Colorado Water Conservation Board

SB06-193 Underground Water Storage Study

March 1, 2007

Final Report

Executive Summary

Senate Bill 06-193 (SB06-193) directed the Colorado Water Conservation Board (CWCB) to conduct a study of potential underground water storage areas in the South Platte and Arkansas River Basins. This report presents the results of the SB06-193 investigation.

In 2004 the Colorado Geological Survey (CGS) completed their report "Artificial Recharge of Ground Water in Colorado – A Statewide Assessment." In that study, large aquifer regions were identified statewide for recharge potential. This SB06-193 study uses the CGS study as a beginning point and goes a step further in the South Platte and Arkansas River Basins. The regional aquifers identified in the CGS study are evaluated here on a subregional basis, and some smaller alluvial aquifers not considered in the CGS study in these river basins are included too.

The aquifers in the two basins were divided into four regions: South Platte River Basin alluvial aquifers, Arkansas River Basin alluvial aquifers, Denver Basin bedrock aquifers, and the Ogallala and Dakota-Cheyenne bedrock aquifers. These regions were further divided into subregions for evaluation purposes, resulting in a total of 44 subregions: 16 alluvial subregions in the South Platte Basin, 10 alluvial subregions in the Arkansas Basin, 15 subregions in the four aquifers of the Denver Basin, two subregions for the Ogallala, and one subregion for the Dakota-Cheyenne. The 15 subregions in the Denver Basin were formed by aquifer layer, by location in the basin, and by whether the portion of the aquifer in question was under confined or unconfined groundwater conditions.

These areas were each evaluated for 10 criteria representing hydrogeologic, environmental and implementation considerations. There are many other pertinent issues that were not covered by the criteria, because they were beyond the scope of this study. They include factors such as available sources of water and scale of project, water rights and potential legal issues, water treatment requirements, and interest from local stakeholders. Any of these factors could affect the feasibility of implementing an underground water storage project within the evaluated areas and should be considered on a site-specific basis.

Technical information from a variety of State, federal and other published sources was assembled and used to characterize the areas. From this information a set of quantitative measures were developed and used to score and rank each of the subregions. The study team consulted over 50 technical experts and stakeholders from all areas of the South Platte and Arkansas River Basins. Their input helped identify key sets of data, provided valuable insight into what factors were considered most important, and imparted local knowledge that benefited the study.

The highest scoring subregions in each the alluvial aquifer regions and for the combined bedrock aquifer regions are listed below.

South Platte River Basin Alluvial Aquifer Subregions
Lower Lost Creek
Upper Lost Creek
Lower Kiowa Creek
South Platte River – Fort Morgan Area
Lower Beebe Draw/Box Elder Creek

Arkansas River Basin Alluvial Aquifer Subregions
Upper Black Squirrel Creek
Arkansas River - Crowley Area
Arkansas River - Lamar to State Line
Arkansas River - Buena Vista to Salida
Fountain Creek

Bedrock Aquifer Subregions
Dawson Unconfined West
Arapahoe Confined Northwest
Ogallala - North
Arapahoe Confined Southwest
Arapahoe Unconfined West
Ogallala - South

