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>
<thead>
<tr>
<th>Contaminant</th>
<th>Hazardous substance</th>
<th>Contaminant</th>
<th>Hazardous substance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aldrin</td>
<td>Yes</td>
<td>Carbon tetrachloride</td>
<td>Yes</td>
</tr>
<tr>
<td>Allyl chloride</td>
<td>Yes</td>
<td>Chlordane</td>
<td>Yes</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Yes</td>
<td>Chloride</td>
<td>No</td>
</tr>
<tr>
<td>Atrazine</td>
<td>No</td>
<td>Chlorobenzene</td>
<td>Yes</td>
</tr>
<tr>
<td>Benzene</td>
<td>Yes</td>
<td>Chloroform</td>
<td>Yes</td>
</tr>
<tr>
<td>Benzothiazole</td>
<td>No</td>
<td>Chlorophenylmethyl sulfide</td>
<td>Yes</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Yes</td>
<td>Chlorophenylmethyl sulfone</td>
<td>No</td>
</tr>
</tbody>
</table>
Table 5.1. Contaminants of concern in the Arsenal groundwater (cont.)

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

<sup>a</sup> As listed in Table 302.4 at 40 CFR § 302.4, Ebasco Services et al., 1988, and/or DOJ, 1986.

<sup>b</sup> Sulfate that is a degradation product of sulfuric acid is treated as a hazardous substance pursuant to 43 CFR § 11.14 (v).

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

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

\(^a\) 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:

\[
\frac{w}{2} = \frac{Q}{2KiH}
\]  

(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>
<thead>
<tr>
<th>Parameter</th>
<th>Representative minimum</th>
<th>Representative maximum</th>
<th>Selected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well pump rate (( Q, ) gpm)</td>
<td>100</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Conductivity (( K, ) ft/day)</td>
<td>60</td>
<td>300</td>
<td>134.2\textsuperscript{a}</td>
</tr>
<tr>
<td>Gradient (( i, ) ft/ft)</td>
<td>0.0047</td>
<td>0.0167</td>
<td>0.0074\textsuperscript{b}</td>
</tr>
<tr>
<td>Saturated thickness (( H, ) ft)</td>
<td>14.2</td>
<td>34.7</td>
<td>21.1\textsuperscript{c}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Geometric mean of minimum and maximum values from Ebasco Services et al. (1989, Table 2.2).
\textsuperscript{b} Harmonic mean of minimum and maximum values derived from Figure 5.2.
\textsuperscript{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>
<thead>
<tr>
<th>Location</th>
<th>Plume</th>
<th>Halo</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-post</td>
<td>8,275</td>
<td>5,395</td>
<td>13,670</td>
</tr>
<tr>
<td>Off-post</td>
<td>4,525</td>
<td>2,640</td>
<td>7,165</td>
</tr>
<tr>
<td>Total</td>
<td>12,800</td>
<td>8,035</td>
<td>20,835</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Effective porosity</th>
<th>Total volume (acre-feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow aquifer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alluvial(^b)</td>
<td>25%</td>
<td>52,550</td>
</tr>
<tr>
<td>Deep aquifers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denver</td>
<td>15%</td>
<td>863,760</td>
</tr>
<tr>
<td>Upper Arapahoe</td>
<td>7%</td>
<td>283,830</td>
</tr>
<tr>
<td>Lower Arapahoe</td>
<td>7%</td>
<td>283,260</td>
</tr>
<tr>
<td>Laramie-Fox Hills</td>
<td>13%</td>
<td>456,930</td>
</tr>
<tr>
<td>Total (deep)</td>
<td></td>
<td>1,887,780</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1,940,330</td>
</tr>
</tbody>
</table>

\(^a\) 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:

$$R + S + GW_{in} = E + GW_{out}$$  \hspace{1cm} (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:

$$GW_{out} = R + S + GW_{in} - E$$  \hspace{1cm} (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.

<table>
<thead>
<tr>
<th>Direction of flow</th>
<th>Component</th>
<th>Volume (acre-feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow</td>
<td>Diffuse recharge</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>Lake/ditch seepage</td>
<td>1,990</td>
</tr>
<tr>
<td></td>
<td>Upgradient groundwater</td>
<td>4,820</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>7,510</strong></td>
</tr>
<tr>
<td>Outflow</td>
<td>Evaporation</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>350</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Alluvial groundwater outflow</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>7,160</strong></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Irondale treatment plant</th>
<th>North Boundary Containment System</th>
<th>Northwest Boundary Containment System</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>1,607</td>
<td>301</td>
<td>1,740</td>
<td>3,648</td>
</tr>
<tr>
<td>1998</td>
<td>448</td>
<td>310</td>
<td>1,817</td>
<td>2,575</td>
</tr>
<tr>
<td>1999</td>
<td>368</td>
<td>310</td>
<td>3,440</td>
<td>4,118</td>
</tr>
<tr>
<td>2000</td>
<td>368</td>
<td>319</td>
<td>3,361</td>
<td>4,048</td>
</tr>
<tr>
<td>2001</td>
<td>NA</td>
<td>319</td>
<td>1,556</td>
<td>1,875</td>
</tr>
</tbody>
</table>

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.

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Irondale treatment plant</th>
<th>North Boundary Containment System</th>
<th>Northwest Boundary Containment System</th>
<th>Total (rounded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>1,160</td>
<td>301</td>
<td>1,740</td>
<td>3,200</td>
</tr>
<tr>
<td>1998–2001</td>
<td>0</td>
<td>310</td>
<td>2,540</td>
<td>2,850</td>
</tr>
</tbody>
</table>

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.


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. 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.
Injury to Groundwater Resources (October 24, 2007)

- 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.

![Graph showing population growth](image)

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


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.

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

<table>
<thead>
<tr>
<th>Provider</th>
<th>Plans and processes</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurora</td>
<td>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.</td>
<td>City of Aurora, 2007</td>
</tr>
<tr>
<td>Brighton</td>
<td>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.</td>
<td>City of Brighton, 2007</td>
</tr>
<tr>
<td>Northglenn</td>
<td>Seeking additional storage to maximize use of existing rights.</td>
<td>CWCB, 2004</td>
</tr>
<tr>
<td>SACWSD</td>
<td>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.</td>
<td>Denver Water, 2002</td>
</tr>
<tr>
<td>Thornton</td>
<td>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.</td>
<td>CWCB, 2004; USACE, 2007</td>
</tr>
<tr>
<td>Westminster</td>
<td>Using lined gravel pits for storage. Expanding reclaimed water system. Transferring agricultural water rights.</td>
<td>CWCB, 2004</td>
</tr>
<tr>
<td>South Metro (providers in Arapahoe, Douglas, and Elbert counties)</td>
<td>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.</td>
<td>CWCB, 1999, 2004; Parker Water &amp; Sanitation District, 2005; Kaunisto and Mullenix, 2006</td>
</tr>
</tbody>
</table>
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.

References


MetroDenver EDC. 2006. Historic and projected population. Prepared by Metro Denver Economic Development Corporation using data from U.S. Department of Commerce, Bureau of the Census and Colorado Department of Local Affairs, Division of Local Government, and


