for land disposal of liquid and solid hazardous substances from the production of pesticides. Approximately 31 unlined trenches were excavated 10 to 20 ft wide and between 5 and 10 ft below the surface. The trenches were used to dispose of organic and inorganic compounds, process intermediates, and off-specification products. The use of these trenches for disposal resulted in the release of hazardous substances, including aldrin, dieldrin, endrin, isodrin, benzene, chlorobenzene, chloroform, DBCP, dicyclopropane, ethylbenzene, hexane, toluene, xylene, 1.1-dichloroethane, 1,2-dichloroethane, 1.2-dichloroethene, methylene chloride, tetrachloroethylene, and trichloroethene (Environmental Science & Engineering et al., 1987f, 1988c; Environmental Science & Engineering and Harding Lawson Associates, 1988f, 1988g; MK-Environmental Services, 1993).

Whereas the basins were used to dispose of the hazardous byproducts of pesticide and herbicide manufacturing, the Shell Trenches were used to dispose of unused pesticide and herbicide products. Documented products disposed in the Shell Trenches include (DOJ, 1986; Ebasco Services et al., 1988b; MK-Environmental Services, 1993):

- 842,000 pounds of endrin
- 5,990,000 pounds of isodrin and isodrin impurities
- 13,000 pounds of methyl parathion
- 13,000 pounds of vapona
- 6,100 pounds of bidrin
- 10,000 pounds of dibrom
- 45,000 pounds of azodrin
- 9,800 pounds of DBCP
- 70,000 pounds of planavin and planavin impurities
- 4,000 pounds of phosdrin.

2.2.4 Motor Pool/Rail Classification Yard

The Motor Pool (Figure 2.3) was constructed in the 1940s to service heavy equipment, vehicles, locomotives and rail cars, and for storing fuel, road oil, and flammable liquids (Ebasco Services et al., 1988e). Various wastes may have been discharged into drainage ditches, including solvents, petroleum products, strong caustics, dilute wastes from the motor pool wash bay, and detergents (Ebasco Services et al., 1988e). A 1984 Compliance Order by the Colorado Department of Health halted the use of degreasing solvents at the Motor Pool. The wastes discharged by activities associated with the Motor Pool resulted in releases of hazardous substances, including benzene, chloroform, 1,1-dichloroethane, ethylbenzene, methylene chloride, tetrachloroethylene, toluene, 1,1,1-trichloroethane, TCE, m-, o- and p-xylene, aldrin, DBCP, arsenic, mercury, cadmium, chromium, and lead (Ebasco Services et al., 1988e; Foster Wheeler, 2000a).

The Rail Classification Yard (Figure 2.3), adjacent to the Motor Pool, was built in the late 1940s for the storage of pesticides, solvents, and acids. In addition, the area was used as open storage for tanks, trailers, crates, and for the temporary storage of railcars, including railcars holding DBCP. There were several reported spills in the Rail Classification Yard, resulting in a groundwater plume emanating from the site. DBCP is the only identified hazardous substance released from the Rail Classification Yard (Ebasco Services et al., 1988h, 1989d).

2.2.5 Toxic Storage Yard

The Toxic Storage Yard (Figure 2.3) was originally constructed in 1952 as a 16-acre storage site for lewisite, mustard, phosgene, Sarin, VX, and decontamination agents. The site was later expanded to the south and west to provide additional storage capacity. By April 1953, the Army had constructed four 10,000 square-foot open storage pads as support facilities for Sarin production in the North Plants Complex. In August 1954, 625 one-ton containers, likely containing Sarin, were in the yard. In the early 1960s, the Army discovered that containers and cluster bombs in the Toxic Storage Yard were leaking Sarin. In the early 1970s, the Army stored 76,000 drums of demilitarized Sarin salts in the Toxic Storage Yard as part of Project Eagle (Ebasco Services et al., 1988f, 1988i).

Spills from leaking containers and bombs are the primary source of contaminants in the toxic storage areas (Ebasco Services et al., 1988f). The use of the Toxic Storage Yard to store lewisite, mustard, phosgene, Sarin, VX, and decontamination agents resulted in the release of hazardous substances, including, but not limited to, chloroacetic acid, arsenic, chromium, and lead (Ebasco Services et al., 1988f, 1988h).

2.2.6 Other areas

The Army identified over 178 different contaminant source areas (Ebasco Services et al., 1992). Not all have been discussed in this Plan. The majority of these sources are in the South Plants and in Section 36, where Basin A and the Army and Shell Trenches, among other sites, are located (Figure 2.3). Some sources not discussed above are addressed in the next chapter that summarize cleanup activities at the site.

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3. Response Actions

The Army addressed contamination at the Arsenal through a series of interim response actions (IRAs) in the 1980s, and through the final remedial action that was selected as a result of the RI/FS process discussed below. The first actions were groundwater treatment and containment systems constructed in the early 1980s on the northwest and northern boundaries of the Arsenal to prevent further migration of known groundwater contamination (Harding Lawson Associates, 1995; Foster Wheeler, 1996).

In 1984, the U.S. Army Toxic and Hazardous Materials Agency, under a separate division created specifically to deal with the contamination at the Arsenal, initiated a series of investigations required under CERCLA. These investigations were incorporated into the RI/FS and the Endangerment Assessment (Foster Wheeler, 1996). As the RI proceeded and more was learned about the site, the parties agreed to a number of IRAs to address some of the most obvious and discrete ongoing sources of contamination. The ROD for the Off-Post Operable Unit (OU) was signed in December 1995, and the ROD for the On-Post OU was signed in June 1996. These RODs memorialized the final selected remedy for each OU. Implementation of the on-post remedy is ongoing and is expected to be completed by 2010.

This chapter discusses the response actions that have taken place at the Arsenal. Section 3.1 presents an overview of the RI/FS process, which formed the basis of remedy selection; Section 3.2 discusses actions taken on-post; and Section 3.3 discusses actions taken off-post.

Summary of response actions

The Army constructed several groundwater containment, extraction, and treatment systems to address contaminated groundwater plumes (discussed further in Chapter 5). Pump-and-treat systems included those on the west/northwest boundaries (including the Irondale Containment System and Northwest Boundary Containment System), and north boundary (North Boundary Containment System), as well as the newer Rail Classification Yard system and the Basin A Neck system. Extraction wells were constructed on-post at the Motor Pool, South Plants Complex, Lime Settling Basins, the Army Section 36 Trenches, north of Basin F, the South Channel wells to the east of the original Basin F system, and northeast of Basin A (Bedrock Ridge). Off-post extraction and reinjection wells and a treatment system were also constructed north of the Arsenal boundary (Figure 3.1).

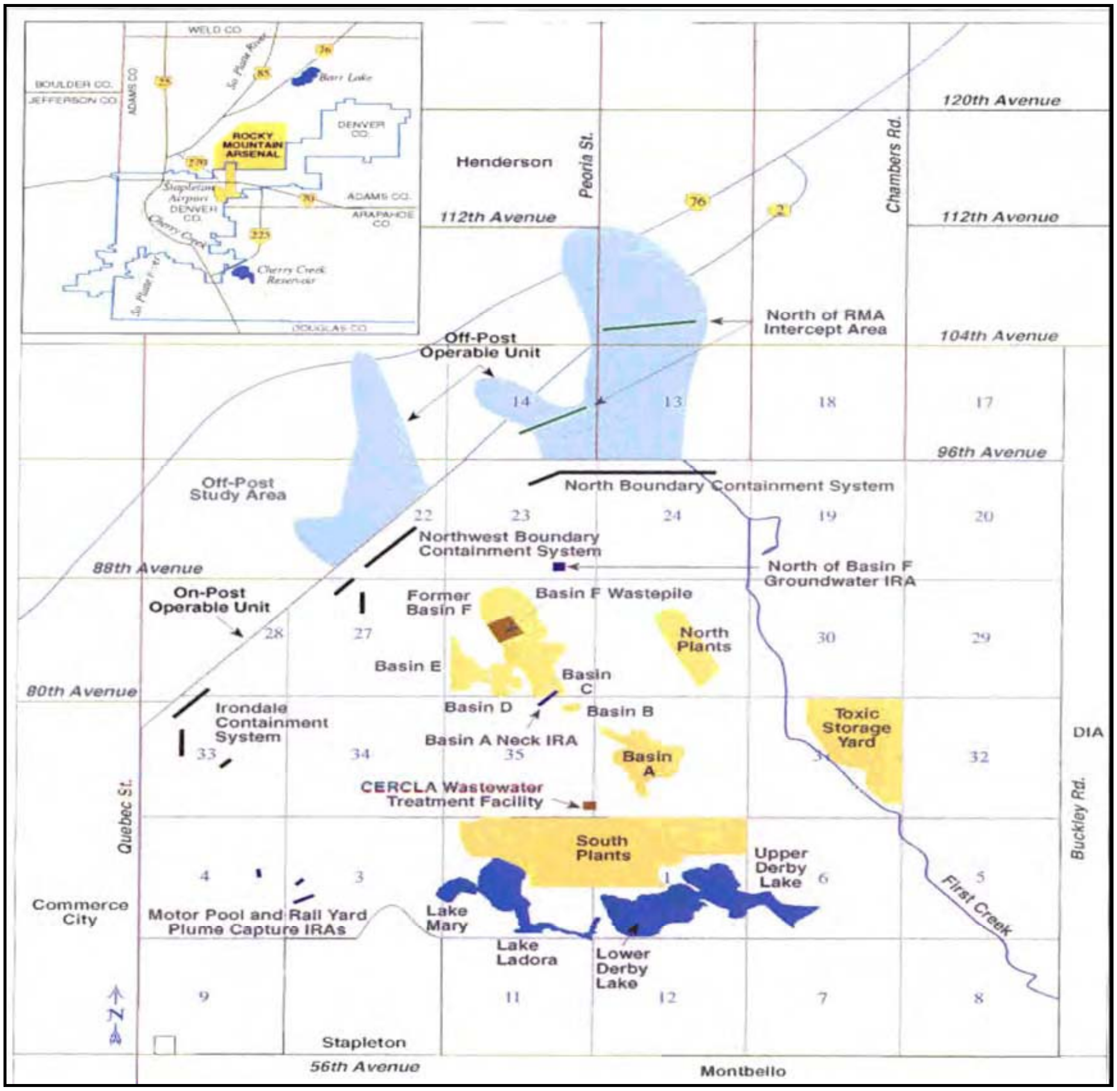

Figure 3.1. Selected areas where some response actions occurred.

Source: Foster Wheeler, 1996, Figure 1.0-1.

In addition, Shell and the Army funded the purchase of water rights and a distribution system for South Adams County Water and Sanitation District (SACWSD) to provide domestic water to residents north of the Arsenal and south of the South Platte River (Figure 3.1). This action prevented these residents from consuming groundwater that would have put them at risk of adverse health effects from diisopropyl methylphosphonate (DIMP), a byproduct of Sarin nerve agent prevalent in shallow groundwater north of the Arsenal (Harding Lawson Associates, 1995).

The response to contaminated soils and sludge included construction of a hazardous waste landfill and an enhanced landfill, with cells triple-lined for particularly contaminated soils, plus reconstruction of Basin A as a soil consolidation area for less contaminated soils. Millions of cubic yards of contaminated soils, sludge, and sediments were excavated and placed in these two landfills and the consolidation area. After excavation, the contaminated areas were covered with a rock biota barrier and soil, and then planted with vegetation. Restoration of the original native prairie grasses on the capped and borrow areas has had mixed success (Foster Wheeler, 1996).

Most of the soil remediation has been completed. Remediation of Basin F is expected to be completed in 2008. Once the final remedy is finished, known residual soil contamination above acceptable levels should be contained in landfills or capped in place (Foster Wheeler, 1996).

3.1 RI/FS Summary

3.1.1 Remedial Investigation

The RI was separated into the On-Post and the Off-Post OUs (Figure 3.2). The formal Off-Post OU was based solely on the spatial extent of off-post groundwater plumes for selected contaminants, while the Off-Post Study Area covered the extent of the areas evaluated for potential risk (Figure 3.2).

On-post

The Army and Shell's releases of hazardous substances extended over a large portion of the 27 square-mile site, and impacted soils, groundwater, surface water, air, and biota. The Army divided the On-Post RI into discrete source areas for study, and carried out the investigation in phases. The results were documented in 124 Phase I Contamination Assessment Reports (CARs), one for each identified or potential waste site and one for areas within each one square-mile section designated by the Army as a "non-source" area. The CARs were subsequently summarized in Study Area Reports for the central, north central, southern, eastern, western, North Plants, and South Plants areas of the Arsenal. In addition, separate RIs were completed for biota, surface water and groundwater, and structures. The Army also instituted Comprehensive Monitoring Programs (CMPs) for water, biota, and air. Ebasco Services et al. (1992) summarized all the foregoing reports in a comprehensive RI summary report. The On-Post RI ultimately covered over 320 locations of suspected contamination and identified 178 contaminated sites at the Arsenal (Ebasco Services et al., 1992).

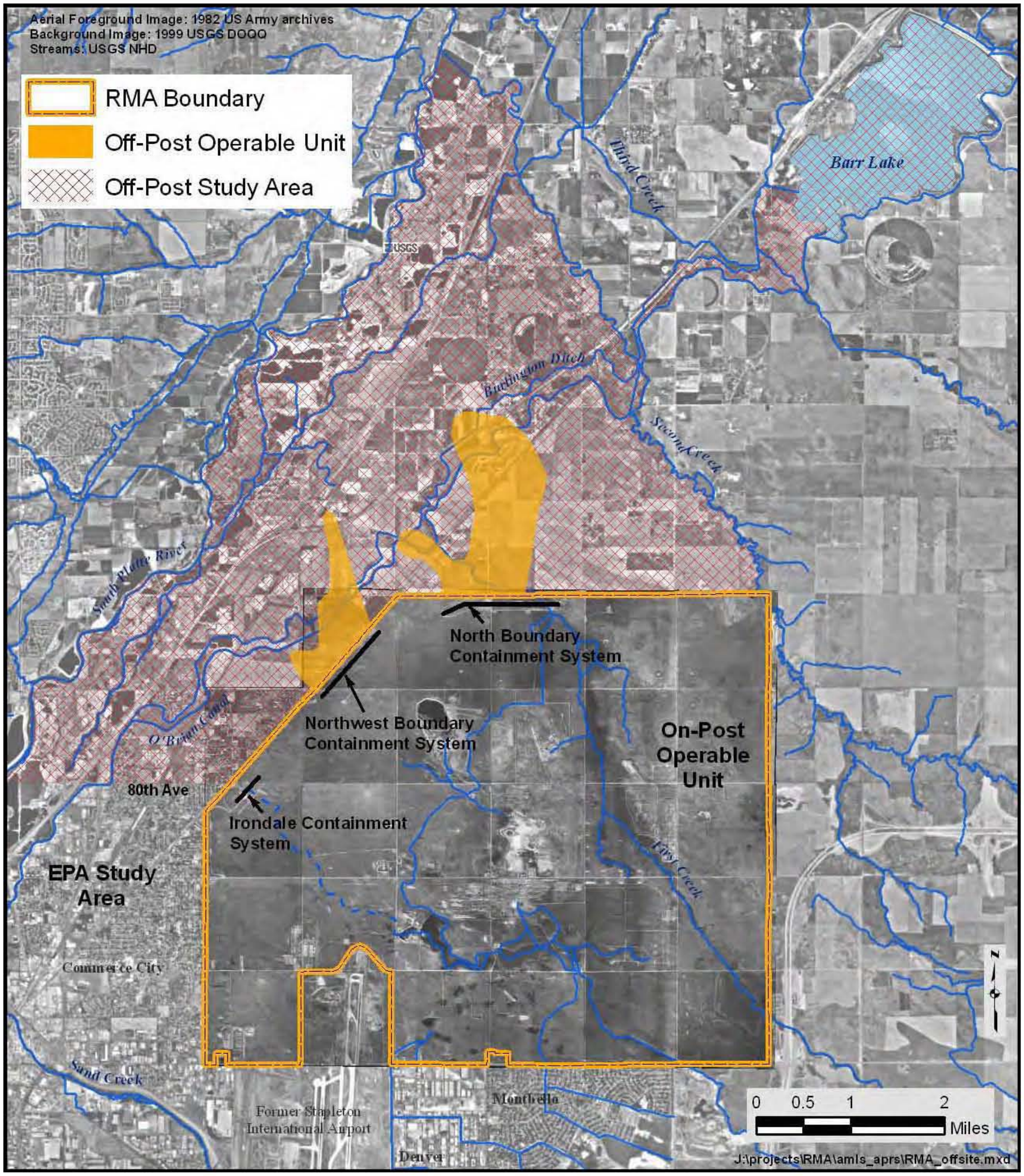

Figure 3.2. On-Post and Off-Post OUs, and the Off-Post Study Area, at the Arsenal. The Off-Post Study Area is the area evaluated for potential risks, while the Off-Post OU covers only the spatial extent of off-post groundwater plumes for selected contaminants.

The Army initiated the CMP in 1987 to collect data for evaluating response actions and to provide continual long-term verification monitoring of environmental conditions, including biota, on- and off-post. Despite the extensive data gathered at the site, the following limitations of the RI and the endangerment assessment should be noted:

- The RI sampling program may have missed hotspots in non-source areas due to limited sampling density and the Army's compositing of soil samples. If highly contaminated soils were composited with less contaminated soils, hot spots could have been missed because the high concentrations may have been diluted to concentrations below a level of concern.

- With the exception of 1,1,2,2-tetrachloroethane, none of the dozens of tentatively identified compounds were considered quantitatively in the endangerment assessment and the characterization of risk. These tentatively identified compounds represent a large number of unknown chemicals that were detected in chemical analysis results but were never positively identified by the Army.

- The extent of contamination at 23 sites identified as areas of potential chemical agent presence may have been underestimated. Detections of chemical agent at these sites were not quantitatively evaluated because the Army considered many of the detections "analytical artifacts" (Ebasco Services et al., 1994).

- The investigation of areas like the Army Complex Trenches and the Shell Section 36 Trenches, known to be highly contaminated and presenting special safety concerns, were intentionally avoided, providing little contaminant data.

- Detection levels for some contaminants in some media, most notably dieldrin in surface water, were often higher than the threshold risk concentration. In these cases, a lack of detection provides no assurance that the contaminant concentration is below the level of concern.

Off-post

The Off-Post Study Area was defined as the area southeast of the Platte River, north of 80th Avenue, southwest of Second Creek, and north of the north and northwest boundaries of the Arsenal (Figure 3.2). The Army divided the Off-Post Area into six "zones" based on possible contaminant types, concentrations, and general distribution. The Off-Post Study Area included the surface waters of O'Brian Canal and Burlington Ditch, along with First Creek and Barr Lake (see Figure 3.2) (Foster Wheeler, 1996).

Investigation of groundwater contamination began in 1975 with the 360° Monitoring Program. This investigation was initiated due to lawsuits filed in the 1950s by residents experiencing crop damage to the north of the Arsenal, along with three Cease and Desist Orders issued by the Colorado Department of Health in 1975. The original program investigated water from 42 locations both on and off the Arsenal. It was later revised to include 117 domestic, irrigation, and monitoring wells. After multiple phases and the sampling of nearly 150 wells, the Army identified 33 target chemicals for inclusion in the Off-Post OU groundwater investigation (Harding Lawson Associates, 1995).

The 1987 Groundwater CMP superseded the 360º Monitoring Program and continued both on-post and off-post monitoring well sampling and analyses. The Off-Post RI was also initiated in 1987 to refine the Army's understanding of groundwater flow patterns and the distribution of contaminants (Environmental Science & Engineering and Harding Lawson Associates, 1987).

Groundwater contamination in the Off-Post OU consisted of three groundwater plumes in the unconfined flow system: the northern paleochannel (extending due north from the Arsenal boundary), the First Creek paleochannel (which runs parallel to First Creek, in a northwest direction from the northern boundary of the Arsenal), and the northwest paleochannel (migrating northwest from the northwest boundary of the Arsenal). The Army consolidated the studies of the north and First Creek pathways, referring to them as the "North Plume Group" (see Figure 3.1) (Foster Wheeler, 1996).

According to the Army, soil contamination in the Off-Post Study Area was the result of the disposition of airborne contaminants from on-post and from the use of contaminated groundwater for irrigation purposes (Harding Lawson Associates, 1995). In 1989, soil in residential areas north of the Arsenal on 96th Avenue was targeted for investigation. The results of this sampling program led to additional sampling from several locations off-site. The Army's final sampling event was in 1991, when it investigated off-post areas where previous studies identified high concentrations of chemicals of concern. The majority of the Army's off-post soil investigations were limited to surface soils (0–2 inches) (Harding Lawson Associates, 1995).

Off-post surface soil samples were collected within 30-foot diameter circles and composited prior to analysis. Approximately 100 soil samples were collected from an area of 18 square miles. These composite samples did not show widespread soil contamination above risk thresholds acceptable to the EPA (Harding Lawson Associates, 1995).

3.1.2 Integrated Endangerment Assessment/Risk Characterization

EPA considers risk assessments to be an integral part of an RI. At the Arsenal, the various components of the human health and ecological risk assessments were combined in the

Integrated Endangerment Assessment/Risk Characterization (IEA/RC) report (Ebasco Services et al., 1994).

3.1.2.1 Human health risk

On-post

The IEA/RC evaluated 27 contaminants of concern for the human health risk assessment, which presupposed use restrictions imposed by the Federal Facilities Agreement that Shell and federal agencies signed in 1989. These controls prevent various uses of resources. Specifically:

- Water on or under the Arsenal cannot be used as a drinking water supply
- Arsenal property cannot be used for residential or agricultural purposes
- Hunting and fishing are restricted to nonconsumptive use, subject to appropriate restrictions.

The Federal Facilities Agreement also included the “goal” of establishing a National Wildlife Refuge at the site. Human health risks that were not evaluated as part of the Endangerment Assessment included those associated with exposure to contaminated groundwater and exposures associated with residential development (Ebasco Services et al., 1994).

Based on the RI results and the anticipated land use as open space/wildlife refuge, the human health risk assessment identified biological workers as most at risk. The Army also performed an assessment related to commercial and industrial development, which were not prohibited by the Federal Facilities Agreement. Based on those land use scenarios, the assessment identified industrial workers as most at risk. For the biological worker land use scenario, 149 of the 178 sites investigated in the RI had elevated cancer risks, with 12 of the sites identified as having highly elevated cancer risks. For the industrial worker land use scenario, 70 of the 178 sites studied had elevated cancer risks, and 16 of the sites studied had highly elevated cancer risks (Ebasco Services et al., 1994). Soils at the following areas had elevated cancer risks for both land use scenarios (Ebasco Services et al., 1994):

- Chemical sewers
- Sanitary/process water sewers
- M-1 Pits
- Section 36 Lime Basins
- Basins A and F
- Shell Trenches
- Five distinct areas within the South Plants.

Isolated soil borings showed elevated cancer risks in Basin C, the Sand Creek Lateral, the North Plants Agent Storage Areas, and the sanitary landfill near the Rail Classification Yard. The contaminants contributing most to potential carcinogenic risks were aldrin, dieldrin, DBCP, and arsenic (Ebasco Services et al., 1994).

Off-post

The Army's endangerment assessment for the Off-Post Study Area included 27 square miles to the north and northwest of the Arsenal. During the early 1990s when the assessment occurred, this area was rural agricultural land and residential neighborhoods, with some industrial use (Harding Lawson Associates, 1995).

For the evaluation of risk to human health, the Off-Post Study Area was divided into six zones. According to the Army, this was done to avoid diluting or averaging contaminant concentrations over the entire Study Area. Based on results of investigations from 1985 to 1991, risks were developed for each of the six zones. The Army recognized a potential cancer risk from benzene, arsenic, and dieldrin, with groundwater being the dominant source contributing to that risk. Non-carcinogenic effects in children exceeded EPA's acceptable level in three of the six zones, primarily due to exposure to dieldrin in groundwater. The Army concluded that no cleanup apart from the existing groundwater intercept systems was necessary because institutional controls would prevent unacceptable exposures to contaminated groundwater (Harding Lawson Associates, 1995).

3.1.2.2 Ecological risk

On-post

The ecological risk assessment went through several iterations due to significant disagreements among the State of Colorado, EPA, Shell, the USFWS, and the Army. Final cleanup levels were agreed upon after the signing of the ROD, based upon additional exposure studies conducted at the Arsenal.

The ecological risk assessment, contained within the IEA/RC (Ebasco Services et al., 1994), focused on three categories of representative species: predators (bald eagle, great horned owl, American kestrel, and great blue heron), species with special feeding niches (including shorebirds such as the mallard, blue-winged teal, and American coot, and small birds such as the mourning dove, vesper sparrow, and western meadowlark), and lastly, prey (deer mouse, thirteen-lined ground squirrel, black-tailed prairie dog, and desert cottontail). Potential ecological risk was evaluated for 14 target compounds, or "chemicals of concern": aldrin, dieldrin, DDT, DDE, endrin, mercury, arsenic, cadmium, copper, chlordane, chlorophenyl methyl sulfide, chlorophenyl methyl sulfone, DCPD, and DBCP (Ebasco Services et al., 1994).

The ecological risk assessment showed that, assuming exposure to all target chemicals combined, most soils at the Arsenal presented a potential risk to at least one representative species, primarily from exposure to aldrin, dieldrin, endrin, DDT/DDE, and mercury (Ebasco Services et al., 1994). Areas where all representative species were at a potential risk include (see Figure 3.1):

- South Plants and most areas in the vicinity of South Plants and north of Lake Mary, Lake Ladora, and the Derby lakes
- Basins A, B, C, D, and F
- Toxic Storage Yard.

Although varying concentrations of pesticides were detected in surface soil samples throughout the Arsenal, exceedences of ecological risk criteria were generally limited to the central processing and disposal areas (Ebasco Services et al., 1994).

3.1.3 Feasibility study

Feasibility studies are conducted to evaluate alternative response actions against regulatory criteria including protectiveness, effectiveness, and cost. Most alternatives for soils remediation involved disposal in an on-post hazardous waste landfill, some covering in place, and some treatment. The selected remedy included a large on-site double-lined landfill with an isolated triple-lined cell to accept the most contaminated waste (Foster Wheeler, 1996). This landfill was designed in accordance with the State's regulatory requirements under the Colorado Hazardous Waste Act. The groundwater remedy was largely reliant on the existing pump and treat systems (Foster Wheeler, 1996). Details of the final remedy are discussed below.

The Army did not evaluate remedial alternatives for soils in the Off-Post Study Area because risks were found to fall within the EPA's acceptable range. The primary component of the off-post groundwater remedy was continued operation of the Arsenal's boundary and off-post groundwater extraction and treatment systems (Harding Lawson Associates, 1995).

3.2 On-Post Actions

3.2.1 Interim response actions

The Army implemented a series of actions in the 1980s to address some of the more urgent contamination problems. With the cooperation of the State, EPA, and Shell, 14 IRAs were identified (13 IRAs on-post and one off-post), with many completed during the RI. The interim responses were intended to be consistent with the final selected response actions (Foster Wheeler, 1996).

The 13 on-post IRAs (Foster Wheeler, 1996), shown in Figure 3.3, were:

- **North boundary system improvements**: The Army assessed and implemented operational improvements to groundwater treatment at the north boundary and constructed recharge trenches to improve the reinjection of treated groundwater.

- **Groundwater interception and treatment north of Basin F**: The Army constructed an extraction system for groundwater contamination migrating north of Basin F. Contaminated groundwater was treated and recharged at the Basin A Neck.

- **Abandoned well closure**: The Army sampled and subsequently plugged wells on the Arsenal that were not part of the ongoing groundwater monitoring program or that were not suitable for future monitoring programs.

- **Groundwater interception and treatment at Basin A Neck**: An intercept and treatment system was installed in a constricted alluvial groundwater channel downgradient of Basin A.

- **Building 1727 sump liquid remediation**: The goal of this project was to treat the contaminated liquid in Sump 1727 in North Plants and control the remaining threat of contaminated liquid that could have been released to the environment.

- **Hydrazine Blending and Storage Facility remediation**: The Army decommissioned above-ground equipment and treated 300,000 gallons of hydrazine wastewater in the Basin F Incinerator.

- **Fugitive dust control**: In 1991, due to concerns with wind-blown dispersion of contaminated soils, the Army reapplied a dust suppressant in Basin A.

- **Sanitary sewer remediation**: In 1992, to eliminate the migration of contaminated groundwater in the sewer system, the Army plugged the sanitary sewer's manholes.

- **Asbestos removal**: The Army sampled and removed suspected friable asbestos from in and around occupied buildings. This work was completed in 1989.

- **"Hot Spot" contamination source remediation**:

  - **Shell Trenches**: The Army constructed slurry walls and caps at the Section 36 Shell Trenches to reduce the vertical and horizontal migration of contamination.

  - **Lime Settling Basins:** The Army constructed a soil cover over the Lime Settling Basins area to isolate them from the ground surface and minimize the amount of rainwater seeping into the basins.

  - **Motor Pool**: A groundwater extraction system and soil vapor extraction system were built to address TCE contamination in groundwater and soils.

  - **Rail Classification Yard**: This action included an assessment of groundwater, followed by the construction of a groundwater intercept system.

  - **South Tank Farm plume**: For the South Tank Farm plume, Shell implemented groundwater sampling to monitor the Light Non-Aqueous Phase Liquids portion of the groundwater plume, verify existing data on contaminant migration, and locate the leading edge of the plume over time. Shell determined that the plume was not migrating toward the Lower Lakes, nor posing a significant threat to humans or other biota, prior to the final remedy. Natural biodegradation of the plume was thought to be occurring (EPA and Army, 2000b).

  - **Army Trenches (or Section 36 Trenches)**: The Army determined that immediate action was not required and selected groundwater monitoring as the IRA, despite highly elevated contaminant concentrations in surface soils, deep soils, and shallow groundwater (Army, 1998).

- **Pretreatment of CERCLA liquid wastes**: The Army constructed a treatment system to treat wastewater generated during investigations and remediation activities.

- **Chemical process-related activities**: This project consisted of the sampling, decontaminating, and dismantling of Army agent- and non-agent-related process equipment in the North and South Plants Complexes.

- **Remediation of Basin F liquids, sludges, and soil:** This extensive multi-phase project included removal of contaminated sludges and soil, as well as removal and incineration of waste liquids. The Basin F IRA is discussed in more detail below.

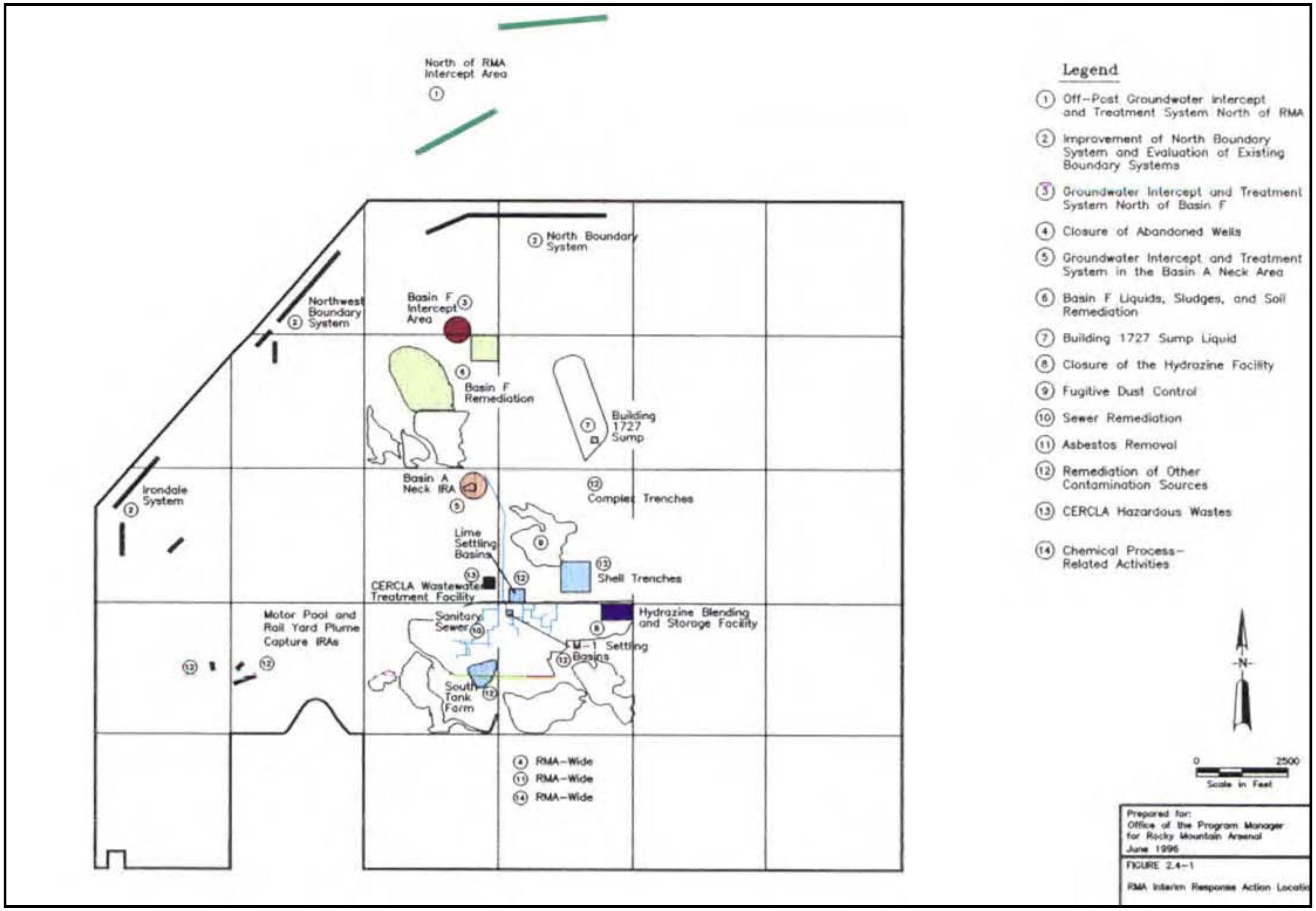

Figure 3.3. Location of interim response actions at the Arsenal.

Source: Foster Wheeler, 1996, Figure 2.4-1.

Basin F IRA

Basin F was by far the most extensive IRA at the Arsenal. The Army implemented this IRA in two phases. The first phase was designed to prevent further infiltration of Basin F waste liquids to the underlying groundwaters; to eliminate adverse effects to wildlife from the contaminated liquids, sludges, and soils in the basin; and to eliminate emissions of volatile chemicals from the basin. The second phase was destruction of the Basin F liquids (Army, 1988).

Phase I of the Basin F IRA (Army, 1988) included:

- Removal of liquid wastes from the basin to three lined steel storage tanks, each with a capacity of 1.33 million gallons, or approximately 4 million gallons total.
- Construction of a 16-acre, three-cell, lined waste pile within the southwest corner of the basin’s existing footprint, to contain materials excavated from the basin.
- Excavation, drying, and transport of the basin’s bituminous asphalt liner and overburden, along with underlying soils and crystallized or solidified sludges, to the waste pile. Soils and sludges were excavated to a depth of 6 inches to 6 ft below the asphalt liner, based on contamination data or visible discoloration.
- Recontouring of the remaining 77 acres in the basin’s footprint, covering with a clay cap, and revegetating the cap.
- Construction of a double-lined surface impoundment, ultimately divided into Pond A (3.77 acres) and Pond B (3.2 acres), to contain contaminated runoff, leachate, and decontamination water.

During implementation of the Phase I IRA in Basin F in the summer of 1988, Army contractors discovered a layer of crystallized salts and sludges ranging from two to almost five feet thick. Under this “false bottom” were an additional 3 to 4.5 million gallons of liquid waste, rendering the 4 million gallon holding tanks insufficient (Harding Lawson Associates, 1996). The crystalline layer added over 150,000 cubic yards of sludge to be excavated, on top of the 405,000 cubic yards originally estimated to be in Basin F (Army, 1988; Woodward-Clyde, 1990).

The excavation, air-drying, and transport of Basin F materials during the Phase I IRA created noxious odors that blew into the residential areas of Commerce City adjacent to the Arsenal. Over 200 odor complaints were lodged from July 1988 through March 1989. As a result, the Army abandoned the Phase I IRA plan in December 1988, ordering all remaining waste in the basin to be capped in place (Ebasco Services, 1989).

Basin F was capped in January 1989, after nearly 4 million gallons of liquid waste were pumped into tanks and another 7 million gallons were placed in Pond A. The excavated waste pile, which covered 16 acres with waste up to 58 ft high, was capped and seeded in the spring of 1989 (Harding Lawson Associates, 1996).

Phase II of the Basin F IRA began in May 1990. The Army selected submerged quench incineration to treat millions of gallons of stored Basin F liquid waste and other stored liquid wastes at the Arsenal. The incinerator operated from June 1993 through July 1995, destroying nearly 12 million gallons of Basin F liquids, Basin F waste pile leachate, wastewater from the HBSF, and decontamination liquids from closure activities (EPA and Army, 2000a). Approximately 16,500,000 gallons of metals-laden brine, a waste product of the incineration, were sent to Encycle in Texas for copper recovery and treatment prior to disposal (EPA and Army, 2000a).

3.2.2 Selected remedies

The contaminated areas within the On-Post OU covered approximately 3,000 acres and included 15 groundwater plumes and 798 structures (Foster Wheeler, 1996). On June 13, 1995, the Army, Shell, the USFWS, the EPA, and the State of Colorado signed the “Conceptual Agreement Among the Parties.” This agreement outlined the components of the remedies which were ultimately set forth in the RODs. The On-Post ROD (Foster Wheeler, 1996) was signed on June 11, 1996. The selected remedy included 31 cleanup projects for soil and structures and additional treatment of groundwater contamination. Upon completion of the site-wide remedy, much of the Arsenal will have been transferred to the USFWS to become a National Wildlife Refuge. Areas where remedial facilities exist, e.g., the treatment systems, landfills, and covered soils, will remain with the Army. The total estimated cost (in 1995 dollars) for the selected remedy was $2.2 billion (Foster Wheeler, 1996).

The On-Post remedy, as described by Foster Wheeler (1996), includes the following:

- Intercept and treat contaminated groundwater
- Construct a hazardous waste landfill in compliance with State law
- Construct an additional landfill in Basin A
- Demolish structures with no designated future use and dispose of the debris in either the on-post hazardous waste landfill or Basin A**,** depending upon the degree of contamination
- Contain contaminated soil in the hazardous waste landfill or under caps or covers, or treat, depending upon the type and degree of contamination
- Continue enforcement of institutional controls from the 1989 Federal Facilities Agreement, and restrict access to capped or covered areas and other remedial facilities.

Groundwater

The selected groundwater remedial alternative included continued operation of all existing groundwater treatment systems, including the North Boundary, Northwest Boundary, and Irondale containment systems, the Motor Pool, Rail Yard, and North of Basin F extraction systems, and the Basin A Neck treatment system (Figure 3.1). It also included construction of the Section 36 Bedrock Ridge extraction and piping system and development of an extended groundwater monitoring program. This program addressed possible upwelling of contaminated groundwater in the lakes and the hydraulic containment of a South Plants groundwater plume. In addition, the program included monitoring of the confined aquifer in South Plants, Basin A, and Basin F; and monitoring and assessing NDMA contamination (Foster Wheeler, 1996). NDMA was discovered in the early 1990s beyond the boundaries of the HBSF, including areas off-post. NDMA was not fully characterized in on and off-post groundwater until after the finalization of both RODs due to unacceptability high Army detection limits.

Other groundwater-related on-post remedial actions include the following:

- Fifty-one wells were identified as potential conduits from the unconfined flow system to the confined flow system and were sealed with grout plugs to prevent contaminated shallow groundwater from coming in contact with the deeper aquifers (Dames and Moore, 2000).
- In 1997, the North Boundary Containment System was upgraded with hydrogen peroxide/ultraviolet light treatment to reduce concentrations of NDMA that had been discovered in groundwater crossing the north boundary of the Arsenal (Morrison-Knudsen, 1998).
- In 1997, the Irondale boundary containment pumping system was shut off when the groundwater quality met the remediation goals. The Motor Pool extraction system was shut down in April 1998. The Irondale treatment plant shut down in July 2001 and was demolished in February 2002. The Rail Classification Yard treatment plant went online when the Irondale treatment system shut down (Washington Group International, 2003).
- In 2000, the Army shut down the North of Basin F extraction well because it was running dry. The well operated from 1990 to 2000, removing from groundwater 995 pounds of contaminants, primarily chloroform, DCPD, and DIMP (Washington Group International, 2005b).
- In 2002, the Army constructed two new extraction wells in Section 24 (South Channel Wells) between the former North of Basin F well and the North Boundary Containment System. The new wells used a new in-situ technology using Hydrogen Release

Compound. The project was completed September 2005 (Chadwick Consulting, 2004; RVO, 2005).

- In 2006, seven extraction wells were placed in the South Plants Tank Farm and four extraction wells were placed in the Lime Settling Basins to extract contaminated groundwater and transport the groundwater to the CERCLA wastewater treatment plant. These wells and the treatment plant are scheduled to be decommissioned in 2010 when the plant will no longer be considered necessary to deal with remedial action-related wastewater (Washington Group International, 2005a).

- In 2008, the Army will install up to five additional dewatering wells inside the Lime Basins barrier wall. This contaminated groundwater will be treated initially at the CERCLA wastewater plant, followed by treatment at the Basin A Neck plant after the CERCLA plant is decommissioned (Tetra Tech EC, 2007).

Soils

The Army selected the following alternative for soils (Figure 3.4; Foster Wheeler, 1996):

- Transporting approximately 1.5 million bank cubic yards (bcy) (a measure of in-place soil volume prior to disturbance and compaction) of soil and debris that exceeded acceptable biota risk levels to Basin A and the South Plants Central Processing Area.

- Engineered caps and covers over 1,100 acres of contaminated soil (including the contaminated soil described above) in the Basins, South Plants, North Plants, and Section 36 sites (including Shell and Army Complex Trenches).[1]

- Treating approximately 207,000 bcy of soil from Basin F, the Hex Pits, and the M1 Pits (all treatment remedies, with the exception of the M1 Pits, were subsequently abandoned as discussed below).

- Disposing of approximately 1.7 million cubic yards of soil and debris in the on-post hazardous waste landfill (Figure 3.5). One cell of the landfill is triple-lined for the disposal of “principal threat” wastes, or wastes containing contaminant concentrations over 1,000 times higher than acceptable risk levels. Principal threat waste from Basin F is being transported to the landfill. Principal threat waste from the Lime Settling Basins was originally slated for the hazardous waste landfill, but the remedy for the Lime Settling Basin was changed as discussed below.

1. Subsequent modifications to the remedy resulted in fewer acres of covered soils.

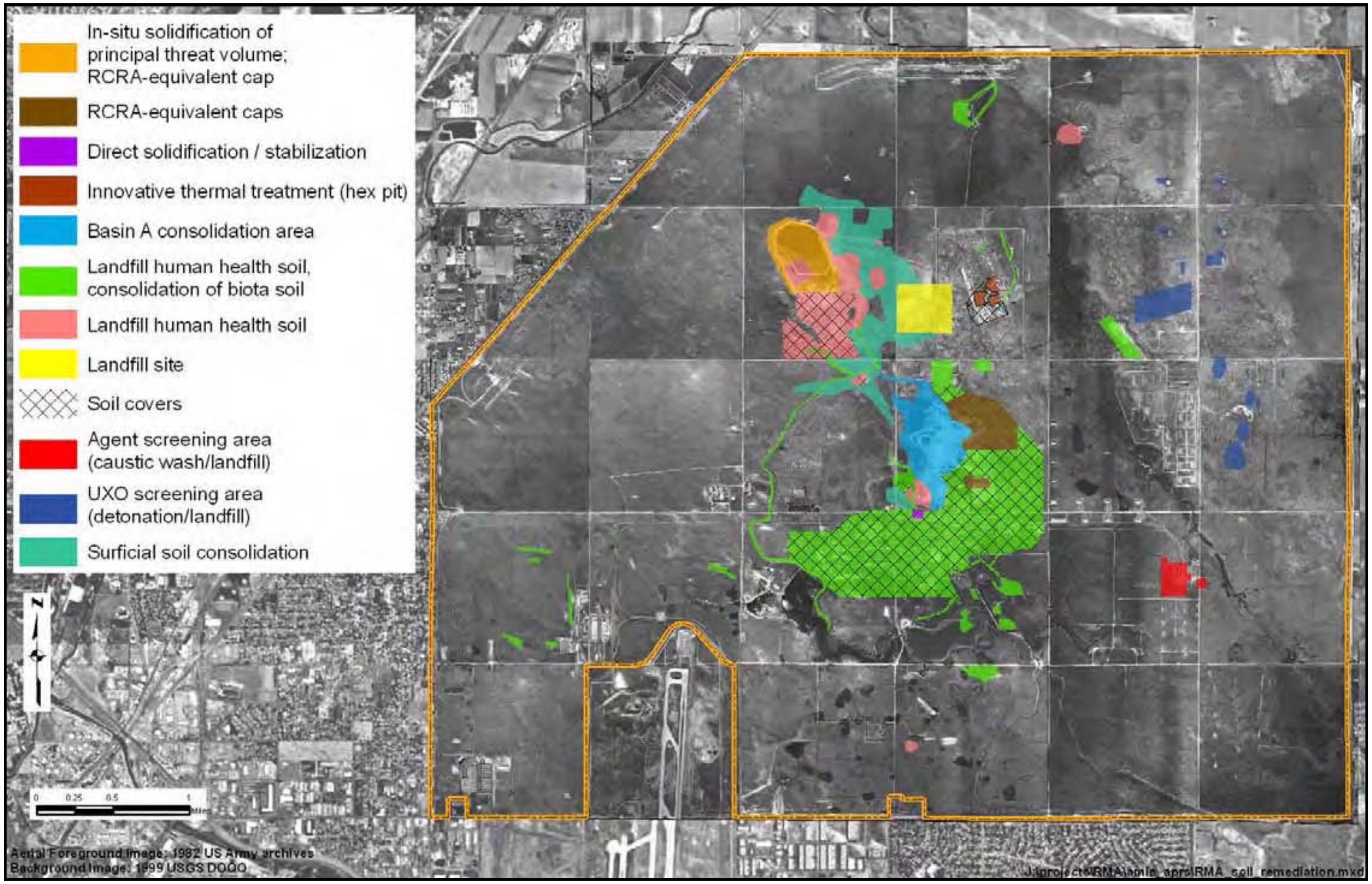

Figure 3.4. Selected soil remedies as depicted in the On-Post ROD. The actual soil remedies were revised as new information became available – see text. Highly contaminated soils were placed in the hazardous waste landfill (yellow) with less contaminated soils consolidated in Basin A (light blue).

Source: Foster Wheeler, 1996, Figure 9.3-1.

Figure 3.5. Construction of the lined on-post hazardous waste landfill for contaminated soils.

Source: Army archives.

Figure 3.4 shows the soil remedies that were selected in the ROD. Some of the soil remedies described in the ROD were later modified as new information became available during remedial design. Below is a brief review of large-scale soil remediation activities that occurred at selected areas of the site (see Figure 2.3 for locations of specific areas).

- South Plants soil that contained contaminant concentrations exceeding human health risk thresholds was excavated and landfilled. Approximately 330,000 bcy of soil was removed from the Central Processing Area, South Plants ditches, and from other South Plants areas. The Central Processing Area was excavated to a depth of 5 ft, and the remaining areas to a depth of 10 ft. An estimated 590,000 bcy of contaminated soils were left in place. These areas were capped with biota barriers below the surface to eliminate potential cap damage from, and prevent exposure to, burrowing animals. The caps covered 220,000 square yards in the central processing area, 120,000 square yards above the ditches, and 1.7 million square yards in the rest of the South Plants area (Foster Wheeler, 2002b).