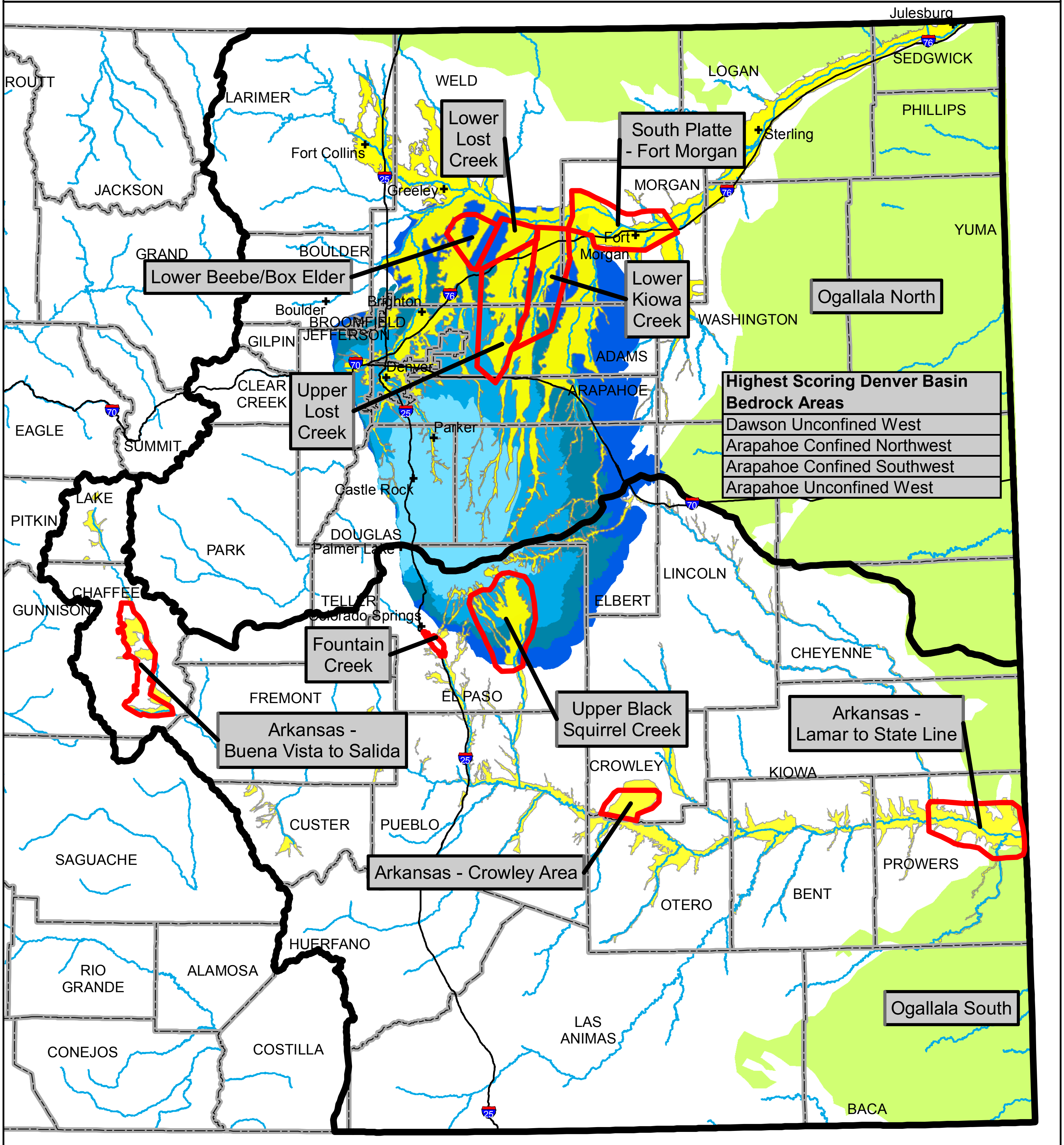
The locations of these areas are shown on Figure ES-1. Specific locations are shown for all subregions except for the Denver Basin. Because of the layered nature of the Denver Basin aquifers, the specific locations of the higher-scoring subregions in the Denver Basin region could not be shown on this figure. Figure 24 in the main report shows the locations of the Denver Basin subregions in more detail.

The scoring results show that for the alluvial aquifers there are high-scoring areas that exist both away from and along the mainstems of the South Platte and Arkansas Rivers. Among the bedrock aquifers, there are high-scoring areas within both unconfined and confined portions of the Denver Basin, as well as the Ogallala. However, there was not much spread in the scores for many of the subregions. Consequently, most of the areas evaluated in this study, regardless of their ranking, could contain feasible underground storage sites worthy of more detailed investigation. The findings in this report, along with site-specific factors outside the scope of this study such as available water supply and local stakeholder interest, should be considered in the selection of areas for further investigation.

The CWCB is a potential source of funding for underground storage projects through means such as the Water Supply Reserve Account created by Senate Bill 06-179 and non-reimbursable grants from the CWCB's Severance Tax Trust Fund Operational Account and Construction Fund. More information can be found at CWCB's web page: http://www.cwcb.state.co.us.

SB06 - 193 Underground Water Storage Study

Highest Scoring Aquifer Areas in the South Platte and Arkansas Basins



Sources: CDM 2004a; CDM 2004b; Topper et al. 2003

N
W
E
S

Scale:
1:2,100,000

10 5 0 10
Miles

✚ City
Highway
County
Alluvial Extent

Denver Basin Aquifers
Dawson Extent
Denver Extent
Arapahoe Extent
Laramie-Fox Hills Extent

Alluvial Subregions
Ogallala Extent

Colorado Water Conservation Board

Prepared by: CDM

Figure ES-1

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Section 1
Introduction

Increasing population in Colorado and recent years of drought has placed an ever greater strain on Colorado's water resources. In addition to increasing water conservation and water reuse, there is a need to increase water storage. Due to increasing difficulties with building surface water storage reservoirs, there has been a growing interest in storing water underground in natural reservoirs associated with groundwater aquifers.

The State of Colorado is actively working to manage its water supplies in a sustainable and environmentally beneficial manner. To identify areas which could be used for underground water storage, Colorado State Senate Bill 06-193 (SB06-193) directed the Colorado Water Conservation Board (CWCB) to evaluate potential underground water storage areas in the South Platte and Arkansas River Basins. A copy of the bill is included in Appendix A. This report presents the results of the SB06-193 investigation.