- Basin A was converted into an unlined landfill primarily for debris and soils containing contaminant concentrations that exceeded risk thresholds for biota but not for human health. A one-foot-thick foundation layer was first placed over the existing contaminated soil in the 100-acre basin. Then, approximately 1.1 million bcy of contaminated soil, and 160,000 bcy of structural debris were placed in the basin. The contaminated soils and debris were capped with a biota barrier and soil, and the cap was revegetated (Foster Wheeler, 1996).

- North Plants soils were remediated by excavating and disposing in the hazardous waste landfill 43,000 bcy of soils containing contaminant concentrations exceeding human health risk thresholds. An additional 7,234 bcy of soils with contaminant concentrations exceeding risk thresholds for biota but not for human health were excavated and placed in Basin A (Tetra Tech FW, 2004a).

- From Basins B, C, and D, approximately 50,000 bcy of contaminated soils were removed and placed in the hazardous waste landfill. Approximately 170,000 bcy of soils exceeding thresholds for biota risk were removed and placed in Basin A (Tetra Tech FW, 2004b).

- For Basin F, the On-Post ROD distinguishes between the Basin F waste pile, a lined landfill of Basin F wastes created as part of the IRA; “Former Basin F,” from which some soils and sediments were removed and placed in the Basin F waste pile; and Basin F Exterior, the soils outside the basin which were contaminated by windblown dust and “enhanced evaporation” spraying. When the Basin F remedy is completed in 2008, approximately 165,000 bcy of soil from the upper 10 ft of Former Basin F, and an additional 600,000 bcy of soil from the Basin F waste pile, will have been removed and placed in the triple-lined cell of the hazardous waste landfill. In addition, over 168,000 bcy of highly contaminated soils from Basin F Exterior have been placed in the hazardous waste landfill, and 73,000 bcy of soils exceeding biota risk thresholds were placed in Basin A. Former Basin F and the former waste pile will be capped with a “Resource Conservation and Recovery Act (RCRA)-equivalent cover” consisting of a concrete biota barrier, 3.5 to 5 ft of soil, and vegetation (Army, 2007).

- The M1 Pits soil remedy included excavation and solidification/stabilization of approximately 26,000 bcy of contaminated materials exceeding principal threat or human health risk thresholds, with subsequent disposal into the hazardous waste landfill. The Pits were then backfilled with clean borrow soil (Foster Wheeler, 2000, 2002a).

- The Lime Settling Basin soils were originally slated for excavation and deposition in the hazardous waste landfill. However, because of increased soil volume and concerns about air emissions during excavation and drying, the remedy was changed. A ROD amendment in 2005 called for leaving the contaminated soil in place, with a vertical groundwater barrier surrounding the basin and a RCRA-equivalent cover. Approximately 89,450 bcy of contaminated soils and material were covered in the Lime Settling Basin (Tetra Tech EC, 2007).

- Groundwater barriers and RCRA-equivalent covers were also implemented at both the Army Complex Trenches and the Shell Section 36 Trenches. Approximately 532,000 bcy of contaminated soils and material were covered in the Army Complex Trenches, and 100,000 bcy of contaminated soils and material were covered in the Shell Section 36 Complex Trenches (Foster Wheeler, 1996).

- The Army tested thermal destruction of the contamination in the Hex Pits as required by the ROD. The pilot project failed. As a result, approximately 4,200 bcy of contaminated soil and materials were placed in the hazardous waste landfill. The Hex Pit site was then covered along with the rest of the South Plants area (Tetra Tech FW, 2004c).

- At the Sand Creek Lateral, 15,000 bcy of contaminated sediments were excavated from within 20 ft of its banks and disposed in the hazardous waste landfill. Also, 90,000 bcy of biota exceedence sediment went to Basin A (Foster Wheeler, 1996).

The above descriptions provide examples of some of the soil remediation conducted at the Arsenal. Large volumes of contaminated soils, exceeding both human health and biota risk thresholds, were also remediated from other areas of the Arsenal. The details of those actions are beyond the scope of this report, but the Trustees will take them into consideration when determining residual NRDs.

Deletion from the National Priorities List

All remedial actions required by the On-Post ROD must be completed before areas can be deleted from the NPL. In the past few years, several parcels have been deleted.

In January 2003, 940 acres of land in the western portion of the Arsenal, known as the Western Tier Parcel, were deleted from the NPL in accordance with the Refuge Act (EPA, 2003). A year later, 917 acres of that land were sold to Commerce City. Also in 2004, 5,053 acres of land along the perimeter of the Arsenal were deleted. From this parcel, 4,927 acres were transferred to the USFWS. In addition, 126 acres were transferred to local and state governments for road improvements. Finally, in 2006, 7,399 acres were deleted and transferred to the USFWS to be part of the National Wildlife Refuge (USFWS, 2006). Figure 3.6 shows the most recent map of the Arsenal after the deletions.

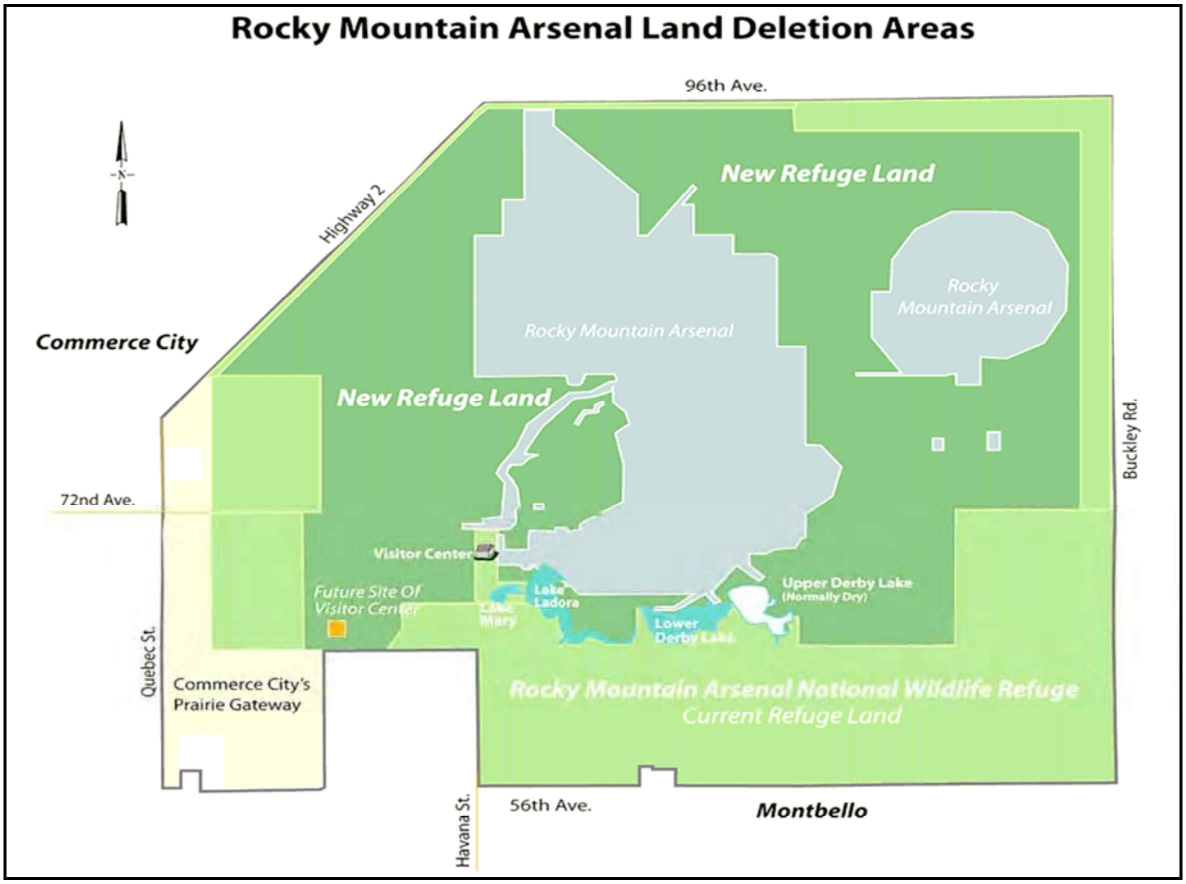

Figure 3.6. Arsenal deletions. The lighter green areas were transferred to USFWS in 2003 and 2004, and the darker green areas in 2006. The Army retains possession of areas in grey, as well as groundwater containment systems and other remedial facilities.

Source: USFWS, 2006.

3.2.3 Anticipated residual contamination following remediation

Soils

The final remedy for the Arsenal did not result in destruction or off-site disposal of contaminated soils. All soils managed as part of the final remedy were either (1) left in place and covered (700 acres), (2) excavated and placed in Basin A and the South Plants Central Processing Area (1.5 million bcy), or (3) disposed of in the on-site hazardous waste landfill (1.7 million bcy) (Foster Wheeler, 1996). Once the remedy is complete these soils will no longer pose a threat to wildlife or individuals visiting or working on the Arsenal because exposure pathways will be eliminated.

Post-remedy soils data do not indicate the presence of widespread areas of surface soil contamination at levels believed to create a risk to human health or biota using the risk thresholds adopted by the Army; however, these concentrations may be compared to different criteria in performing the injury assessment described in Chapter 6.

The highly contaminated soils left under caps and covers continue as sources of contamination to groundwater. These include soils at South Plants, the Army Complex Trenches, the Shell Section 36 Trenches, the Lime Settling Basins, and Basins A and F. The ROD required excavation of contaminated soils only to a depth of 5 ft in the South Plants Central Processing Area and 10 ft in the other South Plants areas and in Former Basin F. Elevated concentrations of volatile and semivolatile organics, pesticides and pesticide-related compounds, organosulfur compounds related to mustard production, arsenic, and mercury have been identified in the South Plants soils at depths greater than 10 ft (Ebasco Services et al., 1994). Many of these chemicals, especially pesticides, are adsorbed onto subsurface soil particles. These chemicals will slowly migrate to underlying groundwater. Although caps and covers at the surface will reduce infiltration of surface precipitation, the deeper soils saturated with liquid chemicals will continue to be a source of hazardous substances to groundwater for hundreds of years.

Groundwater

Because contamination is prevalent in subsurface soils and aquifer materials in the primary source areas at the Arsenal, the major groundwater plumes on the Arsenal property will remain for the foreseeable future. Groundwater treatment systems may reduce the total mass of contamination and the size of some of the chemical plumes, but the plumes will not be entirely eliminated. Some contaminants, particularly dieldrin, are difficult to capture in groundwater because they adsorb to aquifer materials and do not degrade quickly. These plumes in particular are unlikely to diminish significantly despite the ongoing capture and treatment systems on the Arsenal.

Surface water

Most of the contaminants of concern at the Arsenal are hydrophobic (i.e., they sorb to sediments rather than remain dissolved in surface water) and thus are not expected to be dissolved in surface water. Arsenal contaminants were not detected in recent on-post surface water samples from Lake Ladora, Lower Derby, Lake Mary, and First Creek at the North Bog (USGS, 2007).

3.3 Off-Post Actions

3.3.1 Interim response actions

The one off-post IRA was the Off-Post Groundwater Intercept and Treatment Systems (Figure 3.3), where the Army constructed alluvial groundwater intercept systems and a treatment plant north of the Arsenal to mitigate further downgradient migration of contaminated groundwater (Harding Lawson Associates, 1995; Foster Wheeler, 2006).

The types, locations, and configurations of groundwater extraction and recharge facilities were selected in this IRA based on the (1) interpreted location of contaminant plumes; (2) water-table configurations and aquifer parameters; (3) interpretation of paleochannel configuration and lithologies; (4) the location of First Creek and its possible effect on the extraction/recharge system; and (5) access, construction, and logistical considerations. For the First Creek Plume, the groundwater extraction and recharge system consisted of five extraction wells spaced 200 to 500 ft apart, aligned parallel to the plume axis, with one well located off the axis. Six trenches were constructed to recharge treated water. The groundwater extraction and recharge system constructed for the northern plume consisted of 12 extraction wells, placed approximately 200 ft apart and 24 recharge wells, placed approximately 100 ft apart. The extraction wells were placed perpendicular to the direction of groundwater flow. The recharge wells were placed parallel to and approximately 300 ft downgradient of the extraction well (Harding Lawson Associates, 1995).

3.3.2 Selected remedy

The Off-Post ROD was signed in December 1995 (Harding Lawson Associates, 1995).

Soils

Because the Army calculated that the risk from contaminated soils was within EPA's acceptable range (10^{-4} to 10^{-6} excess risk of cancer), it did not evaluate remedial alternatives for off-post soils. Nevertheless, 160 out of the 350 acres previously acquired by Shell were tilled in an effort to dilute surface soil concentrations with uncontaminated subsurface soils. This 160-acre area had the greatest number of detected compounds, and the highest concentrations of Arsenal contaminants in the Off-Post Study Area (Harding Lawson Associates, 1995). At the time of tilling, residents had already been relocated from the area.

Groundwater

The selected alternatives included the continued operation of the Boundary Containment Systems and the Off-Post Intercept and Treatment System, with improvements as necessary to meet Colorado water quality standards and other remediation goals prior to discharge to surface water or reinjection to groundwater. In addition, the Off-Post ROD prescribed long-term groundwater and surface water monitoring, site reviews, and institutional controls to prevent the use of the groundwater as a drinking water supply as long as it failed to meet remediation goals.

In addition, Shell and the Army funded the purchase of water rights and a distribution system for SACWSD to provide domestic water to some residents north of the Arsenal and south of the South Platte River. This action prevented these residents from consuming groundwater that would have put them at risk of adverse health effects from DIMP, a byproduct of Sarin nerve agent prevalent in shallow groundwater north of the Arsenal (Harding Lawson Associates, 1995). Figure 3.7 shows the widespread extent of detectable DIMP in groundwater north of the Arsenal in 1994 (USGS, 1997).

In August 2006, Amber Homes constructed a set of extraction wells within the north plume group, just upgradient of the existing north plume group well field (Chadwick Consulting, 2005). Groundwater extracted from these additional wells is treated at the off-post water treatment plant. This additional extraction and treatment was installed to speed cleanup of the groundwater underlying a large Amber Homes development project that is currently under construction.

3.3.3 Anticipated contaminant levels after remediation

Soils

The total mass of contaminants off-post is unchanged. By tilling the soil, however, the Army may have reduced concentrations in hot spots by mixing the more contaminated soil with less contaminated soil and diluting the concentrations. Adequate data characterizing residual contaminant concentrations on the Shell properties north of the Arsenal are not available.

Groundwater

The off-post groundwater intercept system continues to operate since the groundwater continues to exceed the remediation goals. However, the groundwater immediately upgradient of this system is treated water from the North Boundary Containment System that is reinjected to the aquifer after treatment. Unless contaminated groundwater bypasses the North Boundary Containment System, the off-post plume should continue to contract. It is not known how long the off-post plume will remain. An updated off-post plume map is expected this fall.

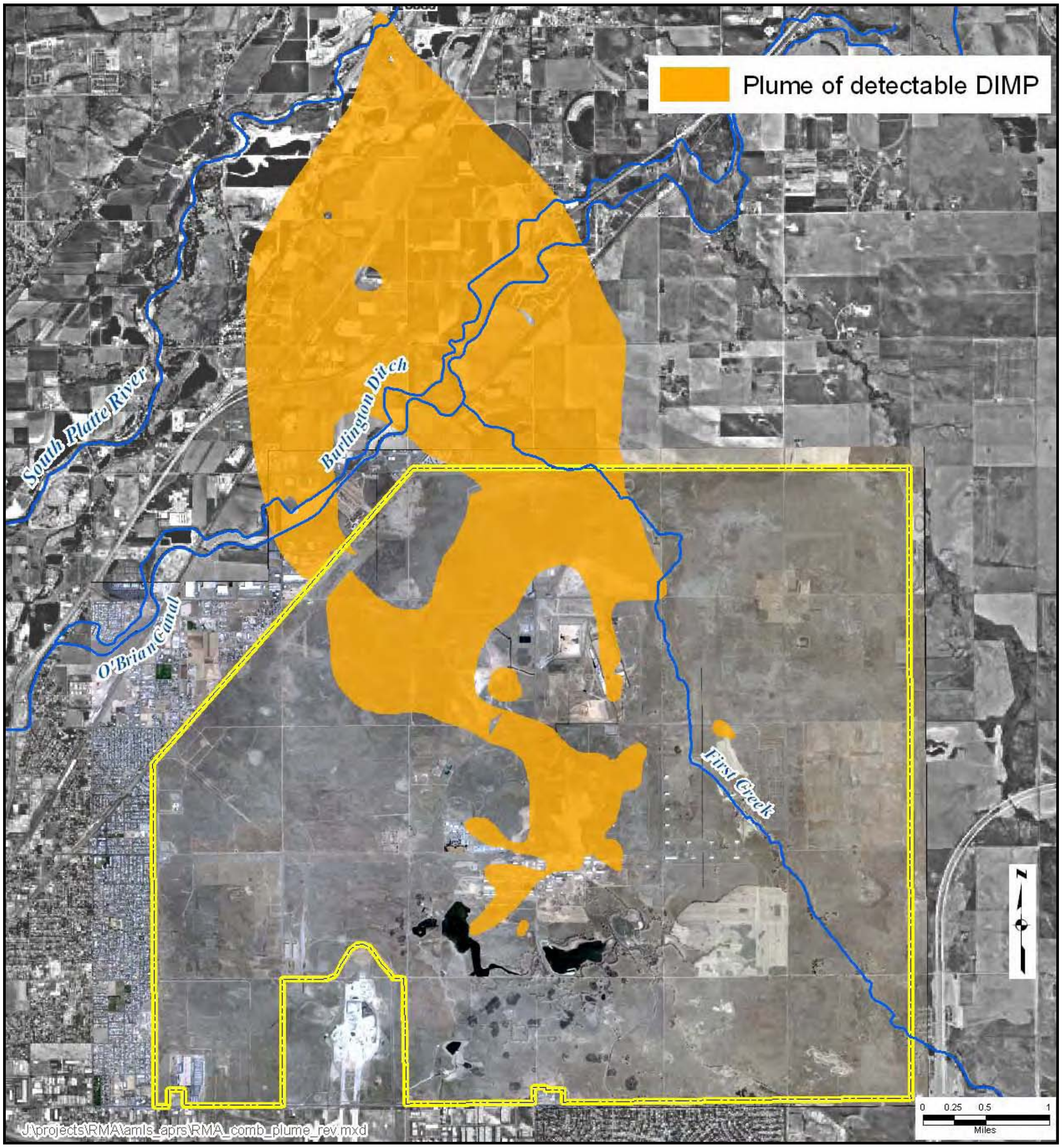

Figure 3.7. Extent of detectable DIMP in shallow groundwater in 1994, according to USGS (1997).

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4. Confirmation of Exposure

DOI regulations require Assessment Plans to confirm that:

> at least one of the natural resources identified as potentially injured in the preassessment screen has in fact been exposed to the released substance [43 CFR § 11.37(a)].

A natural resource has been exposed to hazardous substances if “all or part of [it] is, or has been, in physical contact with . . . a hazardous substance, or with media containing the . . . hazardous substance” [43 CFR § 11.14(q)]. The regulations also state that “whenever possible, exposure shall be confirmed using existing data” from previous studies of the assessment area [43 CFR § 11.37(b)(1)].

This chapter first discusses transport pathways, which are the routes or media through which hazardous substances are or were transported from the source of the release to the injured resource [43 CFR § 11.14 (dd)]. At the Arsenal, most of the hazardous substances were deposited on soils or in waste basins. Section 4.2 then confirms that soils, air, sediments, surface and groundwater, as well as aquatic and terrestrial biota and their supporting habitats, have been exposed to hazardous substances. The conclusions in this chapter rely solely on pre-existing data.

4.1 Contaminant Pathways

CERCLA allows Trustees to recover NRDs for injuries that have resulted from releases of hazardous substances. To make the link between release and injury, Trustees examine pathways through which hazardous substances travel. Pathways may be direct, such as a release into surface water causing injury to that water body. Pathways may also be indirect, such as a release to the ground surface that enters the bodies of earthworms, then into small birds that eat the worms, finally causing injury to the eagles that eat the small birds. In the second example, the soils, worms, and small birds are all pathway resources.

Pathways are determined using information about the nature and transport of the hazardous substances, and data documenting the presence of the hazardous substance in the pathway resource. As part of the assessment, the Trustees will use existing data to confirm that resources have been exposed to hazardous substances directly or through contaminant pathways. Specifically, to determine pathways of hazardous substances, the Trustees consider:

- The chemical and physical characteristics of the released hazardous substance when transported by natural processes or while present in natural media [43 CFR § 11.63(a)(1)(i)]

- The rate or mechanism of transport by natural processes of the released hazardous substance [43 CFR § 11.63(a)(1)(ii)]

- Combinations of pathways that, when viewed together, may transport the released hazardous substance to the resource [43 CFR § 11.63(a)(1)(iii)].

The pathway may be determined by either demonstrating the presence of the hazardous substance in sufficient concentrations in the pathway resource or by using a model that demonstrates that the conditions existed in the route and in the hazardous substance such that the route served as the pathway [43 CFR § 11.63(a)(2)]. Data presented in this chapter show sufficient concentrations in pathway resources. Also included is a discussion of a contaminant uptake model that demonstrates how hazardous substances in contaminated soils can injure wildlife resources. Chapter 6 discusses the model in more detail.

Figure 4.1 is a simplified diagram showing pathways by which hazardous substances are transported from hazardous substance sources at the Arsenal to natural resources of the State. In general, hazardous substances were released directly into surface water, sediments, and soil. Plants and invertebrates accumulate the hazardous substances. Biota that ingest these plants and invertebrates accumulate and sometimes "biomagnify" the hazardous substances, such that tissue concentrations (and adverse effects) of the hazardous substances can be greater in higher-level predators. To reach groundwater, hazardous substances in soil, surface water, and sediment either infiltrate the underlying unsaturated zone or are transferred to groundwater via a direct hydrologic connection. The following sections describe these pathways in more detail.

4.1.1 Groundwater pathways

In general, the sources of hazardous substances in groundwater are chemical spills on the ground or disposal into waste trenches, sewers, ditches, lagoons, and basins. Ebasco Services et al. (1989), contractors for the Army, describe the following mechanisms by which contaminants migrate from source areas to groundwater:

- Direct contact with source areas that are below the water table
- Percolation from soils downward through the unsaturated zone
- Hydraulic interchange with contaminated surface water/sediments
- Downward migration along an improperly constructed well bore.

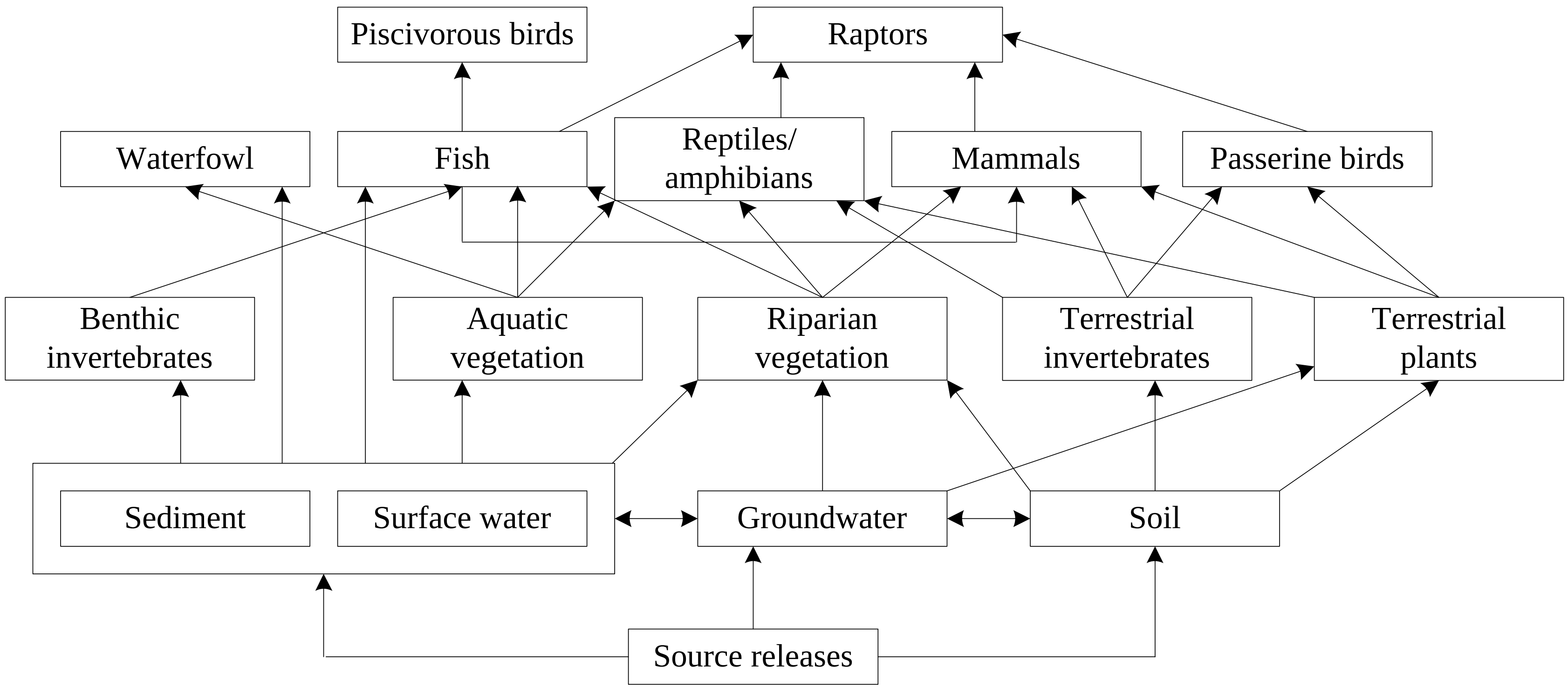

Figure 4.1. Simplified pathways by which hazardous substances are transported from the hazardous substances sources at the Arsenal to natural resources of the State. Pathways to air resources (not shown) include direct releases from source areas and soils.

Stormwater and snowmelt can dissolve contaminants in soils, carrying the contaminants downward through the unsaturated zone to the water table. In addition, large spills of liquid contaminants may percolate through the unsaturated zone and enter the groundwater undiluted. Direct percolation of contaminants may also occur from the waste disposal basins, sewers, and ditches that transported and accumulated industrial wastes at the site (Ebasco Services et al., 1989).

The RI Summary Report (Ebasco Services et al., 1992a) contains the following confirmations of the pathways to groundwater:

- "There are 14 basin and lagoon sites containing approximately 4.3 million bcy of contaminated material. Basins and lagoons formerly used for liquid waste disposal are among the most contaminated sites at the Arsenal . . . contaminant concentrations in soils at several of these sites exceed levels detected elsewhere at the Arsenal, and groundwater contaminant plumes are observed to originate below these sources. The continuous presence of contaminant occurrences throughout the unsaturated soil column below many of these sites supports the conclusion that the more contaminated basins and lagoons are sources of groundwater contamination" (Ebasco Services et al., 1992a, p. 2-12).

- "Like the disposal basins, burial trenches contain a wide variety of contaminants, most notably Army agent breakdown products, volatile organic compounds, and metals . . . These trenches have been identified as sources of pesticides, agent breakdown products, and volatile organics in groundwater" (Ebasco Services et al., 1992a, p. 2-14).

- "Leakage from faulty joints and fractures [of chemical sewers] historically allowed infiltration of wastewater into subsurface soils . . . Several portions of the chemical sewer are characterized by a wide variety of contaminants at moderate to high concentrations . . . [The chemical sewers] are significant because of their potential to contribute large volumes of contaminants to soil and groundwater" (Ebasco Services et al., 1992a, p. 2-19).

Pathways by which contaminants reach deeper aquifers are either through direct contact with the contaminated shallow aquifer, or through improper well construction. The Denver aquifer underlies the shallow aquifer; the upper Denver aquifer includes some weathered sandstone and fractures that have a direct hydraulic connection to the upper alluvium. Chapter 5 discusses the aquifers underlying the Arsenal and the extent of any downward migration of contamination in more detail.

For a period between 1962 and 1966, the Arsenal liquid wastes were directly injected into a well that was over 12,000 ft deep, thousands of feet below all usable deep aquifers underlying the Arsenal. This well was sealed in 1985 (Foster Wheeler, 1996). The direct injection of contaminants into this well served only as a pathway to Precambrian basement rock; these deep contaminants are unlikely to affect any of the usable overlying aquifers.

4.1.2 Surface water/sediment pathways

The banks, beds, and suspended sediments of water bodies are considered part of surface water resources, according to the DOI regulations [43 CFR § 11.14 (pp)].

Hazardous substances were released directly into surface water resources through chemical sewers and ditches, as well as indirectly via groundwater. Some example releases of hazardous substances to surface water resources include:

- Releases directly from the South Plants Complex to Lower Derby Lake and the Sand Creek Lateral (Ebasco Services et al., 1989)
- Releases from the North Plants Complex to ditches that could transport the hazardous substances to First Creek during storm events (Ebasco Services et al., 1989)
- Releases from the Arsenal wastewater treatment plant directly to First Creek (Ebasco Services et al., 1989)
- Releases from contaminated groundwater to First Creek at the northern boundary of the Arsenal (Harding Lawson Associates, 1992).

Hazardous substances may also have been transported to surface water resources from soils through aerial deposition from wind. Most of the contaminants of concern at the Arsenal are hydrophobic and thus are likely to sorb to sediment rather than remain dissolved in surface water.

4.1.3 Soil pathways

Most of the hazardous substances in soils were released directly onto the soils. Some of the waste disposal basins were under water at the time of contaminant disposal; the contaminated sediment in the basins subsequently became contaminated soil when the basins were dewatered.

4.1.4 Biota pathways

Exposure pathways include direct contact of biota with hazardous substances in air, soil, surface water, and sediments, and exposure through aquatic and terrestrial food web pathways (Figure 4.1). Biota comes in direct contact with hazardous substances through dermal contact, inhalation, and ingestion of contaminated soil, sediment, and surface water (Figure 4.1).

Organochlorine pesticides, including dieldrin and aldrin, are primary hazardous substances of concern at the Arsenal. These contaminants are used as an example to discuss the pathways by which these persistent pesticides affect biota. Many of the other hazardous substances released at the Arsenal follow similar pathways. The Trustees' assessment will include an analysis of these pathways for several of the primary contaminants of concern.

Soils and sediments often contain organic matter in which organochlorine pesticides accumulate. Plant roots, and to a lesser extent plant green tissues, also accumulate pesticides (International Programme on Chemical Safety, 1992). Higher trophic-level organisms, such as earthworms, insects, birds, or mammals, ingest contaminated soils, sediments, or lower-order biota (Figure 4.1). The transfer of contamination from media such as soils to animal tissue is called bioaccumulation.

Wildlife that ingest the bioaccumulated hazardous substances in prey may have higher contaminant tissue concentrations through the process of biomagnification, which is an increase in tissue residue concentration in predators compared to the concentration in prey (Schwarzenbach et al., 2003). Organochlorine pesticides become concentrated in fats and lipid membranes of soil-dwelling earthworms or sediment-dwelling aquatic macroinvertebrates (Beyer and Gish, 1980). These organisms can have very high body burdens of toxic compounds because they have direct contact with contaminated soils and are often insensitive to pesticide toxicity. Consumers of these worms accumulate and biomagnify the pesticides in fat and in fatty tissues such as the brain and liver, with organochlorine pesticide concentrations in these tissues increasing by 3–10 times the ingested concentrations (Klaassen, 2001). As a result, predatory birds and mammals at the top of the food web generally have the highest levels of persistent pesticides in their tissues and thus are the most likely species to be injured by releases of organochlorine pesticides and similar hazardous substances.

4.2 Confirmation of Exposure

Hazardous substances released from the Arsenal include organic contaminants and metals (see Chapter 2). The following sections present data confirming exposure of groundwater, surface water and sediment, geologic resources (soil), biota, and air resources to hazardous substances.

Additional natural resources beyond those discussed in this chapter may also be exposed to hazardous substances released from the Arsenal.

4.2.1 Groundwater

According to DOI regulations, groundwater resources are:

> water in a saturated zone or stratum beneath the surface of land or water and the rocks or sediments through which ground water moves. It includes ground water resources that meet the definition of drinking water supplies [43 CFR § 11.14 (t)].

Drinking water supplies are defined as:

> any raw or finished water sources that may be used by the public or by one or more individuals [43 CFR § 11.14 (o)].

The Arsenal RI confirms that contaminants released at the Arsenal have migrated into the groundwater. According to the RI Summary Report (Ebasco Services et al., 1992b, p. 2-12), the principal contaminants in groundwater are relatively mobile volatile compounds (volatile halogenated organics, volatile hydrocarbon compounds, and volatile aromatic organics) and less mobile contaminants, including organochlorine pesticides and arsenic.

The RI found exposure of both the alluvial aquifer and the Denver formation aquifer below it. Data evaluated in the Water RI were primarily collected during the third quarter of 1987 from a total of 296 alluvial wells and 176 wells screened in the Denver formation (Ebasco Services et al., 1989). Table 4.1 presents a summary of the results of these samples for selected contaminants. These concentrations are elevated above background conditions as described in the RI Summary Report (Ebasco Services et al., 1992b, Table RISR B.2-1). Chloroform and dieldrin were found in over 100 different alluvial wells. Chloroform was also found in over half of the wells in the unconfined Denver formation (Table 4.1).

Table 4.1. Summary of groundwater data from the Arsenal Water RI

Analyte	Detections	Wells sampled	Range (μg/L)	Median (μg/L)
Alluvium				
Dieldrin	102	262	0.062–3.48	0.245
Endrin	35	262	0.064–1.51	0.321
Oxathiane	37	230	1.66–68.6	6.610
Dithiane	47	232	1.25–498	19.300

Table 4.1. Summary of groundwater data from the Arsenal Water RI (cont.)

Analyte	Detections	Wells sampled	Range (µg/L)	Median (µg/L)
Chlorophenylmethyl sulfide	74	231	0.68–748	5.345
Chlorophenylmethyl sulfoxide	44	230	2.16–148	11.750
Chlorophenylmethyl sulfone	61	231	2.83–1,390	11.000
Benzene	31	296	1.49–25,000	3.250
Chlorobenzene	49	297	0.582–31,200	6.910
Chloroform	109	297	0.54–38,800	16.500
Methylene chloride	6	295	6.63–5,780	13.735
1,1,1-Trichloroethane	24	297	0.8–102	8.935
1,1-Dichloroethane	9	297	1.2–9.74	3.270
1,2-Dichloroethene	26	297	0.636–143	5.635
1,1-Dichloroethene	14	297	2.28–35.6	8.210
Trichloroethene	90	297	0.71–2,840	5.285
Tetrachloroethene	57	297	0.82–926	8.760
DBCP	55	264	0.146–278	0.586
DCPD	25	262	10.7–1,200	152.000
DIMP	102	259	11.9–12,100	203.500
Arsenic	66	257	2.56–315	5.270
Fluoride	179	259	1,000–13,400	2,290
Chloride	260 [sic]	259	25,700–6,230,000	187,000
Denver unconfined				
Dieldrin	13	35	0.103–8.92	0.221
Endrin	8	35	0.115–1.22	0.234
Oxathiane	10	35	1.79–1,950	8.100
Dithiane	9	35	3.16–7,760	34.800
Chlorophenylmethyl sulfide	10	35	3.38–94.3	7.845
Chlorophenylmethyl sulfoxide	7	35	8.97–392	47.300
Chlorophenylmethyl sulfone	9	35	3.28–520	16.500
Benzene	5	35	2.15–16,000	7.470
Chlorobenzene	3	35	1.74–1,170	55.900
Chloroform	19	35	1.99–16,500	24.500
Methylene chloride	3	32	11.7–7,340	58.900
1,1,1-Trichloroethane	0	35		
1,1-Dichloroethane	3	35	1.57–3.77	2.110
1,2-Dichloroethene	8	35	2.62–474	34.100

Table 4.1. Summary of groundwater data from the Arsenal Water RI (cont.)

Analyte	Detections	Wells sampled	Range (µg/L)	Median (µg/L)
1,1-Dichloroethene	2	35	1.70–4.41	3.055
Trichloroethene	11	35	1.2–175	4.380
Tetrachloroethene	13	35	2.31–184	15.500
DBCP	8	35	0.609–5.57	1.335
DCPD	6	35	16.6–256	128.700
DIMP	19	35	11.9–5,230	322.000
Arsenic	8	34	4.59–410	17.685
Fluoride	32	35	1,200–223,000	2,410
Chloride	35	35	5,730–28,200,000	246,000
Denver confined				
Dieldrin	10	140	> 0.05–1.23	0.123
Endrin	4	140	< 0.057–0.162	0.060
Oxathiane	5	140	3.09–49.5	12.800
Dithiane	6	140	1.68–263	56.500
Chlorophenylmethyl sulfide	5	140	1.25–4.09	2.50
Chlorophenylmethyl sulfoxide	0	140		
Chlorophenylmethyl sulfone	3	140	3.16–9.58	3.650
Benzene	27	141	1.63–73.8	4.500
Chlorobenzene	24	141	0.79–74.7	16.050
Chloroform	19	141	1.71–194	8.790
Methylene chloride	1	138	6.76	6.760
1,1,1-Trichloroethane	0	141		
1,1-Dichloroethane	2	141	5.21–8.82	7.015
1,2-Dichloroethene	2	141	0.97–2.61	1.759
1,1-Dichloroethene	0	141		
Trichloroethene	11	141	1.24–8.68	2.550
Tetrachloroethene	3	141	1.54–6.67	3.060
DBCP	5	141	0.191–0.779	0.370
DCPD	0	139		
DIMP	11	136	17.0–5,350	127.000
Arsenic	16	138	2.57–26.7	6.460
Fluoride	80	139	913–7,870	1,675
Chloride	132	139	5,520–7,290,000	57,450

µg/L = micrograms per liter.

Source: Ebasco Services et al., 1989, Table 4.2-5.

4.2.2 Surface water/sediment

According to DOI regulations, surface water resources are defined as:

> the waters of the United States, including the sediments suspended in water or lying on the bank, bed, or shoreline and sediments in or transported through coastal and marine areas [43 CFR § 11.14 (pp)].

The Arsenal RI confirmed that surface water, when present, was exposed to hazardous substances. Contamination is primarily introduced during precipitation and runoff events, which were not targeted for sampling (Ebasco Services et al., 1992b). Table 4.2 presents a summary of detected contaminants in samples collected from fall 1985 through fall 1987 (Ebasco Services et al., 1989).

Few analytes were detected in samples entering the Arsenal along the south boundary. Contaminants, including DBCP, aldrin, dieldrin, chloroform, and arsenic, were detected sporadically in samples collected along First Creek, the only continuous surface water drainage through the Arsenal (Ebasco Services et al., 1989, 1992b). Sewage treatment plant effluent discharged to First Creek contained detectable levels of the same contaminants. Very few constituents were detected in RI samples from Lower Derby Lake, Lake Ladora, and Lake Mary. However, historically, organochlorine pesticides, including dieldrin, were detected frequently in the lakes (Ebasco Services et al., 1989). When they contained water, Basin A and a pond near the South Plants Water Tower had elevated levels of organic contaminants, arsenic, and chloride (Table 4.2).

Sediment samples from 36 ditch, lake, and pond sites, including the three major lakes on the Arsenal (Upper and Lower Derby Lakes and Lake Ladora), were collected for the Arsenal RI (Ebasco Services et al., 1992b). These samples confirmed that sediment was exposed to hazardous substances. Table 4.3 presents a summary of selected contaminants in samples from these ditch, lake, and pond sites. Sediments contained elevated concentrations of pesticides, arsenic, and mercury. The highest contaminant concentrations were observed in samples collected from depths of less than 5 ft.

4.2.3 Soils

According to DOI regulations, geologic resources are defined as:

> those elements of the Earth's crust such as soils, sediments, rocks, and minerals, including petroleum and natural gas, that are not included in the definitions of ground and surface water resources [43 CFR § 11.14 (s)].

Table 4.2. Summary of surface water data from the Arsenal Water RI

Location description	Sample site	Detections	Number of samples	Analyte	Arithmetic mean (µg/L)[a]	Range (µg/L)
South boundary the Arsenal – water entering the Arsenal						
First Creek at East Boundary entering the Arsenal	08-001	1	10	Aldrin	0.200	< 0.070–0.20
Peoria Interceptor entering the Arsenal	11-001	1	5	Aldrin	0.200	< 0.070–0.200
		1	2	Benzothiazole	12.0[b]	< 1.70–2.93
		2	5	1,1,1-Trichloroethene	2.430	–
Havana Interceptor entering the Arsenal	11-002	1	2	Arsenic	2.56	–
Havana Pond outlet	11-003	1	1	Benzothiazole	2.06	–
South Boundary ditch – surface drainage entering the Arsenal	12-004	1	1	Arsenic	3.79	–
First Creek						
First Creek at 6th Avenue	05-001	1	2	Arsenic	3.79	–
Sewage Treatment Plant effluent to First Creek	24-001	1	5	DBCP	0.15	< 0.13–0.15
		5	5	Aldrin	0.853	0.080–2.98
		4	5	Dieldrin	0.332	< 0.060–0.936
		2	5	Chloroform	8.1	< 1.40–11.4
		2	2	Arsenic	33.7	–
First Creek at North boundary exiting the Arsenal	24-002	1	6	Aldrin	0.200	< 0.070–0.200
Ponds and lakes						
Lake Ladora and Lake Mary overflows	02-004	1	4	Chloroform	18.1	< 1.40–18.1
		1	1	Arsenic	10.5	–

Table 4.2. Summary of surface water data from the Arsenal Water RI (cont.)

Location description	Sample site	Detections	Number of samples	Analyte	Arithmetic mean (µg/L)[a]	Range (µg/L)
Other locations						
Pond south of South Plants Water Tower	01-002	2	4	DBCP	0.708	< 0.130–1.08
		1	4	Aldrin	0.530	< 0.083–0.530
		3	4	Dieldrin	0.571	< 0.055–0.913
		1	1	Benzothiazole	18.4	
		4	4	Chlorophenylmethyl sulfone	198.7	85.8–298
		3	4	Chlorophenylmethyl sulfoxide	89	< 4.20–204
		2	4	Chlorophenylmethyl sulfide	27.5	< 1.30–52.9
		2	4	Toluene	4.94	< 1.21–8.37
		1	4	Benzene	1.98	< 1.34–1.98
		1	1	Arsenic	11.5	–
Basin A – South Plants surface water/groundwater discharges	36-001	4	5	DBCP	3.8	> 2.2–140
		4	5	DCPD	32.8	< 9.31–70.2
		5	5	Methylisobutyl ketone	1,048	> 104–2,800
		2	4	Hexachlorocyclopentadiene	1.85	< 1.40–2.45
		2	5	Aldrin	2.03	< 0.700–3.07
		4	5	Dieldrin	6.7	3.75–> 20.8
		3	5	Endrin	2.70	< 1.04–5.16
		1	5	DIMP	32.0	< 10.5–32.0
		1	5	Dimethylmethyl phosphonate	17.3	< 15.2–17.3
		5	5	Chlorophenylmethyl sulfone	1,389	> 110–1,870
		5	5	Chlorophenylmethyl sulfoxide	58.3	26.0–87.1
		1	5	1,4-Dithiane	1.46[b]	< 1.10–< 1.59
		4	5	Toluene	25	< 12.1–41.2
		5	5	Benzene	53.8	1.72–176

Table 4.2. Summary of surface water data from the Arsenal Water RI (cont.)

Location description	Sample site	Detections	Number of samples	Analyte	Arithmetic mean (µg/L)[a]	Range (µg/L)
Basin A – South Plants surface water/groundwater discharges (cont.)		4	5	Ethylbenzene	54.0	< 1.28–102
		5	5	o- and p-xylenes	214	18.1–286
		5	5	Chloroform	432	188–641
		5	5	Chlorobenzene	1101	15.8–1,700
		1	5	Methylchloride	7.85	< 5.00–7.85
		5	5	Tetrachloroethylene	83.0	43.1–130
		4	5	Trans 1,2-Dichloroethene	4.38	< 1.10–5.70
		3	5	1,1,1-Trichloroethane	2.87	< 1.70–3.25
		4	5	1,1,2-Trichloroethane	4.01	< 1.00–5.93
		4	5	Trans 1,2-Dichloroethene	8.93	1.20–12.2
		5	5	Trichloroethene	45.5	19.7–62.0
Basin A central pool	36-003	1	2	Aldrin	4.98	4.98–< 8.30
		2	2	Dieldrin	45.6	43.3–47.9
		1	2	DIMP	27.6	< 10.5–27.6
		2	2	Chlorophenylmethyl sulfone	172	125–208
		1	2	1,4-Dithiane	3.57	< 1.10–3.57
		1	2	Chloroform	2.14	< 1.40–2.14
		1	2	Chlorobenzene	3.82	< 0.580–382
		1	2	1,1,2-Trichloroethane	7.85[b]	< 1.00–6.85
		1	2	1,2-Dichloroethane	6.14	< 0.610–6.14
		1	1	Arsenic	1,240	–
		1	1	Chloride	252,000	–

Note: Organic contaminants from samples collected fall 1985 to fall 1987; arsenic and chloride from samples collected in spring of 1987.

a. Arithmetic means are based solely on values above the certified reporting limit (CRL).
b. As reported in source. Mean outside of range.

Source: Ebasco Services et al., 1989, Table 4.1-3.

Table 4.3. Summary of ditch, lake, and pond sediment samples from the Arsenal Summary RI

Analyte	Detected	Samples	Detected concentration range (µg/g)	Median of detected samples (µg/g)
Volatile halogenated organics				
Methylene chloride	16	321	0.64–170	1.7
Tetrachloroethene	6	327	0.30–1.0	0.40
Volatile aromatic organics				
Toluene	4	322	0.30–4.0	0.70
Organophosphorous compounds – GB-agent related				
DIMP	23	687	0.19–5.0	3.2
DBCP	31	1,236	0.0068–0.65	0.036
Organochlorine pesticides				
Aldrin	164	1,041	0.0022–1,100	0.14
Chlordane	48	995	0.026–800	0.13
DDE	95	1,041	0.0012–6.6	0.014
DDT	67	1,041	0.0025–10.0	0.041
Dieldrin	263	1,041	0.0015–3,000	0.19
Endrin	96	1,041	0.0020–20	0.040
Isodrin	68	1,041	0.0013–500	0.024
Arsenic	139	601	2.5–190	7.5
Mercury	187	833	0.052–18	0.16

µg/g = micrograms per gram.

Source: Ebasco Services et al., 1992b, Table RISR A3.1-2.

The Arsenal RI identified 178 sites of soil contamination on the Arsenal (Ebasco Services et al., 1992b, p. A3-4). Contaminated soils were found in source areas, including basins and lagoons; ditches, lakes, ponds, and pits (discussed in Section 4.2.2); ordnance testing and disposal areas; solid waste burial sites; building, equipment, and storage sites; spill sites; sewer sites; surficial soils; and other isolated areas. Contamination was also found in soils collected from nonsource areas.

Soils collected from 14 disposal basins and lagoons[1] had the highest rate of detection and the greatest number of detected analytes (Table 4.4). Soils from waste trenches, buildings, equipment and storage sites, spill sites, and sewer sites also contained a wide range of analytes [not presented; see Ebasco Services et al. (1992b) for summary]. Soils collected from 12 ordnance-testing sites used for testing, burning, or disposal of incendiary devices and munitions were associated with elevated metals concentrations, but few organic contaminants (Table 4.5). Soils from 18 solid waste burial sites, which received contaminated solid and liquid waste materials, contained a wide range of contaminants at relatively high concentrations (Table 4.6). Contamination in surficial soils is characterized by widespread, low levels of contamination indicative of windblown transport of contaminants from poorly vegetated soils, such as the dewatered basins.

Table 4.4. Summary of soil samples from basin and lagoon sites. Selected analytes only.

Analyte	Detected	Samples	Detected concentration range (µg/g)	Median of detected samples (µg/g)
Volatile halogenated organics				
Chlorobenzene	9	508	0.34–5.0	1.7
Chloroform	22	538	0.12–70	1.8
Methylene chloride	58	422	0.27–6.7	1.0
Tetrachloroethene	19	537	0.20–40	2.8
Trichloroethene	4	538	0.14–1.0	0.51
Volatile hydrocarbons				
2,2-Oxybisethanol	36	36	0.6–8	2
2-Pentanone	9	9	1–20	10
Bicycloheptadiene	16	541	0.95–5,100	9.7
DCPD	58	1,079	0.35–22,000	24
Volatile aromatic organics				
Benzene	17	552	0.24–6.0	1.2
Ethylbenzene	11	552	0.14–9.3	1.6
m-Xylene	15	552	0.14–12	1.0
o- and p-Xylene	9	553	0.15–12	2.0
Toluene	18	550	0.13–1,000	0.95

1. These included Basins A, B, C, D, E, and F, and other smaller basins and lagoons.

Table 4.4. Summary of soil samples from basin and lagoon sites (cont.). Selected analytes only.

Analyte	Detected	Samples	Detected concentration range (µg/g)	Median of detected samples (µg/g)
Organosulfur compounds – mustard-agent related				
Chloroacetic acid	23	242	43–7,900	140
Dithiane	8	1,065	0.47–370	0.70
Thiodiglycol	11	242	6.0–120	25
Organosulfur compounds – herbicide related				
Chlorophenylmethyl sulfide	18	1,070	0.50–700	5.4
Chlorophenylmethyl sulfone	83	1,070	0.34–300	2.5
Chlorophenylmethyl sulfoxide	25	1,067	0.58–70	2.6
Dimethyldisulfide	3	760	2.0–70	10
Organophosphorous compounds – GB-agent related				
DIMP	119	968	0.12–10	1.3
Dimethylmethyl phosphonate	9	767	3.0–70	6.0
Isopropylmethyl phosphonic acid	34	234	4.6–3,700	39
Methylphosphonic acid	24	122	3.1–400	16
Phosphoric acid, triphenyl ester	33	33	1–20	10
DBCP	14	1,099	0.0061–20	0.019
Fluoroacetic acid	25	124	3.4–200	8.5
Polynuclear aromatic hydrocarbons (PAHs)				
Fluoranthene	4	4	4–8	5
Pyrene	3	3	1–100	4
Semivolatile halogenated organics				
Hexachlorocyclopentadiene	24	1,121	0.0040–2,600	0.018
Organochlorine pesticides				
Aldrin	169	1,249	0.0024–18,000	2.0
Chlordane	56	1,125	0.072–660	0.44
DDE	79	1,256	0.0014–28	0.038
DDT	56	1,251	0.0028–60	0.030
Dieldrin	401	1,247	0.0014–2,100	0.60
Endrin	217	1,246	0.0011–1,100	0.085
Isodrin	108	1,251	0.0014–11,000	1.5

Table 4.4. Summary of soil samples from basin and lagoon sites (cont.). Selected analytes only.

Analyte	Detected	Samples	Detected concentration range (µg/g)	Median of detected samples (µg/g)
Arsenic	531	1,253	2.4–110,000	12
Mercury	313	1,099	0.050–35,000	0.27
Metals				
Cadmium	163	1,047	0.63–3,900	1.3
Chromium	768	1,047	6.9–110	14
Copper	919	1,047	4.8–2,300	12
Lead	305	1,039	10–1,100	25
Zinc	969	1,047	11–910	44

Source: Ebasco Services et al., 1992b, Table RISR A3.1-1.

Table 4.5. Summary of soil samples from ordnance testing sites. Selected analytes only.

Analyte	Detected	Samples	Detected concentration range (µg/g)	Median of detected samples (µg/g)
Volatile hydrocarbons				
2,2-Oxybisethanol	12	12	0.6–2	0.9
Volatile aromatic organics				
Benzene	4	74	0.31–0.47	0.35
PAHs				
Methyl naphthalene	4	4	0.5–1	0.6
Organochlorine pesticides				
Dieldrin	3	315	0.0029–2.8	0.35
Arsenic	56	303	2.8–32	5.8
Mercury	43	310	0.061–0.32	0.084
Metals				
Cadmium	35	313	0.63–59	2.5
Chromium	261	313	7.8–56	17
Copper	306	314	5.0–340	17
Lead	89	313	11–3,400	28
Zinc	295	313	15–57,000	59

Source: Ebasco Services et al., 1992b, Table RISR A3.1-3.

Table 4.6. Summary of soil samples from solid waste disposal sites. Selected analytes only.

Analyte	Detected	Samples	Detected concentration range (µg/g)	Median of detected samples (µg/g)
Volatile halogenated organics				
1,1,1-Trichloroethane	8	510	0.50–3.0	0.79
Carbon tetrachloride	5	510	1.0–8.7	1.0
Chloroform	20	510	0.15–8.8	1.1
Methylene chloride	55	496	0.17–760	0.80
Tetrachloroethene	29	510	0.19–120	1.0
Trichloroethene	11	510	0.11–25	1.0
Volatile hydrocarbons				
Bicycloheptadiene	6	450	0.91–56	5.9
DCPD	15	1,196	1.0–450	37
Methylcyclohexane	4	4	5–100	40
Methylisobutyl ketone	3	459	8.8–20	14
Volatile aromatic organics				
Benzene	25	437	0.12–26	0.74
Ethylbenzene	11	437	0.43–9.9	0.98
m-Xylene	14	437	0.18–13	2.2
o- and p-Xylene	13	437	0.16–14	3.2
Toluene	24	437	0.12–370	3.9
Organosulfur compounds – mustard-agent related				
Dithiane	9	898	0.46–12	3.20
Organosulfur compounds – herbicide related				
Benzothiazole	3	125	1.9–130	60
Chlorophenylmethyl sulfide	10	899	0.50–100	2.7
Chlorophenylmethyl sulfone	8	899	0.68–20	1.3
Chlorophenylmethyl sulfoxide	6	899	1.0–4.2	3.6
Dimethyldisulfide	8	501	0.39–100	13
Organophosphorous compounds – GB-agent related				
DIMP	38	889	0.16–36	1.7
Dimethylmethyl phosphonate	5	569	0.19–0.65	0.2
Isopropylmethyl phosphonic acid	3	61	3.7–17	8.3
Methylphosphonic acid	5	61	2.8–220	3.9
DBCP	51	1,344	0.0076–670	0.15
Fluoroacetic acid	14	58	2.7–27	7.5

Table 4.6. Summary of soil samples from solid waste disposal sites (cont.). Selected analytes only.

Analyte	Detected	Samples	Detected concentration range (µg/g)	Median of detected samples (µg/g)
PAHs				
Pyrene	4	4	0.7–10	2
Semivolatile halogenated organics				
Hexachlorocyclopentadiene	33	871	0.0037–53,000	1.1
Organochlorine pesticides				
Aldrin	109	978	0.0033–670	1.0
Chlordane	46	861	0.18–100	2.0
DDE	32	979	0.0026–1.9	0.015
DDT	29	979	0.0033–26	0.022
Dieldrin	212	978	0.0021–360	0.83
Endrin	98	968	0.0018–370	0.38
Isodrin	62	979	0.0026–870	0.11
Arsenic	184	823	2.0–1,200	7.2
Mercury	219	980	0.053–40	0.17
Metals				
Cadmium	75	830	0.64–1,100	1.6
Chromium	590	829	5.9–4,900	13
Copper	699	829	4.8–27,000	11
Lead	224	829	10–7,100	20
Zinc	798	829	11–12,000	41

Source: Ebasco Services et al., 1992b, Table RISR A3.1-4.

4.2.4 Biota

According to DOI regulations, biological resources (biota) are defined as:

> those natural resources referred to in section 101(16) of CERCLA as fish and wildlife and other biota. Fish and wildlife include marine and freshwater aquatic and terrestrial species; game, nongame, and commercial species; and threatened, endangered, and State sensitive species. Other biota encompass shellfish, terrestrial and aquatic plants, and other living organisms not listed in this definition [43 CFR § 11.14 (f)].

The Arsenal RI confirmed that the contaminants released at the Arsenal followed the pathways described in Section 4.1.4 from sources to predators at the top of the food web. Samples were taken from key terrestrial and aquatic species collected from contaminated sites at the Arsenal and at on- and off-post control areas. Biota were grouped into trophic level categories to develop an analysis of biomagnification of contaminants. Terrestrial trophic levels and representative species were:

- **Primary producers**: morning glory, sunflower
- **Herbivores**: grasshopper, black-tailed prairie dog, cottontail, mule deer, mourning dove
- **Omnivores**: ring-necked pheasant, mallard, blue-winged teal, redhead, American coot
- **Carnivores**: American kestrel, red-tailed hawk, ferruginous hawk, golden eagle, great horned owl, coyote, badger
- **Detritivores**: earthworms.

Aquatic trophic levels and representative species were:

- **Primary producers**: aquatic macrophytes (plants)
- **Primary consumers**: plankton
- **Omnivores**: black bullhead
- **Primary carnivores**: bluegill
- **Top carnivores**: northern pike, largemouth bass.

The RI Summary Report (Ebasco Services et al., 1992b) found elevated concentrations of organochlorine pesticides in terrestrial primary producers (plants) and in wildlife tissue samples compared to plants and wildlife in control sites. Elevated concentrations generally correlated with locations of higher concentrations of organochlorine pesticides in the Arsenal soils. In addition, a pattern of increasing dieldrin biomagnification up the food web was evident. Table 4.7 presents a summary of contaminant concentrations in terrestrial trophic levels. Regarding terrestrial biota, Ebasco Services et al. (1992b) concluded the following:

- Dieldrin was detected in all trophic levels, with higher concentrations in higher trophic-level organisms due to biomagnification
- Aldrin was detected in herbivores
- Endrin was detected in terrestrial herbivores and omnivores
- DDE was detected in terrestrial omnivores and carnivores
- Arsenic was detected most frequently in detritivores and primary producers
- Mercury showed some tendency to bioaccumulate and was most often detected in omnivores.

Table 4.7. Summary of terrestrial biota samples from the Arsenal Summary RI

Analyte	Trophic level	Detections	Samples	Minimum (µg/g)[a]	Maximum (µg/g)	Mean[b]
Dieldrin	Producers	2	19	< 0.044	0.08	0.028
	Herbivores	39	94	< 0.031	56.3	1.2
	Omnivores	55	78	< 0.031	5.38	0.55
	Carnivores	43	73	< 0.031	27.7	2.3
	Detritivores	2	8	< 0.031	5.3	0.92
Aldrin	Herbivores	6	94	< 0.02	5.8	0.1
Endrin	Producers	1	20	< 0.04	0.19	0.029
	Herbivores	5	94	< 0.04	3.74	0.12
	Omnivores	2	73	< 0.04	0.14	0.022
	Detritivores	1	9	< 0.04	0.91	0.12
DDE	Omnivores	10	71	< 0.094	0.92	0.09
	Carnivores	10	72	< 0.094	5.5	0.59
Arsenic	Producers	5	20	< 0.025	4.5	0.46
	Herbivores	7	94	< 0.025	6.6	0.31
	Omnivores	3	59	< 0.025	1.82	0.17
	Detritivores	8	9	< 0.025	1.53	0.93
Mercury	Herbivores	5	94	< 0.05	0.36	0.034
	Omnivores	34	72	< 0.05	1.77	0.25
	Carnivores	16	78	< 0.05	0.405	0.058
	Detritivores	2	9	< 0.05	0.25	0.072

a. Minimum presented as CRL.
b. Mean calculated using one-half the CRL where analyte not detected. Therefore, in some cases where there are many non-detects, the mean will be lower than the minimum.

Source: Ebasco Services et al., 1992b, Table RISR A3.5-1.

Unlike terrestrial biota, a pattern of biomagnification was not generally observed in aquatic biota from the Arsenal lakes. Table 4.8 presents a summary of contaminant concentrations in aquatic trophic levels. Regarding aquatic biota, Ebasco Services et al. (1992b) concluded the following:

- Dieldrin was detected in omnivores, primary carnivores, and top carnivores.
- Aldrin and DDE were detected in top carnivores, in about 20–30% of samples.[2] DDE concentrations were higher than aldrin concentrations.
- Arsenic was detected in primary producers.[3]
- Mercury was detected in primary carnivores and top carnivores.

Table 4.8. Summary of aquatic biota samples from the Arsenal Summary RI

Analyte	Trophic level	Detections	Samples	Minimum (μg/g)[a]	Maximum (μg/g)	Mean[b]
Dieldrin	Omnivores	3	3	0.0851	0.209	0.14
	Top carnivores	16	21	< 0.031	0.161	0.082
	Primary carnivores	15	27	< 0.031	0.86	0.15
Aldrin	Top carnivores	5	27	< 0.020	0.0527	0.015
DDE	Omnivores	1	3	< 0.094	0.098	0.064
	Top carnivores	9	27	< 0.094	0.839	0.2
Arsenic	Primary consumers	1	9	< 0.025	0.432	0.16
	Producers	2	6	< 0.025	0.782	0.29
Mercury	Omnivores	1	3	< 0.050	0.0516	0.034
	Primary carnivores	11	21	< 0.050	0.137	0.058
	Top carnivores	23	27	< 0.050	0.550	0.22

a. Minimum presented as CRL.
b. Mean calculated using one-half the CRL where analyte not detected. Therefore, in some cases where there are many non-detects, the mean will be lower than the minimum.
Source: Ebasco Services et al., 1992b, Table RISR A3.5-2.

DDT and endrin were not detected in any off-post samples. Arsenic, mercury, and dieldrin were detected more frequently and in significantly higher concentrations in on-post specimens than in off-post specimens. DDE was detected more frequently in off-post samples.

2. DDE was also detected in one omnivore sample.

3. Arsenic was also detected in one primary consumer sample.

4.2.5 Air

According to DOI regulations, air resources are defined as:

> those naturally occurring constituents of the atmosphere, including those gasses essential for human, plant, and animal life [43 CFR § 11.14 (b)].

Monitoring data from 1988, the year of the Basin F IRA, indicate that air at the Arsenal has been exposed to hazardous substances and other contaminants (R.L. Stollar & Associates, 1990).

The annual mean concentrations of total suspended particulates (TSP) at 12 air monitoring stations throughout the Arsenal ranged from 40 to 97 micrograms per cubic meter (µg/m^3) (R.L. Stollar & Associates, 1990, p. 53). R.L. Stollar & Associates (1990, p. 53) reported that the secondary 24-hour ambient air quality standard for TSP of 150 µg/m^3 was violated 9 times and the primary standard of 260 µg/m^3 was exceeded twice. Elevated TSP concentrations were most likely influenced by remedial cleanup activity at Basin F because the monitoring stations with the highest TSP levels were immediately adjacent to or downwind of Basin F operations. A peak value of 591 µg/m^3 TSP was measured in the vicinity of Basin F during remediation (R.L. Stollar & Associates, 1990, p. 57). R.L. Stollar & Associates (1990) concluded that disturbances at Basin F, the Borrow Pit, and Basin A, and general TSP from the Denver metropolitan area, were contributing sources.

Metals above background conditions were also detected in air samples collected during remedial activities in 1988 (Table 4.9). Copper and zinc concentrations decreased with distance from Basin F. The highest arsenic concentrations were measured at a location between the South Plants and Basin A, suggesting that Basin A may have been a source of arsenic emissions. The highest average lead values were observed at sites along the western boundary of the Arsenal, and may be associated with Denver traffic activity. The highest cadmium concentrations were observed along the southern boundary of the Arsenal, and may either be associated with Basin A and the South Plants or various industrial activities to the south of the Arsenal (R.L. Stollar & Associates, 1990).

Monitoring in 1988 also identified volatile organic compounds (VOCs) in air samples (R.L. Stollar & Associates, 1990) (Table 4.9). Remedial activities at Basin F appeared to release bicycloheptadiene, methylene chloride, dimethyl disulfide, benzene, ethylbenzene, and toluene to air. Concentrations of these VOCs were highest in the vicinity of Basin F and decreased with distance. Chloroform was frequently identified in air samples collected from near the South Plants. The Denver urban area may also contribute to many of the VOCs identified in air samples at the Arsenal.

Table 4.9. Maximum detected concentrations in air samples collected at the Arsenal in 1988 (mg/m^3)

Analyte	Maximum long-term average	Maximum 24-hour
Metals		
Arsenic	0.0014	0.0041
Cadmium	0.0015	0.0253
Chromium	0.0175	0.2083
Copper	0.1158	0.5671
Lead	0.0270	0.0576
Zinc	0.0745	0.5054
VOCs		
1,1-Dichloroethane	0.139	0.271
1,2-Dichloroethane	0.135	0.358
Bicycloheptadiene	7.153	25.430
Benzene	10.532	44.293
Carbon tetrachloride	0.858	2.609
Methylene chloride	25.201	185.140
Chloroform	6.010	14.520
Chlorobenzene	0.472	2.527
DBCP	2.902	17.039
DCPD	5.392	29.38
Dimethyl disulfide	12.173	159.3
Ethylbenzene	2.394	13.041
Toluene	25.422	91.379
Methyl isobutyl ketone	0.099	0.326
Dimethylbenzene	0.349	0.755
Tetrachloroethene	5.607	23.500
Trichloroethene	0.497	5.500
Xylene	9.604	50.62
Semivolatile organic compounds (SVOCs)		
Aldrin	0.378	2.829
Chlordane	0.004	0.004
Dieldrin	0.397	2.296
Endrin	0.138	0.902
Isodrin	0.112	0.861
p,p-DDE	0.039	0.039
p,p-DDT	0.035	0.058
Parathion	0.131	0.210

mg/m^3 = milligrams per cubic meter.

Source: R.L. Stollar & Associates, 1990, Tables 4.2-15, 4.2-23, and 4.2-34.

SVOCs, including pesticides such as aldrin, endrin, and dieldrin, were also detected in air samples during monitoring at the Arsenal in 1988. The highest levels of pesticides were clustered around Basin F. Pesticide concentrations at locations more distant from Basin F were negligible.

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5. Injury to Groundwater Resources

Chapter 2 described sources of hazardous substances to groundwater; Chapter 3 described some of the remedial actions that have taken place to address groundwater contamination; and Chapter 4 confirmed that groundwater and the pathways to groundwater have been exposed to hazardous substances. This chapter addresses groundwater injury at the Arsenal.

Following a summary of conclusions, Section 5.1 describes the groundwater resources and discusses relevant Denver Basin statutes and regulations related to groundwater use in the Arsenal area. Section 5.2 provides a preliminary determination of groundwater injury, and Section 5.3 provides an example of how the injury would be quantified. Section 5.4 discusses potential lost use of the injured groundwater, and Section 5.5 discusses additional groundwater data analyses that the State anticipates conducting as part of the assessment. References cited in the text are listed at the end of the chapter.

Summary of conclusions

Available data on groundwater contamination indicate that groundwater resources have been injured by releases of hazardous substances from the Arsenal. In 1994, the year for which the most extensive data are available, an estimated 12,800 acre-feet of groundwater contained hazardous substances at concentrations exceeding injury thresholds. An additional volume of groundwater has been rendered unusable because of its proximity to the hazardous substance plume. Calculation of the appropriate size of the buffer surrounding the contaminant plume will be undertaken as part of the injury assessment, but based upon preliminary calculations, this buffer zone could nearly double the volume of water that is unavailable for use.

Institutional controls imposed by the Federal Facilities Agreement because of hazardous substance releases have precluded the use of approximately 52,550 acre-feet of alluvial groundwater as well as 1.89 million acre-feet of deep confined groundwater as a source of drinking water.

If shallow alluvial groundwater at the Arsenal were uncontaminated and available for municipal use, the likely annual yield would be at least equivalent to the calculated annual recharge of the aquifer. Calculation of the annual recharge at the Arsenal will be performed as part of the assessment. Based on estimates of water usage and readily available data, the Trustees calculated an example annual recharge of approximately 6,560 acre-feet over the entire Arsenal. This estimate is generally consistent with the volume of contaminated water captured at boundary systems annually, including approximately 3,200 acre-feet in 1997 and an average of 2,850 acre-feet between 1998 and 2001.

5.1 Description of Groundwater Resources

Groundwater is defined in the DOI's NRDA regulations as water in a saturated zone or stratum beneath the surface of land or water, as well as the rocks or sediments through which groundwater moves [43 CFR § 11.14(t)]. Colorado statutes define groundwater as any water not visible on the surface of the ground under natural conditions [CRS 37-90-103(19)].

There are two distinct groundwater resources in the Arsenal assessment area: shallow, unconfined groundwater in alluvium, and deeper, confined bedrock groundwater in the Denver, Arapahoe, and Laramie-Fox Hills Formations. The cross-section in Figure 5.1 illustrates the location of these deep aquifers. Colorado water law classifies the groundwater in the two systems as *tributary*, *nontributary*, and *not-nontributary* water. The shallow, unconfined aquifer is tributary water. The deeper, confined bedrock aquifers are nontributary water in some locations and not-nontributary water in other locations. The three water categories are described in Section 5.1.1. The shallow and deep aquifers are described in Sections 5.1.2 and 5.1.3, respectively.

5.1.1 Tributary, nontributary, and not-nontributary water

Tributary, nontributary, and not-nontributary are specifically defined in Colorado water law. Tributary groundwater is water that is hydrologically connected to a natural stream and thus is administered in conjunction with waters of a natural stream pursuant to the constitutional doctrine of prior appropriation. All groundwaters of the State are presumed to be tributary unless proven otherwise [*Ready Mix Concrete Co. v. Farmers Reservoir and Irrigation Co*., 115 P.3d 638, 643 (Colo. 2005)].

Nontributary groundwater is "groundwater, located outside the boundaries of any designated ground water basins . . . the withdrawal of which will not, within one hundred years, deplete the flow of a natural stream . . . at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal" [CRS § 37-90-103(10.5)]. Nontributary groundwater is exempt from the doctrine of prior appropriation [CRS § 37-90-102(2); CRS § 37-92-305(11)]. A landowner has the right to use 1% of the estimated volume of nontributary groundwater beneath his land each year.

Some confined groundwater in the Denver Basin is "not-nontributary," defined as "ground water located within those portions of the Dawson, Denver, Arapahoe, and Laramie-Fox Hill aquifers that are outside the boundaries of any designated groundwater basin . . . the withdrawal of which will, within one hundred years, deplete the flow of a natural stream . . . at an annual rate of greater than one tenth of one percent of the annual rate of withdrawal" [CRS § 37-90-103(10.7)]. Regulatory requirements applying to each of these groundwater classifications are described in Section 5.4.

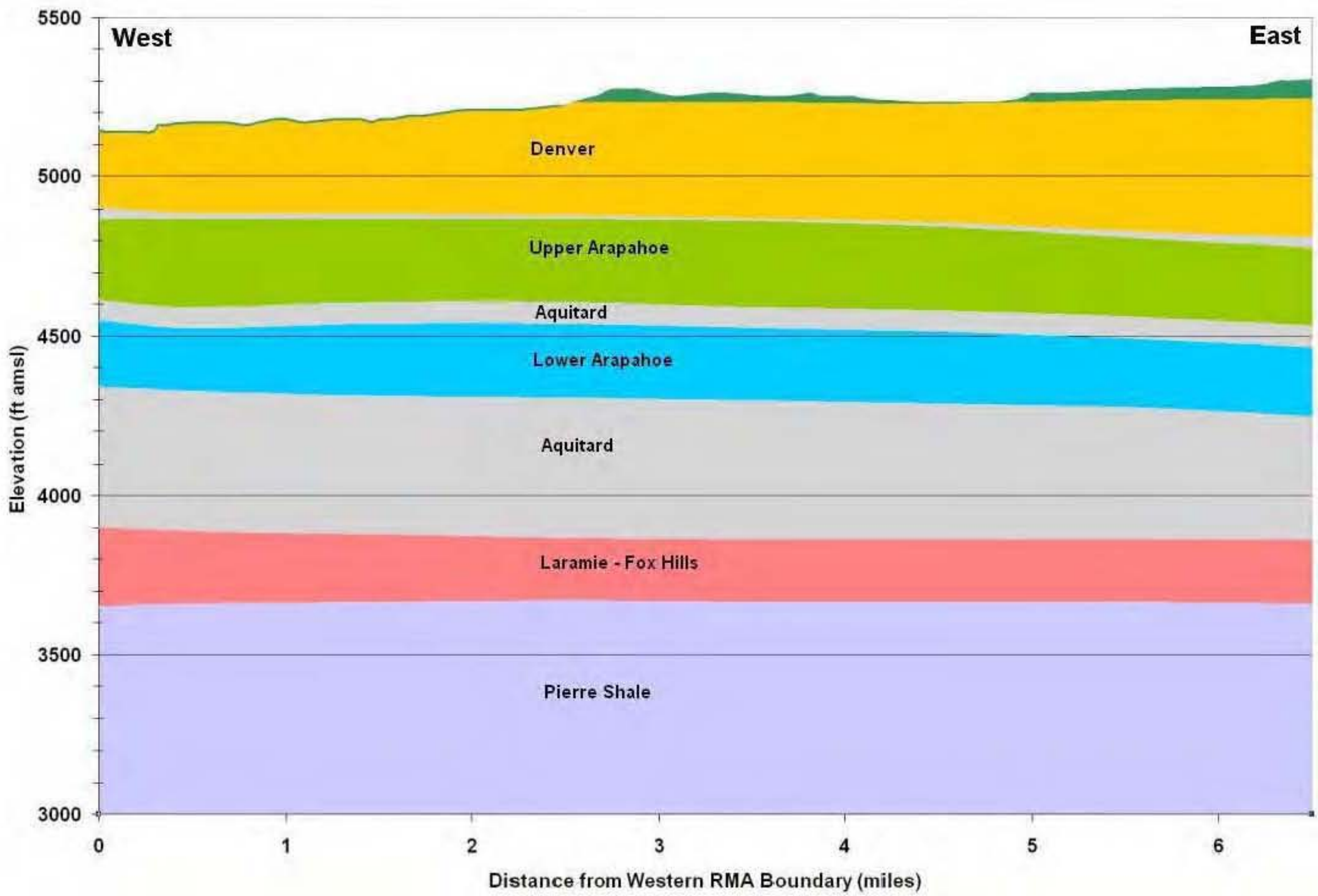

Figure 5.1. Cross-section, from west to east across the center of the site, showing the deep, confined aquifers underlying the Arsenal.

5.1.2 Shallow, unconfined aquifer

Unconsolidated alluvial (water deposited) and aeolian (wind-blown) deposits occupy most of the land surface area at the Arsenal. These unconsolidated deposits sit on the bedrock Denver formation and range in thickness from zero to 130 ft (Ebasco Services et al., 1989). Over much of the area, the unconsolidated deposits are between 20 and 50 ft thick. In some areas, however, unconsolidated materials are absent and rocks of the Denver formation crop out at the ground surface. In addition, several prominent paleochannels (ancient channels associated with a land surface from millions of years ago) have eroded into the rocks of the Denver formation and are filled with unconsolidated deposits between 50 and 130 ft thick.

The water table is typically found from 10 to 50 ft beneath the ground surface at the Arsenal (USGS, 1997b). The unconsolidated materials, together with weathered portions at the top of the Denver formation, comprise the unconfined flow system (UFS). In the preliminary analysis undertaken as part of this Assessment Plan, the shallow alluvial aquifer and the UFS are considered to be synonymous. The saturated thickness of the UFS varies from less than 10 ft to approximately 70 ft, with the greatest thicknesses associated with the buried alluvial paleochannels. The groundwater flow direction is generally to the north and west (Figure 5.2), following the orientation of the paleochannels.

Hydraulic conductivities (the rate at which water moves through the aquifer at a given gradient) for the unconsolidated materials range from less than 1 ft/day (for finer grained deposits) to greater than 1,000 ft/day (for gravels), with typical values on the order of 60 to 300 ft/day (Ebasco Services et al., 1989, Table 2.2). Adjacent weathered bedrock of the Denver formation is somewhat less permeable.

5.1.3 Confined bedrock aquifer

Immediately underlying and transitioning from the unconfined weathered portions of the Denver formation are the unweathered shales and sandstones of the Denver formation. Hydraulic conductivity in the sandstone is generally less than 1 ft/day. An extensive shale unit approximately 30 to 50 ft thick separates the Denver formation from the underlying Arapahoe formation (Black & Veatch et al., 2003). In the study area, a 50- to 100-foot thick shale separates the Arapahoe into an upper and lower zone (Figure 5.1).

Beneath the Arapahoe, approximately 400 ft of shale overlie the extensive permeable sandstone units of the Laramie-Fox Hills aquifer (Figure 5.1). Groundwater within these bedrock units is generally confined.

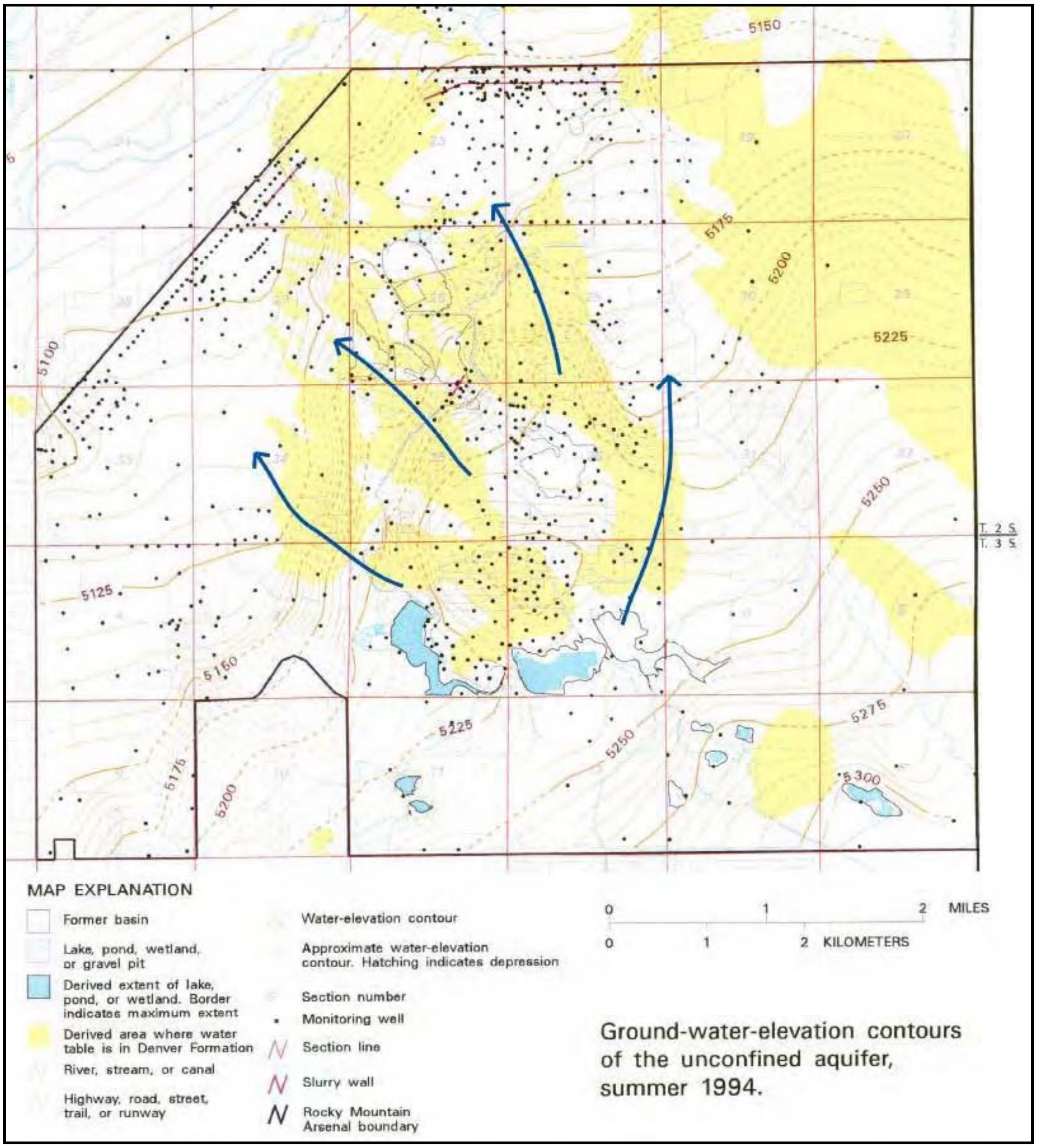

Figure 5.2. Shallow alluvial groundwater contours and flow direction (arrows added) in summer 1994, as depicted in USGS (1997b). Shaded areas indicate the absence of alluvial groundwater (i.e., the water table was in the underlying Denver bedrock formation).

The shale layers between these aquifers form aquitards that prevent vertical mixing of the groundwater. Most of the Denver formation has substantially lower transmissivity than the overlying alluvium. This tends to inhibit the shallow groundwater contamination from reaching water in the deeper formations. Despite their great depth, the extensive permeable layers within these bedrock formations have been tapped in several locations throughout the Denver Basin, particularly in the metropolitan communities south of Denver. Section 5.4 discusses groundwater uses in the vicinity of the Arsenal in more detail.

5.2 Injury Determination

This section presents a preliminary evaluation of groundwater injury, based on a review of groundwater data from 1994, the year in which the most extensive sampling was performed. Section 5.2.1 presents the contaminants of concern in groundwater, Section 5.2.2 contains the regulatory definitions of injury to groundwater, and Section 5.2.3 discusses baseline conditions. Section 5.2.4 shows exceedences of groundwater injury thresholds in 1994, and Section 5.2.5 describes institutional controls preventing the use of Arsenal groundwater as a drinking water source because of the releases of hazardous substances.

5.2.1 Contaminants of concern

Chapter 2 discusses the complete list of contaminants that have been detected at the site. Table 5.1 provides a list of contaminants selected by the Army as chemicals of concern in groundwater. These are chemicals that were targeted in various sampling programs (e.g., Harding Lawson Associates, 1995, Tables 6.1 to 6.4; Foster Wheeler Environmental, 1996, Tables 9.1-1 to 9.1-4).

Table 5.1. Contaminants of concern in the Arsenal groundwater

Contaminant	Hazardous substance[a]	Contaminant	Hazardous substance[a]
Aldrin	Yes	Carbon tetrachloride	Yes
Allyl chloride	Yes	Chlordane	Yes
Arsenic	Yes	Chloride	No
Atrazine	No	Chlorobenzene	Yes
Benzene	Yes	Chloroform	Yes
Benzothiazole	No	Chlorophenylmethyl sulfide	Yes
Cadmium	Yes	Chlorophenylmethyl sulfone	No

Table 5.1. Contaminants of concern in the Arsenal groundwater (cont.)

Contaminant	Hazardous substance[a]	Contaminant	Hazardous substance[a]
Chlorophenylmethyl sulfoxide	No	Lead	Yes
Copper	Yes	Malathion	Yes
Cyanazine (Bladex)	No	Manganese	Yes
DBCP	Yes	Mercury	Yes
DCPD	Yes	Methyl parathion	Yes
DDE	Yes	Methylene chloride	Yes
DDT	Yes	Methylphosphonic acid	No
Dichlorobenzene	Yes	Mustard	No
1,3- dichlorobenzene	Yes	Nitrate (as N)	No
1,2, dichloroethane	Yes	n-Nitrosodimethylamine	Yes
1,2- dichloroethylene	Yes	1,4-oxathiane	No
1,1- dichloroethylene	Yes	Oxychlordane	No
Dieldrin	Yes	Parathion	No
Dimethyl methyl phosphonate	No	Polychlorinated biphenyls	Yes
DIMP	No	Selenium	Yes
Dithiane	No	Sulfate	No[b]
Endrin	Yes	TCE	Yes
Ethylbenzene	Yes	Tetrachloroethylene (PCE)	Yes
Fluoride	No	Thiodiglycol	No
Heptachlor	Yes	Toluene	Yes
Heptachlor epoxide	Yes	1,1,1-trichloroethane	Yes
Hexachlorobicycloheptadiene	No	Xylenes (total)	Yes
Isodrin	Yes	Zinc	Yes

a. As listed in Table 302.4 at 40 CFR § 302.4, Ebasco Services et al., 1988, and/or DOJ, 1986.
b. Sulfate that is a degradation product of sulfuric acid is treated as a hazardous substance pursuant to 43 CFR § 11.14 (v).

Sources: Ebasco Services et al., 1988; State of Colorado, 2007.

5.2.2 Definition of injury

"Injury" is defined as "a measurable adverse change, either long- or short-term, in the chemical or physical quality or the viability of a natural resource resulting either directly or indirectly from exposure to a release of a hazardous substance, or exposure to a product of reactions resulting from the release of a hazardous substance" [43 CFR § 11.14(v)]. The relevant injury definitions for groundwater resources include the following:

- Concentrations and duration of hazardous substances in excess of drinking water standards as established by Sections 1411-1416 of the Safe Drinking Water Act (SDWA), or by other federal or state laws or regulations that establish such standards for drinking water, in groundwater that was potable before the release [43 CFR § 11.62(c)(1)(i)]

- Concentrations and duration of hazardous substances sufficient to have caused injury to other resources when exposed to groundwater [43 CFR § 11.62(c)(1)(iv)].

Groundwater may also be injured when the releases of hazardous substances require institutional controls that prevent the future use of the groundwater, constituting an unavoidable injury as a result of a response action [43 CFR § 11.15(a)(1)]. Such institutional controls were imposed on the Arsenal property with the signing of the Federal Facilities Agreement in 1989 and on Shell properties north of the Arsenal as required in the Off-Post ROD (Harding Lawson Associates, 1995).

Groundwater resources include both "water in a saturated zone or stratum beneath the surface of land or water" and "the rocks or sediments through which ground water moves" [43 CFR § 11.14(t)]. There are no promulgated standards that define injury to the aquifer materials. Aquifer materials are likely to be injured if the water moving through the aquifer materials contains contaminant concentrations above groundwater injury thresholds. Most of the contaminants of concern at the Arsenal are hydrophobic and tend to sorb to aquifer materials rather than dissolve into the groundwater. Thus, if the contaminants are in groundwater samples, they are likely sorbed to the aquifer materials as well.

Relevant injury thresholds for groundwater include concentrations in excess of Sections 1411-1416 of the SDWA and Colorado groundwater and drinking water standards [5 CCR 1002-41; 5 CCR 1003-1]. Table 5.2 presents maximum contaminant levels (MCLs) from the SDWA and groundwater standards from 5 CCR 1002-41 for selected contaminants of concern at the Arsenal. Exceedences of these standards indicate injury to groundwater. Table 5.2 also presents containment system remediation goals (CSRGs), which are the target cleanup concentrations for the groundwater containment systems at the Arsenal (see Chapter 3) and in some instances are lower than the relevant standards.

Table 5.2. State and federal groundwater standards for selected contaminants of concern

Contaminant of concern	CSRG[a] (µg/L)	CO standard[b] (µg/L)	MCL[c] (µg/L)
Aldrin	0.002	0.0021	–
Arsenic	2.35	50	10
Benzene	3	5	5
Carbon tetrachloride	0.3	5	5
Chlordane	0.03	2	2
Chloride	250,000	250,000	–
Chloroform	6	6[d]	–
DBCP	0.2	0.2	0.2
1,2-dichloroethane	0.4	5	5
Dieldrin	0.002	0.002	–
DIMP	8	8	–
Fluoride	2,000	4,000	4,000
Methylene chloride	5	5	–
Sulfate	540,000	250,000	–
Tetrachloroethylene (PCE)	5	5	5
TCE	3	5	5

a. CSRG for the Arsenal containment systems.
b. Colorado groundwater standards at 5 CCR 1002-41.
c. MCLs from the SDWA.
d. The current Colorado chloroform standard of 3.5 µg/L was calculated incorrectly and is expected to change back to 6.0 µg/L (Ed LaRock, CDPHE, personal communication, October 11, 2007).

5.2.3 Baseline conditions

Baseline conditions are the conditions that would have existed had the releases of hazardous substances not occurred [43 CFR § 11.14 (e)]. Groundwater at the Arsenal under baseline conditions is potable, with an exception noted below.

Groundwater at the Arsenal generally moves from southeast to northwest (see Figure 5.2). Groundwater upgradient of the hazardous substance sources at the Arsenal does not exceed groundwater criteria and therefore is potable (Ebasco Services et al., 1989; USGS, 1997a, 1997b). The one exception is groundwater in the UFS in the southwest corner of the Arsenal. A plume of TCE emanates from sources south of the Arsenal and flows north/northwest toward Irondale and the west side of the Arsenal (Figure 5.3). This plume will be excluded from the injury and damage analysis. A narrower plume of TCE and other contaminants originates from the Motor Pool and Rail Classification Yards in this southwest portion of the site (Ebasco Services et al., 1989, p. 4-45); this Arsenal plume is evident on the TCE map (Figure 5.3). The TCE plume downgradient from the Motor Pool and Rail Yards will be included in the injury analysis.

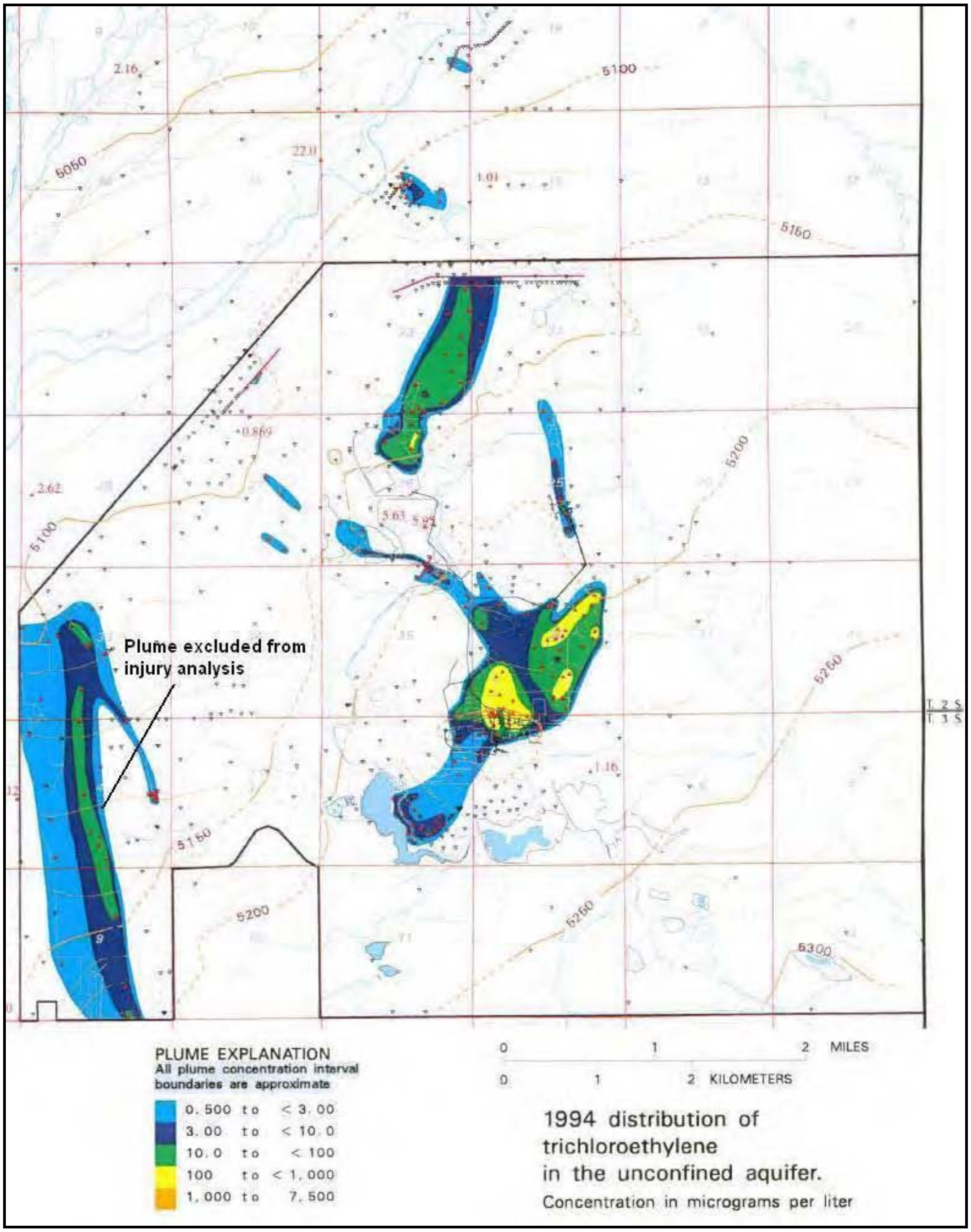

Figure 5.3. TCE plume in water year 1994, as depicted in USGS (1997b). The plume originating south of the Arsenal is excluded in the evaluation of groundwater injuries and damages.

5.2.4 Exceedences of groundwater standards

The U.S. Geological Survey (USGS, 1997a, 1997b) conducted a comprehensive study of groundwater contamination at the Arsenal in water year 1994 (October 1993 through September 1994) and mapped groundwater plumes of various contaminants that exceeded CSRGs (Table 5.2). While CSRGs are not always identical to regulatory injury thresholds, they provide a preliminary indication of contamination. Figures 5.4 through 5.8 present the contaminant plumes that USGS contoured for TCE, benzene, chloroform, DBCP, and dieldrin, respectively. These plumes show the estimated extent of contamination from these five contaminants in water year 1994, and provide an approximation of the extent of injury based on exceedences of Colorado and EPA injury thresholds for these selected hazardous substances (Table 5.2).

Figures 5.4 through 5.8 confirm that groundwater resources have been exposed to hazardous substances at the Arsenal, and that hazardous substances were present at concentrations far exceeding injury thresholds in water year 1994. Other contaminants exceeded injury thresholds as well, but the spatial extent of those plumes was not included in this analysis.

5.2.5 Institutional controls

Institutional controls were placed on the Arsenal and Shell properties to prevent the use of groundwater as a drinking water source. According to the 1989 Federal Facilities Agreement [§ 44.2(c)], "to assure continued protection of human health and the environment . . . the use of groundwater located under, or surface water located on, the Arsenal as a source of potable water shall be prohibited."

In the Off-Post ROD (Harding Lawson Associates, 1995, Appendix B), to "eliminate the potential exposure to contaminated groundwater under the Shell Oil Company properties," Shell was required to place covenants on its properties that:

> (i) preclude drilling of all groundwater wells into any alluvial aquifer water under Shell's property for future use until such groundwater no longer contains contamination in exceedence of groundwater containment system remediation goals established in the ROD, and (ii) preclude any use of any deeper aquifer water (e.g., Denver Basin) containing contamination in exceedence of groundwater containment system remediation goals established in the ROD.

Figure 5.9 shows the area covered by institutional controls. The unrestricted use of this groundwater has been lost to the State due to releases of hazardous substances.