1.1 Background and Study Objectives

In 2004, the Colorado Geologic Survey (CGS) prepared a statewide assessment of artificial recharge potential in Colorado (Topper et al., 2004). The CGS report evaluated aquifers throughout the state that had the potential for artificial recharge. In order to be considered in that study, alluvial aquifers had to have at least 80 square miles in total surface area, and bedrock aquifers had to exceed 100 square miles in area. Because of those criteria, the emphasis was on larger regional aquifers. Smaller aquifer areas with potential for underground water storage were not considered. This study looks in more detail at the underground water storage areas in the South Platte and Arkansas River Basins identified in the CGS study, as well as smaller aquifers in these basins not previously considered.

The CWCB's Statewide Water Supply Initiative (SWSI) study (CDM, 2004) identified and cataloged water supplies and water demands throughout Colorado, (termed 'gaps' in that study). Projected unmet municipal and industrial (M&I) and agricultural demands in the South Platte and Arkansas River Basins are estimated to exceed 500,000 acre-feet by the year 2030. Additional water storage during wet years is one way to address those gaps in demand in drier years. Thus a goal of this study is to help focus efforts to increase underground water storage in these basins in Colorado where water is in great demand.

Following up on the CGS and SWSI reports, the objectives of this study are to undertake a more detailed assessment to identify potential underground water storage areas within the South Platte and Arkansas River Basins (Water Divisions 1 and 2), and to evaluate the potential recharge areas using a variety of technical, economic and ecological considerations. A map of the study area is presented in Figure 1.

1.2 Study Limitations

This study examines artificial recharge at a regional scale. There are a number of site-specific issues that are outside the scope of this study, as defined by SB06-193. They include but are not limited to:

- Identifying specific sources and amounts of water available for underground water storage
- Water rights issues associated with storage and later withdrawal of water at specific sites
- The level of water treatment required before water can be stored underground at a specific site
- Site-specific issues associated with land access and subsurface hydrogeologic characteristics
- Identifying potential partnerships between water management agencies and other stakeholders that might facilitate use of some sites compared to others
- The lack of a regulatory framework for artificially recharging and extracting recharged water in aquifers other than in the non-designated portions of the Denver Basin bedrock aquifers
- Evaluating temporary surface storage and other water infrastructure components at specific sites
- Using engineered structures such as slurry walls to enhance the natural storage potential at specific sites

This study considers potential underground water storage areas at a regional and sub-regional scale. There are likely to be many site-specific evaluations and data required (including percolation rates, depth to water, and proximity of local infrastructure) that may affect the likelihood of implementing aquifer recharge at a given location, in addition to the issues noted above that are not addressed in this study.

1.3 Key Technical Terms

Underground water storage is viewed for the purposes of this study as implementing some form of artificial recharge of water into subsurface materials of an aquifer. A number of technical terms used throughout this report are defined in this section to facilitate the reader's understanding of the information presented. Most of these terms relate to groundwater hydrology and may not be familiar to readers.

Alluvial Aquifer - A near-surface geologic formation, typically consisting of unconsolidated sand and gravel. In Colorado an alluvial aquifer is typically highly permeable, unconfined, and may be hydraulically connected to a nearby stream. The South Platte and Arkansas River alluvial aquifers are capable of yielding significant quantities of water to wells, as well as being recharged with large quantities of water.

Artificial Recharge – The process of adding water to an aquifer through constructed devices such as spreading basins, canals, or wells. In an alluvial aquifer, artificial recharge can be accomplished by allowing water to seep into the ground and flow directly to the underlying aquifer. In a confined aquifer, artificial recharge usually occurs through wells that inject the water at pressures greater than what exists in the aquifer.

Aquifer – A permeable geologic formation capable of storing and yielding usable quantities of water to wells. Aquifers typically consist of predominantly gravel and sand in unconsolidated deposits and of sandstone, siltstone, or limestone in consolidated rocks.

Bedrock Aquifer - An aquifer consisting of consolidated geologic rocks. The process of consolidation results in decreased permeability and porosity and thus decreased well productivity and injection potential relative to unconsolidated aquifers. For example, the aquifers referred to as the Denver Basin aquifers are bedrock aquifers. Bedrock aquifers can have both confined and unconfined portions.

Confined Aquifer - A fully saturated aquifer that is bounded above and below by impermeable layers, resulting in the water being pressurized in the aquifer. The water level in a well drilled into a confined aquifer will rise to a level higher than the physical top of the water bearing layer due to the water pressure within the aquifer. The level to which water rises is called the potentiometric surface. When water is pumped from a confined aquifer, the water pressure is decreased and the potentiometric surface falls as the aquifer is depressurized. If the potentiometric surface falls below the top of the aquifer, the aquifer becomes unconfined. Large portions of the Denver Basin bedrock aquifers and the Dakota bedrock aquifer are confined.