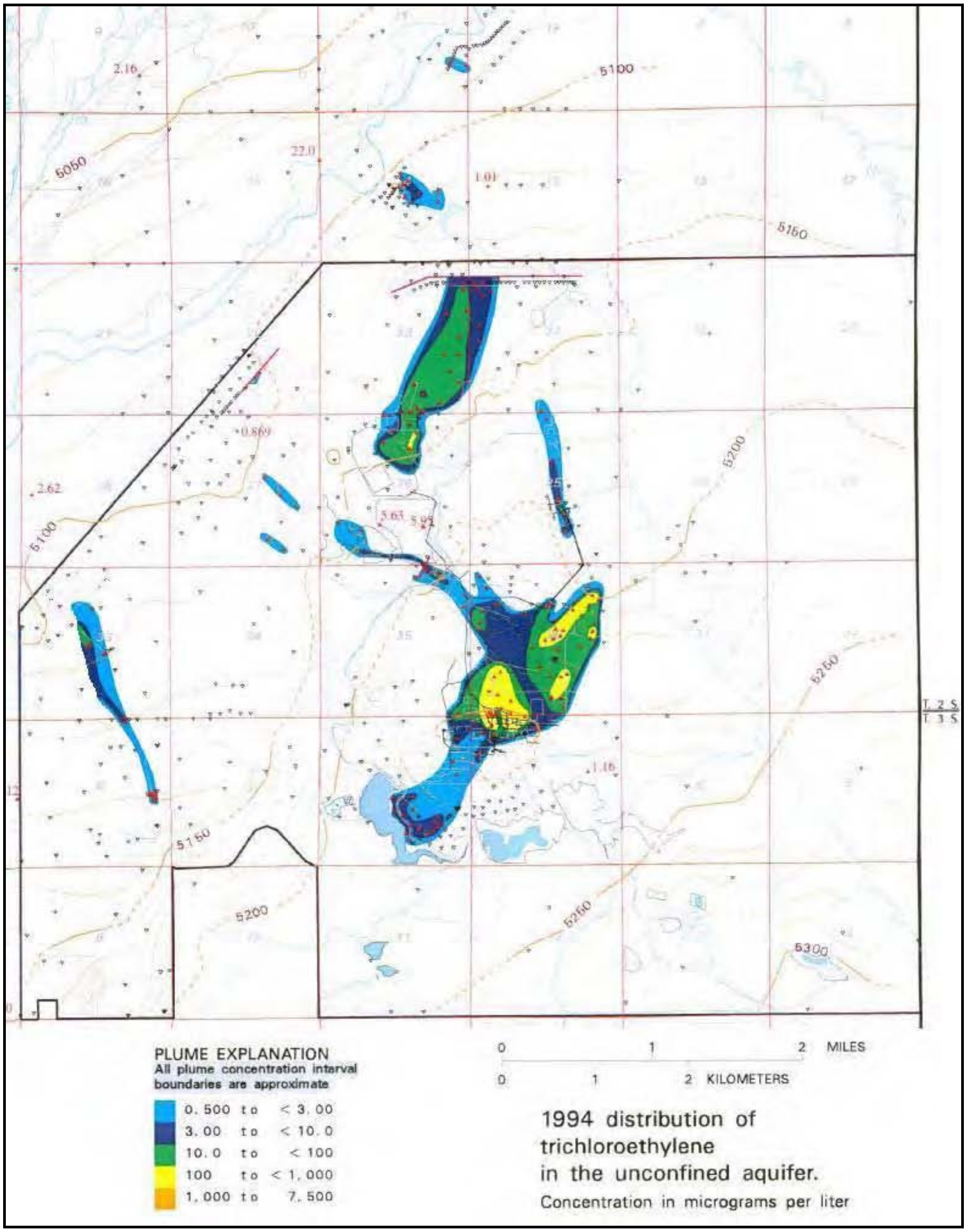

Figure 5.4. TCE plume in the unconfined aquifer in water year 1994, modified from USGS (1997b). The Colorado injury threshold for TCE is 5 µg/L; shaded areas, except light blue, have TCE concentrations exceeding 3 µg/L and are likely to be injured. The part of the TCE plume in the southwest corner that originates offsite (Figure 5.3) is not included in this evaluation of injuries and has thus been removed from this figure.

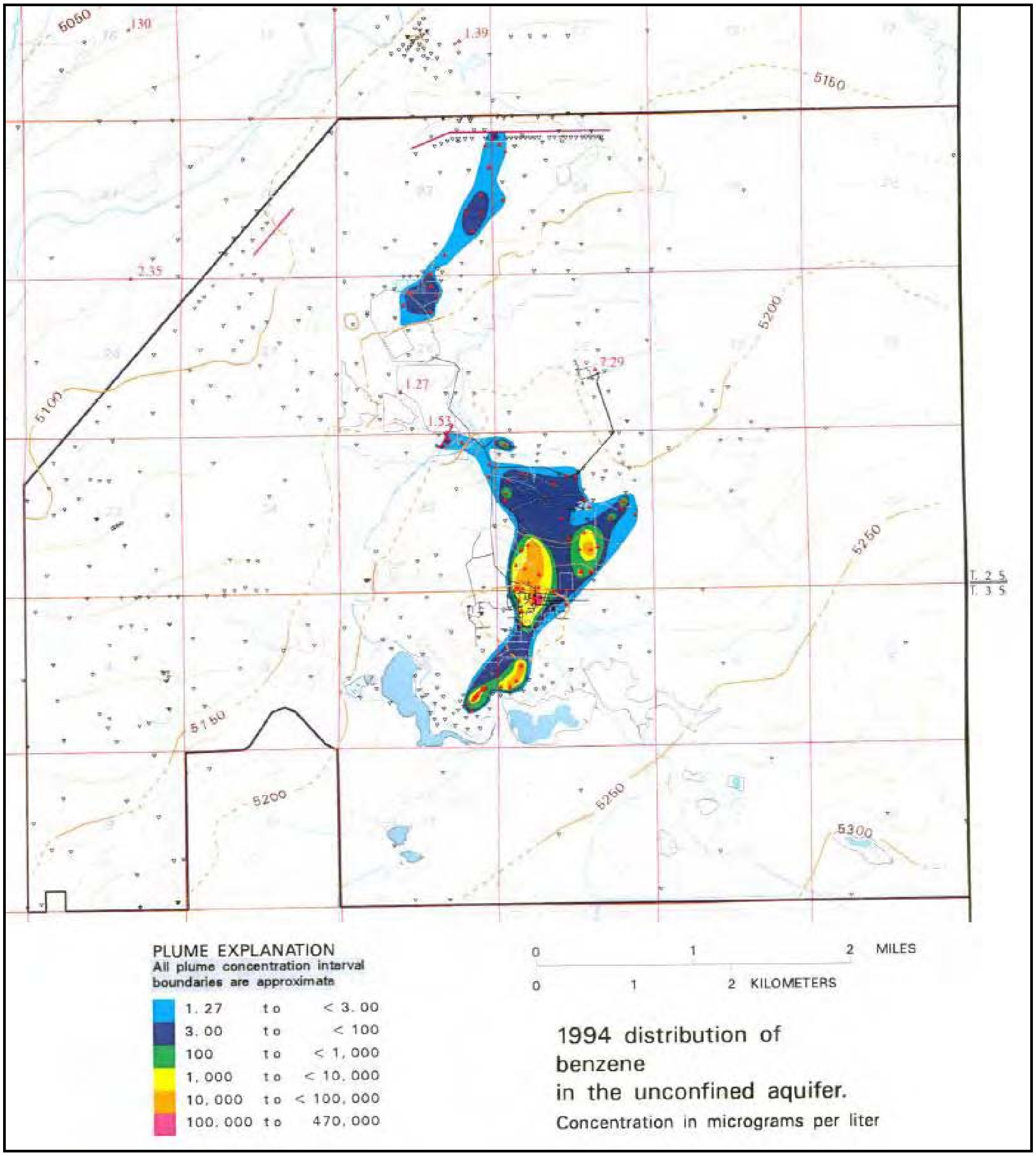

Figure 5.5. Benzene plume in the unconfined aquifer in water year 1994, as depicted in USGS (1997b). The Colorado injury threshold for benzene is 5 µg/L; shaded areas except light blue have benzene concentrations exceeding 3 µg/L and are likely to be injured.

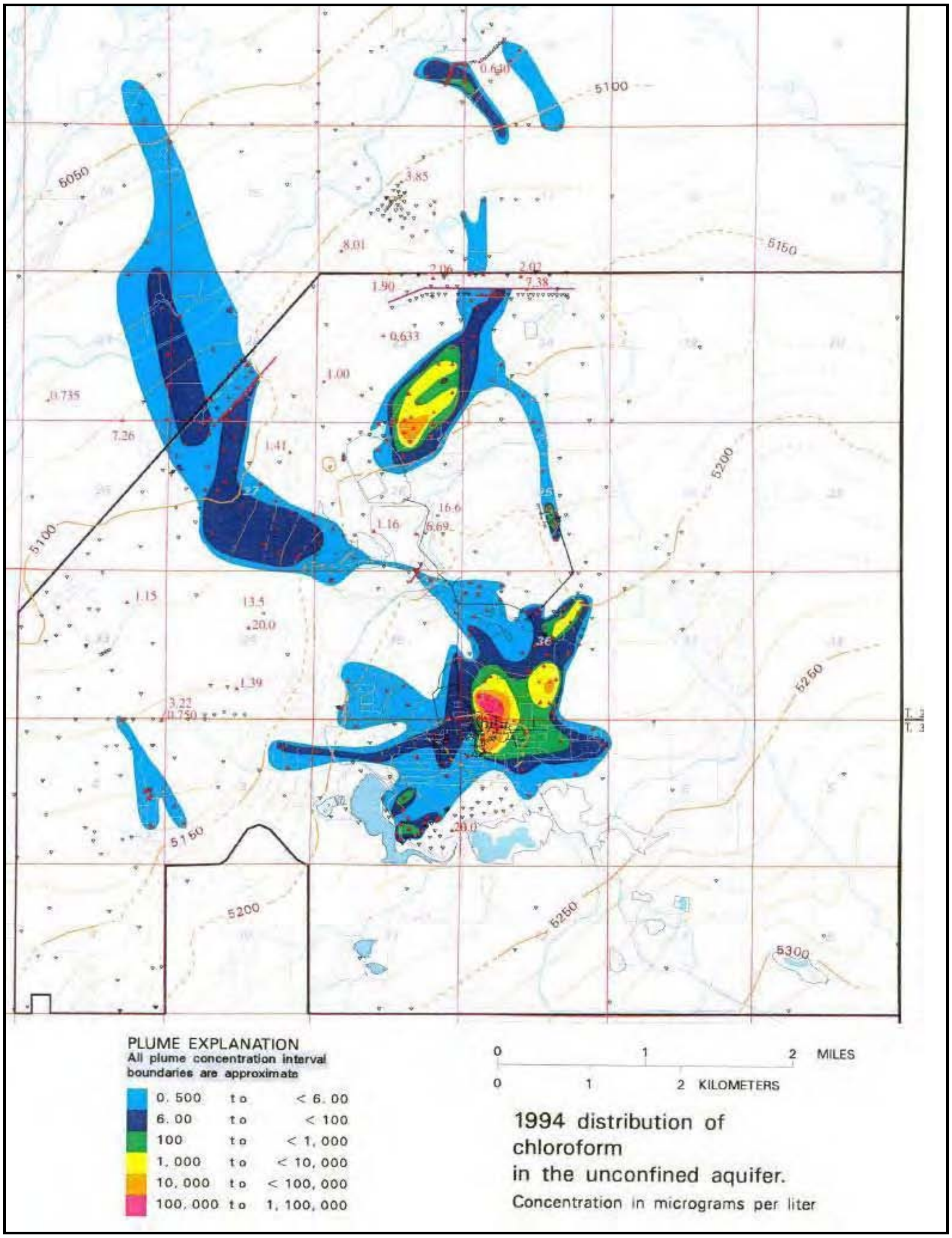

Figure 5.6. Chloroform plume in the unconfined aquifer in water year 1994, as depicted in USGS (1997b). Shaded areas, except light blue, have chloroform concentrations exceeding the injury threshold for Colorado groundwater.

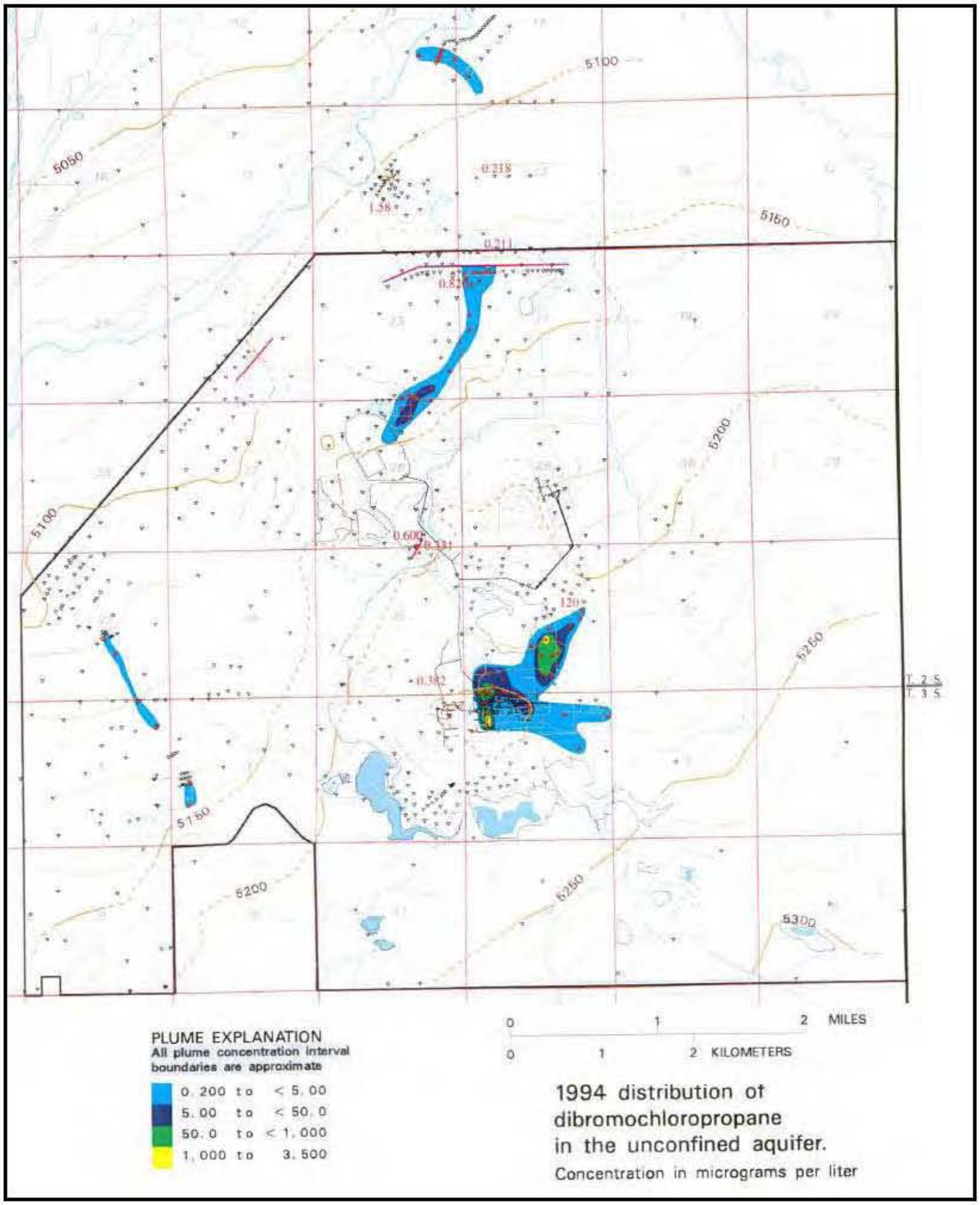

Figure 5.7. DBCP plume in the unconfined aquifer in water year 1994, as depicted in USGS (1997b). All shaded areas contain DBCP concentrations exceeding the 0.2 µg/L injury threshold for Colorado groundwater.

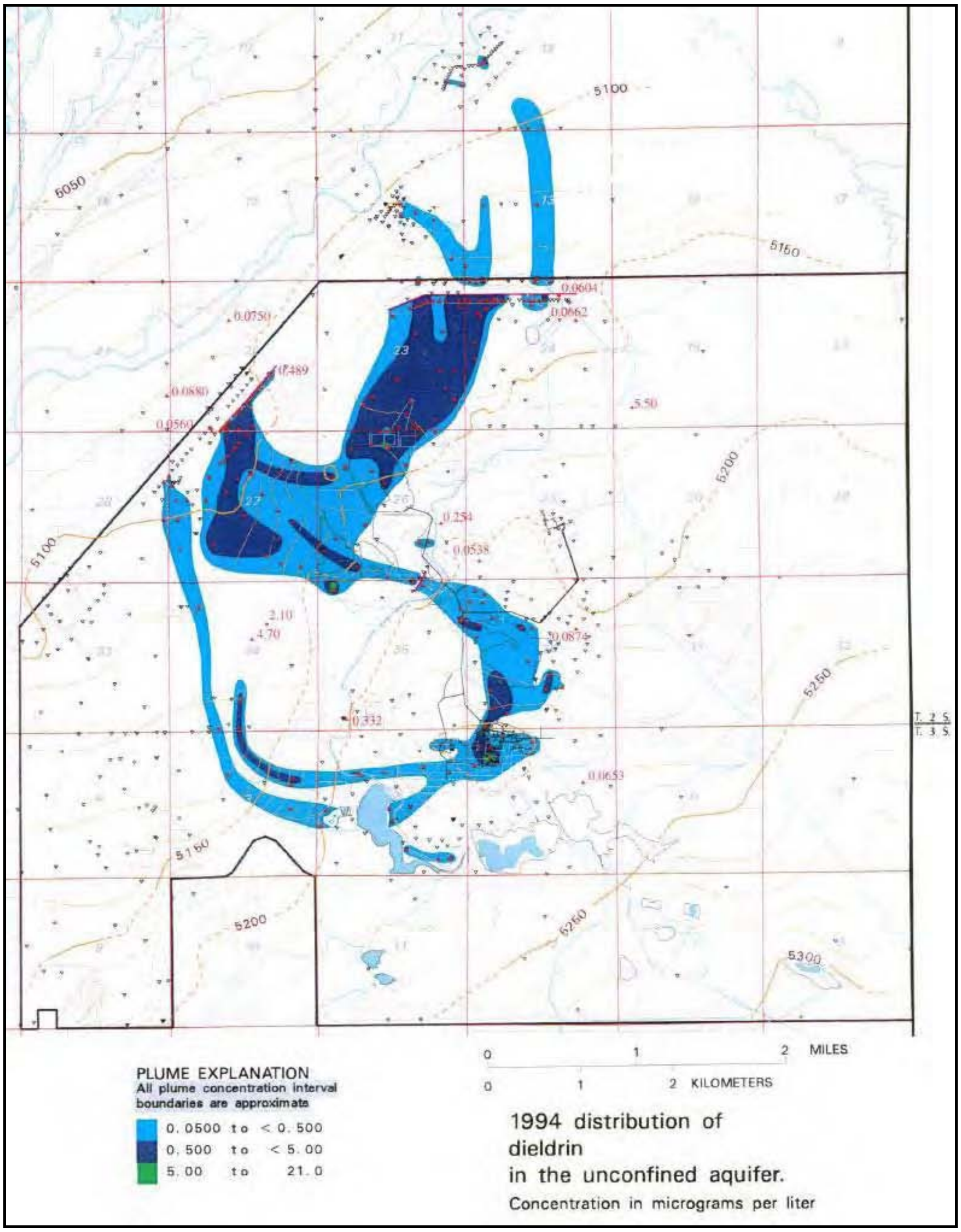

Figure 5.8. Dieldrin plume in the unconfined aquifer in water year 1994, as depicted in USGS (1997b). All shaded areas contain dieldrin concentrations exceeding the 0.002 µg/L injury threshold for Colorado groundwater. The lowest concentration depicted in this figure is 0.05 µg/L; thus, this plume map may underestimate the spatial extent of injury.

Figure 5.9. Geographical area under institutional controls that prevent unrestricted use of groundwater. Off-post institutional controls preclude the use of contaminated groundwater.

5.3 Injury Quantification

This section presents initial estimates of the static volume of groundwater containing hazardous substances exceeding State or federal injury thresholds (Section 5.3.1) in 1994; an example calculation of groundwater adjacent to the plume that is unusable because of proximity to the plume (Section 5.3.2); and the volume of groundwater unusable because of institutional controls (Section 5.3.3). Section 5.3.4 presents an example calculation of the annual recharge and potential "safe yield" of the shallow alluvial aquifer. Thus, this section provides preliminary, conservative estimates of the quantity of groundwater that could have been used had the releases of hazardous substances at the Arsenal not occurred. Section 5.4 discusses how this water might have been used but for the release, and Chapter 9 discusses approaches to estimating damages to compensate for injuries to the public's water resources.

5.3.1 Plume of hazardous substances

The USGS plume maps shown in Figures 5.3 through 5.8 were scanned and digitized to estimate the area of each contaminant plume. These individual plumes were then combined into one composite plume (Figure 5.10). This combined plume includes the light blue shaded areas from Figure 5.4 (TCE < 3 μg/L), Figure 5.5 (benzene < 3 μg/L), and Figure 5.6 (chloroform < 6 μg/L), where concentrations may not exceed injury thresholds. Thus, this map may overestimate the spatial extent of injury from these contaminants. However, with only five out of dozens of contaminants in the analysis, the extent of injury may in fact be underestimated. For purposes of this preliminary evaluation of injury, the combined plume in Figure 5.10 is a reasonable depiction of the spatial extent of contamination in water year 1994. The shaded areas in Figure 5.10 cover approximately 4,300 acres, or 6.7 square miles, of which 3,255 acres are on-post and 1,045 acres are off-post.

The combined plume in Figure 5.10 does not include the extensive plumes of DIMP and chloride shown in USGS (1997b). Both DIMP and chloride exceed State groundwater standards in areas outside of the combined plume in Figure 5.10 but are not hazardous substances as defined by CERCLA. Figure 5.11 shows the combined plume from Figure 5.10 plus the spatial extent of the combined DIMP and chloride plume from water year 1994 (USGS, 1997b). The spatial extent of the entire contaminant plume including DIMP and chloride is approximately 5,450 acres, or 8.5 square miles.

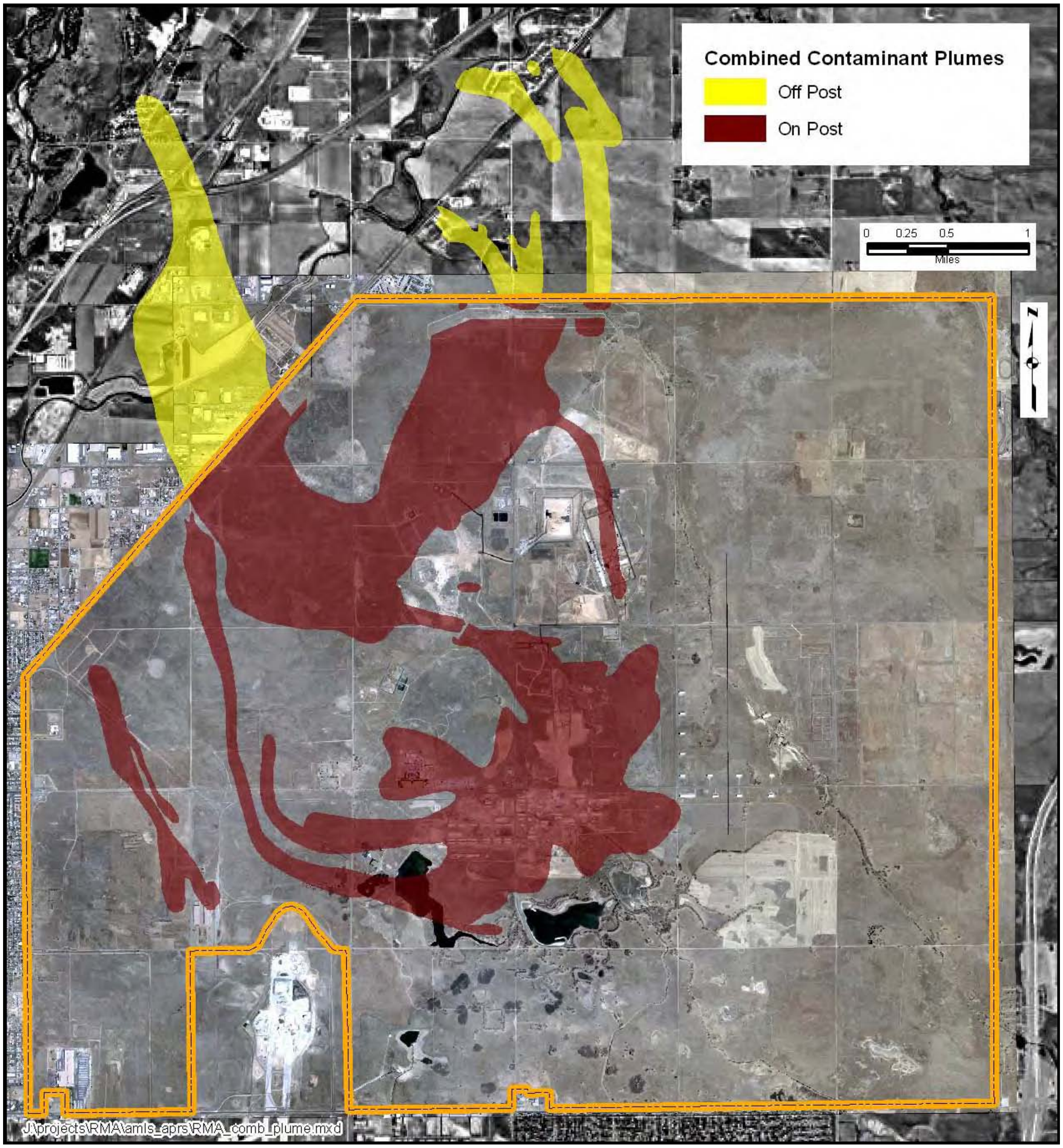

Figure 5.10. Estimated extent of the combined contaminant plume in the unconfined aquifer in water year 1994, based on USGS (1997b). The TCE plume that originates south of the Arsenal is not included in this combined plume.

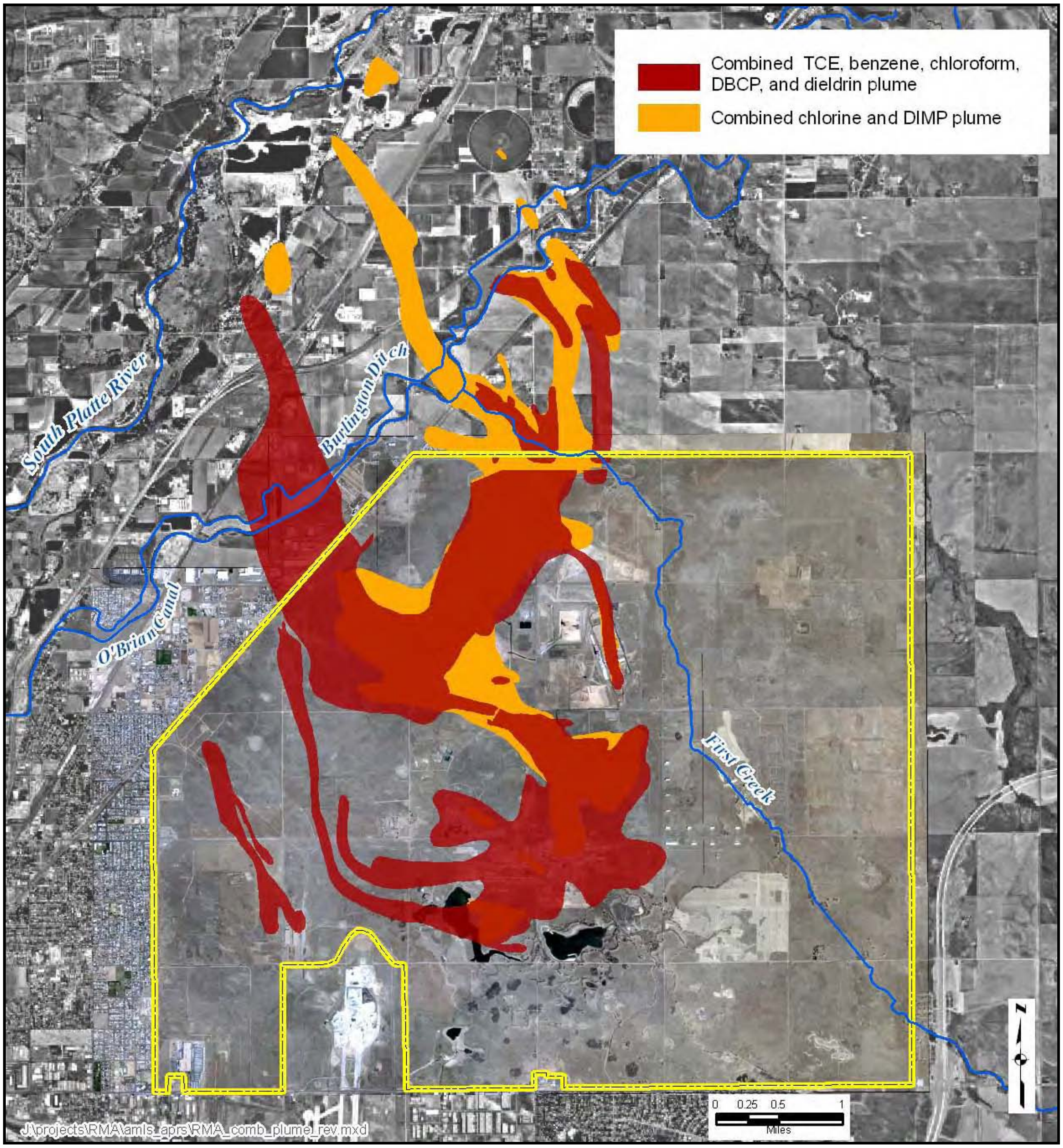

Figure 5.11. Estimated extent of the combined contaminant plume (Figure 5.10) and a combined DIMP and chloride plume in water year 1994, based on USGS (1997b). Because DIMP and chloride are not hazardous substances as defined by CERCLA, they will not be considered in the injury quantification.

The saturated thickness of the alluvial aquifer was calculated as the difference between the water table elevation and the elevation of the upper bedrock surface. While this provides a reasonable preliminary estimate of contaminated saturated thickness, it is likely an underestimate. As mentioned previously, the UFS includes weathered, permeable bedrock at the top of the Denver formation. Given the direct hydraulic connection to the contaminated alluvium, the weathered bedrock of the upper Denver is likely to be contaminated as well. The contaminated groundwater within the permeable weathered bedrock is not included in this initial estimate of the saturated thickness of the UFS.

The water table elevation from the fall of 1994 was used to estimate the top of the saturated thickness because these water table data were readily available. While water table elevations vary over time, the fall of 1994 is a reasonable representative upper boundary of the UFS, based on seasonal water elevation data presented in USGS (1997b). Figure 5.12 shows the estimated saturated thickness of the UFS in fall 1994.

To estimate the static volume of extractable groundwater containing hazardous substances exceeding injury thresholds in water year 1994, the Trustees used a geographic information system (GIS) grid model to compute the total saturated volume of the shallow aquifer materials underlying the plume footprint in Figure 5.10. This volume was multiplied by the assumed effective porosity or specific yield (i.e., the fractional volume of the aquifer from which water could easily be drained) of 25% (Robson, 1989; Fetter, 1994), yielding a total volume of 12,800 acre-feet of contaminated groundwater, of which approximately 8,275 acre-feet were on-post, and 4,525 acre-feet were off-post.

Based on the data presented in USGS (1997b), the vast majority of the contaminants have remained in the shallow alluvial aquifer. The data showing contamination in deeper aquifers suggest that poorly constructed wells drilled through the contaminated alluvium may have transported some contaminants to the deeper aquifer, but there is little evidence to suggest a defined contaminant plume in the deeper aquifers. Evaluation of deep aquifer contamination will be included in future assessment work.

5.3.2 Halo/buffer

Wells drilled and pumped adjacent to a plume of contaminated groundwater may draw contaminated water laterally into the well. The area from which a well draws water is the "capture zone" for a well. The capture zone width expands as the pumping rate increases. To prevent pumping of contaminated water, a halo or buffer area must be estimated to determine how far outside the edge of a contaminated plume one must go before one could safely drill and pump a well. While the groundwater within a halo may not contain concentrations of hazardous substances exceeding groundwater standards, there is a lost use of that groundwater because of the release of hazardous substances.

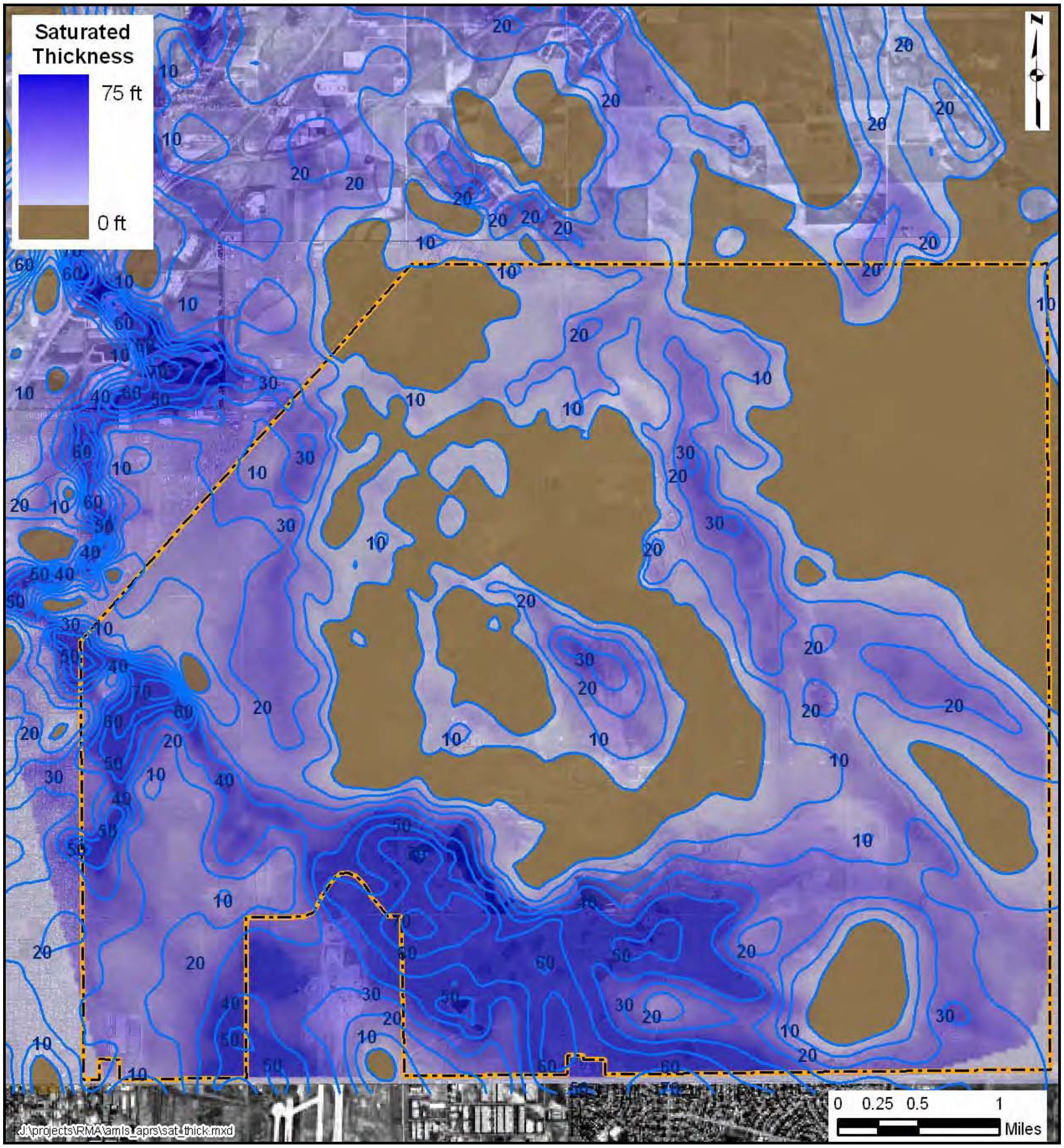

Figure 5.12. Estimated saturated thickness of the UFS in fall 1994. Contour interval = 10 ft. In brown shaded areas, the bedrock elevation is at or above the water table, and the saturated thickness of the UFS is 0.

A reasonable extent of the halo can be calculated using standard capture zone equations (e.g., Javandel and Tsang, 1986; Fetter, 1993; Kraemer et al., 2005). The equation for an asymptotic capture zone half width, w/2, is:

$$\frac{w}{2} = \frac{Q}{2KiH} \tag{5.1}$$

where K is a representative hydraulic conductivity, i is the hydraulic gradient, and H is a representative aquifer saturated thickness. This simple equation is for a well pumping in uniform, unbounded aquifer materials. However, most of the flow in the UFS is concentrated within paleochannels bounded by aquifer materials of lower hydraulic conductivity. In some areas, the plume is passing through weathered bedrock of much lower hydraulic conductivity. Because capture zone width increases as hydraulic conductivity decreases (Equation 5.1), this equation may underestimate the appropriate capture zone width for the alluvial contaminant plume under the Arsenal.

To present an example halo calculation, the Trustees assumed an average pumping rate (Q) for wells at the Arsenal of 100 gallons per minute (gpm), a reasonable rate for a community well serving approximately 160 households. Using that assumption plus representative values for other input parameters (Table 5.3), the capture zone width (halo) to prevent pumping of contaminated water would be 461 ft. Figure 5.13 shows the combined contaminant plume from Figure 5.10, with a surrounding 461-foot halo. As part of the assessment, the Trustees will evaluate the effects of other hydrogeologic features and other well pumping scenarios, including a calculation of the capture zone width assuming wells with higher pumping rates that municipalities would be likely to use if the Arsenal groundwater were available.

Table 5.3. Input parameters for calculating the appropriate width of the capture zone adjacent to the contaminant plume at the Arsenal

Parameter	Representative minimum	Representative maximum	Selected value
Well pump rate (Q, gpm)			100
Conductivity (K, ft/day)	60	300	134.2[a]
Gradient (i, ft/ft)	0.0047	0.0167	0.0074[b]
Saturated thickness (H, ft)	14.2	34.7	21.1[c]

a. Geometric mean of minimum and maximum values from Ebasco Services et al. (1989, Table 2.2).
b. Harmonic mean of minimum and maximum values derived from Figure 5.2.
c. Geometric mean of the mean saturated thickness beneath each plume segment, calculated using GIS.

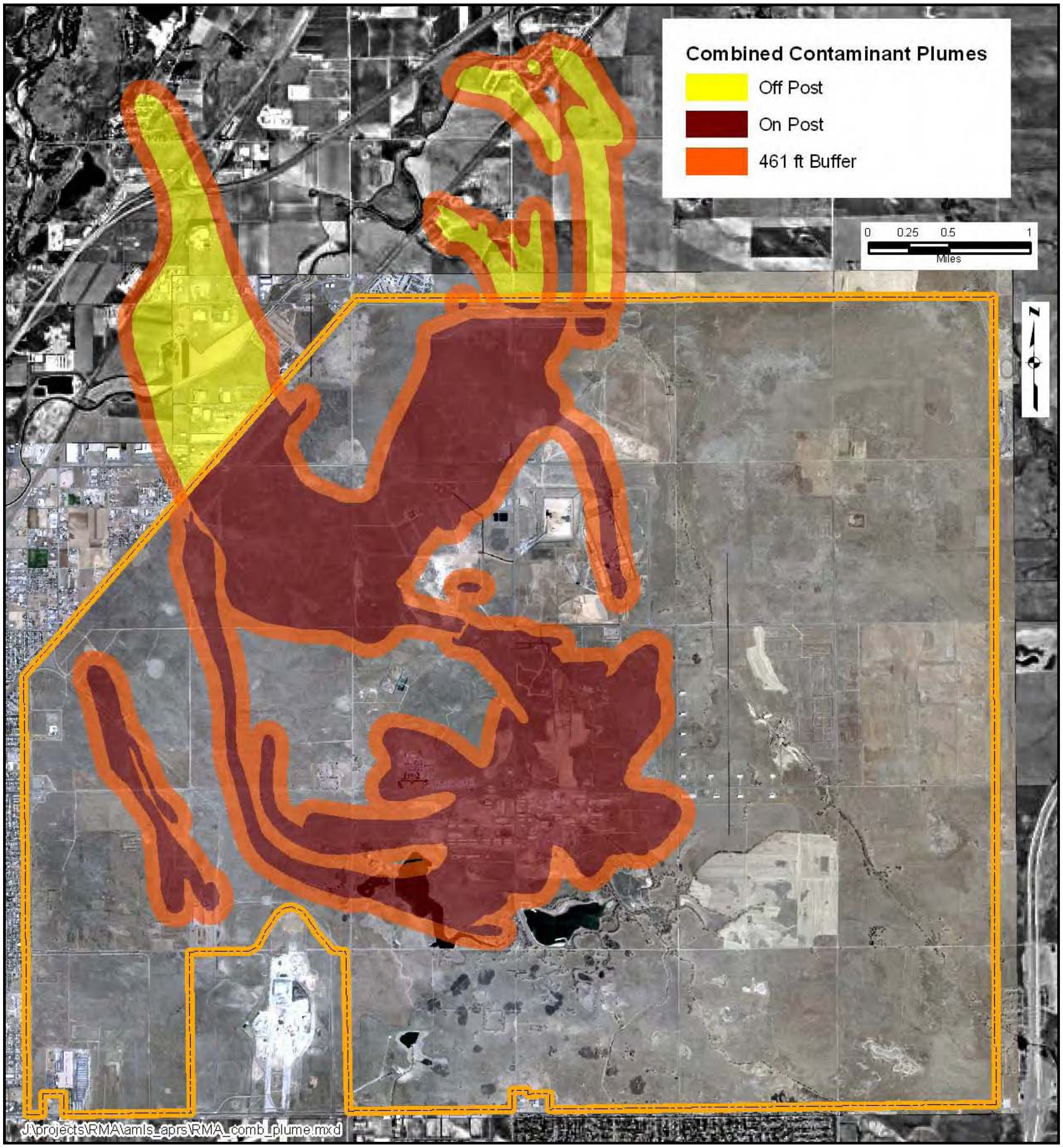

Figure 5.13. Estimated extent of the combined contaminant plume in the unconfined aquifer in 1994 with a surrounding buffer.

The volume in the contaminant plume plus the volume in the calculated halo provide one estimate of the total volume of groundwater that cannot be used because of hazardous substance releases. The GIS grid model was again relied upon to compute the total saturated volume of the aquifer materials underlying the combined plume plus halo described above and shown in Figure 5.13. This volume of impacted alluvial aquifer was then multiplied by the 25% effective porosity, yielding a total volume of 20,835 acre-feet of impacted groundwater, of which approximately 13,670 acre-feet were on-post and 7,165 acre-feet were off-post (Table 5.4).

Table 5.4. Estimated volume (acre-feet) of impacted groundwater, water year 1994

Location	Plume	Halo[a]	Total
On-post	8,275	5,395	13,670
Off-post	4,525	2,640	7,165
Total	**12,800**	**8,035**	**20,835**

a. The halo in this example assumes a 100-gpm extraction rate in a uniform, unbounded alluvial aquifer.

5.3.3 Institutional controls

Figure 5.9 shows the area affected by institutional controls, using the Arsenal boundary when the Federal Facilities Agreement was signed in 1989. The Arsenal covers roughly 26.5 square miles, or 16,940 acres. The Shell properties north of the Arsenal cover approximately 350 acres. As described previously, the grid of saturated alluvial thickness in fall 1994 was overlaid on the surface affected by institutional controls and multiplied by 25% effective porosity. Excluding the TCE plume in the southwest of the site where baseline conditions would have prevented shallow groundwater use, an estimated 52,550 acre-feet of alluvial groundwater are unavailable for drinking water use or storage because of the institutional controls (Table 5.5).

A similar method was used to quantify the volume of groundwater unavailable for unrestricted use in deep aquifers. The on-site institutional controls prevent the drinking water use and storage of both deep and shallow groundwater, and the off-site institutional controls prevent drinking water use or storage of deep groundwater under the Shell properties if contaminants exceed CSRGs (see Section 5.3.5). This preliminary evaluation of data did not reveal consistent CSRG exceedences in off-post deep groundwater, so no estimated quantity of injured off-post deep groundwater is provided. Contamination in deep aquifers will be evaluated more closely as part of the assessment.

Table 5.5. Total volume of groundwater in five aquifers that is unavailable for drinking water use because of institutional controls

Aquifer[a]	Effective porosity	Total volume (acre-feet)
Shallow aquifer		
Alluvial[b]	25%	52,550
Deep aquifers		
Denver	15%	863,760
Upper Arapahoe	7%	283,830
Lower Arapahoe	7%	283,260
Laramie-Fox Hills	13%	456,930
Total (deep)		1,887,780
Total		**1,940,330**

a. The shallow aquifer includes both on-post and off-post institutional controls. The deep aquifers are on-post only.
b. Excludes TCE plume originating south of the Arsenal.

The total volume of restricted on-post groundwater in deep aquifers was calculated by multiplying the surface area by the average saturated thickness for each bedrock aquifer under each one square-mile section using the Colorado State Engineer Office SB-74 MODFLOW model of the Denver Basin (Black & Veatch et al., 2003) and the effective porosity (or specific yield). Total volumes of groundwater unavailable for drinking water use or storage because of institutional controls are shown in Table 5.5.

5.3.4 Shallow aquifer recharge

The State of Colorado assumes that the deep aquifers do not recharge in the timeframe that the aquifer is pumped. The State Engineer's Office allows the aquifer to be pumped at a rate of 1% of the available volume per year [2 CCR § 402-7, Rule 8A (Statewide Nontributary Ground Water Rules)]. The shallow aquifer, on the other hand, is recharged every year by infiltrating rain and snowmelt, infiltrating surface water from lakes, ponds, and ditches, and by upgradient groundwater. While there are no statutory restrictions on pumping rates in the shallow aquifer, for practical purposes, the Trustees have assumed that a user would not pump the alluvial aquifer at a rate greater than the rate at which the aquifer recharges on an average annual basis. In this case, the total recharge can be considered a conservative safe yield for the shallow aquifer.

To demonstrate a method of estimating aquifer recharge and safe yield without developing a complicated groundwater flow model, the Trustees developed a simple groundwater budget. The groundwater budget balances the amount of new water entering the shallow aquifer under the

Arsenal each year with the amount of shallow groundwater leaving the existing stock. This equates the amount of groundwater leaving the existing stock annually to the annual groundwater recharge (and safe yield). In general, the inflows to groundwater comprise:

1. Effective precipitation, i.e., diffuse groundwater recharge, R
2. Seepage from streams, ditches, and lakes, S
3. Lateral groundwater inflows from upgradient areas to the south-southeast, GW_{in}.

Outflows comprise:

1. Evaporation from surface water bodies, E
2. Groundwater outflows, GW_{out}.

This can be expressed in a groundwater budget equation:

$$R + S + GW_{in} = E + GW_{out} \tag{5.2}$$

Solving for GW_{out} provides an estimate of the amount of alluvial groundwater that could be pumped from under the Arsenal without depleting the original stock:

$$GW_{out} = R + S + GW_{in} - E \tag{5.3}$$

Below is an example of a groundwater budget for the alluvial aquifer at the Arsenal. Although it incorporates site data, the input data are from different years, and water use at the Arsenal has changed over time. Should the Trustees elect to use this method of calculating groundwater recharge at the Arsenal (see Section 5.5), additional data will be required to account for changes in groundwater recharge and groundwater use over time, as well as to differentiate between groundwater in the contaminant plume and groundwater under institutional controls. Separate groundwater budgets for different years or for different water use scenarios may be calculated.

For this simple example calculation of groundwater recharge, the input data are:

- **Diffuse groundwater recharge, *R***: Diffuse recharge, or effective precipitation, is the areal average amount of precipitation that infiltrates the soil and is not consumed by plants. Diffuse recharge thus accounts for both precipitation and transpiration at the site. The USGS (Wolock, 2003) estimates that 0.5 inches per year is an appropriate average annual value for the Arsenal area. Multiplying this value by the site acreage provides an estimate for the annual volume of diffuse recharge at the Arsenal.

- **Ditch and lake seepage, *S***: Seepage has occurred from several surface water bodies (e.g., Lake Ladora, Upper and Lower Derby Lakes, Lake Mary, Havana Pond, First Creek, and from several ditches and canals (e.g., Uvalda Interceptor, High Line Lateral). Flow data from 2005 were available from several locations along the Uvalda Interceptor and First Creek, and at other ditches that enter the site and discharge into one of the on-site lakes.[1] Ditch seepage was estimated by subtracting the sum of the flow out of the ditch and ditch evaporation from the flow into the ditch. Lake seepage was estimated using lake level gauge records, with seepage estimated to be the total volume of water lost in the lake minus the volume lost to evaporation.

- **Lateral groundwater inflows, GW_{in}**: Groundwater inflows were computed using Darcy's Law (Fetter, 1994) with observed groundwater gradients, estimated aquifer thickness (from fall 1994 measurements), and an estimated hydraulic conductivity of 134 ft/day (Table 5.3). This calculation was undertaken for each section along the groundwater inflow boundary on the southern border of the Arsenal.

- **Open-water evaporation, *E***: Evaporation was measured in on-post lakes at various periods between 1997 and 2005. The surface area of the ditches was estimated assuming an average width of 5 ft. Because no ditch evaporation data were readily available, the same open-water evaporation rate from the lakes was used to estimate the evaporation from the ditches. This likely overestimates ditch evaporation and underestimates aquifer recharge, since ditch water may be shaded by levees and/or vegetation.

- **Lateral groundwater outflow, GW_{out}**: Groundwater outflow, an estimate of the annual volume of available alluvial groundwater, is computed from each of the other variables (Equation 5.3).

Table 5.6 provides a summary of this example groundwater budget developed for the Arsenal using 2005 seepage data and 1994 groundwater inflow data. Based on these example data, approximately 7,160 acre-feet per year of alluvial groundwater could be extracted from under the Arsenal without depleting the overall groundwater stock and lowering the water table (Table 5.6).

1. Seepage varies annually based on precipitation and ditch usage. Annual precipitation for water year 2005 at the nearby Brighton weather station was roughly 20% lower than the annual average of 13.9 inches per year. More importantly, the High Line Lateral was no longer in use by 2005, after running dry in 2002 and nearly dry in 2003 (Denver Water, 2003). Prior to the 2002 drought, Denver Water provided the Army with 2,800 acre-feet per year in the High Line Lateral, and they estimated that 60-70% of water delivered in High Line seeped into the ground (Denver Water, 2003). Thus, using only 2005 data, the calculated seepage in this groundwater budget is considerably lower than seepage in earlier years.

Table 5.6. Example groundwater budget for the Arsenal, calculating total groundwater outflow. See text for explanation of the components.

Direction of flow	Component	Volume (acre-feet)
Inflow		
	Diffuse recharge	700
	Lake/ditch seepage	1,990
	Upgradient groundwater	4,820
	Total	**7,510**
Outflow		
	Evaporation	350
	Total	**350**
Alluvial groundwater outflow		
	Total	**7,160**

To verify that the estimate of approximately 7,000 acre-feet of groundwater recharge using the simplistic groundwater budget above is reasonable, the Trustees examined pumping data from the on-post groundwater containment systems. LaRock (2004) compiled annual pumping data from the Irondale water treatment plant, the Northwest Boundary Containment System, and the North Boundary Containment System from 1997 through 2001 (Table 5.7).

Table 5.7. Annual volume of water (acre-feet) treated at the Arsenal boundary groundwater treatment and containment systems, 1997 to 2001

Year	Irondale treatment plant[a]	North Boundary Containment System	Northwest Boundary Containment System	Total
1997	1,607	301	1,740	**3,648**
1998	448	310	1,817	**2,575**
1999	368	310	3,440	**4,118**
2000	368	319	3,361	**4,048**
2001	NA	319	1,556	**1,875**

a. The 1997 volume includes groundwater from the Irondale Containment System and the Motor Pool and Railyard extraction systems. The 1998 volume includes only the Motor Pool and Railyard extraction systems, and the 1999 and 2000 volumes include only the Railyard system.

Source: LaRock, 2004.

The Irondale water treatment plant treated groundwater from the Irondale Containment System along the western boundary of the Arsenal, as well as groundwater from the Motor Pool and Railyard extraction wells upgradient of the boundary. The Irondale Containment System was decommissioned after 1997, when data indicated that there was no longer a contaminant plume leaving the western boundary of the Arsenal. The Motor Pool extraction system was decommissioned after 1998, and the Irondale Treatment System was demolished in 2001.

For this example analysis, discrete volume data from the Irondale Containment System on the western boundary were not readily available. Thus, to estimate the volume of contaminated groundwater leaving the western boundary in 1997 and prior years, the sum of the Motor Pool and Railyard extraction wells in 1998 (448 acre-feet) was subtracted from the total Irondale treatment plant volume in 1997 (1,607 acre-feet), resulting in an estimated volume of 1,160 acre-feet of contaminated groundwater at the Irondale Containment System along the western boundary. In total, approximately 3,000 acre-feet per year are captured in the boundary systems (Table 5.8). The containment systems are intended to capture only the contaminated alluvial groundwater outflows from the Arsenal. Therefore, the volume of annual captured groundwater should be less than (but within the same order of magnitude as) the calculated groundwater outflow for the Arsenal as a whole. Thus, if the boundary systems capture approximately 3,000 acre-feet per year of contaminated alluvial groundwater, the 7,000 acre-feet per year estimate of total alluvial aquifer recharge is reasonable.

Table 5.8. Estimated annual volume of water (acre-feet) at the Arsenal boundary systems in 1997, and the average annual volume from 1998 to 2001

Year	Irondale treatment plant[a]	North Boundary Containment System	Northwest Boundary Containment System	Total (rounded)
1997	1,160	301	1,740	**3,200**
1998–2001	0	310	2,540	**2,850**

a. The 1997 volume includes groundwater from the Irondale Containment System and the Motor Pool and Railyard extraction systems. The 1998 volume includes only the Motor Pool and Railyard extraction systems, and the 1999 and 2000 volumes include only the Railyard system.

Source: LaRock, 2004.

5.3.5 Temporal extent of injury

Groundwater subject to institutional controls has been unavailable for drinking water use since the signing of the Federal Facilities Agreement in 1989 and the Off-Post ROD in 1995. Unrestricted use of this groundwater will be lost until the institutional controls are lifted or modified, which is not anticipated.

The spatial extent of the contaminated groundwater plume changes over time. The maximum extent of contamination probably occurred immediately before the installation of groundwater treatment plants at the site in the late 1970s and early 1980s. After some 13 years of pumping and treating, the groundwater plume that USGS identified in 1994 (Figures 5.3 to 5.8) was probably smaller than the groundwater plume that existed in 1981 and larger than the current plume.

The plumes should continue to decrease in size; however, a plume of pesticides probably will remain for hundreds of years. As discussed in Chapter 3, the On-Post ROD did not call for complete removal of all sources of hazardous substances to groundwater. In some areas, the ROD called for removal of the upper 5–10 ft of soil, leaving in place many feet of soils and alluvium saturated with organochlorine pesticides (see Chapter 3) that will continue to enter groundwater. Thus, while the spatial extent of groundwater contamination will decrease with time, these areas of pesticide-laden soils will continue to be a source of hazardous substances to the groundwater for the foreseeable future. For these reasons, the groundwater downgradient of these sources is not expected to recover.

As part of this assessment, the Trustees will model the size of the contaminated groundwater plume over time (see Section 5.5).

5.4 Lost Groundwater Services

The releases of hazardous substances at the Arsenal have made thousands of acre-feet of groundwater unavailable for human uses, including municipal, residential, and agricultural uses. This groundwater contamination under and downgradient of the Arsenal removed a potential source of clean, easily obtained water in the semi-arid Front Range. Municipal water supply is the most important service that groundwater provides in the Denver metropolitan area and qualifies as the "highest-and-best use of the injured resource or services" that the NRDA regulations specify should be used for determining damages [43 CFR § 11.84(b)(3)(i)]. This section first describes conditions that would apply to groundwater use at the Arsenal irrespective of the release of hazardous substances. It then describes the importance of municipal water supply as a groundwater service in the Front Range, and summarizes the lost groundwater services at the Arsenal as a result of hazardous substance releases.

5.4.1 Groundwater use considerations at the Arsenal

In considering whether, absent contamination, the groundwater beneath the Arsenal could have been used as a municipal water supply in the past, or could be so used in the future, the Trustees examined physical and institutional, or legal, considerations, including the adequacy of water quality for potable use, the quantity of water that would have been available (extractable or "safe" yield), and regulatory requirements.

Water quality

As described previously, except for the TCE plume in the southwest corner of the Arsenal (see Figure 5.3), the groundwater upgradient of the hazardous substance sources at the Arsenal is potable (USGS, 1997a, 1997b; Ebasco Services et al., 1989). Therefore, the alluvial groundwater from the Arsenal, which under baseline conditions would have been free of the pesticides and municipal effluent found in South Platte River surface water and alluvium, would not only have been potable, but would have required less treatment than many of the sources of water upon which area providers currently rely for drinking water (Dennehy et al., 1998).

Annual extractable yield and regulatory requirements

Section 5.3 presents an example calculation of approximately 7,000 acre-feet per year of alluvial groundwater that could have been extracted on a sustainable basis from the Arsenal. An approved augmentation plan and compliance with a 600-foot spacing requirement for alluvial wells [CRS 37-90-137(2)] are the only regulatory restrictions on the amount of water that a user can pump from the alluvial aquifer in the vicinity of the Arsenal. The Trustees will continue to examine this issue, but based on current knowledge, these requirements would not have limited the potable use of Arsenal alluvial water.

Extractable yield for not-nontributary water will be calculated during the assessment. As discussed below, augmentation requirements for not-nontributary groundwater are similar or less than those for alluvial groundwater and are therefore not perceived to create impediments to use.

Fewer regulatory requirements apply to the deep aquifer. The State Engineer's Office permits a pumping rate of 1% of the total available volume per year in deep aquifers, including the Lower Arapahoe and Laramie-Fox Hills aquifers in the vicinity of the Arsenal [2 CCR 402-7, Rule 8A]. Based on a preliminary review of existing data, these aquifers contain nearly 1.9 million acre-feet of deep groundwater that is inaccessible for potable use due to institutional controls (Table 5.5). Of this total, about 750,000 acre-feet are nontributary and 1.15 million acre-feet are not-nontributary. One percent of the nontributary deep groundwater is roughly 7,500 acre-feet per year that could hypothetically be extracted annually but for the institutional controls.

Replacement requirements for tributary groundwater

By definition, tributary groundwater is groundwater that has a direct hydrological connection to a natural stream. The right to use tributary groundwater and the natural streams of the State is governed by the doctrine of prior appropriation, which is constitutionally mandated and codified in Colorado statutes [Colo. Const. Art. XVI § 5; CRS § 37-92-102]. The doctrine has its origins in the mining industry, and later agriculture, and was driven by the arid climate of the west:

> The climate is dry and the soil, when moistened by the usual rainfall, is arid and unproductive; except in a few favored sections, artificial irrigation for agriculture is an absolute necessity. Water in the various streams thus acquires a value unknown in moister climates. Instead of being a mere incident to the soil, it rises, when appropriated, to the dignity of a usufructuary estate, or right of property. [*Coffin v. Left Hand Ditch Co*., 6 Colo. 443, 446 (1882)].

Usufructuary rights are the rights to use, not own, property. This usufructuary water right derives from the dates of the appropriation and water decree. Appropriation generally occurs when water is diverted through a ditch or well and applied to a beneficial use. The senior appropriator has a superior right to use water over any junior-in-time appropriator, or "first in time, first in right," assuming the appropriator duly adjudicated the right in water court.

In times of scarcity, a senior appropriator can place a "call" on the river and its tributary groundwater, asking the State Engineer to curtail the junior or undecreed diversion of water that might be interfering with the senior water right holder's use of allocated water. The Colorado Division of Water Resources (State Engineer's Office) enforces the decrees and otherwise administers the waters of natural streams. Decrees obtained from the court specify the location of the diversion, the amount of water (expressed as flow in cfs) and the type of beneficial use, as well as any replacement water necessary to protect senior rights.

Most Colorado stream systems, including the South Platte River, are over-appropriated. This means that at times there is not enough water in the stream to satisfy all decreed appropriations [*Hall v. Kuiper,* 510 P. 2d 329, 330 (Colo. 1973)]. In an over-appropriated stream system, the uncontrolled drilling of wells in tributary groundwater has the potential to intercept water necessary to satisfy senior decreed water rights. However, new rights can be decreed in an over-appropriated basin, providing there is no harm to senior appropriators. To prevent such harm to senior users, the junior user augments the supply of water to make up for what is consumed, or "depleted." Such augmentation must be documented in a plan that describes the source of water to be made available to offset any groundwater depletions, and any return flows that would need to be maintained to avoid injury to senior rights [CRS 37-92-305]. The Water Right Determination and Administration Act of 1969 [CRS 37-92-102 *et seq.*] provides the framework for integrating the administration of tributary groundwater and surface water to prevent groundwater use from injuring senior surface water right holders.

Replacement requirements for nontributary groundwater

Water in the Lower Arapahoe and the Laramie-Fox Hill aquifers is nontributary. The withdrawal of this water does not require judicial approval of an augmentation plan, but the landowner must relinquish the right to consume two percent of the amount withdrawn [CRS § 37-90-137(9)(b); 2 CCR § 402.6, Rule 8 (Denver Basin Rules)]. Withdrawals on the basis of an aquifer life of 100 years are allowed by law [CRS § 37-90-137(4)(b)(I)]. The State Engineer thus permits a withdrawal rate of 1% of the total available volume per year [2 CCR § 402-7, Rule 8A].

Replacement requirements for not-nontributary groundwater

In the vicinity of the Arsenal, the waters in the Denver and Upper Arapahoe aquifers are not-nontributary, as specified by the Denver Basin Atlas. Therefore, the use of this groundwater requires the approval of an augmentation plan similar to that for tributary groundwater. The replacement requirement, however, varies with the location of the well [CRS § 37-90-137(9)(c)]. If the well is greater than one mile from the intersection of the stream alluvium and the aquifer's outcrop, the water user must replace 4% of the amount withdrawn on an annual basis. If the well is within one mile of the intersection of the stream alluvium and the aquifer's outcrop, the applicant must replace the actual amount of depletions. Regardless of the location, the applicant may be required to replace the actual amount of depletions after the groundwater pumping stops.[2] The rights to this type of groundwater are administered under the Groundwater Management Act [CRS § 37-90-102 *et seq*.].

Application of requirements to Arsenal groundwater

The requirements associated with different types of groundwater could be relevant in quantifying services lost due to hazardous substance releases, and potentially in calculating compensable damages. The shallow alluvial aquifer is tributary to the South Platte River. Therefore, alluvial wells need augmentation plans to ensure that senior rights are not injured. Groundwater users need to augment 100% of depletions, or "net pumping," i.e., water that is not returned to the aquifer at the same time and location as that from which it was pumped. Augmentation is not required for that portion of the tributary groundwater that is pumped and returns to the aquifer ("return flow"), for example, through percolation. The most significant consumptive use of water is irrigation and subsequent evapotranspiration during the growing season.

Unlike groundwater used for irrigation, groundwater pumped for household use is subsequently transported to the municipal wastewater treatment system, and then discharged to the river as treated effluent. In such cases, engineers calculate the effects of groundwater pumping on other

2. From July 1, 2009 to July 1, 2012, post-withdrawal replacement will be mandatory [CRS § 37-90-137(9)(c)(II) and (c.5)].

water users, based on the distance of the alluvial wells from the river, aquifer properties, and other factors. This analysis is presented in an augmentation plan, which also includes sources of water to augment, or replace, any depletions. Treated effluent is a common source of augmentation water for municipalities; water released to the river from the wastewater treatment plant can replace tributary groundwater that was pumped several months prior.

In winter, up to 95% of the water used by a municipality is transported to the wastewater treatment plant. Even during the heaviest usage months of July and August, about 40% is returned to the river through wastewater discharge. For example, the SACWSD augmentation plan [CO District Court W-8440-76] states that 95% of non-irrigation water returns to the river via the wastewater treatment plant, and 48% of lawn irrigation water recharges the aquifer. This 48% is considered return flow, but augmentation will be needed for the rest of the pumped water. Such augmentation water might come from effluent or from surface water rights, storage ponds that capture surface water during high flows, or deep groundwater. These sources of augmentation would only be tapped, however, when there is a call on the river.

According to State records, the South Platte River was often a “free river” from 1981 through 2001, meaning there was enough water for everyone and senior rights holders did not make a call for more water. Well augmentation organizations were able to provide adequate replacement water during this period. Drought conditions in 2002 started a period of nearly continuous calls on the South Platte River (Simpson, 2006). These calls on the river, combined with statutory changes to augmentation requirements, made replacement of depletions more difficult. Section 5.4.2 discusses some of the elaborate plans that have been implemented to allow development of South Platte Basin tributary groundwater resources.

Deep aquifer withdrawals from the aquifers below the Arsenal are subject to the Denver Basin Rules. Withdrawals from the Upper Arapahoe and Denver aquifers (not-nontributary) that are not within one mile of the intersection of stream alluvium and an outcrop require an approved augmentation plan for 4% of the amount withdrawn. If within one mile, 100% of actual depletions need to be augmented. For the lower Arapahoe and Laramie-Fox Hills groundwater (nontributary), a user must return 2% of the amount withdrawn to the South Platte River.

Summary

The following legal and practical conditions must be examined when considering the Arsenal as a potential municipal water supply source:

- For shallow alluvial groundwater (tributary) and for Upper Arapahoe and Denver groundwater (not-nontributary) within one mile of the intersection of stream alluvium and an outcrop, a user must have an approved augmentation plan to offset all depletions.

- Tributary groundwater that is pumped and then recharges the aquifer via return flow generally does not require augmentation.

- Alluvial groundwater placed into a municipal system and returned to the South Platte River or its tributaries via a wastewater treatment plant can be used as a source of augmentation for depletions caused by well pumping.

- Augmentation water need only be supplied when senior rights are not being satisfied and there is a call on the river.

- Wells drilled into the shallow aquifer are subject to a 600-foot spacing requirement [CRS 37-90-137(2)].

- Other than an approved augmentation plan and compliance with the 600-ft spacing requirement, there are no other legal restrictions on the amount of water that a user can pump from the shallow aquifer.

- For Upper Arapahoe and Denver groundwater (not-nontributary) greater than one mile from the intersection of stream alluvium and an outcrop, a user must have an approved augmentation plan to supply the South Platte River system with 4% of the amount withdrawn.

- For lower Arapahoe and Laramie-Fox Hills groundwater (nontributary) in the vicinity of the Arsenal, Colorado nontributary groundwater rules allow a property owner to pump 1% per year of the volume of nontributary groundwater underlying the property. The user must relinquish to the South Platte River system 2% of the amount withdrawn.

5.4.2 Water demand in the Front Range

Demand for groundwater in the Front Range is high and growing as the population in the region increases. Water supply sources are finite, and drought in the past decade has reduced surface water supplies and shallow aquifer recharge. The major municipal and industrial water providers in the South Platte Basin are essentially meeting the growing urban and suburban demand (with periodic use restrictions), but many will be at or near their build-out capacity within two decades. To access additional water resources in the future, Front Range municipalities will likely have to go far away at great cost to find additional sources of potable water.

Figure 5.14 shows recent historical and projected growth to 2030 in the Denver Metropolitan Area (MetroDenver EDC, 2006). Between 1990 and 2000, the population of the seven-county Denver Metropolitan Area (Adams, Arapahoe, Boulder, Broomfield, Denver, Douglas, and Jefferson counties) grew from 1.8 million to 2.4 million, an increase of 30% (MetroDenver EDC, 2006). By 2030, the population of the Denver Metropolitan Area, which will extend over some 750 square miles, is expected to reach almost four million people.

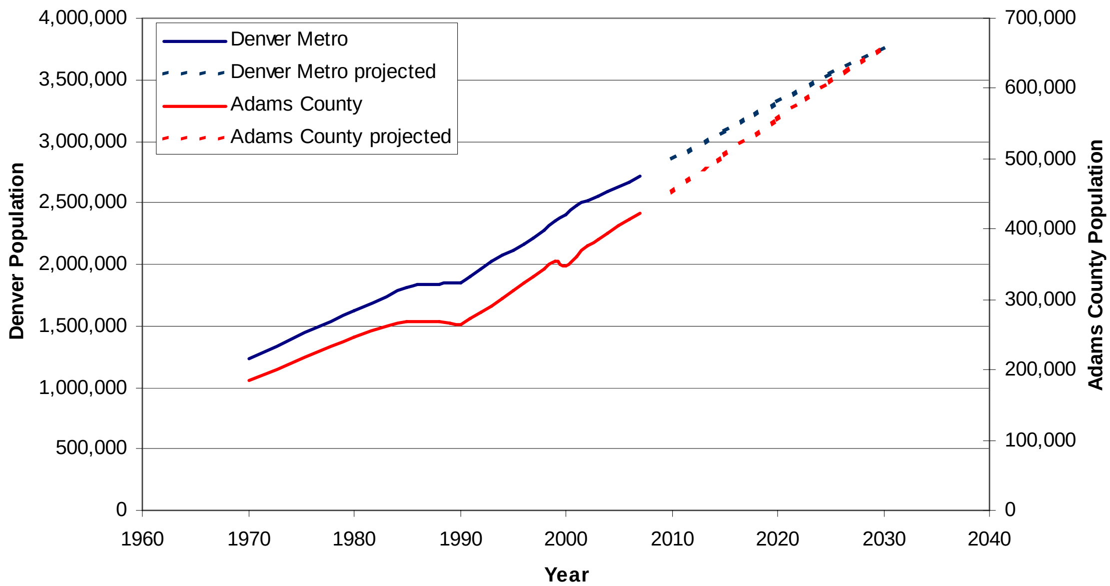

Figure 5.14. Past and projected future population growth for the City of Denver and for Adams County.

Source: MetroDenver EDC, 2006.

The population of Adams County, where the Arsenal is located, is projected to grow even faster (Figure 5.14). The Colorado Demography Section projects growth from an estimated 423,300 people in 2007 to about 660,000 by 2030, a 56% increase (MetroDenver EDC, 2006). Municipalities expected to realize the greatest growth include southern Adams County and the cities of Brighton, Thornton, Aurora, and Denver (DRCOG, 2005).

5.4.3 Efforts to find additional water supply near the Arsenal

Communities in the metropolitan Denver area invest heavily in the acquisition and development of water supplies, the creation of water storage, and distribution of water from the source area to the metro Denver area. Below are examples of projects in which communities near the Arsenal have participated. Given the effort and expense of these projects, it is clear that clean groundwater under the Arsenal in the past would have been, and in the future would continue to be, attractive to Front Range water suppliers.

- In 1982, Denver and 47 water providers in Denver, Adams, Arapahoe, Douglas, and Jefferson counties entered into the Metropolitan Water Development Agreement (MWDA) to design and construct water projects to meet increasing water demands. MWDA proposed the Platte and Colorado River Project Participation Agreement, also known as the Two Forks Project, in 1986, at a cost of $1 billion. The EPA vetoed the project, and the MWDA was forced to seek other alternative water supplies.

- Aurora is constructing the Prairie Waters Project (Figure 5.15), which will deliver 10,000 to 15,000 acre-feet per year at a capital cost of $800 million (Russell and Serlet, 2007). The project will be paid for, in part, by increasing user fees and tap fees.

- Brighton and SACWSD plan to acquire additional surface rights and to drill more alluvial wells to meet anticipated growth in demand. Water providers in both communities plan to meet augmentation requirements using surface water rights, including the Burlington Ditch, Fulton Ditch, and Wellington Reservoir (Leonard Rice Engineers, 2001; BBA, 2004). Brighton and SACWSD are two examples of water providers who use their surface water rights for augmentation in order to use alluvial groundwater in the South Platte River Basin as a drinking water supply.

- In 2004, Denver Water completed a 30-million gallon per day water recycling plant that treats wastewater for non-potable uses. The initial (Phase I) cost of the project was $95 million, including the infrastructure to deliver the water from the plant. When completed, the recycling plant will produce almost 19,000 acre-feet per year of reclaimed water for landscape irrigation, fire protection, and industrial and commercial uses (Denver Water, 2007). The Public Service Company plant located just a few miles west of the Arsenal uses about 5,400 acre-feet per year of the reclaimed water.

- To offset declines in the productivity of the Arapahoe aquifer in the South Metropolitan Denver area, East Cherry Creek Valley (ECCV) and other members of the South Metro Water Supply Authority will spend approximately $150 million for water rights and initial construction of the Northern Water Project (Figure 5.16; ECCV, 2007). The initial phase of the project, called the H2'06 Project, includes the purchase of rights to 3,000 acre-feet per year of South Platte River water for $45 million. Water will be stored in Beebe Draw, near Barr Lake (Figure 5.16). The cost to build two pumping stations and a 31-mile pipeline to deliver the water from Beebe Draw to ECCV is $74 million.

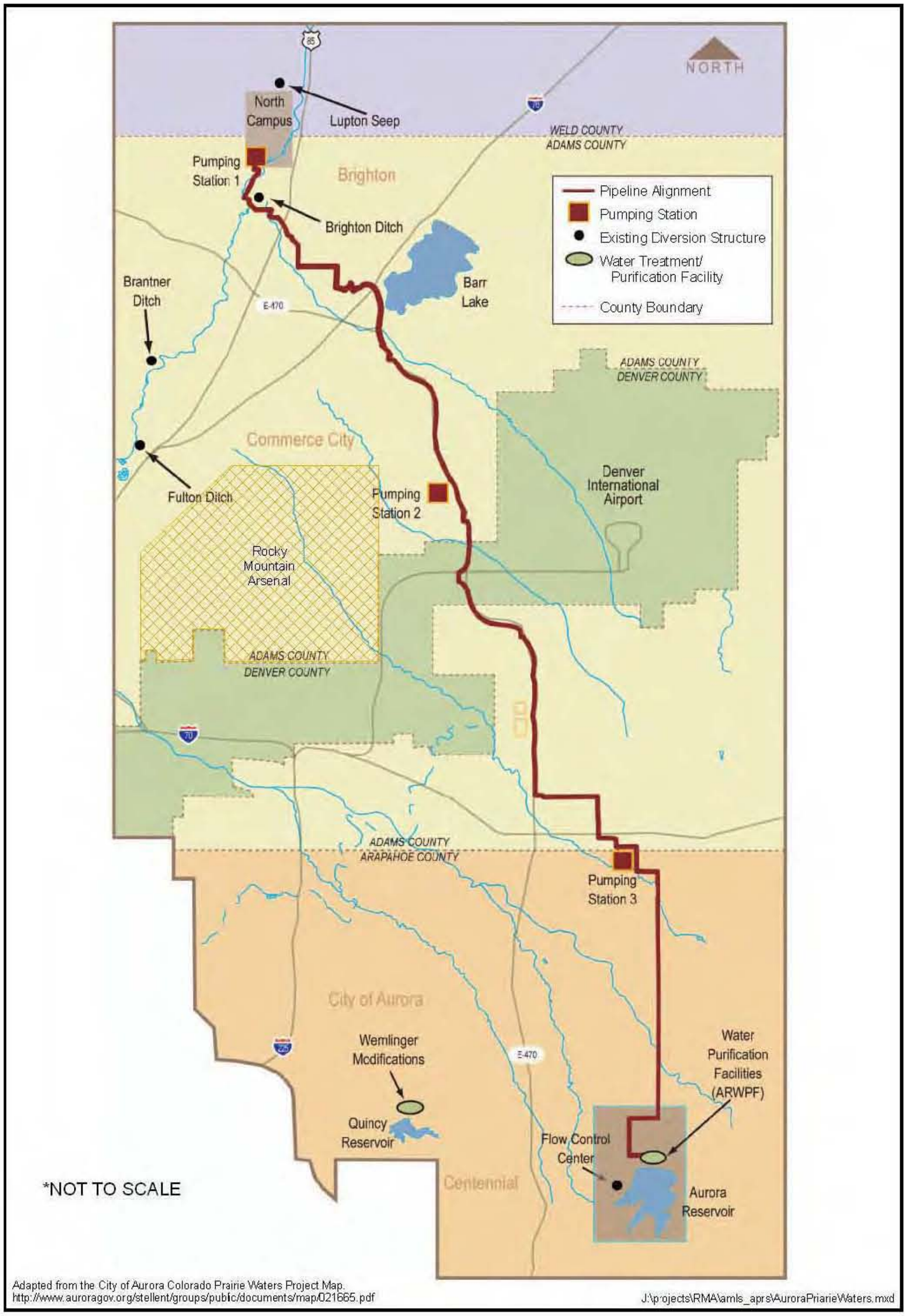

Figure 5.15. Aurora's Prairie Waters Project, currently under construction. South Platte River ditch and tributary groundwater will be pumped 38 miles south to the Aurora Reservoir.

Source: City of Aurora, 2007.

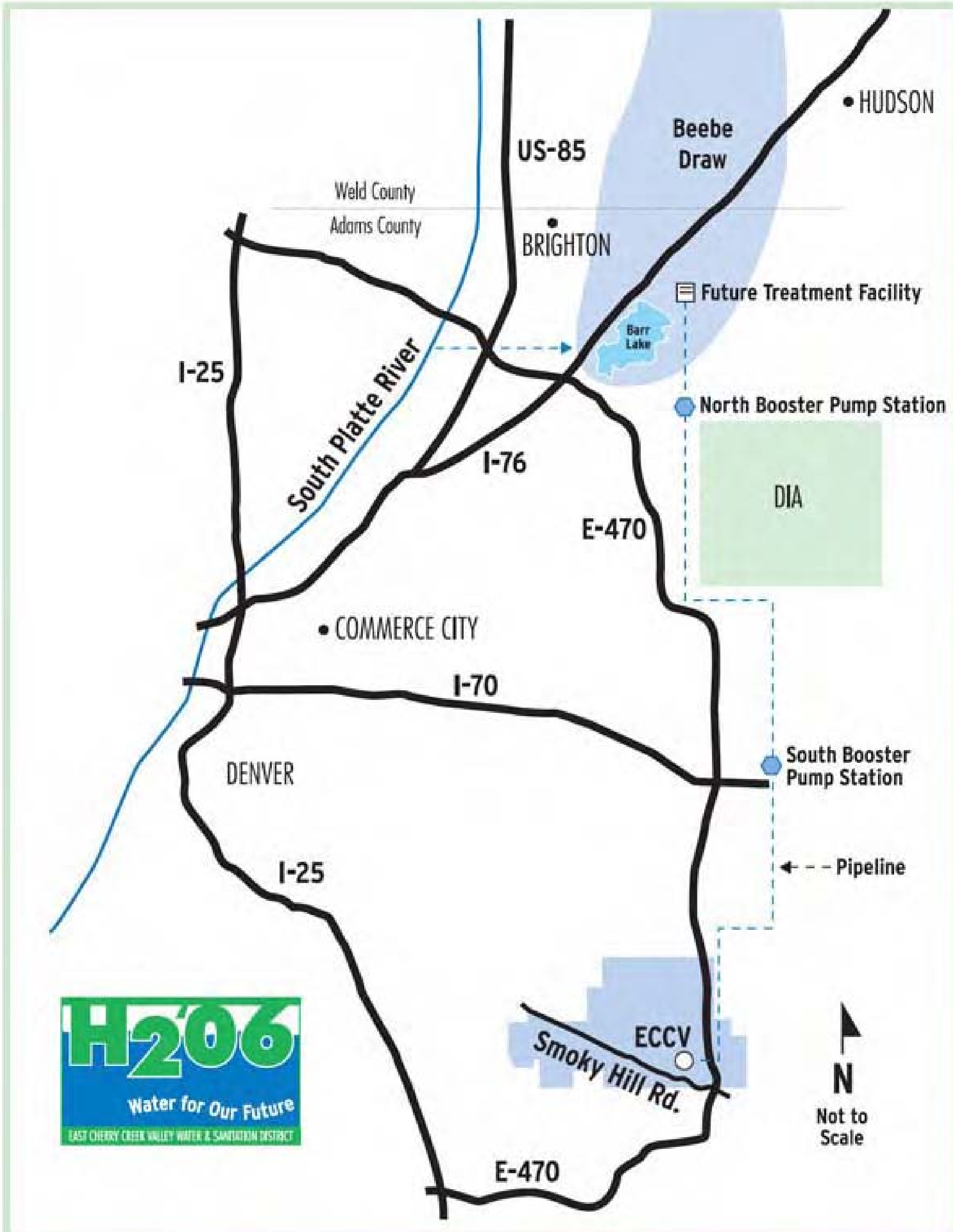

Figure 5.16. ECCV H2'06 project map. ECCV will store water in Beebe Draw and transport it south via a pipeline passing by the east boundary of the Arsenal.

Source: ECCV, 2007.

The scarce water supply in the Front Range requires water providers to encourage or require water conservation. Most water providers in the Denver Metropolitan Area provide their customers with educational materials on voluntary water conservation. In response to the 2002–2003 drought, when water levels in many reservoirs dropped to 50% or less of capacity, many Front Range cities, including Arvada, Aurora, Boulder, Brighton, Broomfield, Castle Rock, Centennial, Colorado Springs, Denver, Englewood, Erie, Ft. Collins, Golden, Greeley, Lafayette, Lakewood, Northglenn, South Adams County (Commerce City), Thornton, and Westminster enacted restrictions on water use (CSU, 2003). Water restrictions, for at least part of the summer, have become common since then (e.g., CSU, 2006).

In 2003, the Colorado Water Conservation Board (CWCB) commissioned the Statewide Water Supply Initiative to examine water supply needs in Colorado through the year 2030. For the South Platte River Basin, the study reported that water acquisition and conservation projects that water providers are implementing or planning to implement will meet approximately 80% of the projected water needs through 2030 (CWCB, 2004). Water providers in the South Platte River Basin plan to meet the increased demand with a combination of solutions, including conservation, water reuse, water transfers, enlargement of storage facilities, purchase of additional rights (including transfers from agricultural use), and new facilities (Table 5.9; CWCB, 2004). Figure 5.17 shows how far water providers reach to bring water to the Front Range. Even after accounting for all these projects, the CWCB concluded that a shortfall of some 90,600 acre-feet per year will remain, and water providers continue to search for solutions to address the projected shortfall.

5.4.4 Lost water supply services

Absent the presence of hazardous substances, groundwater underlying the Arsenal would have been an attractive water supply to surrounding communities, particularly because:

- Groundwater-derived water supply is more reliable and of higher quality than many other sources (Dennehy et al., 1998)
- Many water providers near the Arsenal already have surface water rights to use as augmentation to offset withdrawals from the Arsenal (e.g., SACWSD augmentation plan, [CO District Court W-8440-76])
- The Arsenal is much closer to existing water distribution systems than other sources of water that are currently being acquired and that have been acquired in the past (Figure 5.16).

Table 5.9. Selected plans to meet future water supply needs in the Front Range

Provider	Plans and processes	Source
Aurora	Prairie Waters Project: gravel storage near Brighton using existing rights; collector wells will recover the water from the alluvium; water will be pumped by three new pumping stations 34 miles to Aurora, then treated at a new facility near the Aurora Reservoir.	City of Aurora, 2007
Brighton	Purchasing land for augmentation water storage in Beebe Draw. Seeking additional storage in Chatfield Reservoir. Using lined gravel pits for storage along South Platte River. Applying in Water Court for augmentation plans that will allow pumping from alluvial wells. Well withdrawals will be augmented during times of river calls using municipal wastewater return flows, storage releases, and retired senior agricultural water rights. Constructing non-potable irrigation systems in parks.	City of Brighton, 2007
Denver	Seeking additional storage to maximize use of existing rights from Fraser River (Moffat Firming Project). Using lined gravel pits for storage along South Platte River. Constructed a Recycle Plant to treat wastewater for industrial use and non-potable irrigation water.	Denver Water, 2002, 2007; CWCB, 2004
Northglenn	Seeking additional storage to maximize use of existing rights.	CWCB, 2004
SACWSD	Plans to acquire additional surface rights and to drill more South Platte River alluvial wells. With Denver, using lined gravel pits for storage along South Platte River.	Denver Water, 2002
Thornton	Using gravel pits to develop water by either exchange or pump back. Applying in Water Court for augmentation plans that will allow pumping from alluvial wells. Planning construction of non-potable irrigation systems in parks.	CWCB, 2004; USACE, 2007
Westminster	Using lined gravel pits for storage. Expanding reclaimed water system. Transferring agricultural water rights.	CWCB, 2004
South Metro (providers in Arapahoe, Douglas, and Elbert counties)	Most municipalities and water district reliant on non-renewable deep groundwater. Most seeking renewable water supplies, including surface water and tributary groundwater. Examples: ECCV is purchasing South Platte River water rights and constructing a water treatment facility, pumping facilities, and pipelines (ECCV, 2007). Part of the water will be stored in Beebe Draw until needed, pumped from the ground, treated in the new facility near Barr Lake and Brighton, and pumped 31 miles south to the ECCV. Members of the South Metro Water Supply Authority, which serves adjacent communities, also joined the project. Parker Water and Sanitation District is constructing the Rueter-Hess Reservoir, intended to increase reliability of aquifers by storing surplus water and re-injecting this water into aquifers during non-peak demand. Parker has filed an application in Water Court to divert water from the South Platte River near Sterling and to pipe the water over 80 miles to Parker.	CWCB, 1999, 2004; Parker Water & Sanitation District, 2005; Kaunisto and Mullenix, 2006

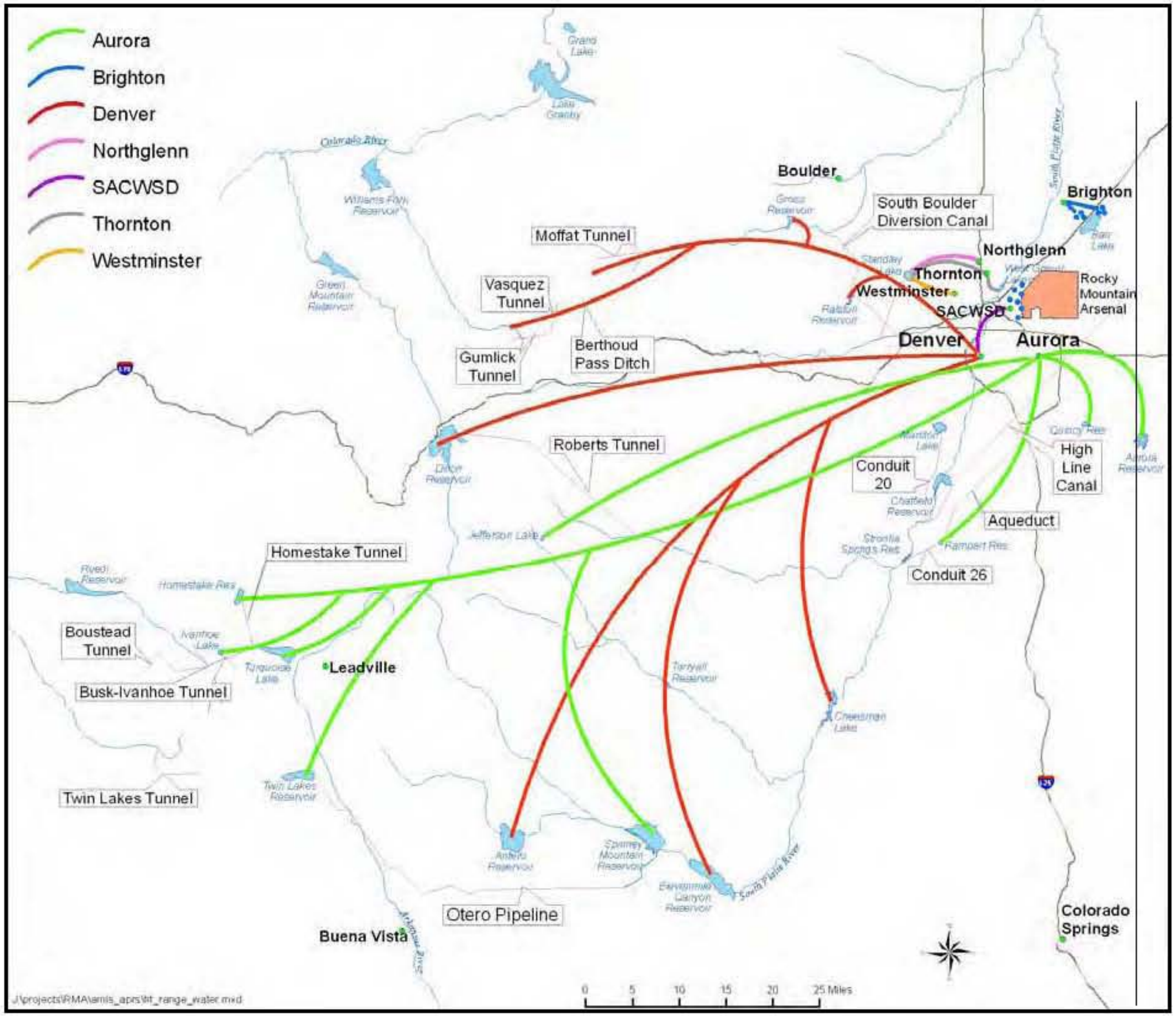

Figure 5.17. Examples of the distance that communities near the Arsenal have gone to obtain reliable water supplies.

When the Denver wastewater treatment plant contaminated Thornton's well field in the 1980s, Thornton's replacement water was surface water of impaired quality, stored in lined gravel ponds where the water could evaporate. Aurora and ECCV are spending tens of millions of dollars to pump alluvial groundwater from well fields near the Arsenal. For these municipalities, clean alluvial groundwater from the Arsenal would likely have been an attractive water source.

Groundwater in the immediate vicinity of the Arsenal (but unaffected by the releases of hazardous substances from the Arsenal) is currently in high demand. Figure 5.18 shows municipal wells near the Arsenal, as listed in the State Engineer's database. Although it is not known how many of the wells shown in Figure 5.18 are actively pumped, the map demonstrates that the groundwater in this area is a popular water source. Verification of the use of the wells shown in Figure 5.18 may be conducted as part of the assessment.

These facts demonstrate that there is and has been great demand for groundwater, particularly shallow alluvial groundwater, in the vicinity of the Arsenal. Despite the fact that surface water in the South Platte River Basin is over-appropriated, water providers in the basin have plans for securing water and for augmentation that will allow them to continue to meet consumer demands by developing additional tributary groundwater.

5.5 Anticipated Assessment Activities

The preliminary evaluation of groundwater injury described in Sections 5.2 and 5.3 is based on a USGS interpretation of the extent of plumes of hazardous substances in water year 1994. To help estimate injuries prior to and after 1994, additional groundwater modeling may be undertaken. Several other tasks may also be undertaken in this assessment to further quantify groundwater injury at the Arsenal. Depending on the modeling approach selected, the following tasks may be performed:

- Develop a groundwater distributed-parameter flow and transport model to calculate the spatial extent of groundwater injury in the past, present and future. This approach would use a model using the MODFLOW/MT3D or MODFLOW-SURFACT flow and transport codes, parameterized with site-specific hydrologic and chemical data. A MODFLOW-based groundwater model would likely provide the most robust tool for extrapolating the groundwater plume forward and backward in time when observational data are limited or unavailable.

- Develop a hazardous substance plume degradation/decay model to estimate the future spatial extent of groundwater injury. This empirical approach would rely on observed plume trends over time.

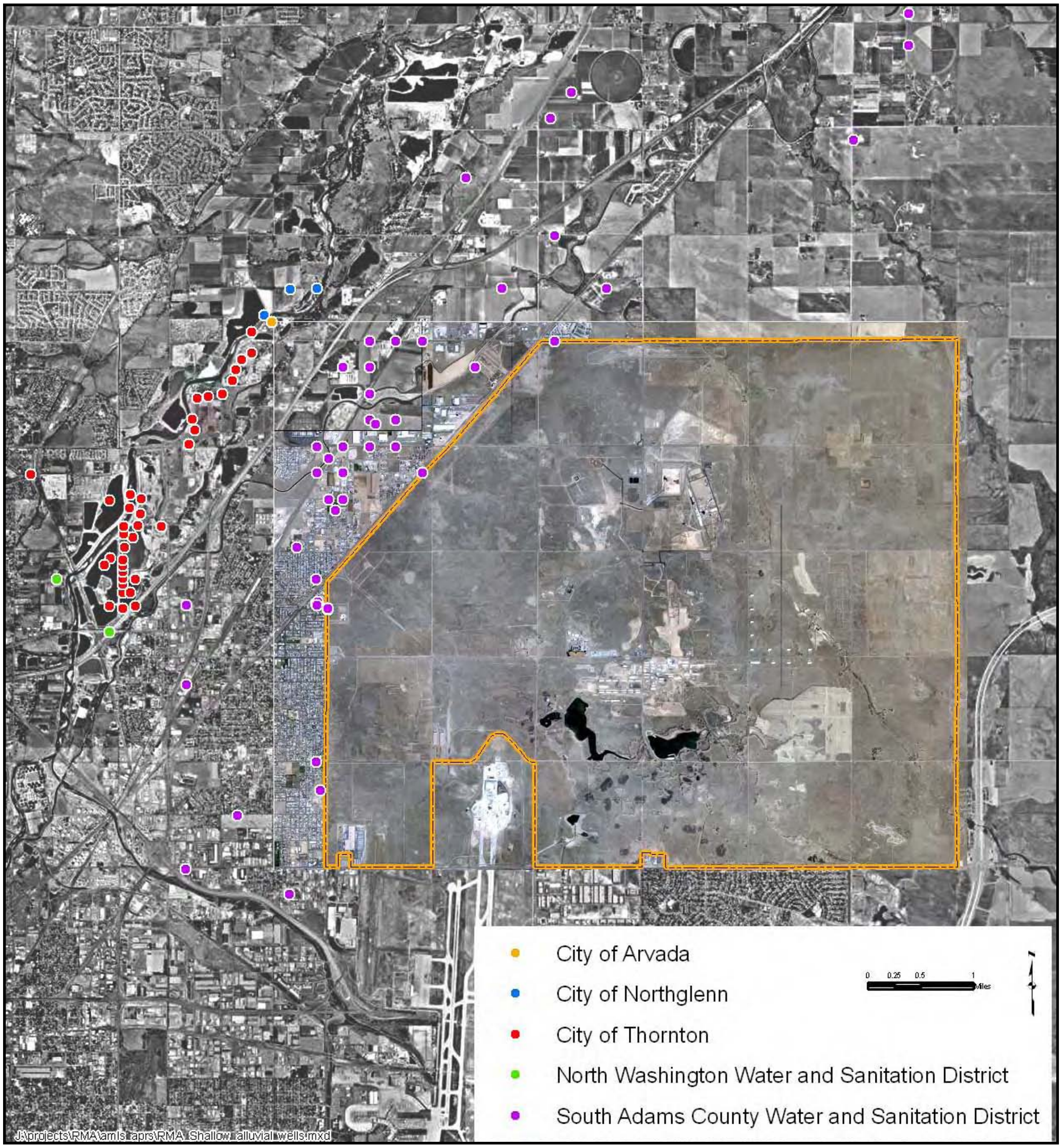

Figure 5.18. Wells near the Arsenal owned by municipal water suppliers. Data from the State Engineer's Office database. It is not known how many of these wells are currently in production. The assessment may include verifying the State Engineer's well data in this area.

- Evaluate groundwater contamination data collected since 1994 to estimate more recent contaminant plume and to calibrate any models of the plumes.