Denver Basin Aquifers – A set of four stacked bedrock aquifers present in a large area in eastern Colorado extending from Greeley to Colorado Springs and from the foothills to Limon. They are the primary source of municipal water supply for areas south of Denver. Water in these aquifers is unconfined along the margins but confined over most portions. Compared to current groundwater pumping rates, there is very little natural recharge to the confined portions or these aquifers so the supply is considered to be nonrenewable.

Groundwater – Water present in subsurface geologic deposits that flows under the force of gravity or from the pumping or injection by wells.

Head – A term that describes the water level in an aquifer or in a well that taps into an aquifer.

Nontributary Groundwater – A legal designation used in Colorado for groundwater found in certain bedrock aquifers outside the boundaries of any designated groundwater basin, including parts of the Denver Basin aquifers, where there is deemed to be negligible interaction with overlying stream systems, defined as less than one-tenth of one percent of the amount of pumping after 100 years of pumping. Extraction and use of this water is administered under a permit system that is separate from the Prior Appropriation Doctrine of water rights.

Porosity – The void space in geologic materials, usually expressed as a percent of the total volume of a rock or unconsolidated deposit. For unconsolidated aquifer materials the porosity ranges typically from 20 to 40 percent and for consolidated aquifer materials it is usually from 5 to 20 percent.

Potentiometric Surface - The level to which water will rise in a well that taps into a confined aquifer. In a confined aquifer, the potentiometric surface will be above the physical top of the aquifer due to the water pressure within the aquifer and may even exceed the elevation of the land surface, in which case it is sometimes referred to as artesian pressure.

Residence Time – The amount of time that recharged water remains in the same general area within an aquifer. For unconfined aquifers it is the length of time that recharged water would remain underground before being discharged to a nearby stream or other surface water body.

Specific Retention – The ratio of the volume of water that can be held within the aquifer against the force of gravity to the total volume of a given amount of an unconfined aquifer. The sum of specific retention and specific yield is equal to porosity. This would be the amount of recharged water that could not be recovered from an unconfined aquifer.

Specific Yield – The ratio of the volume of water that can be released under the force of gravity to the total volume of a given amount of an unconfined aquifer. It is less than the porosity and typically ranges from 1 to 30 percent.

Storage Coefficient – The amount of water released from a unit volume of a confined aquifer due to a unit drop in head. It is a function of the elasticity, porosity, and thickness of the aquifer and the elasticity of water. Values typically range from 0.005 to 0.00005 in confined aquifers.

Stream-Aquifer Interaction - The flow of water between a stream and the adjacent aquifer. This concept is important to aquifer recharge and underground storage, because water recharged to an aquifer adjacent to a stream may flow to the stream.

Stream Depletion Factor (SDF) - Stream depletion refers to either direct removal of water from a stream or indirect capture of stream water by pumping groundwater that would have flowed to the stream. The stream depletion factor (SDF) is an analytical technique developed by C.T. Jenkins (1968) that has been widely used in groundwater/surface-water management. The SDF has units of time and indicates when the volume of stream depletion equals 28% of the volume removed by a pumping well.

Travel Time – The amount of time for groundwater to flow from one location to another, typically from the point of recharge to the point of discharge, typically a receiving stream.

Tributary Groundwater - A legal designation used in Colorado for groundwater that will eventually flow into a stream naturally and contribute to the streamflow or be used by senior appropriators under the Prior Appropriation Doctrine of water rights.

Unconfined Aquifer – An aquifer that is not confined on top by an impermeable layer and contains water that is under atmospheric pressure. Also referred to as a "water table aquifer." The water level in a well tapping an unconfined aquifer reflects the water level in the aquifer adjacent to the well. Most alluvial aquifers are unconfined.

Underground Water Storage - The use of natural void spaces in subsurface materials as a water storage reservoir. Artificial recharge is a method by which water is placed in the subsurface. The terms "underground water storage", "artificial recharge," and "aquifer recharge" are used interchangeably in this report.

Water Table - The water table is that surface in an unconfined aquifer at which the water pressure is atmospheric. It is defined by the levels at which water stands in wells. It is possible that the water level in wells could stand above or below the water table if an upward or downward component of groundwater flow exists.

1.4 Aquifer Recharge Overview

Aquifers are typically recharged naturally by precipitation or surface water percolating into an underlying aquifer. In a semi-arid climate, such as Colorado's, natural recharge rates can be very slow and are often exceeded by groundwater pumping, a condition referred to as aquifer depletion or groundwater mining. Recharging aquifers by engineered methods, referred to as artificial recharge, offers a solution to slow or reverse aquifer depletion and to increase the amount of water in storage. Artificial recharge has been practiced in a rudimentary form for centuries in arid areas, and since the 1930s it has been used increasingly for water resource management (Topper et al., 2004).