- Evaluate contaminated groundwater in the weathered upper Denver formation that is connected to and contaminated by the alluvial aquifer but is not included in preliminary estimates of groundwater contamination.

- Refine the estimate of alluvial groundwater that would have been available for municipal use absent the releases of hazardous substances and institutional controls:

  - Calculate the appropriate size of a buffer surrounding contaminant plumes
  - Calculate the annual recharge to the alluvial aquifer.

- Refine the estimates of nontributary and both categories of not-nontributary groundwater that would have been available for municipal use absent the releases of hazardous substances and institutional controls, and determine safe yields for each.

- Further delineate past, existing, and future uses of groundwater at and downgradient of the Arsenal.

- Determine whether deep groundwater was exposed to hazardous substances; and if so, quantify the affected volume.

Other activities related to quantification of groundwater injuries may occur as part of this assessment. If the Trustees decide to make substantial changes to this plan, such as conducting new sampling, a revision to this Plan will be made available for comment.

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6. Injuries to Biological Resources

This chapter reflects the State Trustees' current understanding regarding injury to biological resources at the Arsenal, and identifies proposed approaches for completing an injury assessment for these resources.

Biological resources are defined in the DOI regulations as "those natural resources referred to in Section 101(16) of CERCLA as fish and wildlife and other biota. Fish and wildlife include marine and freshwater aquatic and terrestrial species; game, non-game, and commercial species; and threatened, endangered, and State sensitive species. Other biota encompass shellfish, terrestrial and aquatic plants, and other living organisms not listed in this definition" [43 CFR § 11.14 (f)].

Outside the central facilities area, the Arsenal consists largely of undeveloped, open grassland. Approximately 20% of the site is currently native grassland, and the rest of the area consists of exotic grasses and forbs, wetlands, riparian woodlands, intermittent streams, and permanent lakes (USFWS, 1997). A wide variety of wildlife use or inhabit the site and has been exposed to contamination. Wildlife at the Arsenal includes fish, reptiles, amphibians, small and large mammals, and more than 200 species of birds (Environmental Science and Engineering, 1989). Injured wildlife includes species that are resident at the site year-round and migrant species that use other habitats outside the Arsenal. Migrants include local migrants such as red fox and coyotes, seasonal migrants such as over-wintering bald eagles, and short-term migrants that use the site during annual migrations.

Section 6.1 of this chapter provides a summary of conclusions. Section 6.2 describes biological resources at the site. Section 6.3 presents relevant injury definitions from the DOI NRDA regulations and their application to the Arsenal. Section 6.4 discusses baseline conditions at the Arsenal. Section 6.5 describes approaches for determining injury for different biological resources. Section 6.6 presents preliminary information relevant for injury quantification. Section 6.7 describes the State Trustees' planned assessment activities, and references are included at the end of this chapter.

6.1 Summary of Conclusions

As described in preceding chapters, much of the habitat at the Arsenal was historically contaminated with elevated concentrations of hazardous substances in soil, surface water, and sediments. In addition, exposure to highly contaminated wastes in disposal basins such as Basin F proved acutely lethal to thousands of waterfowl. Contaminants include the toxic pesticides aldrin, DBCP, dieldrin, endrin, and isodrin. Prior to remediation, the pesticide dieldrin was detected in surface soils across most of the Arsenal property (Rocky Mountain Arsenal Environmental Database, as described in Potomac Research International, 2006). The highest concentrations of dieldrin were found in the central area (Figure 6.1). Remediation of these areas, in accordance with the 1996 ROD, is anticipated to be complete in 2010.

The PASD and other preliminary observations indicate that injuries at the site include wildlife mortality, sub-lethal adverse effects, gamebird exceedences of U.S. Food and Drug Administration (FDA) safe levels for dieldrin, and exceedences of water quality criteria that are indicative of injuries to aquatic biota. These injuries have been reduced but not eliminated by past and ongoing remediation efforts. When completed, the remediation is expected to prevent any future biota exposures to harmful concentrations of hazardous substances.

In addition to injuries due to contamination exposure, some of the remedial activities themselves have caused injury, such as the construction of “biota barriers” to protect burrowing mammals from exposure to contamination in soils, and the excavation of borrow areas for the construction of landfill caps. Anticipated future assessment activities would expand the injury determination and quantify injuries and ecological service losses at the Arsenal.

Injury quantification will be used as inputs for a habitat equivalency analysis (HEA) or a resource equivalency analysis (REA), as described in Chapter 8. These approaches will allow the Trustees to determine the amount of restoration required to compensate for natural resource injuries at the Arsenal.

6.2 Biological Resources at the Arsenal

The Arsenal is located in the shortgrass prairie “ecoregion” in the Great Plains. The shortgrass prairie extends east from the Rocky Mountains and south from Montana into the high plains of Oklahoma, New Mexico, and Texas (Samson et al., 1998), and is characterized by ankle-high vegetation dominated by the characteristic grasses blue grama and buffalo grass. At a regional level, shortgrass prairie habitat is threatened by land conversion for urban development and agriculture (Neely et al., 2006). The Arsenal contains locally important habitat because of the extensive urban development that surrounds the site.

Within the Arsenal, there are three major habitat categories that each support different types of biological resources: upland prairie, perennial and intermittent surface water, and wetlands and riparian woodlands (Figure 6.2). The vast majority of the site (15,065 acres; 89% of total) is covered by prairie-type habitat, including weedy forbs and grasses, native perennial grasses, and shrubland/succulents. The area of surface water is limited (158 acres, 0.9%), but provides important habitat for waterfowl and other wildlife. Wetlands and riparian woodlands also cover a small area of the site (4%), but provide key habitat for wildlife, including large cottonwoods that are used as winter roosting sites for bald eagles (Table 6.1).

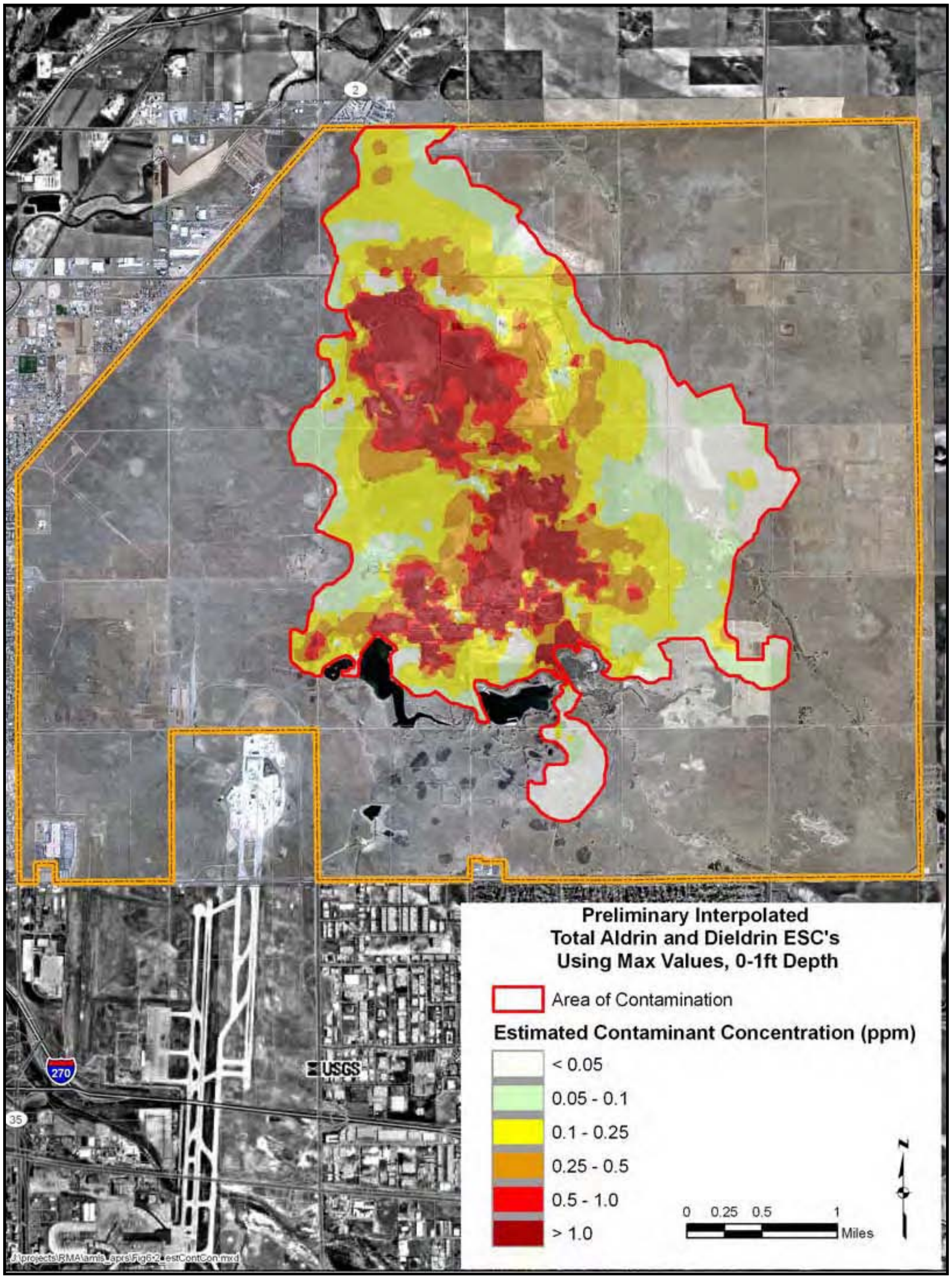

Figure 6.1. Estimated concentrations of aldrin and dieldrin in soils at the Arsenal before remediation.

Source data: BAS, 2002, Figure A1.6-2.

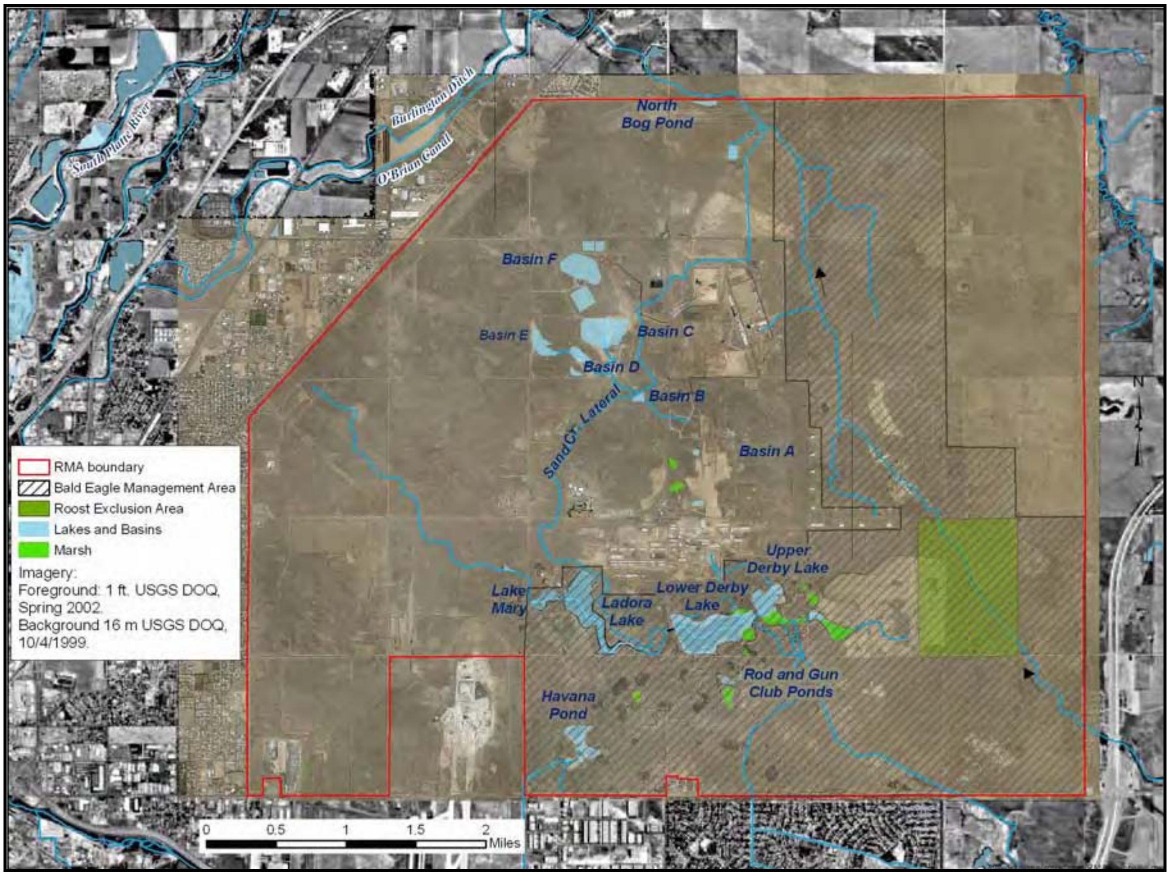

Figure 6.2. Map of the Arsenal showing major habitat features.

Table 6.1. List of habitat types at the Arsenal with associated acreages and percent of total area

Habitat type	Acres	Percent of site
Weedy forbs/grasses	10,002.1	58.9%
Native perennial grasses	4,032.3	23.8%
Shrubland/succulents	1,030.5	6.1%
Disturbed	458.2	2.7%
Wetlands	434.7	2.6%
Unclassified (e.g., Section 9 runway)	356.5	2.1%
Riverine/riparian	258.5	1.5%
Upland trees	240.6	1.4%
Lacustrine	157.9	0.9%
Total	**16,971.3**	**100%**
Source: Adapted from USFWS (1999).		

6.2.1 Upland prairie

The upland prairie at the Arsenal includes areas classified as weedy forbs and grasses, native perennial grasses, and shrubland/succulents. Resident or migrant species found in upland prairie habitat at the Arsenal include a wide variety of birds, reptiles, and mammals (Table 6.2).

Table 6.2. Examples of species found in prairie habitat at the Arsenal

Wildlife category	Functional group	Species
Birds	Raptors	Bald eagle, sharp-shinned hawk, Cooper's hawk, Swainson's hawk, red-tailed hawk, ferruginous hawk, golden eagle, American kestrel, merlin, prairie falcon
	Breeding songbirds	Western meadowlark, horned lark, grasshopper sparrow, vesper sparrow, lark sparrow, lark bunting
	Game birds	Pheasant, mourning dove
	Migrants	Brewer's sparrow, clay-colored sparrow, Cassin's sparrow, chestnut-collared longspur
Reptiles	Snakes	Bull snake, rattlesnake, hognose snake
Mammals	Rabbits and hares	Eastern cottontail, desert cottontail, black-tailed jackrabbit
	Rodents	Black-tailed prairie dog, Northern pocket gopher, many species of mice and voles
	Carnivores	Coyote, red fox, least shrew, badger
	Ruminants	Mule deer, white-tailed deer

Sources: Morrison-Knudsen Environmental Services, 1989b; Denver Audubon Society, 1994; USFWS, 1994a, 1994b.

6.2.2 Perennial and intermittent surface water

Both perennial and intermittent bodies of water exist on or flow across the Arsenal (Figure 6.2). The Lower Lakes at the Arsenal (also called the "south lakes") are man-made: they include Lakes Mary, Ladora, Upper Derby, Lower Derby, and Rod and Gun Club Pond(s). Two natural ponds are also found on the Arsenal: North Bog Pond is on the northern edge of the Arsenal, and Havana Pond is on the southern edge. First Creek is the only natural stream at the site, but many man-made canals, including the Highline Lateral, Sand Creek Lateral, Uvalda Interceptor, and Havana Interceptor, also transported water at the site. First Creek is 5.9 miles long and is semi-perennial, with 39 acres of associated wetlands. It flows during the majority of the year in non-drought years (Ebasco Services et al., 1989), and discharges to O'Brian Canal approximately one-half mile north of the site. The creek and its associated wetland area pre-date the Arsenal. The size of the wetland and open water areas fluctuates based on hydrologic conditions and on manipulations by site personnel. Some of the wetland areas are ephemeral, particularly in dry years.

The water bodies on the Arsenal currently support a variety of organisms (Table 6.3). Phytoplankton, micro- and macro-zooplankton communities, and other aquatic plants known as macrophytes, as well as invertebrates, fish, and birds, are found in the Lower Lakes (BAS, 2003). Aquatic plants help provide habitat for aquatic invertebrates, fish, and water birds. Aquatic invertebrates are an important food source for fish, amphibians, reptiles, and birds. Fish populations at the Arsenal are primarily maintained by USFWS stocking from off-site hatcheries, although some species are able to reproduce. Reptiles, amphibians, waterfowl, and wading birds also make use of surface water resources at the Arsenal.

Table 6.3. Examples of species found in perennial and intermittent surface water at the Arsenal

Organism category	Species
Aquatic plants	American pondweed, leafy pondweed, sago pondweed, water-milfoil, watercress, water plantain, arrowhead, sedges, rushes, cattail, coontail
Aquatic invertebrates	Snails, dragonflies, damselflies, midges, crayfish
Fish	Rainbow trout, largemouth bass, smallmouth bass, northern pike, black crappie, bluegill, channel catfish, black bullhead, green sunfish, carp, yellow perch
Reptiles	Bullsnake, western hognose snake, common garter snake, western terrestrial garter snake, yellow-bellied racer, plains garter snake, rattlesnake, lesser earless lizard, short-horned lizards, many-lined skink
Birds – waterfowl	Canada goose, mallard, gadwall, blue-winged and green-winged teal, pintail, wigeon, shoveler, redhead, canvasback, ring-necked duck, lesser scaup, common goldeneye, bufflehead
Birds – wading birds	Great blue herons, black-crowned night herons, white pelican
Amphibians	Tiger salamander, plains spadefoot toad, Woodhouse’s toad, striped chorus frog, bullfrog, northern leopard frog

Sources: Morrison-Knudsen Environmental Services, 1989a, 1989b; USFWS, 1994a; BAS, 2003.

6.2.3 Wetlands, riparian woodland, and upland trees

For the purpose of this Assessment Plan, wetlands and riparian woodland habitat are distinguished from surface water areas. Substantial overlap of wildlife species is expected between the two habitat types because fluctuations in surface water levels can result in areas classified as surface water taking on the characteristics of wetlands. The wetlands and riparian woodland habitats currently support a variety of resident and migrant semi-aquatic and terrestrial organisms (Table 6.4). Migrant diversity through woodlands and upland groves is high: 33 migrant bird species have been noted, with yellow-rumped and yellow warblers, house wrens, and chipping sparrows the most common (Morrison-Knudsen Environmental Services, 1989b). Riparian woodland habitat includes large galleries of cottonwoods along intermittent stream channels and ditches. This habitat is somewhat rare in arid prairie environments and is very valuable for the over-wintering bald eagles that use the trees as roosts (USFWS, 1992).

Table 6.4. Examples of species found in wetlands, riparian woodland, and upland tree habitat at the Arsenal

Wildlife category	Habitat	Species
Birds	Wetlands	White pelican, double-crested cormorant, avocet, killdeer, sandpiper, white-faced ibis, migrant rail, migrant Wilson's phalarope, great blue heron, black-crowned night-heron, bobolink, marsh wren sandpiper, herring gull, ring-billed gull, Franklin's gull
	Marshes and wet meadows	Common yellow throat, red-winged blackbird, yellow-headed blackbird, song sparrow, grebe, American coot, common snipe, Virginia and sora rail, Canada goose, and a variety of ducks
	Riparian woodlands and upland groves	House wren, yellow-rumped and yellow warbler, chipping sparrow, American goldfinch, yellow-billed cuckoo, common nighthawk, downy woodpecker, western wood-peewee, violet-green swallow, blue jay, black-capped chickadee, gray catbird, red-eyed vireo, warbling vireo, black-headed grosbeak, blue grosbeak, indigo bunting, lazuli bunting, rufous-sided towhee
	Upland groves	Northern flicker, western kingbird, eastern kingbird, black-billed magpie, American robin, northern mockingbird, loggerhead shrike, lark sparrow, starling, Brewer's blackbird, common grackle, northern oriole, lesser goldfinch, house finch, house sparrow
Amphibians	Wetlands, floodplains	Northern chorus frog, great plains toad
Mammals	Riparian woodlands	Eastern cottontail, white-tailed deer, red fox, raccoon, fox squirrel, beaver, muskrat, badger, mink, and weasel
Reptiles	Wetlands and moist areas	Common garter snake, western terrestrial garter snake, western box turtle, racer snake, common and plains garter snake
Sources: Morrison-Knudsen Environmental Services, 1989b; USFWS, 1992		

In addition, a small area of upland trees (241 acres; 1.4%) was planted at the Arsenal by settlers. A number of bird species nest in this habitat (Table 6.4).

6.3 Injury Definitions

DOI regulations state that "an injury to a biological resource has resulted from the . . . release of a hazardous substance if the concentration of the substance is sufficient to:

- Cause the biological resource or its offspring to have undergone at least one of the following adverse changes in viability: death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions (including malfunctions in reproduction), or physical deformations [43 CFR § 11.62(f)(1)(i)]

- Exceed action or tolerance levels established under section 402 of the Food, Drug and Cosmetic Act, 21 USC 342, in edible portions of organisms [43 CFR § 11.62(f)(1)(ii)]

- Exceed levels for which an appropriate State health agency has issued directives to limit or ban consumption of such organism [43 CFR § 11.62(f)(1)(iii)].

The DOI regulations then go on to state that an injury can be demonstrated "if the biological response under consideration can satisfy all of the following acceptance criteria" [43 CFR § 11.62(f)(2)]. These criteria are:

- The biological response is often the result of exposure to . . . hazardous substances . . . [43 CFR § 11.62(f)(2)(i)]

- Exposure to . . . hazardous substances is known to cause this biological response in free-ranging organisms . . . [43 CFR § 11.62(f)(2)(ii)]

- Exposure to . . . hazardous substances is known to cause this biological response in controlled experiments . . . [43 CFR § 11.62(f)(2)(iii)]

- The biological response measurement is practical to perform and produces scientifically valid results . . . [43 CFR § 11.62(f)(2)(iv)].

In addition, DOI regulations list a number of biological responses that satisfy the criteria stated above. For the injury category of death, "biological responses" that meet the criteria for demonstrating that death resulted from exposure to hazardous substances include [43 CFR § 11.62(f)(4)(i)]:

- Brain cholinesterase (ChE) enzyme activity that has been inhibited by at least 50% compared to the mean for normal brain ChE activity for the wildlife species

- Wildlife kill investigations that indicate increased number of dead or dying birds or mammals

- Laboratory or field toxicity testing that reveals increased mortality.

For the injury category of behavioral abnormalities, the relevant biological response that has been found to meet the criteria is [43 CFR § 11.62(f)(4)(iii)]:

- Increased clinical behavioral signs of toxicity in the exposed population.

For the injury category of physiological malfunctions, the biological responses that have been found to meet the criteria include [43 CFR § 11.62(f)(4)(v)]:

- Eggshell thinning resulting from the adult bird having assimilated the hazardous substance
- Reduced avian reproduction
- ChE enzyme inhibition
- Delta-aminolevulinic acid dehydratase (ALAD) inhibition.

For the injury category of physical deformation, the biological responses that have been found to meet the criteria include [43 CFR § 11.62(f)(4)(vi)]:

- Overt external malformations
- Skeletal deformities
- Internal whole organ and soft tissue malformation
- Histopathological lesions.

In addition, according to DOI regulations, "injuries that are reasonably unavoidable as a result of response actions taken or anticipated" at a site are natural resource injuries for which damages can be recovered [43 CFR § 11.15(2)(1)]. Chapter 3 discussed response actions and remediation activities at the Arsenal. Section 6.5.4 provides a preliminary analysis of how specific response actions and remediation activities at the Arsenal have injured biological resources.

6.4 Baseline

For the purposes of defining injuries to biological resources, the baseline condition for the Arsenal is assumed to be a clean Army facility converted to a Wildlife Refuge. It is assumed the Refuge would have been created regardless of whether hazardous substances were released. Because baseline is assumed to be the Arsenal facility absent the releases of hazardous substances, impacts to wildlife from facilities and infrastructure on-site will not be included as part of the biological resource injury assessments. Only wildlife and habitat injuries resulting from the releases of hazardous substances and responses to those releases will be quantified. This assumption recognizes that the Arsenal was an industrial facility developed in a location with a history of agricultural use. Infrastructure such as buildings and roads reduced or eliminated wildlife habitat regardless of hazardous substance releases, while other infrastructure such as surface water impoundments may have increased wildlife diversity. Under baseline conditions, it is assumed that this infrastructure would have existed with no releases of hazardous substances.

To evaluate injuries to wildlife from the hazardous substance releases, the Trustees may compare Arsenal data to data from control sites that represent baseline conditions. For example, evaluations of body burdens of contaminants in organisms might take into account background levels of contamination found in organisms at uncontaminated sites. Baseline conditions are discussed in more detail in subsequent sections.

6.5 Approaches for Determining Injury

The State has identified existing data that can be evaluated for each of the main categories of injury: exceedence of federal action levels for contaminants in edible portions of organisms, exceedence of levels that trigger consumption advisories, and exceedence of levels sufficient to cause adverse changes in viability, including wildlife kills. The Trustees included evidence of injury for biological resources in perennial and intermittent surface water. Each category is discussed further below.

6.5.1 Exceedence of FDA action levels in organisms

Injuries to wildlife occur when concentrations of hazardous substances in edible portions of an organism exceed FDA action or tolerance levels for safe consumption. Although the FDA exerts authority over domesticated poultry and not over wild gamebirds, exceedences of action levels for poultry are indicative of injuries to gamebirds.

Concentrations of dieldrin found in four different species of commonly consumed gamebirds at the Arsenal have exceeded the FDA action level of 0.3 milligrams per kilogram (mg/kg) for dieldrin residues in fatty tissue (Food Safety and Inspection Service, 1998) (Table 6.5). Moreover, the data shown in Table 6.5 were from carcasses (whole body) and muscle tissues. These concentrations would likely underestimate the concentrations of dieldrin in fatty tissue, which tends to have the greatest concentration of assimilated pesticide.

In addition, dieldrin concentrations in five largemouth bass samples from Lower Derby Lake in 1988 ranged from 0.067 to 0.644, with a mean concentration of 0.375 mg/kg (Environmental Science and Engineering, 1989, Table 4.3-5). This mean concentration exceeds the FDA action level of 0.3 mg/kg dieldrin for human consumption of fish (FDA, 2000).

Table 6.5. Examples of dieldrin concentrations in gamebirds at the Arsenal in excess of the FDA level of 0.3 mg/kg for poultry

Species	Tissue type	Maximum concentration (mg/kg)
Mallard	Adult carcass	4.53
Mallard	Juvenile carcass	0.52
Ring-necked pheasant	Juvenile carcass	1.33
Ring-necked pheasant	Adult carcass	2.92
Redhead	Muscle	0.32
American coot	Muscle	1.77

Source: Environmental Science and Engineering, 1989, Tables 4.3-1 and 4.3-2.

6.5.2 Exceedence of levels sufficient to trigger consumption advisories

Concentrations of hazardous substances in fish and wildlife at the Arsenal are sufficient to have triggered a ban on consumption. Elevated concentrations of pesticides in fish at the Arsenal led to the imposition of a catch-and-release policy in 1978, and a consumption ban for fish from the Arsenal lakes in 1984 (BAS, 2003). Consumption of all fish and wildlife was prohibited in the 1989 Federal Facilities Agreement, and these prohibitions were subsequently incorporated into the Arsenal National Wildlife Refuge Act of 1992. These bans indicate that fish resources and wildlife resources at the Arsenal have been injured by exposure to hazardous substances released at the site.

6.5.3 Adverse changes in viability

Concentrations of hazardous substances in biological resources have been sufficient to cause adverse changes in the viability of the organisms. In addition, extensive wildlife kills have been documented at the Arsenal. The State Trustees conducted a preliminary evaluation of these biological injuries by (1) collecting evidence related to wildlife kills, and (2) comparing the estimated exposure of wildlife at the Arsenal to toxicity benchmarks and injury thresholds for organochlorine pesticides.

This section is organized as follows: First, background is provided on the toxic effects of organochlorine pesticides. Next, available information on wildlife kills is described. Finally, toxicity benchmarks, injury thresholds, and exposure modeling are discussed and a comparison is made between estimated exposure levels and potential injury thresholds.

6.5.3.1 Toxicity of organochlorine pesticides

Many of the injuries to wildlife at the Arsenal have been caused by exposure to organochlorine pesticides, particularly the class of pesticides known as cyclodienes. Cyclodiene pesticides include aldrin, dieldrin, chlordane, endrin, and isodrin. Other injuries likely have been caused by pesticides from the class known as dichlorodiphenylethanes. This class includes DDT and associated metabolites DDE and dichlorodiphenyldichloroethane (DDD). Both classes of pesticides affect the neurological system of organisms by interfering with ion movements across nerve cell membranes (ATSDR, 1993, 1994, 1996, 2002). In birds and mammals, symptoms of toxicity include rigid paralysis, convulsions, respiratory failure and death. Emaciation is another characteristic symptom of organochlorine poisoning.

Over time, organochlorine pesticides have the potential to accumulate in fat deposits within a living organism and eventually reach toxic levels. These chemicals also tend to “biomagnify” up the food web, meaning that a top carnivore, for example, will accumulate the pesticide present in prey items. Therefore, lower concentrations of pesticides in prey items can become magnified into high concentrations in top predators. In addition, when organisms mobilize their fat stores during times of stress such as migration, they can be poisoned by the pesticides that are released into their circulatory system, even if the actual consumption of the pesticides happened days, weeks, or months previously (e.g., Henriksen et al., 1996).

The organochlorine pesticides discussed here all affect the neurological system in their toxic mode of action; thus the toxicity of multiple compounds may be additive. Additive toxicity means that the toxicity of a mixture of compounds will be approximately equal to the sum of the individual toxicities for each chemical present in the mixture. For example, the literature reports field collections of 425 birds killed by mixtures of dieldrin and chlordane at levels below the demonstrated lethality of either compound (Stansley and Roscoe, 1999). Additive toxicity in bobwhite quail also was reported based on feeding trials with chlordane and endrin (Ludke, 1976). An approach to evaluate the toxicity of compound mixtures is particularly important at the Arsenal, given the presence of multiple organochlorine pesticides that have been produced and identified at the site.

6.5.3.2 Evidence of wildlife kills

Wildlife mortality from chemical poisoning at the Arsenal was reported by the USFWS as early as 1951 (Finley, 1959), and continued at least through 1999 (USFWS, 2000). This mortality is consistent with numerous published accounts that describe poisoning of birds and other wildlife from agricultural use of aldrin and dieldrin. The introduction in 1956 of aldrin and dieldrin in the United Kingdom as seed treatments resulted in immediate poisonings of birds, particularly wood pigeons (*Columba livia*) and pheasants (*Phasianus colchicus*) (Peakall, 1996). Those poisonings involved hundreds of incidents a year and thousands of individual birds. The deaths continued unabated until use of dieldrin as a wheat seed treatment was discontinued in 1975. At the Arsenal, other chemicals in addition to aldrin and dieldrin would have contributed to mortality.

The following sections give a brief overview of some of the reports of fish and wildlife mortality This is not a comprehensive review of all mortality data from the site.

1950s–1980

These injuries predate the enactment of CERCLA in 1981 and will not be included in the injury quantification for the site. However, they provide evidence of pesticide poisonings at the Arsenal.

- An estimated 1,200 ducks died in the spring of 1952 at the Lower Lakes. The USFWS reported that "experiments indicated that the cause of death was a toxic agent or agents carried on the surface of the water and probably entering the lakes through the process-water drain from the chemical plant area" (Finley, 1959, p. 1).

- In April 1959, 119 dead birds and animals were counted on a single day around the shore of Lake Ladora. An interview with a Shell employee revealed that he had gathered approximately 500 dead ducks for burial during the first three months of 1959 (Finley, 1959, p. 3).

- The USFWS stated that 2,000 ducks would be a conservative annual estimate of duck mortality in the Lower Lakes area, with 20,000 or more ducks dying over a 10-year period (Finley, 1959). The report noted that high wildlife mortality occurred at the lakes when extensive mud flats were exposed. In addition, the USFWS reported that Upper Derby, Lower Derby, and Ladora Lakes did not support fish, amphibians, or aquatic insects.

- At the Lower Lakes, more than 100 ducks were found dead on March 28, 1962, and 163 waterfowl deaths were reported between January and May 1966 (Environmental Science and Engineering, 1989, Table 1.3-1).

- In 1964, the Army removed contaminated sediments from Upper and Lower Derby Lakes and Lake Ladora, and waterfowl mortality declined from previous years. According to the Biota Remedial Investigation, "In subsequent years waterfowl and other wildlife continued to be found dead at the Lower Lakes but in smaller numbers" (Environmental Science and Engineering, 1989, p. 4-7).

- In a two-week period in early April 1973, approximately 750 dead ducks and grebes were collected from the area of Basin F in three visits, with several hundred additional carcasses observed on June 13 and 14, 1973 (Ward and Gauthier, 1973). The death of 136 ducks occurred in April 1973 at Basin C (Environmental Science and Engineering, 1989, Table 1.3-1).

- During two days in May 1975, 291 bird carcasses were removed from the shoreline of Basin F, including waterfowl, raptors, pheasants, and songbirds (Environmental Science and Engineering, 1989, Table 1.3-1).

- In June 1976, a die-off of juvenile starlings was noted at a roosting location on the Arsenal, outside of the contaminated basins area (Olds, 1976).

- Deaths of a great horned owl, five hawks, a coyote, and starlings were reported between 1976 and 1979 (Environmental Science and Engineering, 1989, Table 1.3-1).

- On May 7, 1980, the DOW, accompanied by the USFWS, inspected the perimeter of Basin F and found 389 wildlife carcasses, including 344 waterfowl, 40 birds other than waterfowl, and 5 small mammals (Seidel, 1980).

- An additional 49 waterfowl carcasses were collected at Basin F between October and December 1980 (Environmental Science and Engineering, 1989, Table 1.3-1).

In addition to waterfowl deaths, fish kills and amphibian deaths have been reported at the Lower Lakes:

- An unpublished USFWS report found an absence of frog choruses, egg masses, and tadpoles at the Lower Lakes in 1960 (USFWS, 1961).

- Stocking of channel catfish, bluegill, and northern pike in Lake Ladora in 1967 and 1968 was unsuccessful: only a single fish was caught in three 48-hour gill net attempts in 1968 (BAS, 2003).

- Catfish stocking in Lower Derby Lake in 1968 also was unsuccessful. A fish kill of largemouth bass, bluegill, and catfish was noted on May 16, 1973, following the release of aldrin into lake waters (Environmental Science and Engineering, 1989, Table 1.3-1).

- Death of rainbow trout in the Lower Lakes was noted on April 18, 1977 (Environmental Science and Engineering, 1989, Table 1.3-1).

Bird hazing devices, including flashing light pontoons, repeating-fire "Zon" guns, and "Avalarms," were installed around Basin F in 1975 in an attempt to reduce bird mortality (Environmental Science and Engineering, 1989, p. 4-4). In 1980, these devices were found to be inoperable during field inspections by the USFWS. In addition, USFWS personnel observed waterfowl landing and taking off from Basin F even when the devices were operating (Grieb, 1981).

1981–1988

Substantial wildlife mortality at the Arsenal continued in the 1981–1988 time period. Regular quarterly waterfowl mortality counts were conducted at Basin F from 1981 to 1987, and between 139 and 444 dead birds were found each year (Table 6.6). An IRA at Basin F in 1988, which moved contaminated liquids to storage tanks and lined holding basins, and covered the basin site with a clay cap, ended direct waterfowl mortality from exposure to contaminated liquid waste at Basin F.

Table 6.6. Reported waterfowl mortalities at Basin F (1981–1987)

Year	Number found dead
1981	202
1982	222
1983	444
1984	418
1985	140
1986	236
1987	139
Total	1,801

Source: Environmental Science and Engineering, 1989, Table 4.1-1.

1989–1999

Between 1989 and 1999, wildlife mortality data at the Arsenal were gathered through three programs: the fortuitous specimen program, the Building 111 program, and the avian mortality program. These sampling and collection programs indicate that substantial wildlife mortality continued at the Arsenal through 1999.

- From 1989 to 1993, 192 bird samples and 52 mammal samples were collected at the Arsenal by the USFWS as "fortuitous specimens" because the animals were either dead or dying (CDPHE, 1994). Bird species collected represented more than 30 different species, including raptors, waterfowl, and passerines.

- The 1999 USFWS Annual Progress Report for the Rocky Mountain Arsenal (USFWS, 2000) provides a cumulative list of the bird species for which mortalities were attributed to dieldrin or endrin poisoning between 1990 and 1998. A total of 102 bird mortalities in 19 species were attributed to dieldrin or endrin poisoning (USFWS, 2000, Table 1.8). The report also noted that "several birds had pronounced keels and displayed other symptoms of dieldrin poisoning" (USFWS, 2000, p. 28). A pronounced keel indicates emaciation.

These mortality reports are likely to underestimate substantially the total amount of wildlife mortality at the site caused by pesticide poisoning. For example, a bird that died from a collision with a building or power line would not be attributed to pesticide poisoning, even if exposure to pesticides decreased the bird's ability to avoid the obstacles. Interestingly, the USFWS reported that more birds were found dead at the Arsenal after periods of cold or foul weather, and dead birds were often emaciated (USFWS, 1997). These observations are consistent with the biological mechanisms and toxicokinetics of organochlorine pesticides.

The evidence presented above indicates that organochlorine pesticides have been the causative agent in wildlife mortalities from the mid-1950s through at least 1999.

6.5.3.3 Concentrations of pesticides in animal tissues above mortality thresholds at the Arsenal

In 1994, the USFWS developed guidelines for diagnosing contaminant-related deaths of birds at the Arsenal (USFWS, 1995, 1996, p. 1-35). Under these guidelines, mortality or morbidity of birds with brain levels of dieldrin greater than 9 mg/kg was attributed to dieldrin poisoning, while birds with clinical signs diagnostic of dieldrin poisoning, or with supporting necropsy data and brain dieldrin levels between 5 and 9 mg/kg, were considered evidence of suspected dieldrin poisoning. Levels of brain dieldrin of 1–5 mg/kg indicate a dangerous level of exposure, but it is likely that other factors contributed to or caused the death of the bird. Endrin was considered to be lethal at 0.8 mg/kg in the brain (USFWS, 1998, p. 6). The USFWS also appeared to apply these same diagnostic criteria to other animals collected through the fortuitous specimen program (USFWS, 1998).

As discussed previously, the number of mortalities attributed to dieldrin or endrin poisoning based on the USFWS guidelines is likely to be a substantial underestimate of the total number of mortalities resulting from pesticide exposure because of the additive toxicity of related organochlorine pesticides, among other reasons.

Tissue data available for dead or dying birds collected since 1955 indicate that bird tissue concentrations were high enough to cause or contribute to mortality.

- Chemical analysis in 1955 of a dead duck from the Lower Lakes revealed 261 mg/kg dieldrin in fat tissue and 32.7 mg/kg dieldrin in the liver (Jensen, 1955, p. 3).

- Chemical analysis of three ducks in 1959 found dieldrin concentrations between 30 and 64 mg/kg (Finley, 1959, Table 1).

- In 1982, 1 great blue heron, 1 black-billed magpie, 1 European starling, and 2 Brewer's blackbirds had dieldrin concentrations in brain tissue above 5 mg/kg, with additional specimens having brain concentrations between 1 and 5 mg/kg (McEwen, 1983).

- Between 1986 and 1988, contaminant analysis was completed for 5 ferruginous hawks, 3 red-tailed hawks, 4 great-horned owls, 2 golden eagles, and 2 mourning doves found dead (Environmental Science and Engineering, 1989, p. 4-37, p. 4-50). Contaminant levels in brain tissues of raptors ranged from < 0.175 to 15.6 mg/kg dieldrin and 0.475 to 10.3 mg/kg DDE. Both golden eagles and one ferruginous hawk had brain tissue dieldrin levels below detection. One additional ferruginous hawk had brain tissue dieldrin of less than 1 mg/kg. Two ferruginous hawks had brain tissue dieldrin levels between 5 and 9 mg/kg, and one ferruginous hawk, two red-tailed hawks, and two great horned owls had brain tissue dieldrin levels of more than 9 mg/kg. Brain tissue dieldrin was not reported individually for the remaining great horned owl and red-tailed hawk, but summary statistics indicate that one of these two samples had brain tissue dieldrin of 15.6 mg/kg.

Because many of the samples of dead wildlife were collected opportunistically, the actual wildlife mortality at the site is likely to have been substantially greater than the number reported. Additionally, the USFWS noted in 1997 that:

> …more birds are likely dying than what is found by the Service. Telemetry data in 1994 showed that some poisoned birds die in areas where they are unlikely to be found and not necessarily near contaminated areas. In 1996, a magpie that died from endrin poisoning was found in Section 10 on the abandoned Stapleton runway, a fair distance from contaminated soil areas. Birds that could not be evaluated due to decomposition may also have died from poisoning (USFWS, 1997, p. 53).

In addition to bird kills, evidence exists that pesticide poisoning resulted in the death of mammals at the Arsenal between 1989 and 1999. In 1997, the death of a cottontail rabbit found at Building 111 was attributed to endrin poisoning, based on a brain concentration of 1.05 mg/kg (USFWS, 1998, p. 11). Results of tissue analyses for fortuitous mammal specimens collected in previous years indicated that mammals accumulate high concentrations of pesticides in their tissues. For example, two coyotes that were hit by a vehicle in 1994 had liver concentrations of dieldrin above 4 mg/kg (USFWS, 1996, Table 1-9). A badger collected in 1992 had a brain concentration of 2.46 mg/kg dieldrin and a liver concentration of 9.65 mg/kg, but the official cause of death reported on the necropsy was "undetermined" (USFWS, 1995, Tables 1-16, 1-17).

All of this information indicates that wildlife deaths have occurred at the Arsenal as a result of exposure to hazardous substances, including, but not limited to, aldrin and dieldrin. The anecdotal nature of the sampling likely substantially underestimates the actual wildlife deaths caused by pesticide poisoning on-site. Additional investigation of wildlife deaths will be undertaken as part of the State Trustees' assessment activities.

6.5.3.4 Historical benchmarks and potential injury thresholds for pesticide exposure

As discussed above, concentrations of pesticides in animal tissues above injury benchmarks can indicate that mortality of a specimen was caused by exposure to pesticides. It is also possible to develop injury thresholds based on exposure to pesticides in an animal's diet (or through dermal absorption or inhalation).

Mortality caused by short-term exposure to a hazardous substance is considered "acute toxicity." An acute oral dose, typically measured as a 50% Lethal Dose (LD_{50}), is the chemical dose sufficient to cause mortality in 50% of test animals in a laboratory study. Chemical doses are measured as mg of chemical per kg of body weight of the animal. When something is highly toxic, it means that ingestion of a small amount of the chemical will cause toxicity. Therefore, chemicals with higher toxicity have lower LD_{50} values – a lower LD_{50} value means that it takes a smaller amount of the chemical to cause mortality.

As shown in Table 6.7 for a variety of bird species, different pesticide compounds have different toxicities. Cyclodiene pesticides such as aldrin and dieldrin are among the most toxic organochlorine pesticides. However, aldrin is rapidly converted to dieldrin in environmental media, such as soil or water, and in the tissues of biological organisms. Therefore, aldrin is rarely detected at high concentrations. Endrin is about 10 times more toxic than dieldrin for common bird test species (Table 6.7). Other cyclodiene pesticides (chlordane, oxychlordane, heptachlor, heptachlor epoxide, and isodrin) are somewhat less toxic than dieldrin to birds (Friend and Trainer, 1974). For each compound, there also is marked variation in toxicity among bird species. For example, mallards are less sensitive to pesticides than California quail, meaning that mallards can ingest a higher dose of pesticide without being killed. The variation in toxicity among species is likely a result of differences in the birds' ability to metabolize these compounds (Ronis and Walker, 1989).

Table 6.7. Concentrations of different pesticides that cause mortality ("acute toxicity") in birds

Chemical	Test species	Number of samples	Sex	Age (months)	Acute oral dose (LD_{50} mg/kg)
Aldrin	Mallard	16	F	3–4	520
	Bobwhite	12	F	3–4	6.59
	Pheasant	12	F	3–4	16.8
Dieldrin	Mallard	12	F	6–7	381
	California quail	12	M	7	8.8
	Pheasant	9	M	10–23	79
	Rock dove	15	M, F	–	26.6
DDT	Mallard	8	F	3	> 2,240
	California quail	12	M	6	595
	Pheasant	15	F	3–4	1,334
Chlordane	Mallard	12	F	4–5	1,200
	California quail	12	M	12	14.1
	Pheasant	4	F	3	24.0–72.0
Endrin	Mallard	12	F	12	5.6
	California quail	12	F	9–10	1.2
	Pheasant	12	M	3–4	1.8
	Rock dove	16	M, F	–	2.0–5.0

Source: Hudson et al., 1984.

Low-level exposure to organochlorine pesticides (below lethal levels) has the potential to alter wildlife behavior and cause chronic health problems. Chronic low-level dosing results in a steady accumulation of dieldrin in an animal. For example, dogs fed a diet with just 0.01% dieldrin in food by weight (0.1 µg/g dieldrin) showed high concentrations of dieldrin accumulating in fat (Richardson et al., 1967). Similar results have been found in chronic dosing studies with birds. Altered behavior occurring as a result of this low-level dosing includes reduced alertness to predators, altered courtship behavior, and altered aggression (Sharma et al., 1976). Other chronic toxicity effects include increased genetic mutations, higher cancer rates, and endocrine disruption (WHO, 1989). Population effects of pesticide exposure for birds include delayed egg-laying, decreased egg production, reduced egg weights, and reduced eggshell thickness, all of which contribute to reduced hatchability and post-hatching mortality (Dahlgren et al., 1970; Sharma et al., 1976; Busbee, 1977; Newton, 1988; Walker and Newton, 1999).

The EPA (2005a) produced a comprehensive review of literature on dieldrin with the purpose of developing Ecological Soil Screening levels. EPA was particularly interested in papers reporting toxicity responses other than lethality, such as biochemical, behavioral, physiological, pathological, and reproductive impairment. These data were compiled to determine a Toxicity Reference Value (TRV) for birds. EPA defined the TRV as the “Dose above which ecologically relevant effects might occur to wildlife species following chronic dietary exposure and below which it is reasonably expected that such effects will not occur” (EPA, 2005b, p. 4-11). The TRV established by the EPA was 0.0709 mg dieldrin/kg body weight (bw)/day, based on adverse effects on reproduction.

The Rocky Mountain Arsenal Biological Advisory Subcommittee (BAS) established a TRV of 0.028 mg dieldrin/kg bw/day as an “estimated safe level” for small birds at the Arsenal. This number is lower than the TRV established by the EPA (BAS, 2002). The BAS TRV was based on a toxicity benchmark or “critical dose” of 0.28 mg dieldrin/kg bw/day from a study with homing pigeons (Robinson and Crabtree, 1969) and the application of a ten-fold uncertainty factor.

In summary, according to DOI regulations, injuries to wildlife can be evaluated based on the exposure of organisms to pesticides at levels that exceed toxicity thresholds or benchmarks. These thresholds vary by the type of pesticide, by species, and by toxicity endpoints, with sublethal effects occurring at lower exposure levels compared to lethal effects. Thresholds will be compared to Arsenal data to calculate the amount of lost ecological resources and services.

Exposure modeling

Exposure modeling is used to estimate contaminant exposures of different wildlife species, based on concentrations in environmental media such as soil and water. Measurements of pesticide concentrations in soil can be used to predict daily dietary doses of pesticides, based on assumptions about bioaccumulation of pesticides through the food web. Exposure modeling also can be used to predict tissue concentrations of pesticides in animals, based on assumptions about pesticide concentrations in the animal’s diet.