There is a broad range of applications for artificial recharge, including water treatment, wastewater disposal, and water storage. Due to the seasonal nature of Colorado's streamflow, the principal source of water supply, the application of artificial recharge most relevant to this study is for water storage. Underground water storage has a number of benefits that are described in the CGS statewide artificial recharge report (Topper et al., 2004). These potential benefits include:

- Managing water supplies more effectively
- Meeting legal obligations such as interstate compacts
- Mitigating adverse water quality
- Reducing water level declines in aquifers
- Protecting the environment

Underground water storage offers a number of benefits over more traditional water storage in surface reservoirs once the surface water has been recharged to an aquifer. These include the reduction in evaporative losses, which can be very large in low-elevation reservoirs, minimal adverse environmental impacts compared to surface reservoir construction, improving the water quality of the aquifers being recharged, reduced concerns with water quality degradation associated with algal blooms and/or potential vandalism, and, for surface infiltration recharge facilities, natural treatment of recharge water by soil filtration, microorganisms and other in-situ physical and chemical processes.

One of the first artificial recharge projects in Colorado was conducted using surface infiltration at an abandoned reservoir that was too leaky to keep filled. Water from the South Platte River was diverted to Olds Reservoir by farmers in 1939, successfully recharging the aquifer near Prospect Valley and raising water levels in irrigation wells (Warner et al., 1986). Artificial recharge of bedrock aquifers began in a formal way in the 1980s, when testing of deep well injection was begun in the Denver Basin aquifers. Soon after was the first full scale project to recharge deep bedrock aquifers, begun in the early 1990s beneath Highlands Ranch in northern Douglas County. In Colorado's South Platte and Arkansas River Basins, a significant amount of aquifer recharge occurs due to seepage of water from unlined irrigation ditches and infiltration of excess irrigation water to the underlying aquifer (Topper et al., 2004; Gates et al., 2006). This aquifer recharge results in higher water tables, which are a benefit to many groundwater users, but this can also cause waterlogging and water quality problems in other locations. More details on aquifer recharge activities within the study area are provided in Section 1.5.

1.4.1 Aquifer Recharge Methods

Aquifer artificial recharge in Colorado is typically performed by either of two methods: surface infiltration or deep well injection (Topper et al., 2004). Surface infiltration is typically used in the unconfined alluvial aquifers and deep well injection is used in confined bedrock aquifers such as those in the Denver Basin.

Surface infiltration is the practice of allowing water to seep directly into the subsurface by way of deep percolation of applied water through recharge ponds, leaky ditches, impoundments in stream channels, or other structures that allow water to percolate into the underlying aquifer. Surface infiltration uses relatively simple technology, does not require significant pre-treatment of water, and is most effective when recharging highly permeable aquifers. Surface infiltration can be very effective for recharging very large volumes of water into alluvial aquifers with high porosity and permeability, as is practiced in the South Platte and Arkansas River basins. This method also filters out sediment and can remove some contamination from applied surface water.

Deep well injection is accomplished by use of wells drilled into the bedrock aquifers. Well injection requires that recharged water be treated to drinking water standards, that relatively sophisticated flow valves and controls be installed, and that a substantial testing program occur prior to full-scale implementation. Recharge rates for individual wells are controlled largely by the hydraulic properties of the receiving aquifer. Deep well injection has proven to be effective in Colorado and throughout the U.S.

Artificial recharge is often more complex than simply applying water to a shallow basin or pumping it down a well. A successful program may require pre-treating water to remove silt or air bubbles that can clog the aquifer, and chemical stabilization to reduce encrustation of the well screen or adjacent aquifer materials from dissolved salts or metals. The feasibility of an aquifer recharge project depends on many site- and project-specific issues such as the aquifer characteristics, the project goals, water quality, water availability, water rights issues, and the intended use of the water. The ability to temporarily store excess surface water runoff can have a large effect on the amount of water that is recharged in locations where artificial recharge rates are low. In addition to technical factors, economics can influence whether an underground water storage program can be implemented successfully. For example, while deep bedrock aquifer recharge might be too costly for agricultural use, it might be economically feasible for municipal water supply.

1.5 Current Aquifer Recharge Activities in the Study Area

Artificial recharge has been practiced on a local level for over a century in the South Platte and Arkansas River Basins. In recent decades aquifer recharge has been undertaken to address specific water management issues. The following sections describe the aquifer recharge activities within the study area.