More specifically, in an exposure model, a dose is calculated for each route of exposure: ingestion, inhalation, and dermal absorption. The total dose is compared to a TRV to determine whether it exceeds a safe level. All exposure routes are initially considered, but some may not be included in the exposure model if the route would not be expected to contribute very much to the overall dose. For a simple example of a dietary exposure model, the animal’s average daily food intake is calculated in kilograms of food per day. Then, for each food type in the animal’s diet, the animal’s average daily food intake is multiplied by the fraction of the diet that each type represents. This gives the mass of each food type the animal consumes in an average day. This mass is multiplied by the concentration of pesticide in that type of food, to give a total amount of the pesticide for that food. Finally, pesticide amounts for all foods are summed, giving a single total daily intake that is divided by the average body weight of the animal. Thus, dose is expressed as mg of pesticide per kilogram body weight per day.

This simple example of exposure modeling relies on single point estimates for average daily food intake, average food type mass, and contaminant concentration in the food source. In more complicated models, ranges and distributions of these variables are used rather than single point estimates. A computer runs multiple simulations, and the resulting dose estimate incorporates information on the uncertainty of variables included in the model.

An extensive risk assessment completed for the site (the IEA/RC; Ebasco Services et al., 1994) developed dietary exposure models for a range of organisms at the Arsenal. A refinement of this approach was subsequently presented in the Terrestrial Residual Ecological Risk (TRER) report (BAS, 2002). The exposure modeling in the TRER predicted that an average soil concentration of 0.065 mg/kg for aldrin/dieldrin across the home range of a small bird would result in a bird exposure dose of 0.028 mg aldrin/dieldrin per kg body weight per day. This exposure modeling was based on dietary intake and did not consider potential exposure through inhalation or dermal pathways, so it likely underestimates total exposure.

This exposure calculation is an example of an exposure calculation for a small bird. Similar exposure calculations can be conducted for other types of birds and wildlife to predict whether soil concentrations could result in wildlife exposure at levels exceeding injury thresholds and benchmarks for either dietary doses or tissue concentrations.

Comparison of estimated exposure to potential injury thresholds

The IEA/RC evaluated the dietary exposure of a variety of species or species groups to different chemicals, and compared exposure estimates to TRVs to quantify ecological risk (Ebasco Services et al., 1994). Comparisons were expressed as “hazard quotients,” where:

Hazard quotient = Exposure estimate / TRV.

The TRVs were developed by finding the lowest chemical dose associated with adverse effects to a particular class of organisms such as small birds, and then dividing this “critical dose” by a set of uncertainty factors to develop an estimated safe level, below which no adverse effects are expected to occur. For example, as mentioned above, the BAS established 0.028 mg dieldrin/kg bw/day as the TRV for small birds based upon a “critical dose” of 0.28 mg dieldrin/kg bw/day (Ebasco Services et al., 1994). The BAS divided the critical dose by an uncertainty factor of 5 to consider potential interspecies differences in sensitivity, and an additional uncertainty factor of 2 to account for differences between laboratory and field conditions and the potential for variability within a species (Ebasco Services et al., 1994). A calculated hazard quotient of 10 for small birds would mean that an organism was exposed to a dose 10 times the TRV of 0.028 mg dieldrin/kg bw/day.

Figure 6.3 shows areas at the Arsenal where, prior to remedial activities, the hazard quotient for small birds exceeded 10 based on respective TRVs advocated by the different parties. Regardless of thresholds and exposure models used, the injury will be greatest in the central core of the Arsenal.

6.5.4 Injuries from response actions

Remediation work has occurred extensively across the site (Figure 6.4). Although this work has been necessary to reduce the pervasive contamination, collateral injuries to wildlife have been unavoidable. Soil remediation activities have included physically removing contaminated surficial soils using heavy equipment. Also, some areas with clean soils were excavated to use as soil covers for the landfills and in-place containment of soils. In addition, the Army, Shell, and the USFWS tilled soils for revegetation. These activities disturbed existing habitat on-site. Injuries to biological resources that would have inhabited or utilized this disturbed habitat will occur until the habitat is returned to baseline conditions.

Wildlife also has been injured by the intentional eradication of species at the Arsenal. In 1989, the Army exterminated prairie dogs in Section 36 and the southeast corner of Section 25 because high concentrations of dieldrin present in the prairie dogs were endangering wintering bald eagles that ate the prairie dogs (R.L. Stollar & Associates et al., 1992, p. IV-10).

Permanent remediation injuries to biological resources have also occurred. Specifically, biota intrusion layers are designed as part of the caps on hazardous landfills. For example, an 18-inch-thick layer consisting of crushed concrete is part of the landfill cap design. The crushed concrete layer is specially engineered to prevent burrowing animals such as prairie dogs and badgers from re-exposing buried hazardous substances (CDPHE, 1995; Foster Wheeler, 1996). While this cap is necessary to prevent additional exposure of wildlife to contaminants, the biota intrusion layer will limit habitat available to the Arsenal wildlife and constitutes a permanent injury to biological resources. Biota intrusion layers are also included in the acres of covers over contaminated South Plants soils. As part of the assessment, the State will consider these collateral injuries in addition to the habitat improvements that occur following remediation and revegetation.

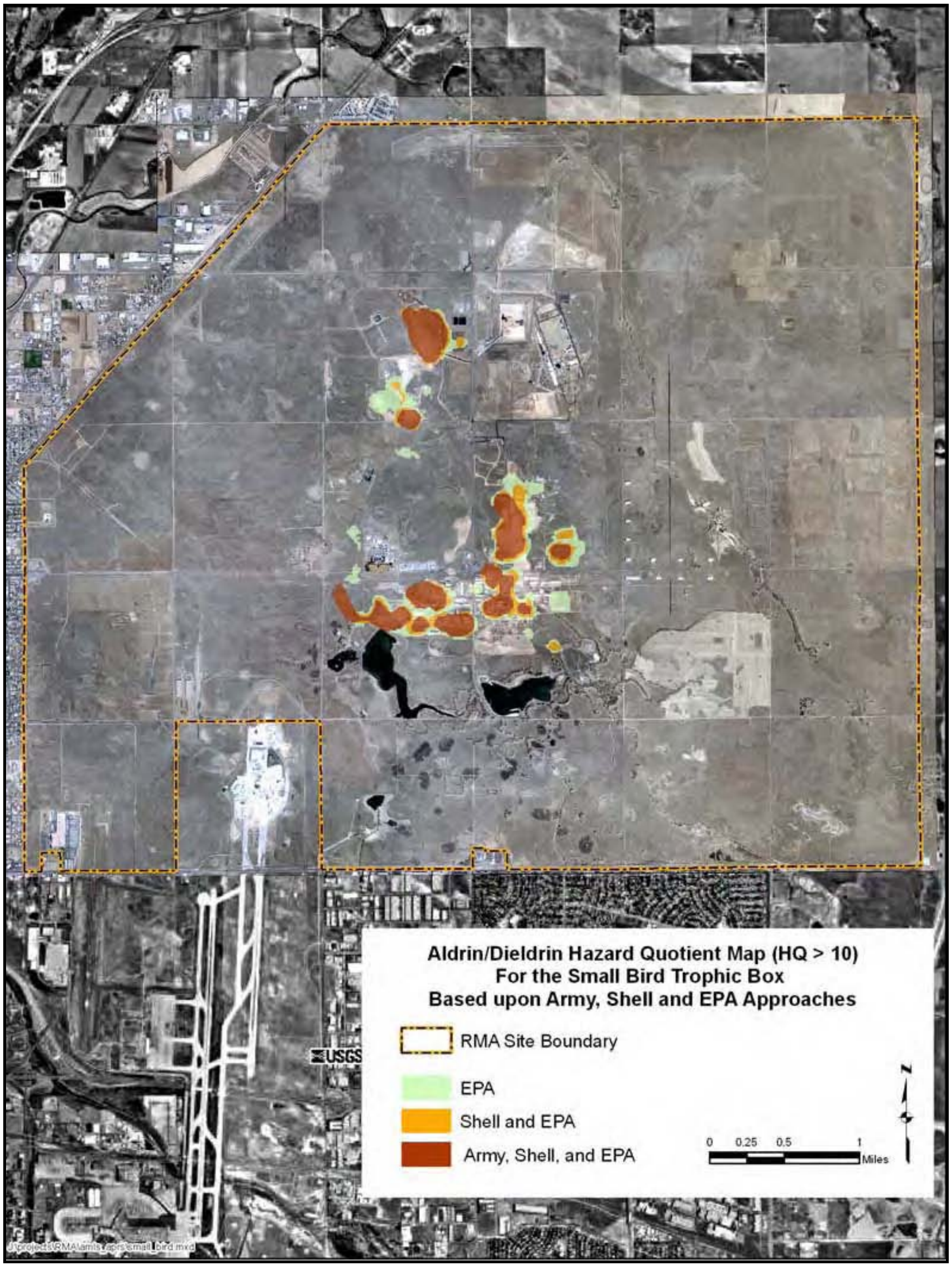

Figure 6.3. Example map of injured areas at the Arsenal for small birds exposed to dieldrin, based on data developed for the Arsenal risk characterization report.

Source: Ebasco Services et al., 1994, Figure C.3-33.

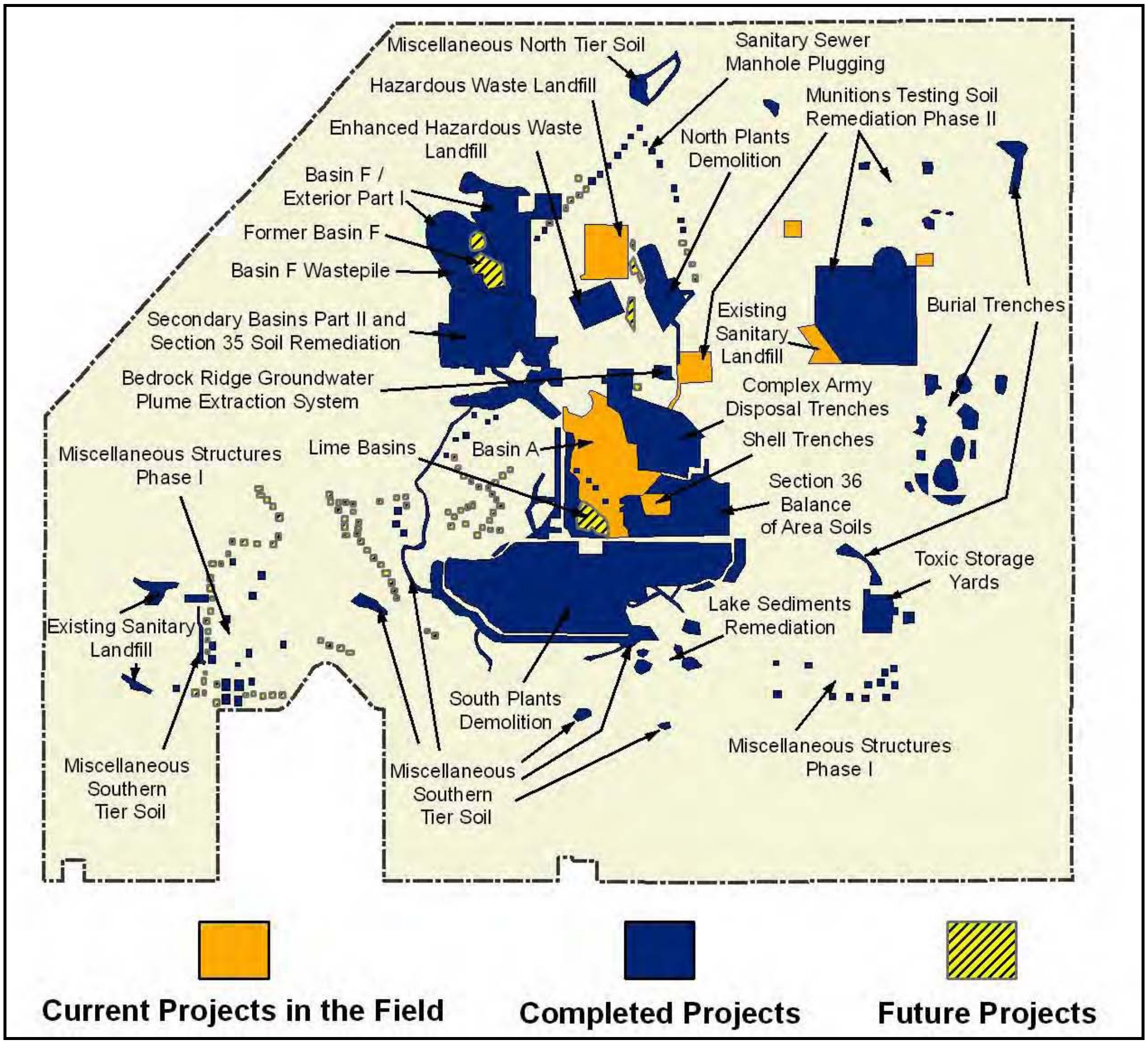

Figure 6.4. Spatial extent of soil remediation activities at the Arsenal as of September 2007.

Source: Rocky Mountain Arsenal, 2007.

6.5.5 Evidence of injury to biological resources associated with surface water

Biological resources at the Arsenal have been exposed to contaminants in surface water and associated sediments. Concentrations of contaminants that exceed established State and federal water quality criteria demonstrate potential injury to biological resources because water quality criteria are derived using exposure effects data from laboratory studies using a diverse assemblage of test organisms (Stephen et al., 1985).

Below is a brief list of water quality exceedences that have occurred in waters of the Arsenal. This is not a complete assessment, but an example using readily available data from the Arsenal reports.

- Surface water quality data for the Sand Creek Lateral drainage ditch indicated that aldrin and dieldrin were measured above respective water quality criteria between the fall of 1985 and the spring of 1987 (Ebasco Services et al., 1989, pp. 4-9–4-12)
- Chlordane was measured above the chronic criteria in Lower Derby Lake in April 1989 (Ebasco Services et al., 1994)
- Endrin was measured above the chronic criteria in Upper Derby Lake in September 1989 (Ebasco Services et al., 1994).

In addition, concentrations of contaminants in sediments have exceeded benchmark levels that indicate the probability of adverse effects on aquatic biota (Table 6.8). The sediment benchmarks that are used for comparison include consensus threshold effects concentrations (TECs), which represent concentrations below which adverse effects to sediment-associated biota would not be expected, and consensus probable effects concentrations (PECs), above which adverse effects to sediment-associated biota are likely (MacDonald et al., 2000). Additional aquatic sediment benchmarks criteria developed by the Ontario Ministry of Environment and Energy include the lowest observed effect levels, below which adverse effects would not be expected, and the severe effect levels (SEL), where "the sediment is considered heavily polluted and likely to affect the health of sediment-dwelling organisms" (Persaud et al., 1993).

6.6 Approaches to Injury Quantification

According to the DOI regulations, quantification of injuries is conducted to "quantify the effects of the discharge or release on the injured natural resources for use in determining the appropriate amount of compensation" [43 CFR § 11.70(c)]. Injuries to natural resources can cause reductions in the services those resources provide relative to baseline conditions, where baseline is defined as conditions that would have existed at the assessment area had the discharge of oil or release of the hazardous substance under investigation not occurred [43 CFR § 11.14(e)]. Services are the "physical and biological functions performed by the resource, including the human uses of those functions" [43 CFR § 11.14 (nn)].

Injury quantification involves determining the spatial extent where injuries have occurred as well as the timing and duration of injuries. Quantification also can involve estimates of the "degree of service loss" in an area – that is, what percentage of services has been lost at a site compared to baseline condition.

Table 6.8. Examples of exceedences of benchmark levels in contaminated sediments at the Arsenal

Water body	Date	Contaminant	Benchmark concentration (ppm)	Maximum sediment concentration (ppm)[a]	Benchmark type[b]
Lake Mary	1998	Arsenic	9.8	11.7	TEC
		Mercury	0.18	0.46	TEC
Lake Ladora	1995	Aldrin	0.08–0.8	0.15	SEL[c]
		Arsenic	9.8	11	TEC
		Dieldrin	0.0019	0.016	TEC
		Mercury	1.1	2.2	PEC
Lower Derby Lake	1985–1994	Aldrin	0.08–0.8	50	SEL[c]
	1995	Aldrin	0.08–0.8	0.56	SEL[c]
		Chlordane	0.018	0.103	PEC
		Dieldrin	0.062	0.063	PEC
		Mercury	1.1	3.2	PEC

ppm = parts per million.

a. All sediment data from the BAS (2003).

b. TEC = "Threshold Effects Concentration;" PEC = "Probable Effects Concentration" (both from MacDonald et al., 2000); SEL = "Severe Effects Level" from Persaud et al. (1993).

c. Severe effects levels based on a benchmark of 8 μg Aldrin/g of organic carbon. The benchmarks given here are calculated for a sediment sample with an assumed total organic carbon concentration between 1% and 10%.

To illustrate such potential quantifications, the Trustees estimated the spatial extent of injuries prior to remediation based on areas where soil concentrations of aldrin and dieldrin would result in small bird exposure that exceeds potential injury thresholds (Table 6.9). Three concentration ranges were defined based on the hazard quotient ranges for small birds in specified areas. All three ranges exceed the EPA (2005a) threshold for birds, while the > 0.65 ppm category also exceeds the critical dose threshold for small birds used in the Arsenal risk evaluation (Ebasco Services et al., 1994). Regardless of selected thresholds, the total spatial extent of injury will have decreased over time at the Arsenal, as remediation activities have cut off exposure pathways to contaminated soils and remediated areas have been revegetated.

Injury quantification also must be conducted for injuries caused by remedial activities. The USFWS estimated that 3,650 acres would be directly disturbed by remedial activities (USFWS, 1999). The duration of injury will depend on the time required to return the habitat to baseline conditions.

During the assessment process, the Trustees will conduct a full injury quantification that takes the timing and benefits of remediation into account more precisely and will also make sure that there is no "double-counting" of the same injured areas, using different injury tests.

Table 6.9. Comparison of injury thresholds for different concentrations of aldrin and dieldrin in soils at the Arsenal

Soil concentration (ppm aldrin/ dieldrin)	Acres at the Arsenal (pre-remediation)[a]	Estimated bird exposure dose (mg aldrin-dieldrin/kg bw/day)	Hazard quotient from Ebasco Services et al. (1994)	Exceeds EPA (2005a) threshold (0.0709 mg dieldrin/kg bw/day)	Exceeds the Arsenal threshold for small birds (0.28 mg dieldrin/kg bw/day)
0.130–0.325 (midpoint = 0.2275)	1,114	0.098	2–5	Yes	No
0.325–0.650 (midpoint = 0.4875)	672	0.21	5–10	Yes	No
> 0.65 (midpoint = 0.6500)	1,067	> 0.28	> 10	Yes	Yes
Total	**2,853**				

a. Acres estimated from a digitized version of Figure B-5 in BAS (2002).

6.7 Anticipated Assessment Activities

During the assessment phase of the NRDA, the Trustees will undertake activities to determine and quantify the full range of injuries to biological resources that have taken place at the Arsenal. Specific activities that the Trustees anticipate undertaking may include the following:

- **Injury determination**
  - **Revise and update bioaccumulation and dietary toxicity models.** The Trustees will review recent scientific literature and potentially expand the number of evaluated species, revise exposure scenarios, and identify additional toxicity references upon which to base injury thresholds. These may include those underlying EPA's Ecological Soil Screening Levels established for avian and mammalian herbivores, ground insectivores, and carnivores (EPA, 2005a), and any recent references regarding tissue concentrations related to adverse effects.
  - **Assess injuries to biological resources based on tissue and media concentrations.** The Trustees will assess injuries to biological resources by comparing tissue concentrations and media concentrations for different chemicals reported in the Rocky Mountain Arsenal Environmental Database to injury threshold values.

- **Address the additive toxicity of organochlorine pesticides.** The Trustees will use existing data to evaluate the potential additive toxicity of organochlorine pesticides. For example, wildlife specimens with brain concentrations of dieldrin below injury thresholds may also have had high concentrations of other pesticides that would result in an exceedence of injury thresholds when using additive toxicity models.

- **Assess injuries to reptiles, amphibians, fish, and bats.** The Trustees will assess injuries to reptiles, amphibians, fish, and bats based on a literature review to establish injury thresholds. Previous work at the Arsenal has focused on birds and ground-dwelling mammals, with little known about potential injuries to other types of wildlife.

- **Assess injuries to biological resources from exposure to metalloids.** The Trustees will assess injuries to biological resources from exposure to arsenic and other metalloids, using a literature review to establish injury thresholds. Previous work at the Arsenal has focused on organochlorine pesticides and also has evaluated risk from mercury exposure.

- **Assess injuries to biological resources associated with perennial and intermittent surface water and associated sediments.** The Trustees will assess injuries to biological resources associated with perennial and intermittent surface water and sediments, including the Lower Lakes. Trustees would use existing data on concentrations of contaminants in surface water, sediment, and biota to assess injury.

- **Injury quantification**

  - **Quantify spatial extent of injuries over time.** The Trustees will use GIS techniques to quantify the spatial extent of injury and how this injury has changed over time with remediation.

  - **Quantify injuries from remediation.** The Trustees will examine information and maps of completed and anticipated remediation activities to determine the spatial extent and duration of injury resulting from loss of wildlife habitat during remediation as well as the degree of habitat improvement associated with the remediation.

  - **Quantify resource losses over time.** The State Trustees would develop models to predict injury over time based on existing wildlife kill data, existing data on contaminant concentrations in environmental media, and toxicity thresholds.

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7. Injury to Air Resources

Hazardous substance releases at the Arsenal injured Trustee air resources via windblown dispersion of dried contaminated sediments from disposal basins, vapor emissions from surface impoundments, and emissions resulting from response actions – most notably the 1988 Basin F IRA discussed in Chapters 3 and 4. This chapter contains a qualitative discussion of injury to air resources during the Basin F IRA. A quantitative assessment of injury may be explored as part of the assessment, depending on the availability and reliability of data.

Summary of conclusions

Releases of hazardous substances during the Basin F IRA resulted in a measurable adverse short-term change in the chemical and physical quality or viability of air resources. Technical reports, transcripts of meetings, correspondence, and odor logs confirm that hazardous substances were released into the air from Basin F and migrated off-post. Offensive odors were prevalent to the north and northwest of the Arsenal boundary. Emissions not only created noxious odors but are also believed to have caused significant adverse health effects. Because of these adverse effects, local residents reported that they modified their behavior to avoid exposure to the ambient air. Thus, releases from Basin F during the IRA resulted in the loss of human services provided by the State's air resources.

7.1 Injury Determination

Chapter 4 confirms that air resources were exposed to hazardous substances during the Basin F IRA in 1988. However, inadequate sampling and laboratory techniques at the time complicate the determination and quantification of injury to air resources. Regardless of air monitoring results, parties involved in the Basin F IRA recognized that chemicals at concentrations below selected risk-based levels, and sometimes below detection limits, were sufficient to cause the highly noxious odors that were associated with health problems (Basin F Transcripts, October 26, 1988).

7.1.1 Injury definition

According to the DOI regulations, an injury to the air resource has resulted from the release of a hazardous substance if one or more of the following changes in the physical or chemical quality of the resource is measured:

- Concentrations of emissions in excess of standards for hazardous air pollutants established by section 112 of the Clean Air Act, 42 USC § 7412, or by other federal or state air standards established for the protection of public welfare or natural resources [43 CFR § 11.62(d)(1)]

- Concentrations and duration of emissions sufficient to have caused injury as defined in paragraphs (b), (c), (e), or (f) of this section to surface water, groundwater, geologic, or biological resources when exposed to the emissions [43 CFR § 11.62(d)(2)].

Neither EPA nor the State of Colorado has established standards for relevant hazardous air pollutants.

7.1.2 Baseline conditions

The area affected by Basin F emissions is an industrial area, with several other sources of odors and, potentially, airborne hazardous substance emissions. Industries near the Arsenal include Ralston Purina, refineries, and gasoline stations, in addition to urban air releases associated with automobile traffic. Although the air quality near the Arsenal was not pristine in the 1980s, the odors and health effects experienced from the beginning to the end of the Basin F IRA were more extreme and numerous than those reported before or after the response, and most of the odor complaints cited a distinct and familiar odor that was attributable to Basin F (R.L. Stollar & Associates, 1990). Thus, the adverse effects on air resources during the Basin F response exceeded baseline conditions.

7.1.3 Qualitative evidence of injury

The Basin F IRA began on March 22, 1988. Within days, contractors were raising concerns about Basin F emissions, and discussing plans to ascertain the source of the odors (Ebasco Services, 1988). Excavation activities and pumping of Basin F commenced on the last day of April. Prior to commencement, no testing was conducted to characterize the potential emissions, identify target compounds, or design appropriate monitoring and response protocols.

After removal of all free-standing liquid in the northern end of Basin F during the last week of July 1988, the Army and its contractors discovered a false bottom: 26 to 54 inches of stratified, crystallized salts and sludges. Beneath this hard layer were at least 3 million gallons, and possibly as much as 4.5 million gallons, of additional liquid wastes. The capacity of the tanks was inadequate to hold all the liquid waste in Basin F (Campbell, 1988).

In addition to the excess liquids, crystallized salts and material beneath the liner added over 150,000 cubic yards to the estimated 405,000 cubic yards of contaminated sludge expected to be excavated (Woodward-Clyde, 1990). These saturated soils and sludges had to be dried prior to placement in the Basin F waste pile. To enhance the drying, a piece of equipment called the "Brown Bear" began operations on August 23. The Brown Bear mixed the wet materials with dry soils, exposing more surface area to air in order to dry the materials. This mixing and air-drying of soils and sludges increased the noxious odors released to air. Consequently, the Army discontinued use of the Brown Bear in September (Basin F Transcripts, September 28, 1988).

The first of 200 logged complaints about foul odors came from off-post neighbors during the summer of 1988 (Ebasco Services et al., 1991). In the fall of 1988, with Basin F sludges exposed and the start of Denver's meteorological inversion season, complaints about noxious odors and adverse health effects from the fumes increased. Multiple complaints per night were recorded. In response, the Army asked Ebasco to commence off-post odor tracking on October 5, 1988. Complaints were registered nearly every day in December 1988 (Ebasco Services et al., 1991).

As a result of the odor complaints, the Army abandoned the Phase I IRA plan in December 1988, ordering all remaining waste in the basin to be capped in place (Ebasco Services, 1989). By January 21, 1989, the "final" cover was placed over the Basin F floor, and by the end of February 1989, the waste pile was closed to contaminated material. The last complaint about odors from off-post neighbors was recorded on March 10, 1989 (Ebasco Services, 1989).

The air monitoring during the Basin F IRA was flawed for several reasons. For example, in early August 1988, Ebasco Services discovered that post calibration of real-time air monitoring instruments was not being performed as required, rendering data "questionable" (Lewis, 1988). More significantly, the analytical methodology used for air sampling of aldrin and dieldrin had a recovery of only 28%, meaning as much as 72% of the compound present was not measured or recorded (EPA, 1984; Sullivan Environmental Consulting and E.H. Pechan & Associates, 1991). Alternative methods may have resulted in 90% recoveries (EPA, 1988, 1989). In addition, hexachlorobutadiene (HCBD), an extremely odorous compound, was not monitored at all during the months of maximum emissions. HCBD was not identified as a target compound until January 1989, when air quality tests indicated that HCBD and ammonia were the most prominent contaminants in gases emanating from Basin F soils and sludges (Ebasco Services, 1989; Ranum, 1989). Thus, much of the Army's analytical data cannot be considered reliable for determining contaminant concentrations that were released into the air.

Compounds released to the air were associated with noxious odors, and pesticides in particular were linked to the adverse health effects experienced by exposed individuals. Army documents acknowledge that its cleanup activities caused noxious odors that adversely affected downwind individuals during implementation of the Basin F interim action (Basin F Transcripts, September 28, 1988; Ebasco Services, 1989; Ebasco Services et al., 1991). Reported adverse health effects included:

> …headaches, nausea, vomiting and anorexia, insomnia, burning and tearing eyes, conjunctivitis, wandering eye and visual disturbances, skin rashes, sore throats, runny noses and nose bleeds, respiratory problems including coughing and shortness of breath, muscle and joint pain, tingling and numbness, ringing in the ears, chronic fatigue and perceived weakness, dizziness, taste perversions, chest pain, abdominal pain, diarrhea, tremors, facial twitches, amnesia, disorientation, irritability, incoordination and depression (Burnett, 1990, pp. 20–22).

Many of these symptoms were also experienced by CDPHE employees and Army contractors (Ebasco Services et al., 1991) and were consistent with the known toxicology of Basin F chemicals (Burnett, 1990).

The Army's Odor Response Program logged 200 complaints between August 1988 and March 1989. The program was terminated in May 1989. The EPA, CDPHE, and Tri-County Health Department received additional complaints (Basin F Transcripts, September 6, 1988). In addition to the symptoms described above, nearby residents suspected the noxious emissions from Basin F of causing or exacerbating cancer, lupus, epileptic seizures, sores in the mouth and the unexpected deaths and illnesses of pets (Basin F Transcripts, October 26, 1988; Ebasco Services et al., 1991).

Because of noxious odors, adverse health effects, and fear of serious long-term illness, residents reported that they avoided the outdoors and shut their doors and windows, even during hot summer months, as much as possible. They employed air purifiers provided by the Army for their homes but concerns and discomfort remained (Basin F Transcripts, October 26, 1988).

The qualitative evidence presented above demonstrates that services provided by the State's air resources were lost as a result of Basin F emissions. A more quantitative analysis of air quality data and lost services is anticipated as part of the assessment.

7.2 Injury Quantification

This section contains a preliminary estimate of the spatial and temporal extent of air resources injury as a result of the Basin F response action. A more detailed analysis may be conducted as part of this assessment.

Spatial extent of injury

Odor complaints were clustered around the Arsenal, with most of the more vocal and persistent complaints coming from residents of 96th Avenue just north of the Arsenal and in the Irondale trailer park, located one mile northwest of Basin F. Sullivan Environmental Consulting and

E.H. Pechan & Associates (1991) included a map of the most persistent complainants (Figure 7.1). Other complainants were located as far away as 46th and York Street, and one complainant resided near the south border of the Arsenal.

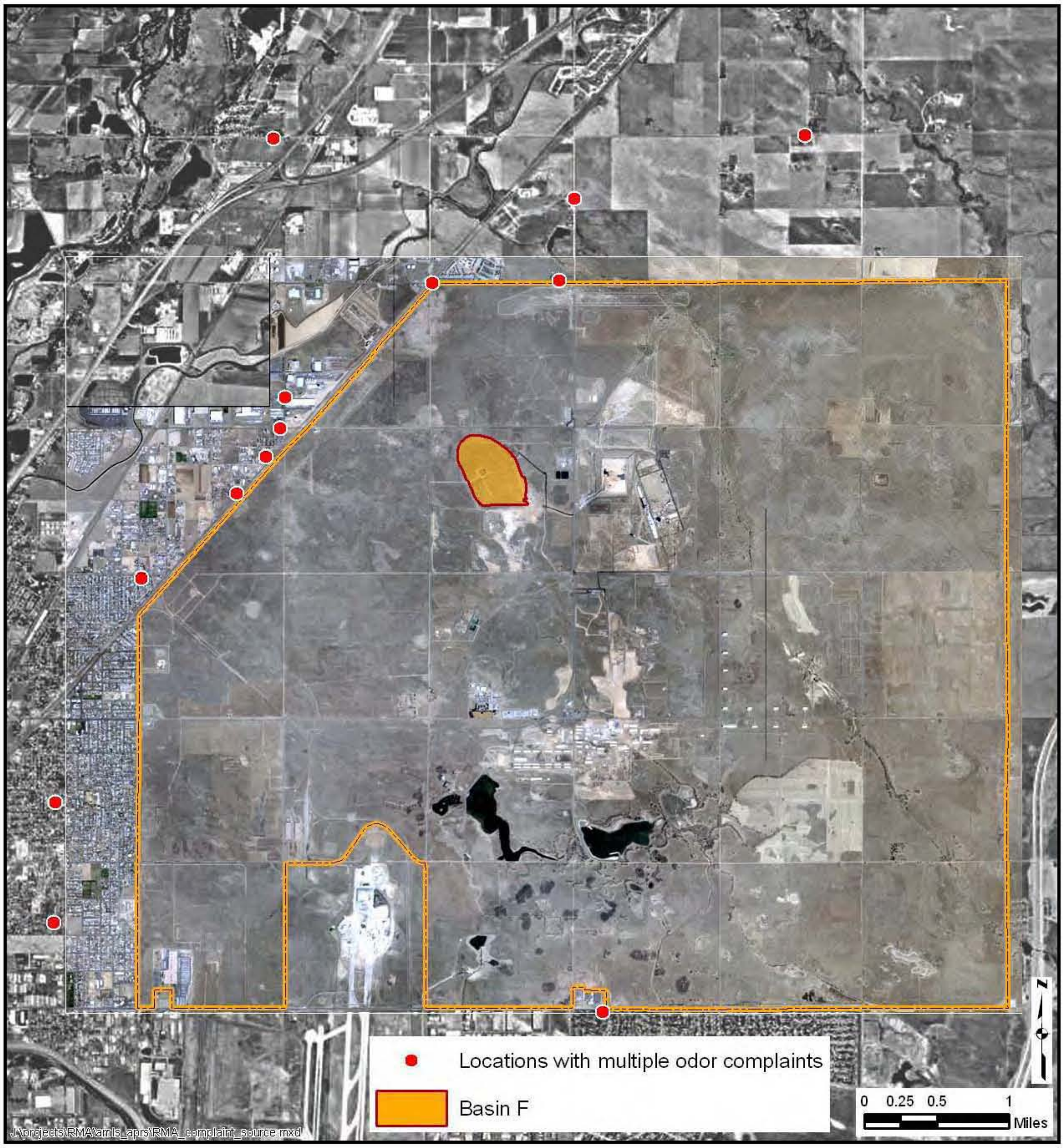

Figure 7.1. Location of complainants noting persistent noxious odors during the Basin F interim response action.

Source: Sullivan Environmental Consulting and E.H. Pechan & Associates, 1991, Figure 7.

Temporal extent of injury

The Basin F response action began on March 22, 1988. By March 28, 1988, contractors were expressing concerns to the Army about the odors (Ebasco Services, 1988). Odor response monitoring for offsite complaints commenced on August 5, 1988 and continued through May 5, 1989. A formal odor response program, which included plume tracking, was initiated in October 1988 and terminated in May 1989 after complaints ceased (Ebasco Services et al., 1991).

7.3 Assessment Activities

As part of the assessment, the Trustees may perform a more quantitative evaluation of injuries to air resources. In particular, the Trustees may:

- Review quantitative data from air quality monitoring during the Basin F IRA to determine if specific injury thresholds were exceeded, or if injury to air resources may have occurred but was not measured due to inadequate technology and human error
- Compile odor complaints to assess the likely spatial and temporal extent of injury during the Basin F IRA
- Review air dispersion models to better quantify hazardous substance releases to air, and the transport of those release through air resources
- Review on-post fugitive dust emissions data to evaluate other potential injury to air resources.

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8. Damage Determination and Restoration Planning Approaches

Chapters 5, 6, and 7 describe injuries to and anticipated injury assessment activities for groundwater, biological, and air resources, respectively. This chapter briefly introduces general approaches to estimating damages from those injuries, then describes in more detail the restoration-based approach to damage determination. Section 8.1 explains damage determination in general and describes three approaches that the State will use to determine damages at the Arsenal. Section 8.2 presents an introduction to the restoration-based approach. Section 8.3 discusses the most common restoration-based approach: habitat and resource equivalency analyses. Section 8.4 discusses restoration project identification, selection, scaling, and costing. References cited in this chapter follow.

8.1 Damage Determination

A damage determination is intended to "establish the amount of money to be sought in compensation for injuries to natural resources resulting from a . . . release of a hazardous substance." The DOI regulations identify as the primary measure of damages the cost of "restoration, rehabilitation, replacement, and/or acquisition of the equivalent of the injured natural resources and the services those resources provide" [43 CFR § 11.80(b)]. In addition, the Trustees seek "the compensable value of all or a portion of the services lost to the public for the time period from the release until the attainment of the restoration, rehabilitation, replacement, and/or acquisition of equivalent of the resources and their services to baseline" [43 CFR § 11.80 (b)], also known as interim losses.

The State will quantify damages using three alternative methods for calculating damages:

- **Cost of restoration**: A restoration-based approach determines damages by quantifying how much restoration is needed to adequately restore, replace, or acquire the equivalent of the injured resources and the lost services provided by such resources. This approach is recognized as an accepted method for quantifying NRDs in the DOI regulations [43 CFR § 11.82; 43 CFR § 11.84(g)]. The State expects to use a restoration-based approach to calculate damages for terrestrial and aquatic resources, groundwater, surface water, and air resources.

- **Total value equivalency**: The State intends to determine the amount of natural resources and/or services that must be provided to produce the same value as that lost to the public due to hazardous substance releases into groundwater. This approach will determine the restoration required to compensate for losses of both use and non-use values for groundwater.

- **Use value – market price methodology**: The Front Range has a strong demand for water resources, including groundwater, and these resources are openly traded in a competitive market. The diminution in the market price of injured resources and associated lost services may be used to determine the compensable value of the injured resources [43 CFR § 11.83(c)(2)(i)]. The State will evaluate lost groundwater services and use a market price approach to estimate damages from these lost services.

As these methods measure many of the same values, the results of each analysis will not be additive. Rather, by using three approaches, the Trustees will have more robust information upon which to rely in formulating its ultimate claim for NRDs.

The remainder of this chapter describes generally the restoration-based approach to quantifying all of the State's NRDs. Chapter 9 focuses on the three damage assessment methodologies in the context of groundwater.

8.2 Restoration-Based Damage Determination: Introduction

8.2.1 Conceptual underpinnings of damage determination

Figure 8.1 is a conceptual diagram that depicts what happens to natural resource services over time following the release of a hazardous substance that causes injury. Area A represents the initial loss of services that occurs after the release of a hazardous substance and before remedial actions begin. Area B represents the time when initial recovery of natural resource services takes place as a result of remedial actions at the site. Area C represents the increase in natural resource services that occurs as a result of restoration activities that could be on-site or off-site. The goal of such activities is to restore to baseline conditions resources and services lost due to hazardous substance releases.

In addition to the costs of restoring resources and services to baseline, Trustees may also calculate damages for the interim losses of resources and services from the time of the release (or the enactment of CERCLA, whichever comes later) until full restoration to baseline is achieved. This compensatory restoration would equal the total service loss represented by the sum of the three areas representing less than baseline conditions (A + B + C) in Figure 8.1.

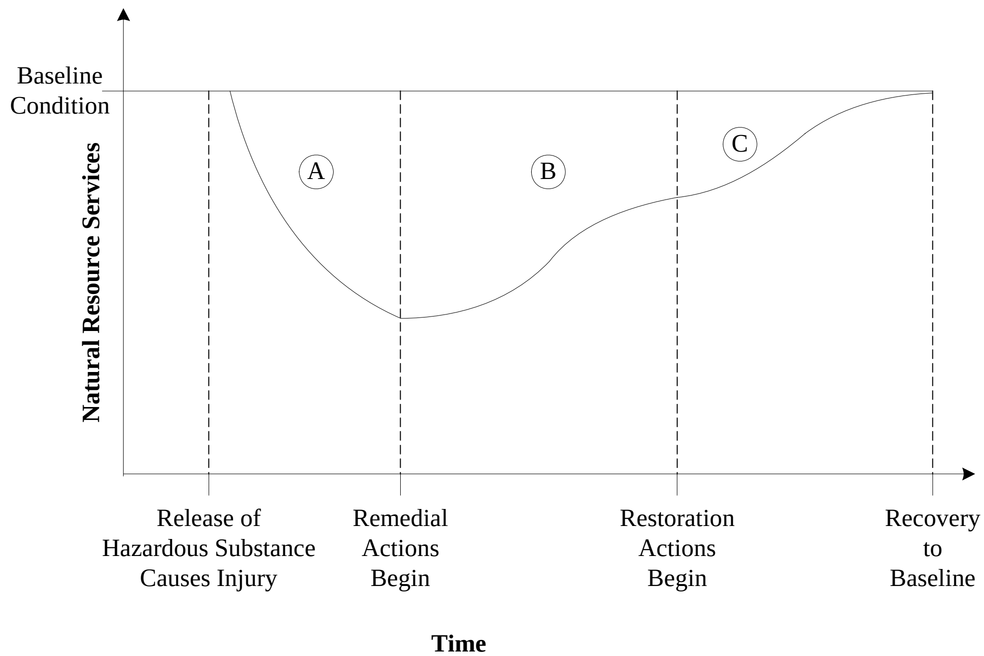

Figure 8.1. Conceptual diagram showing adverse impacts to a natural resource from the time of a release until baseline conditions are restored.

8.2.2 Summary of approach

The State Trustees plan to seek recovery for both components of NRDs: (1) costs of restoring injured resources to baseline conditions, and (2) compensable damages to account for lost services in the past, present, and future until the natural resources have been restored to baseline.

The State's NRD calculations will take into account the remedial actions at the Arsenal. For resources where the remedial actions will return or have returned resources to baseline conditions, the State's damage calculations will include the period from the onset of injury (or 1981) until baseline conditions are (or were) achieved. The State may also account for remedial actions that restore natural resources beyond baseline conditions.

For all injuries, the amount of restoration required for offset will be determined using service-to-service scaling methods such as HEA or REA. These methods are described in Section 8.3.

The State will use input from the public and interested stakeholders to identify potential restoration projects for evaluation using criteria established by the State; select potential restoration projects; scale those projects to offset quantified injuries; and determine the cost of restoration projects at the identified scale of implementation. Section 8.4 describes each of these components of the restoration-based damage determination approach in more detail.

8.3 Overview of HEA and REA

HEA and REA methods have been published in peer-reviewed literature, codified in the National Oceanic and Atmospheric Administration's regulations for NRDA, accepted by Federal Courts [*United States v. Melvin A. Fisher et al., Case No. 92-10027-CIVIL-DAVIS; United States v. Great Lakes Dredge and Dock Co., 259 F. 3d 1300 (11th Cir. 2001)*], and are routinely performed by Trustees and responsible parties at NRD sites throughout the United States.

Under HEA, service losses are expressed in terms of habitat (e.g., acres of grassland) and are offset by restoration of similar habitat. Under REA, losses are expressed in terms of resource units (such as numbers of fish or birds or acre-feet of groundwater), and are offset by projects that restore equivalent resource units. The HEA method has been described in a number of published technical articles (e.g., Unsworth and Bishop, 1994; Chapman et al., 1998; Peacock, 1999; Strange et al., 2002, 2004; Allen et al., 2005; NOAA, 2006).

HEA/REA is used to quantify the impacts to services resulting from injuries to natural resources (i.e., the debit) as well as the expected benefits from restoration (Figure 8.2). Determining equivalency (scaling) between the debit and credit is conceptually simple:

- Sum the reductions in services caused by the injury
- Determine the amount and timing of improvement in services expected per unit of restoration
- Divide the total losses by the benefit per restored unit to calculate the scale of required restoration.

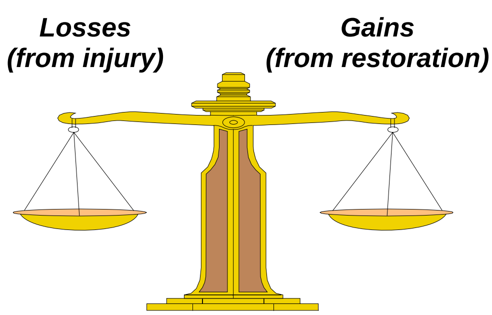

Figure 8.2. HEA and REA are used to determine the type and amount of restoration needed to balance losses from natural resource injuries.

8.3.1 Variables in a HEA/REA model

Necessary input parameters for HEA or REA include:

Start year. A start year must be specified for both the debit and the credit sides of the model. On the debit side, the start year usually is either the year in which injuries began or 1981 (following enactment of CERCLA in December 1980). On the credit side, the start year is the year in which restoration actions are expected to begin generating services.

End year. An end year can be specified, if appropriate. On the debit side, the end year is the year in which injuries stop because resources have returned to baseline conditions, through natural recovery, remedial actions, or projected restoration. On the credit side, the end year is the last year in which the credit from the restoration project is expected. For some restoration projects, benefits are expected to accrue in perpetuity. In that case, one typically specifies an end year at least 100 years after implementation.

Spatial extent. On the debit side, the spatial extent is the area where natural resource services have been degraded as a result of the release of hazardous substances. On the credit side, the spatial extent defines the area where restoration actions will be implemented and where resource service flows will improve.

Service loss. For a HEA, this is the degree of resource or service loss within the spatial extent relative to baseline conditions. Loss can vary from 0% (no loss) to 100% loss (complete loss). The degree of loss can vary over time (as can baseline conditions). The degree of loss will decrease over time if resource conditions improve and will eventually become 0% (no loss) when resource services return to baseline conditions. For a REA, the degree of loss can be expressed in terms of numbers of individuals lost, population reductions, loss of reproductive output or viability (including lost lifespan or reduced number of young), or other measures ("metrics") of resource impairment. Toxicity data such as soil contaminant concentrations can be an important source of information for determining the degree of loss by translating dose-response models into either a service loss assignment (for HEA) or a measure of resource impairment (for REA). If soil concentrations decrease over time as a result of remedial actions, then service or resource losses decrease as well.

Service gain. This is the amount of benefit expected to derive from implementation of a restoration project. Once a project is implemented, benefits begin to accrue, but full services might not be expected until some time in the future. Service gain could be 100% if entirely new habitat is created that functions at baseline levels, or it could be some percentage of baseline if actions enhance the services of habitat that already exists. As with debit calculations, the amount of service gain is estimated relative to baseline conditions.

Baseline conditions. The conditions that would have existed absent the releases of hazardous substances.

Metric. This is not an input parameter to HEA or REA, but instead is the unit of measure of the service loss and gain.

Damage or recovery trajectory. This also is not an input parameter, but a description of the service losses or gains over time.

Discount rate. To make past, current, and future losses and gains comparable, while accounting for well established time preferences, (i.e., people are generally willing to pay more for things in the present as opposed to the far future), the changes in service flow levels from past and future years are discounted to present-day terms (i.e., "present value"). An annual "social" discount rate of 3.0% is typically used in HEA and REA present value calculations for service flows (NOAA, 1999).

Base year. The base year is typically the year in which the analysis is conducted. The present value factor is greater than one for years before the base year and less than one for years after the base year.

Present value factor. The present value factor in the base year is one. Because of the discount rate, the value of a service in the past is greater than the value of the service today; thus, the present value factor is greater than one. Similarly, the value of a service in the future is less than the value of that service today; thus, the present value factor is less than one. Present value factors are calculated as follows:

$$\textit{Present value factor} = 1 / (1+ \text{discount rate})^{(\text{year} - \text{base year})}.$$

8.3.2 Calculation methods

For a HEA, all of these variables are used to equate injured areas and restored areas in summary units that integrate space and time. For example, a debit of 1 acre-year could reflect 1 acre of land having 100% loss of habitat for one year or 2 acres with 50% loss of services for one year. However, the HEA method incorporates a discount rate into the calculations, so that impacts and benefits that occur in different years are converted to present-value equivalents. Impacts and benefits are therefore generally quantified using units of "discounted service-acre years" (DSAYs), which account for the acreage of habitat impacted or benefited, the duration of impacts or benefits, the level of services provided by the impacted or benefited parcels, and time values, to convert changes in services in different years to a common currency.

Table 8.1 demonstrates how the HEA debit would be calculated for one acre of land with a constant service loss of 50%, from the start of 2000 to the end of 2010. The total HEA debit for one acre during this time period is 5.9 DSAYs.

Table 8.1. Example of HEA debit calculations. This example assumes 1 acre of land with a 50% service loss from the beginning of 2000 to the end of 2010, with a 2007 base year and 3% discount rate.

Year	**Percent service loss**	**Present value factor**[a]	**Debit**[b] **(DSAYs)**
2000	50%	1.23	0.62
2001	50%	1.19	0.60
2002	50%	1.16	0.58
2003	50%	1.13	0.56
2004	50%	1.09	0.55
2005	50%	1.06	0.53
2006	50%	1.03	0.52
2007	50%	1.00	0.50
2008	50%	0.97	0.48
2009	50%	0.94	0.47
2010	50%	0.92	0.46
		Total	**5.9**

a. Present value factor = 1 / (1+ discount rate)$^{(\text{year} - \text{base year})}$. Values rounded to two decimal places for presentation.
b. Debit is calculated by multiplying percent service loss by present value factor.

HEA credits for service gains associated with restoration are calculated similarly. Table 8.2 demonstrates how HEA credits would be calculated for a restoration project on one acre of land that improves service flows, as a percentage of baseline, by 50% in equal annual increments over the five-year time period from 2010 to 2014, and then maintains the 50% service improvement for the next five years (2015–2019). Again, the base year in this example is 2007 and the discount rate is 3%. The total HEA credit for this acre, for the period 2010–2019, is 3.1 DSAYs.

REA is similar to HEA but uses resource metrics (such as numbers of birds injured) instead of habitat units to quantify changes in services over time. An example of a simple REA might be a single event bird kill. The metric might be lost bird-years, where the loss is the sum of the expected remaining years of life for the killed birds. The data to support expected life spans come from bird population and survival models. Multiplying the estimated number of killed birds by years of life lost gives lost bird-years. This value is discounted to quantify the injury in discounted-lost-bird-years.

Table 8.2. Example of HEA credit calculations. This example assumes 1 acre of land with a service gain increasing from 0% to 50% over baseline service levels from 2010 to 2014 and the 50% improvement maintained from 2015–2019, assuming a 2007 base year and 3% discount rate.

Year	**Percent service flow above baseline at end of year**	**Present value factor[a]**	**Credit[b] (DSAYs)**
2010	10%	0.92	0.09
2011	20%	0.89	0.18
2012	30%	0.86	0.26
2013	40%	0.84	0.34
2014	50%	0.81	0.41
2015	50%	0.79	0.40
2016	50%	0.77	0.38
2017	50%	0.74	0.37
2018	50%	0.72	0.36
2019	50%	0.70	0.35
		Total	**3.1**

a. Present value factor = 1 / (1+ discount rate)$^{(\text{year} - \text{base year})}$. Values rounded to two decimal places for presentation.
b. Credit is calculated by multiplying percent service gain by present value factor.

REA approaches can be used for other resources as well. For example, if one quantified air injury in units of volume of air injured, then one could quantify air improvements from restoration projects in units of volume of air restored. The metric for scaling the restoration project would then be discounted-volume-years.

8.3.3 Assessment approach

The State plans to quantify natural resource injuries using HEA and/or REA approaches. The State will choose the appropriate approach (HEA or REA) based on the results of the injury assessment process and the types of information available, including restoration benefit information. Once injury is quantified using appropriate units (DSAYs for HEA; discounted lost-resources or resource years for REA), the State will select potential restoration projects using the project evaluation criteria, and calculate the scale of required restoration to offset the injury.

8.4 Restoration Projects

8.4.1 Identification

Consistent with DOI regulations, the State plans to identify a "reasonable number of possible alternatives for the restoration, rehabilitation, replacement, and/or acquisition of the equivalent of the injured natural resources" [43 CFR § 11.82 (a)]. The State will consider projects from existing regional restoration plans (e.g., from the Northeast Greenway Corridor project) and solicit proposals from State agencies such as the DOW, interested nonprofit organizations, and the general public when identifying a list of potential restoration projects. Such projects would benefit the resources that have been injured at the Arsenal. Examples include:

- *Projects that provide benefits to terrestrial grassland (e.g., prairie) habitats and species.*
- *Projects that provide benefits to riparian-wetland habitats and species*.
- *Projects that provide benefits to groundwater systems, aquifers, groundwater-surface water interactions, or water users*. These potential projects are discussed further in Chapter 9.

Specific types of projects may include:

- *Preservation of existing habitat at risk for development.* The State may identify parcels of land with high habitat value for wildlife or high rates of groundwater recharge that can be preserved through acquisition or conservation easements. Preservation provides benefits when potential future development would result in the loss of natural resource services.
- *Restoration and enhancement of existing degraded habitats.* The State may identify degraded grasslands, wetlands or stream corridors that can be restored or enhanced to increase the wildlife services provided.
- *Preservation of protective buffers for core areas of high wildlife value.* The State may preserve land to protect areas of high wildlife value that would be lost if the surrounding land use changed. Residential development near habitat areas, for example, can result in impacts to birds and wildlife from a variety of factors, including the introduction of non-native predators such as domestic cats and dogs (USDA NRCS, 2007).

8.4.2 Evaluation and selection

Potential restoration projects will be evaluated and ranked using criteria developed by the State. These criteria build on factors identified in the DOI NRDA regulations [43 CFR § 11.82]. The State has grouped criteria into “threshold acceptance criteria” and “project preference criteria” (Table 8.3). Projects will first be evaluated against threshold acceptance criteria. Failure to meet all the threshold criteria would result in elimination of a project from consideration. Projects that meet threshold criteria would then be investigated further to gather information necessary to evaluate the projects using the preference criteria. Projects that best meet the preference criteria will be used for restoration scaling (see Section 8.4.3) and costing (see Section 8.4.4).

Table 8.3. Summary of Trustee criteria for evaluating restoration projects

Threshold acceptance criteria
1. Project must restore, replace, or acquire natural resources, not merely human services.
2. Project must be subject to a reasonable degree of State management, control, and monitoring.
3. Project must have a reasonable likelihood of success. The project should be technically feasible and viable.
4. Project must comply with laws and be protective of health and safety.
5. Project must be generally acceptable to the public.
Project preference criteria
1. Projects that are consistent with existing state, regional, and local resource management and development plans will be strongly preferred.
2. Projects that provide higher flows of services throughout the project lifetime will be preferred. It is preferable and more cost-effective for projects to provide higher levels of near-term benefits as compared to projects that require protracted periods to realize benefits. Projects that provide long-term sustainable service flows are also preferred.
3. Projects with less long-term operations and maintenance (O&M) will be preferred unless those costs are assumed by other parties and the State is assured that O&M will be adequately carried out for as long as necessary.
4. Projects that are likely to benefit more than one resource will be preferred.
5. Projects that can be reasonably monitored and have benefits that can be measured and verified will be preferred.
6. Projects that provide actual resource improvements will be preferred over projects that entail only conservation of open space, unless development threats are imminent or the conservation opportunity is of an advantageous scale or timing.
7. Projects that provide a high ratio of expected benefits compared to expected long-term costs for planning, implementation, operations, and maintenance will be preferred. Cost-effectiveness may be assessed relative to other projects that benefit the same resources.
8. Projects will be preferred if they are not likely to be funded through other mechanisms, or if implementation of the project would free restoration funding sources to finance other restoration projects.
9. Projects will be preferred if they leverage damage recoveries to match other funding sources and thereby enable projects to be larger or more comprehensive in scope.

8.4.3 Scaling

After quantifying reductions in services from injured resources, Trustees will determine the appropriate scale of restoration projects. For wildlife, service flow reductions may include:

- Loss of species diversity
- Loss of threatened and endangered species
- Loss of common wildlife species
- Loss of human active-use services (such as hunting or wildlife viewing)
- Loss of human passive-use services (such as bequest values – valuing the availability of resources for future generations).

Reductions in services provided by surface water may include:

- Loss of aquatic habitat
- Loss of species diversity or density
- Loss of clean water for recharge of alluvial groundwater.

Reductions in services provided by groundwater and aquifers may include:

- Loss of human active-use services such as drinking water
- Loss of human passive-use services
- Loss of clean water for recharge to surface water and wetlands
- Loss of aquifers for recharge, storage and transportation of groundwater.

Reductions in services provided by air may include:

- Loss of human active-use services such as unhampered breathing.

For the restoration scaling phase, the State will determine the required size (or "scale") and timing of implementation for the preferred restoration projects such that increases in services from restoration is equal to the loss of services from injured resources at the Arsenal, with both losses and gains adjusted to present-value equivalents. This scaling would compensate for interim losses and quantify any restoration required to return injured resources to baseline conditions.

As part of the scaling effort, the spatial connectivity, and the timing and magnitude, of anticipated service flow improvements will be considered. For example, acquisition of or habitat restoration on, two adjacent parcels would likely provide greater benefits than identical acquisitions or restoration on parcels separated by miles of developed land. Likewise, projects that yield dramatic improvements in a short period of time would likely provide greater benefits than projects with more subtle improvements that would take longer to accrue. Also, a project that involves creating riparian habitat around a two-acre gravel pit pond may be fixed in its scope because it involves habitat improvements to an existing site with fixed dimensions. In contrast, a river restoration project often can vary in size depending on the resources available to the project. Projects also can vary in the degree and duration of service improvement depending on the intensity of the restoration work and the commitment to long-term monitoring and maintenance. For example, a project that removes invasive species a single time would generate benefits over a shorter period of time than a project that provides ongoing control of invasive species as necessary.

The State plans to determine the best size and scope for each proposed project to maximize project benefits and overall cost-effectiveness across the suite of selected restoration projects. The State will take advantage of “economies of scale” where possible – sizing projects to get the maximum per-unit benefit, while at the same time being conscious of “diminishing returns” where additional resources spent on a project yield lower per-unit benefits.

The type of scaling described above for HEAs and REAs is called “service to service” scaling, where the services gained from restoration offset the services lost from injury. Projects that involve replacement or acquisition of equivalent resources can be scaled directly using the same metric. However, the State may also consider replacement or acquisition projects that provide services of a different type or quality than those lost if, for example, the replacement or acquisition of equivalent resources is technically infeasible or prohibitively expensive. When a replacement or acquisition project provides services that are not the same as those lost, additional information may be needed to determine when the project has produced “equivalent” resources as measured by the services. Alternative scaling methods such as weighting factors or value-to-value analysis, as opposed to “service-to-service” scaling, may be employed in these situations.

The State expects to use service-to-service scaling for terrestrial and aquatic wildlife injuries because restoration alternatives are available that provide the same or similar types and quality of services as those lost. The State may also use service-to-service scaling for injuries to air and surface and groundwater resources, if appropriate restoration alternatives that provide services of the same or similar type and quality can be quantified.

8.4.4 Costing

After determining the required size of each proposed restoration project, the State will estimate the cost to implement these projects. Costs will be based on preliminary project designs because full engineering designs are not feasible or appropriate to develop during the assessment process. Total cost estimates will include project design, implementation, monitoring, continued operation and maintenance, contingencies, Trustee oversight, and adaptive management. Adaptive management allows project changes to be made if monitoring indicates that goals are not being achieved. As part of this process, information will be developed that can be used to adjust project cost estimates according to the scale of implementation for projects where the size of the project can vary.

8.4.5 Summary

The determination of damages using the restoration-based cost approach involves the following steps:

- Quantification of the spatial and temporal extent of natural resource service losses as a result of the release of hazardous substances
- Identification of projects that can provide restoration, rehabilitation, replacement, and/or acquisition of equivalent of the resources and their services
- Scaling of the projects such that the service gains that the project provides offset the service losses as a result of the hazardous substance releases
- Estimation of the total cost to implement the restoration projects that will provide equivalent resources and their services.

The responsible party may either choose to implement the restoration projects directly or provide the Trustees with monetary compensation for the estimated cost of implementing the projects.

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9. Valuing Groundwater

This chapter provides an overview of the NRDA economic valuation approaches to be used to quantify damages to groundwater.

Section 9.1 provides an overview of damage assessment concepts and definitions. Section 9.2 presents a market-based approach to estimating damages resulting from loss of groundwater use services. Section 9.3 describes a restoration-based approach, and Section 9.4 then presents a total value equivalency (TVE)/restoration scaling approach, including a description of the foundations of the approach; the steps and data necessary for implementing this non-market method; and future work that may be conducted as part of this assessment.

9.1 Damage Assessment Concepts and Definitions

As noted in Chapter 8, the purpose of the damage determination phase is to establish the amount of money to be sought in compensation for injuries to natural resources resulting from a release of hazardous substances, including the *cost of restoration* and, at the discretion of the authorized official, the *compensable value* of all or a portion of the interim loss [43 CFR § 11.80(a)(2)(b)]. Compensable values include "the value of lost public use of the services provided by the injured resources, plus lost non-use values such as existence and bequest values" [43 CFR § 11.83(c)(1)].

These terms are defined in the regulations as follows:

- *Compensable value* is the amount of money required to compensate the public for the loss in services provided by the injured resources between the time of the release and the time the resources and the services those resources provided are fully returned to their baseline conditions [43 CFR 11.83(c)(1)]

- *Use value* is the value of the resources to the public attributable to the direct use of the resources [43 CFR 11.83(c)(1)(i)]

- *Direct use values* are generally associated with well-identified, active, and often on-site, uses such as recreational and commercial activities

- *Non-use value* is the difference between compensable value and use value [43 CFR 11.83(c)(1)(ii)]. Non-use values (or passive use values) arise from the values individuals place on resources apart from their own readily identified and measured direct or active use. Non-use values may include bequest values, which are the values individuals place on the availability of resources for future generations, existence values, which are those values individuals place on a resource even if they never use it [56 FR 19760], or option values, which are values held by individuals who wish to preserve the resources for their own potential use.

Service flow losses and selection of economic assessment methods

Economic methods are used to identify, characterize, quantify, and value human use service losses. Based on the potential groundwater service losses, the Trustees anticipate using both market price methods and restoration-based approaches for estimating damages. Specifically,

- **Market price methods.** Market prices can be used to establish the diminished value of the injured groundwater.
- **Resource equivalency analysis**. REA can be used to develop the cost of restoring, replacing, or acquiring the equivalent groundwater and aquifer resources and services, including interim losses.
- **Total value/restoration scaling methods.** Methods such as conjoint or stated choice methods can be used to establish the type and amount of restoration actions that provide value to the public equivalent to the value held for the injured resource.

9.2 Market Price Approaches

For water resources, including groundwater, that are traded in reasonably competitive markets, one of the valuation methods available to the Trustees is the market price method [43 CFR §11.83 (c) (2)(i)]. This section describes how market prices for the direct consumption of water in municipal and industrial activities, or for its use as an input to other commodities such as irrigated agriculture, reflect the value of water in the Front Range region of Colorado.

Water that could have been available from the Arsenal absent the contamination can be valued using market data that are readily available, comprehensive, and consistent. Initial evaluation of data indicates that sufficient information is available to form an accurate representation of the willingness to pay for water over the past 15 years in the Front Range area of Colorado. This can provide a basis on which to calculate contaminated groundwater damages from the Arsenal site.

9.2.1 Water market literature overview

Over the past 15 years, natural resource agencies in the western United States have gradually accepted water markets as a way to encourage the efficient allocation of water among competing uses. In this period, the 14 contiguous western states have enacted legislation that clarify water rights, and in particular the conditions under which water is transferred by a temporary lease or permanent sale. Economists have recognized differences in the value of water depending on the geographic regions and sectors of the economy using the water. They have advocated water markets as a method to allow for the increased benefits that can be realized by allowing water to move between sectors of the economy and across geographic regions. Potential gains in efficiency have been shown by Hartman and Seastone (1970), Vaux and Howitt (1984), and Hearne and Easter (1997). These gains from trade have led to active water markets in many parts of the western United States including Colorado.

The wide range of transferable water rights in western states breaks down into two broad classes commonly termed leases and sales. Leases of water are generally for a single year and for a known quantity of water. Some lease contracts are for longer periods of time and can be contingent on hydrologic conditions. Such contingent leases are a way of sharing the supply risk between the buyer and seller. Sales of water rights, on the other hand, usually entitle the purchaser to a permanent share of a water supply system that may yield varying amounts of water depending on weather and other factors. The seniority of the rights affects their expected yield and their sale price.

Table 9.1. Cumulative volume and volume-weighted prices for reported water transactions in Western states, 1990–2005[a]

	Volume				
	Lease	Sale	Total		
State	(thousand acre-feet)			Lease/sale ratio	Transactions as % of total use
AZ	10,869	1,958	12,826		
CA	18,407	2,557	20,965	7.20	3.13
CO	516	2,977	3,494	0.17	1.52
ID	4,338	408	4,746	10.64	1.42
MT	52	9	62	5.56	0.04
NM	837	258	1,095	3.24	1.82
NV	236	960	1,196	0.25	2.38
OR	1,070	2,406	3,476	0.44	2.61
TX	5,351	3,907	9,258	1.37	2.17
UT	262	190	452	1.38	0.55
WA	128	298	427	0.43	0.37
WY	234	207	441	1.13	0.42
Average				2.62	2.35
Total	42,302	16,135	58,437		

a. Water transferred under sale or long-term lease is counted each year for which the transfer occurs.

Source: Data from the *Water Strategist* (1990–2006).

9.2.2 Market value of groundwater: Conceptual approach

Using the market price approach, damages will be estimated based on observed market trades for water in the Front Range region to ascertain a market value (i.e., water users' willingness to pay) for the groundwater that, in the absence of contamination, would have been available.

Many of the Front Range water utilities that purchase surface water supplies also use groundwater that is blended with surface water for consumption, thus creating a single commodity with a shared market price. In addition, the cost of obtaining the rights to use shallow, tributary groundwater is often related to the cost of obtaining sufficient augmentation water. Augmentation water can be other sources of groundwater, including bedrock supplies, but more often is obtained by purchasing and retiring senior surface water rights. Thus, the Trustees will consider both groundwater and surface water transactions in determining appropriate market prices.

As with any market price valuation, the ultimate estimate of appropriate value will depend upon an analysis of variables affecting the price for each transaction. Such variables may include quality, location, reliability of supply, quantity of water transacted, seniority of rights, and consumptive use percentage of the water right. Transactions for sales of permanent rights as well as temporary leases will be analyzed.

To develop market prices for groundwater in the Arsenal region, the Trustees will use observed market data, including associated variables, to establish appropriate prices that water would sell for in the Front Range region at a given date. The sale price of water would then be used to calculate the annual diminished value of injured resources. Market prices for dates after those available in the collected transactions would be based on statistical forecasts using projections of variables that help explain changes in water prices, such as urbanization and development in the region. Values may also be based on differences in water quality and any use restrictions or other constraints not related to the injury.

9.2.3 Illustration of market price approach

To demonstrate the applicability of the market price method, the Trustees identified 1,118 observations of water rights sales in Colorado from 3,696 transactions compiled from the *Water Strategist* (Hansen et al., 2007). The *Water Strategist* reports permanent transfers and leases (including price, quantity, buyer and seller identification, buyer and seller use, and some additional contract terms) in 14 western states on a monthly basis.[1] The details of transactions

1. The implicit assumption is that the *Water Strategist* data are, if not comprehensive, at least representative of trades taking place in western states.

that occurred in Colorado over 16 years allow estimates of the economic, hydrological, and institutional factors that determine the price of water in Colorado, and thus allow direct estimates of water values in monetary terms. Table 9.2 provides information on transactions for the Colorado water market.

Table 9.2. Water purchasers in the Denver area, with number of transactions (1990–2005)

Buyer	Number of permanent transfers	Buyer	Number of permanent transfers
Arkins WA	2	Kersey	6
Arvada	1	LaSalle	20
Ault	6	Left Hand WD	36
Aurora	2	Little Thompson WD	81
Berthoud	4	Longmont	4
Boulder	41	Longs Peak WD	16
Brighton	1	Louisville	25
Broomfield	47	Loveland	3
Central Weld County WD	38	Lower Latham Reservoir Co.	8
Dacono	22	Lyons	5
East Larimer County WD	13	Mead	5
Erie	42	Milliken	19
Estes Park	5	North Weld County WD	28
Evans	29	Northglenn	3
Firestone	44	Nunn	11
Fort Collins-Loveland WD	86	Pierce	10
Fort Lupton	32	Platteville	22
Fort Morgan	17	Severance	1
Frederick	36	St. Vrain and Left Hand WCD	14
Gilcrest	13	Superior Metro District No. 1	5
Golden	1	West Fort Collins WD	1
Greeley	24	Westminster	8
Hudson	6	Windsor	19
Johnstown	6		

WD = water district.

Buyers were included in this list if they made at least one trade through the Colorado Big Thompson (CBT) over the study period or if they are located within the Denver Metropolitan Statistical Area.

Water in Colorado is traded in the form of three different property rights: a short-term lease of a quantity of water (lease), a permanent sale of a water right (sale), and a permanent sale of a share in large water projects (e.g., share in a ditch company or in the CBT project). Shares vary in their yield of water from year to year. In Colorado, like many western states, leases of water are common. However, as shown in Table 9.1, when considering the total volume of water transacted, the ratio of leases to actual sales is relatively low in Colorado. (Colby et al., 1993). On the other hand, Table 9.3 shows the average quantities and prices of transfers by type of water and year. All types of water are traded, but clearly, the number of trades in leases and shares greatly exceeds the number of permanent sales of water rights.

Table 9.3. Water transfers in Colorado by year (1990–2005)

	Total quantity (acre-feet)			Average price		
Year	**Lease**	**Sale**	**Share**	**Lease**	**Sale**	**Share**
1990	14,000		3,626	$70		$2,991
1991	10,000	250	12,579	$93	$5,851	$2,890
1992	2,000		4,492	$27		$2,734
1993	14,300		2,019	$25		$2,334
1994	37,558	200	2,509	$18	$5,338	$2,234
1995	23,312		2,128	$34		$2,935
1996	62,534		2,841	$489		$3,806
1997	7,000		8,254	$83		$3,916
1998	38,857		3,569	$539		$4,620
1999	35,256	5,800	7,352	$8	$3,666	$6,839
2000	15,674		4,055	$10		$16,800
2001	25,603		2,861	$73		$15,850
2002	1,221	450	2,513	$170	$9,468	$20,687
2003	14,946	7,596	2,087	$159	$4,845	$15,862
2004	15,640		3,367	$347		$18,365
2005	22,478	873	2,279	$212	$948	$15,797

To demonstrate how water market data are used to estimate a time series of representative prices for the Colorado Front Range water market, a statistical regression analysis was developed to measure those factors that are associated with changes in the price of water rights. The regression results presented here are intended to be illustrative, as the effect of different explanatory variables will be investigated further during the assessment. However, this illustration demonstrates how regression analysis can be used to reveal the factors associated with changes in prevailing water market prices. The ability to measure these factors enables estimation of a market clearing price. Table 9.4 shows the results of an initial regression applied to 1,118 observations of prices and quantities of water rights sales from 1990 to 2005. In this illustrative example, the data available on annual prices are in constant 2004 dollars, and sale price was related to five variables to explain changes in price through time: the annual quantity of water rights sold in Colorado, a variable that accounts for sales originating from shares in the CBT (see below), a time trend, the number of acre-feet in the particular contract, and an index of the relative level of drought in a given year called the Palmer Drought Index.[2] Water rights based in the CBT are hypothesized to be more valuable than other sources, as they are for transmountain diversions and have fewer augmentation requirements than many other sources.

Table 9.4. Regression of Colorado water rights sales, 1990–2005

Water price (2004 dollars)	Annual volume traded (1,000 acre-feet)	Transaction volume (acre-feet)	CBT (= 1 if trade occurs within CBT)	Annual Palmer Drought Index (larger numbers = higher precipitation)	Time trend	Constant
	-52.0497	-1.3741	815.7813	-996.6406	1,033.028	738.5783
	(3.02)[a]	(2.08)[b]	(0.38)	(7.26)[a]	(7.77)[a]	(0.53)

Observations: 1,118.
R-squared: 0.24.
Robust t-statistics in parentheses.

a. Significant at 1% level.
b. Significant at 5% level.

The regression equation from Table 9.4 for calculating water price in 2004 dollars is:

Water Price = 738.57 – 52.05 × (Annual Volume Traded/1,000) – 1.374 Transaction Volume + 815.78 CBT – 996.64 Drought Index + 1,033.03 Year Index.

This illustrative regression equation has some explanatory power, with an R^2 of 0.24. Three of the six variables are highly statistically significant in explaining changes in the observed water prices: the total quantity of rights sold, time, and drought severity. The total annual quantity of water rights sold in a year is negatively related to the prevailing market price, as would be

2. The Palmer Index was developed by Wayne Palmer in the 1960s and uses temperature and rainfall information in a formula to determine dryness. The Palmer Index uses 0 as normal, and drought is shown in terms of minus numbers; for example, minus 2 is moderate drought, minus 3 is severe drought, and minus 4 is extreme drought. The Index can also reflect excess rain using a corresponding level reflected by plus figures, e.g., 0 is normal, plus 2 is moderate rainfall.

expected from basic demand theory. The time trend of prices is increasing, as expected given the increased water demand from residential development and economic growth in the Front Range region over the 16-year time period. In addition, water prices increased with the severity of drought conditions, as measured by the Palmer Drought Index. The quantity of the water traded has a moderately significant effect on the price, with smaller quantities requiring a higher unit price.

Using regression results such as those in Table 9.4, the resulting average price of water can be calculated under different conditions and times. Figure 9.1 shows a plot of actual and estimated average prices over the 16 years in the sample. The illustrative regression annual price predictions fit the actual average price quite well, except in the extreme drought years of 2002–2003. Figure 9.1 also shows a pronounced increase in average water prices after 2000, when the current drought cycle began. Average sale prices after 2000 have fluctuated around $15,000 per acre-foot (in 2004 dollars), providing a reliable estimate of the current value of groundwater rights.

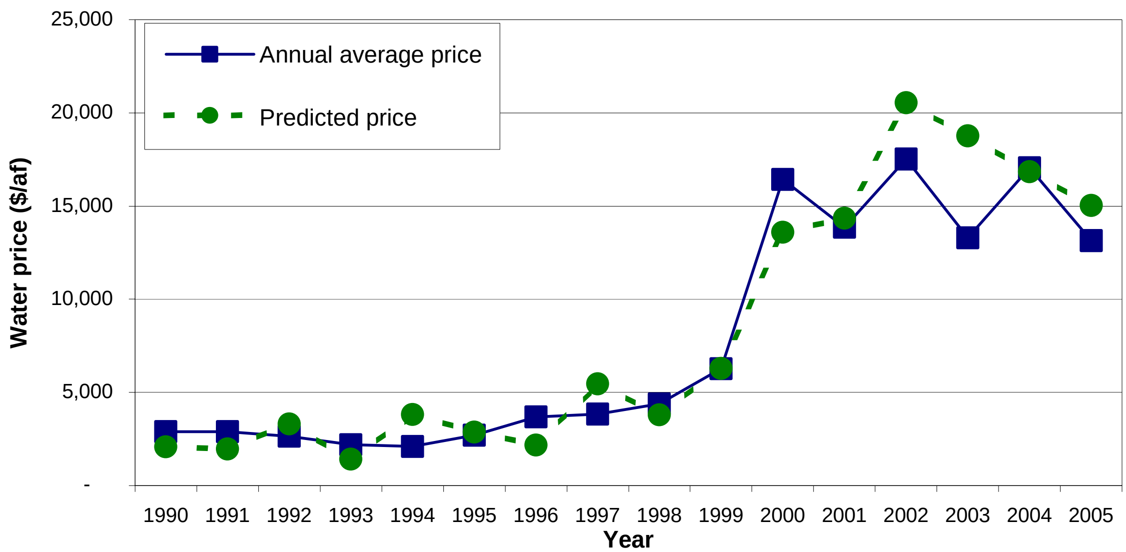

Figure 9.1. Observed and predicted price of permanent water transfers in Colorado over time (2004 dollars).

Water Strategist sales data and other information will be used to measure the actual valuation of water rights in terms of real monetary transactions. Damage recoveries based upon this market price approach would be used for implementing restoration actions. Restoration planning to identify appropriate restoration actions will be undertaken as described in Chapter 8.

9.2.4 Anticipated assessment activities

In the assessment, determination of damages through the market price valuation of groundwater will be pursued. Detailed market price valuation activities will include:

- Updating and refining a water transactions database to allow for more detailed comparisons to groundwater values in the region
- Incorporation of regional water demand conditions
- Refinement of statistical analysis of water market prices
- Forecasting to future water prices
- Application of water valuation to estimation of groundwater damages resulting from contamination and institutional controls.

9.3 Restoration-Based Equivalency Approaches

As discussed in Chapter 8, equivalency approaches such as REA can be used to determine the appropriate amount of restoration required to adequately compensate the public for its loss of natural resources and services.

The State will use the selection criteria discussed in Chapter 8 to identify potential restoration projects that would provide compensation for injuries to groundwater. These projects would provide benefits to groundwater systems, aquifers, groundwater-surface water interactions, or water users. Specific types of projects may include:

- *Water quality protection and improvement programs.* The State may choose to implement projects that protect water quality by reducing urban or agricultural runoff or that improve water quality.
- *Water reuse programs.* The State may choose to work with municipalities to implement non-potable water reuse programs that would result in measurable savings of potable groundwater. Such a project might involve construction of facilities to transport, store, and apply non-potable irrigation water to public parks, recreational areas, roadway medians, and landscaping around public buildings.
- *Water conservation programs.* The State may choose to work with municipalities and other appropriate entities to implement water conservation programs that would result in measurable savings of groundwater with no reductions in groundwater services.

- *Water recharge programs.* The State may choose to create wetlands or detention basins to contain high water flows and allow slower infiltration to groundwater, thereby reducing evaporative losses, increasing the quantity of available groundwater, and restoring groundwater-surface water interaction.

- *Water salvage programs*. The State may undertake to salvage water lost to invasive species such as tamarisk.

After quantifying reductions in services from injured groundwater resources, the Trustees will determine the appropriate scale of restoration projects. As discussed previously in Chapter 8, reductions in services provided by groundwater may include:

- Loss of human active-use services such as drinking water
- Loss of human passive-use services
- Loss of clean water for recharging surface water
- Loss of aquifers for recharge, storage and transportation of groundwater.

The Trustees will then determine the required size ("scale") and timing of implementation for the preferred groundwater restoration projects such that increases in services from restoration would be equal to the loss of services from injured resources at the Arsenal, with both losses and gains adjusted to present-value equivalents. This scaling could compensate for both interim losses and restoration that is required to return injured resources to baseline conditions. Once the required size of each proposed groundwater restoration project is established, the State will estimate the cost to implement these projects. Where the size of the project can vary, unit costs may be developed to enable the Trustees to scale up or down.

9.4 Total Value/Restoration Scaling Method

As discussed previously, when groundwater is injured by releases of hazardous substances, both use and non-use values are lost. Market price approaches, as described in Section 9.2, can measure use values, which make up a portion of total economic value. To estimate total damages for the groundwater injury, however, an alternative to the market price approach is necessary. This alternative approach will identify and quantify the amount and type of restoration that would provide value to the public equivalent to the value of the groundwater that has been injured. These values are ascertained by:

1. Obtaining public preferences for the types and mix of restoration alternatives
2. Providing value-based methods to scale resource restoration projects to provide services of equivalent societal value to the total value of the injured groundwater.

The results of the survey and analysis would determine the restoration plan selected by the Trustees; the cost of the plan would become the amount of damages sought by the Trustees.

A TVE study would support groundwater restoration planning in two ways. First, the study would explicitly obtain the public's input regarding the preferences and values for alternative types of restoration projects. This would aid the Trustees in evaluating the benefits of alternatives [43 CFR § 11.82(d)(2)] and provide additional input into the selection of alternatives [43 CFR § 11.90]. Second, the study provides value-based, as opposed to service-based, methods to determine the appropriate scale of potential restoration actions.

As described in Chapter 8, scaling restoration projects that provide similar services is referred to as *service-to-service* scaling, where the amount of restored services are scaled to be equal to the amount of lost services now and through time. For a large share of the service flow losses in the assessment area, providing restoration with similar groundwater services may not be technically feasible, may be undesirable, or may be too expensive. Thus, it may be preferable to select restoration actions that provide resources and services with similarly held value to those injured in determining the appropriate restoration. *Value-to-value* equivalency analysis ensures that the societal value of the services gained through restoration equals the societal value of losses. Value reflects the benefits or satisfaction that people derive from all active and passive uses of the resources lost due to contamination and gained through restoration.

9.4.1 Conceptual approach

At least since the mid-1960s, environmental economists have argued that people may hold both use (active use) and non-use (passive use) values for environmental resources (Krutilla, 1967). These use and non-use values make up what economists call total value. Passive use values are typically described as values that people hold for goods independent of any direct or active use of the goods. For example, they may gain satisfaction from knowing that an environmental resource will be preserved for others to enjoy, including others alive today and members of future generations. In the case of the Arsenal, even though citizens do not personally use the groundwater from a specific aquifer or area, they might still hold values for it because they would like it to be available to future generations or for other reasons. As the National Research Council (NRC, 1997, p. 2) has stated, "A fundamental step in valuing a ground water resource is recognizing and quantifying the resource's total economic value. Knowing the resource's total economic value is crucial for determining the net benefits of policies and management actions."

Passive values are routinely measured in benefit-cost analysis and have been used in the courts. The D.C. Circuit Court of Appeals confirmed the legitimacy of passive use values in damage assessments in *Ohio v. U.S. Department of the Interior* [880 F.2d 432 (1989)] and these values have been recognized in other cases as well (Freeman, 2003).

Damages for injured groundwater at the Arsenal will be measured using TVE, which considers both active use and passive use values. People's values will be measured by asking them appropriately crafted survey questions. The survey-based approach that is best suited to restoration planning involves stated-choice questions, where members of the public are presented with two or more restoration alternatives with different combinations of environmental resources and services. They are then asked to either choose their preferred alternative or to rank the alternatives. Typically, a cost is also associated with each alternative.

The history of applications of stated-choice questions is presented by Holmes and Adamowicz (2003). Stated-choice questions are now routinely used in nonmarket valuation studies, routinely conducted by state and federal agencies, and the results are accepted in benefit-cost analysis by federal agencies (OMB, 2003). An example of this approach, used on behalf of the USFWS and co-Trustees as part of the Lower Fox River/Green Bay NRDA, is discussed in the Fox River RCDP for the Lower Fox River/Green Bay NRDA (Stratus Consulting, 2000).

9.4.2 Anticipated assessment activities

An approach similar to that undertaken at the Fox River will be applied to determine the types and amount of restoration necessary to compensate for groundwater injuries at the Arsenal. The goal of the TVE approach for the Arsenal assessment will be to develop a variety of restoration projects that provides the public with value equivalent to that lost as a result of groundwater injuries.

Development of restoration options

To identify the potential of restoration options for a TVE study, the Trustees anticipate soliciting projects from a number of sources, including ongoing restoration planning efforts by local resource managers (e.g., Northwest Greenway Corridor); direct solicitation from the public at large through public comment; and focused discussions with identified stakeholder groups and State agencies. Restoration options would then be evaluated for possible inclusion in the TVE survey instrument.

Qualitative survey research

Qualitative survey research such as focus groups and structured individual interviews would be used in the initial stages of TVE survey development. These activities would allow the Trustees to investigate the public's understanding of the injury and its associated value, to identify aspects of greatest concern to the public, to confirm that the exercise is likely to be successful in soliciting the requisite feedback, and to identify types of restoration actions seen as appropriate for compensation.

Development of a survey instrument

Based on findings from the qualitative research phase, and in coordination with the ongoing injury studies, a TVE survey instrument would be designed to measure the public's value for the restoration options in relation to the value of the lost groundwater resources and services due to contamination at the site. Survey development will include peer review of the survey and overall implementation process.

Implementation of survey

The survey would be administered to a representative sample of the relevant population of Colorado. The relevant population would be determined during the qualitative survey research efforts. The survey would be administered in a format (e.g., mail, in-person) determined to obtain reliable results.

Data analysis and reporting

Data collected through the administration of the survey would be evaluated and statistically analyzed to estimate the damages to the public based on a TVE approach.

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Glossary

This section presents definitions of terms in this report.

Baseline. The condition of a natural resource that would have existed but for the release of hazardous substances. Baseline conditions are not necessarily pristine or optimal conditions. See 43 CFR § 11.14(e).

CDPHE. The Colorado Department of Public Health and Environment, the State agency responsible for hazardous waste site compliance and oversight.

CERCLA. The Comprehensive Environmental Response, Compensation and Liability Act of 1980 (42 USC § 9601 to § 9675). This Act, commonly referred to as "Superfund," is the statutory basis for natural resource damage assessment.

Compensable value. The amount of money required to compensate the public for the loss in services provided by the injured resources between the time of the release and the time the resources and the services those resources provided are fully returned to their baseline conditions. The compensable value includes the value of lost public use of the services provided by the injured resources, plus lost nonuse values such as existence and bequest values. See 43 CFR § 11.83(c).

Damages. The amount of money needed to assess injury and to restore injured natural resources. Damages are sought from the responsible parties. Past damages accrue from the earliest point that injuries from releases can be determined, or authorization of the statute (December 1980 for CERCLA), to the present. Future damages include interim damages, which run from the present until restoration actions return injured resources to baseline conditions. Residual damages, a component of interim damages, accrue after remedial activities have ceased, if the remediation did not fully restore natural resources services to baseline levels.

Discounting. An economic procedure that weights past and future benefits or costs such that they are comparable with present benefits and costs. Discounting converts benefits or costs from different years so that they are mutually comparable.

Discount rate. The rate at which the future is discounted, i.e., the rate at which the future does not count as much as the present. Economists generally agree that the discount rate on social investments such as natural resource services is 3%.

DOI NRDA Regulations. Regulations promulgated by the U.S. Department of the Interior, pursuant to CERCLA, at 43 CFR Part 11.

Exposure. Contact between a hazardous substance or oil and a natural resource. Exposure alone does not constitute an injury, but exposure to a hazardous substance (or byproduct) is necessary to cause an injury. Pursuant to the DOI Regulations, 43 CFR § 11.14(q), exposure occurs when all or part of a natural resource is, or has been, in physical contact with oil or a hazardous substance, or with media containing oil or a hazardous substance.

Groundwater. Groundwater is defined as any water not visible on the surface of the ground under natural conditions; CRS 37-90-103(19).

- ***Tributary groundwater*** is hydraulically connected to the surface waters of a stream, and is classified as if it were surface water, subject to the constitutional right of prior appropriation (see below). *Colorado Ground Water Com'n v. North Kiowa-Bijou Groundwater Management Dist*., 2003, 77 P.3d 62.

- ***Nontributary groundwater*** means groundwater having no hydrological connection to surface water; it is administered on the basis of overlying land ownership and is exempt from the doctrine of prior appropriation. See *State Dept. of Natural Resources v. Southwestern Colorado Water Conservation Dist*., 671.P.2d 1294 (Colo. 1983).

- ***Not-nontributary groundwater*** means " . . . ground water located within those portions of the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers that are outside the boundaries of any designated groundwater basin . . . the withdrawal of which will, within one hundred years, deplete the flow of a natural stream . . . at an annual rate of greater than one tenth of one percent of the annual rate of withdrawal" CRS 37-190-103(10.7).

Habitat. The physical, chemical, and biological attributes that together provide basic needs for plant and animal species and communities of organisms. Habitat includes temperature, moisture, light, structural features such as stream banks and trees, food sources, and nesting, hiding, and thermal cover. The term can be used to define surroundings on almost any scale from very large regions to very small microhabitats.

Habitat equivalency analysis (HEA). An accounting model used to calculate the service losses from past, ongoing, and future injuries (the debit side of the model) and the future service gains from proposed restoration needed to equal the debit (the credit side of the model). HEA is used in cases of habitat injury when the service loss of the injured habitat is comparable to the service gain that will be provided by the replacement habitat.

Harmonic mean. The harmonic mean is calculated by dividing the number of values in a data set by the sum of the reciprocals of those values. It is a more representative central tendency value for skewed data sets than is the geometric mean.

Hazardous substances. Hazardous substances include metals, solvents, pesticides, and other contaminants as specified in Section 101.14 of CERCLA.

Injury. Injury to natural resources is a measurable adverse effect on a physical, biological, or chemical quality of a natural resource. Injuries can occur directly or indirectly. Categories of injury include, but are not limited to, adverse changes in survival, growth, and reproduction; health, physiology and biological conditions; behavior; community composition; ecological processes and functions; physical and chemical habitat quality or structure; and public services. Injury means a measurable adverse change, either long- or short-term, in the chemical or physical quality or the viability of a natural resource resulting either directly or indirectly from exposure to a discharge of oil or release of a hazardous substance, or exposure to a product of reactions resulting from the discharge of oil or release of a hazardous substance. As used in this part, injury encompasses the phrases "injury," "destruction," and "loss." See 43 CFR § 11.14(v) and 43 CFR § 11.62.

Integrated Endangerment Assessment/Risk Characterization (IEA/RC). The combined human health risk assessment and ecological risk assessment performed as part of the RI/FS at the Arsenal. The report estimated the magnitude of possible exposure and risk to human and ecological receptors. The Army issued the final report in July 1994.

Interim losses. Interim losses accrue from the time of release of the hazardous substance or 1981, whichever is later, until restoration is complete. See 43 CFR § 11.80(b).

Interim Response Action (IRA). A series of 14 response actions at the Arsenal that were identified before the final On-Post FS or Record of Decision. The IRAs were intended to clean up areas of serious contamination before the final remedy was selected or implemented but were intended to be consistent with the final remedy.

Natural resource. Surface water, groundwater, air, geologic resources, and biological resources. See 43 CFR § 11.14(z). Biological resources include those natural resources referred to in section 101(16) of CERCLA as fish and wildlife and other biota. Fish and wildlife include marine and freshwater aquatic and terrestrial species; game, nongame, and commercial species; and threatened, endangered, and State sensitive species. Other biota encompass shellfish, terrestrial and aquatic plants, and other living organisms not otherwise listed in this definition. See 43 CFR § 11.14(f).

Natural resource damage assessment (NRDA). The process of collecting, compiling, and analyzing information to determine damages for injuries to natural resources due to the release of hazardous substances. The purpose of NRDA is to determine the amount of damages necessary to compensate the public for loss of resources and services provided by natural resources resulting from releases of hazardous substances. This compensation comes in the form of restoration or replacement of injured resources, or acquisition of equivalent resources, paid for by the parties who caused the contamination.

NPL (National Priorities List). A list of the hazardous waste sites eligible for long-term remedial action under CERCLA (Superfund). Sites are added to the list through a formal process that evaluates the hazards associated with each site.

Pathway. The route or medium through which a hazardous substance travels from the source of discharge or release to the injured resource. See 43 CFR § 11.14(dd).

Preassessment Screen Determination (PASD). The PASD is a document containing determinations about whether a discharge or release of a hazardous substance warrants conducting a NRDA; it "ensure[s] that there is a reasonable probability of making a successful claim." 43 CFR § 11.23(a)(b). The PASD is not intended to serve as an actual assessment of natural resource injuries or damages.

Prior appropriation. The doctrine of prior appropriation is constitutionally mandated and codified in Colorado statutes. See COLO. CONST. art. XVI § 5 and CRS § 37-92-102, and simplistically means first in time is first in right. The doctrine has its origins in the mining industry and the arid climate of the west.

Record of Decision (ROD). The document that details the decision-making process and the final selected remedy for an operable unit. The ROD describes the components of the remedy and includes regulatory determinations as required by CERCLA. See 42 USC §§ 121 *et seq.* and, generally, 40 CFR § 300.430.

Release. This term refers specifically to the release into the environment of a hazardous substance. It can mean a leak, a spill, an intentional disposal, the migration of contaminants (e.g., through wind dispersion).

Remedial Investigation/Feasibility Study (RI/FS). The remedial investigation and feasibility study process pursuant to the NCP that forms the basis for selection of a final remedy documented in a ROD. The RI/FS generally occurs before the NRDA process begins.

Remediation/remedy. An action that alleviates contamination or injury; cleanup actions.

Replacement or acquisition of the equivalent. The substitution for injured resources with other resources that provide the same or substantially similar services, when such substitutions are in addition to any substitutions made or anticipated as part of response actions, and when such substitutions exceed the level of response action determined appropriate to the site as described in the ROD. See 43 CFR § 11.82(b)(ii).

Resource equivalency analysis (REA). Similar to HEA but specifically used for scaling losses of resources such as fish, birds, and other wildlife, rather than losses of habitat.

Response actions. Activities taken to reduce threats from contaminants to acceptable levels. Short-term actions are generally termed *removals*, and long-term, final response actions are considered *remedial actions* [42 USC § 9601(23) and (24)]. Short-term response actions include initial response actions such as spill containment. Longer-term actions include permanent treatment or containment of contamination. Under CERCLA, remedial actions must be protective of human health and the environment.

Responsible party. Responsible parties (and potentially responsible parties) mean a person or persons described in or potentially described in one or more of the categories set forth in section 107(a) of CERCLA. 43 CFR § 11.14(kk). Responsible parties may be owners, operators, transporters, or generators of the hazardous substances that cause the contamination at a CERCLA site and that may cause injury to natural resources.

Restoration. Actions that help return injured resources to baseline conditions. Restoration can be accomplished by actual restoration or rehabilitation of resources, or by replacing or acquiring the equivalent of the injured resources and their services. The term “restoration” is shorthand for any such actions. Restoration should be distinguished from “remediation” or “response actions” undertaken pursuant to CERCLA to protect human health and the environment from the threat of hazardous substance releases. See 43 CFR § 11.14(ll).

Restoration and Compensation Determination Plan (RCDP). A document that describes possible alternatives for restoration, rehabilitation, replacement, and/or acquisition of equivalent resources and related services lost to the public. In the RCDP, the Trustees select an alternative, provide justification for the selection of that alternative, and identify the methodologies that will be used to determine the costs and the compensable value of the alternative to the public.

Section. A land section, one square mile, according to the Public Land Survey System for lands in the public domain, which began with the Land Ordinance of 1785 and the systematic survey of public lands, and the Northwest Ordinance of 1787, which established a rectangular survey system designed to facilitate the transfer of Federal lands to private citizens. At its largest extent, the Arsenal comprised sections numbering 1 through 12, 19 through part of 22, 23 through part of 28, and 29 through 36. Section 10 was later ceded to the City and County of Denver for the north-south runway of the old Stapleton International Airport, and since the cleanup, portions of the western tier 9 Section 9, 4, 33, and part of 28 have been sold.

Service flows. The services provided by a resource over time. For example, remediation and restoration activities can increase the service flows provided by a resource.

Services. The physical and biological functions performed by the resource, including any human use of those functions. 43 CFR § 11.14(nn). Natural resources provide ecological and human use and non-use services. Examples of ecological services include nutrient cycling, habitat, water storage and release, and erosion control. Examples of human use services include recreational use such as fishing, hiking, or bird watching, and extractive and consumptive uses, such as mining or grazing. Human non-use services include, for example, the appreciation people feel knowing that habitat is protected for wildlife and for enjoyment by future generations of humans.

Superfund. See CERCLA.

Target analytes. Chemicals or compounds selected for possible monitoring during the Arsenal RI and endangerment assessment. Initially, 666 chemicals and compounds were identified as related to Arsenal activities. Of these, a select subset of 88 compounds served as *target analytes* for the RI.

Trophic level. A group of organisms that occupy the same position in a food chain, or the position of an organism in the food chain. Levels are typically ranged according to how far particular organisms are along the chain from the primary producers (plants) at level 1, to herbivores (level 2), to predators (level 3), to carnivores or top carnivores (level 4 or 5).

Trustee. Any federal agency, state agency, or Indian Tribe that may prosecute a natural resource damage claim.

Water year. October 1 through September 30. October 1, 2007 is the start of water year 2008.