1.5.1 South Platte River Basin Alluvial Aquifers

Most, if not all, current aquifer recharge activity in alluvial aquifers in the South Platte River Basin is conducted for the purpose of streamflow augmentation. According to augmentation records maintained by the State Engineer's Office, annual recharge for augmentation has increased steadily since 1979 to a total of over 190,000 acre-feet recharged in 2005. During this period a cumulative total of approximately two million acre-feet of water have been recharged to alluvial systems in the South Platte River Basin. Figure 2 shows the annual amount of water recharged into the alluvial aquifer system of the South Platte River. In addition, a significant amount of incidental aquifer recharge occurs via percolation of irrigation water from fields and irrigation ditches into the underlying aquifers.

In recent years a managed recharge project has been operated in the lower South Platte River Basin to help enhance streamflow and riparian habitat in downstream areas. The project, located at the Tamarak State Wildlife Refuge, uses recharge ponds near the river to increase return flow (Halstead and Flory, 2003). At least one project in the South Platte Basin has been constructed where water from non-tributary Denver Basin bedrock aquifers can be pumped to recharge the alluvial aquifer. This project has been constructed but is not being used due to the present availability of surface water for augmentation (Sanchez, 2007).

1.5.2 Arkansas River Basin Alluvial Aquifers

The percolation of irrigation water from fields and irrigation ditches through highly porous soil into the underlying aquifers has resulted in a high water table and significant waterlogging and salinity issues through much of the lower Arkansas River Basin (Gates et al., 2006). Recharge for augmentation is not being performed in the Arkansas Basin (Dash, 2007), but a study is underway to evaluate the feasibility of a project in the vicinity of Salida (Pueblo Chieftain, 2007). In addition, preliminary artificial recharge pilot testing has been performed in the Upper Black Squirrel Creek Basin (Cherokee, 2005). The El Paso Water Authority has engaged the CGS to begin detailed feasibility studies in this area in 2007 (Barber, 2007). This study has been funded in part by CWCB and through Interbasin Compact Committee Roundtables, as per Senate Bill 06-179. Artificial recharge is also being considered for the Widefield Aquifer in the Fountain Creek drainage by the towns of Widefield and Security (Thompson, 2006).

1.5.3 Denver Basin Bedrock Aquifers

In the bedrock aquifers of the Denver Basin, pilot testing was performed at the Willows Water District as early as 1983 (JCHA, 1997) and has been practiced full-scale since 1992 at the Centennial Water and Sanitation District's well field in Highlands Ranch (Topper et al., 2004). This project has operated successfully for over 13 years with no observed limitations due to water quality or loss of well productivity associated with recharge activities.

There are currently four artificial recharge projects in the Denver Basin bedrock aquifers whose locations are shown in Figure 3. The projects are operated by the Centennial Water and Sanitation District, Castle Pines North Metropolitan District, the Consolidated Mutual Water Company, and Colorado Springs Utilities. The bedrock aquifer recharge projects generally use treated surface water to recharge underlying aquifers for long-term storage and to maintain aquifer hydraulic heads. These projects have recharged a cumulative total of approximately 8,000 acre-feet.

The transmissivity of the Denver Basin bedrock aquifers is much lower than for the alluvial aquifers and so the well injection rates are relatively low. A challenge to these projects is the availability of water. The Willows Water District project relied on water provided by the Denver Water Board in cooperation with the Bureau of Reclamation.

Many water districts have been limited in their ability to recharge the bedrock aquifers by the access to water supplies.

Section 2
Study Methods

Underground water storage areas in the South Platte and Arkansas River Basins have been identified and evaluated using a variety of methods that are described in this section. The first step was to establish criteria by which potential recharge areas could be evaluated. Technical information was then compiled and reviewed for each of the evaluation criteria. This information became the basis for defining subregions within each basin and for establishing quantitative measures for each criterion. The quantitative measures were then used to score and rank each of the areas in each basin. The study team involved a series of basin stakeholders and technical experts, whose input was sought throughout the process. The feedback received led to improvements in many areas of the study. The following sections describe the site criteria development, data collection and analysis, area evaluation and stakeholder involvement aspects.

2.1 Criteria Development

A series of evaluation criteria were developed to evaluate the feasibility of implementing underground water storage in various subregions within each basin. The criteria take into account hydrogeologic, environmental, and implementation considerations and are intended to help identify subregions that appear to be the most suitable for underground storage based on these factors. As noted in Section 1.2, this study does not consider the sources of water, water rights, water treatment, nor many other issues that may be specific to individual recharge sites or operations; therefore, there are no evaluation criteria for these parameters. Table 1 lists the criteria and provides brief descriptions of each. The criteria are numbered for organizational purposes only and not in terms of their relative importance. The following paragraphs describe the criteria in more detail.

2.1.1 Hydrogeologic Considerations

The following three criteria take into account the physical characteristics of the subsurface deposits.

Available Storage Capacity

This criterion describes the availability of additional storage in an aquifer. The available storage consists of the unsaturated zone of an unconfined aquifer and the availability to inject water under pressure into a confined aquifer, which is dependent on the depth to the potentiometric surface below land surface.

For unconfined aquifers the uppermost ten feet of subsurface materials is not considered as available storage to minimize potential problems associated with minor inaccuracies in water level and digital elevation map surfaces, flooding basements, waterlogging soils, and nonbeneficial use by phreatophytes. For confined aquifers, ten feet was subtracted from the difference between land surface and the potentiometric surface. The subtraction of ten feet from the potential storage volume was done to prevent injecting water into the confined aquifers that would result in the potentiometric surface reaching a level close to or above the ground surface.

The first step in calculating the available aquifer storage capacity was to determine the depth below ground surface to the water table for the unconfined aquifers or the depth to the potentiometric surface for confined aquifers. The depths to the water table or potentiometric surfaces were determined using geographical information system (GIS) methods. Water table or potentiometric surface elevations developed for the CWCB's South Platte Decision Support System project (CDM, 2006b,c,e) and other sources (Principia Mathematica, 2006; Robson and Banta, 1987; Watts, 2005; Watts and Linder-Lundsford, 1991) were interpolated using automated algorithms to produce a gridded data set with elevation data points corresponding to locations of land surface elevations from digital elevation maps (DEMs) obtained from the USGS (2006a).

There is little data available for water levels in the unconfined portions of the Denver Basin bedrock aquifers. As a result, in some locations the contoured water table rose above the contoured land surface DEM. In these cases it was decided to set the water level elevation equal to 10 feet below ground surface. Areas in which the water table did not exceed the land surface were not changed. The water table or potentiometric surface elevations were then subtracted from land surface elevations, and a GIS shapefile was produced containing data with location and the depth from the land surface to water or to the aquifer's potentiometric surface throughout the aquifer regions.

The volumes of the unsaturated materials for the unconfined aquifers that was calculated from these depths were then reduced by excluding the uppermost 10 feet, for the reasons stated above. Areas determined to have less than ten feet to the water table were excluded from the analysis. For the alluvial aquifers, the remaining volume was multiplied by an assumed specific yield value of 20 percent (0.20) to obtain the potential storage volume of the unsaturated materials. This value is consistent with information obtained under the South Platte Decision Support System study (CDM, 2005; CDM, 2006a). For the unconfined portions of the bedrock aquifers, a storage coefficient of 0. 01 was used. This represents an average value for the range of confining conditions expected for these portions of the bedrock aquifers, from completely unconfined at their outer edges and shallow depths to almost completely confined at their borders with the confined portions.

It should be noted that the available storage volume in the confined portions of the bedrock aquifers is actually a measure of the available water pressure and is not a physical volume as with an unconfined aquifer. This is because the confined aquifers are completely saturated with water and changes in storage are shown by changes in their potentiometric surface, a water pressure surface. The potentiometric surface of a confined aquifer represents how far above the physical top of the confined aquifer the water level would rise if intercepted by an open well. The calculated volumes for the confined aquifers were multiplied by a storage coefficient of 0.001 for the Arapahoe, Laramie-Fox Hills and Dakota aquifers and by a storage coefficient of 0.0003 for the

Denver aquifer to determine their potential water storage volume. The Denver Basin bedrock aquifer storage coefficient values are based on a comprehensive data assessment undertaken for the South Platte Decision Support System (CDM, 2005). Maps and data for the land surface, water table and potentiometric surface and storage coefficient values are presented in Appendix D.1.

For all aquifers the available water storage volumes were divided by their respective areas to obtain the available volume on an acre-foot per acre (ac-ft/ac) basis. This was done to assist in the comparison of available storage volumes between the various potential recharge areas. The available storage capacity estimates are presented in Tables 2 through 4 and discussed in Section 3.

Hydrogeologic Suitability

The ability to move water into and/or out of an aquifer is the subject of this criterion, with a higher rate being more favorable. It is assumed that in unconfined alluvial aquifers the surface soils would be removed before creating an aquifer recharge system, such as an infiltration ditch or basin; therefore, the properties of the underlying aquifer are important. This physical property of an aquifer is important because surface water might be available for aquifer recharge on a limited basis, such as during high streamflows during heavy runoff events, and aquifers that can accept water more quickly will be able to store more water in that situation. Even when recharge water may be available in a more steady supply, this criterion is important for efficiency of a recharge project, and for ease in extracting the recharged water at a later date. Maps of hydraulic conductivity (K) for the alluvial aquifers and of transmissivity (T) for the bedrock aquifers were used as representative of this criterion, on the basis that K and T are suitable indicators of relative rates of water infiltration and injection capacity, respectively. The maps were developed as part of the South Platte Decision Support System project (CDM, 2005; CDM, 2006a) and other studies (Buckles and Watts, 1988; Hurr and Schneider, 1972 a-f; Jehn, 1997; Londquist and Livingston, 1978; Radell, Lewis and Watts, 1995; Robson, 1983; Topper et al., 2003; Watts, 2005).

Residence Time

This criterion takes into consideration the amount of time a recharged volume of water will remain in the aquifer before it flows away and cannot be retrieved without additional infrastructure. For the alluvial aquifers, residence times of 120 and 480 days to a nearby stream were used. These were based on currently available data, published maps of stream depletion factors (SDFs) developed by Hurr and Schneider (1972a-f) for the South Platte and by and Jenkins and Taylor (1972) for the Arkansas River alluvial aquifers for these durations, which are felt to be reasonable approximations of residence times for water to remain in storage for part of a growing season or for more than a year. In areas without SDF maps, estimates of residence times were made based on aquifer properties and groundwater hydraulic gradients.

Engineered structures such as slurry walls constructed within an alluvial aquifer could increase the residence time of water stored behind them and enhance the score for potential underground storage areas located near major rivers. This criterion, however, does not address the use of slurry walls since this would be a site-specific implementation issue. In addition, there could be water rights issues associated with how slurry walls affect the timing of return flows to the river and potentially cause injury to senior water rights.

For the unconfined portions of bedrock aquifers, the proximity of alluvial aquifers was used to evaluate this criterion, under the assumption that proximity to alluvium would result in faster travel to surface streams and shorter residence time in the aquifer. Maps showing the locations of alluvial aquifers that overlie the unconfined portions of the bedrock aquifers were used for the bedrock aquifer evaluation.

The residence time in the confined portions of bedrock aquifers is anticipated to be decades or longer. This is because the water in confined aquifers migrates very slowly and will have a negligible effect on the outflow to overlying alluvial aquifers or stream systems. As a result, potential storage areas in confined aquifers will receive a higher residence time score.

2.1.2 Environmental Considerations

These three criteria relate to potential environmental and ecological effects from a potential artificial recharge area.

Water Quality

The water quality within the aquifer is the focus of this criterion, both for how it affects the quality of the recharged water and how it might be affected by it. It considers the potential added treatment costs when extracting originally high-quality recharge water that has been placed into an aquifer with lower water quality and the need for additional treatment when the water is extracted. However, the possibility also exists that water quality will be improved in the aquifers receiving recharge water. The criterion also addresses the concern of degrading aquifer water quality by leaching of minerals naturally found in soils, such as selenium, when recharge water is added. Locations where there is a high leaching potential for selenium or other metals could render that area unsuitable for aquifer recharge. Where available, maps of total dissolved solids (TDS) in the groundwater were used as an indicator for general water quality in the aquifers (Becker at al., 2002; Buckles and Watts, 1988; Cain and Edelmann, 1986; Cain and Emmons, 1980; CDPHE, 1998; Goddard, 1978; Topper et al., 2003; Watts, 2005). Where TDS maps were not available, water quality information obtained through reports and basin experts was utilized whenever possible.

Habitat Concerns

This criterion addresses the presence of habitat for federally designated threatened and endangered (T&E) species, as well as wetlands, which could be adversely impacted by construction or operation of potential underground water storage projects. Maps showing proximity of various T&E species habitat to recharge sites were used in evaluating the likelihood of potential negative impacts caused by recharge activities (CDOW, 2006a-f; USBLM, 2006). The T&E species that have habitat in the South Platte and Arkansas River Basins include:

- Preble's Meadow Jumping Mouse
- Bald Eagle
- Plains Sharp-Tailed Grouse
- Least Tern
- Piping Plover

The habitat maps used to evaluate this criterion are graphical representations of the generalized habitat domains and do not guarantee that a given species occupies habitat in the entire area shown on the regional maps. The information portrayed on the habitat maps should not replace more detailed field studies that would be necessary for localized planning efforts.

In addition, 'Areas of Critical Environmental Concern' have been mapped on lands managed by the U.S. Bureau of Land Management. These are defined as lands identified as having important riparian corridors, threatened and endangered species habitat, cultural and archeological resources and unique scenic landscapes that the agency believes need special management attention (USBLM, 2006).

Depending on timing and operation of a recharge project, the impacts on habitat can both be positive and negative. For example, the recharge ponds on the Lower South Platte provide beneficial waterfowl habitat in the fall and winter months. The scoring measures considered in this analysis look only at potential negative impacts and are limited only to a very cursory analysis based on limited regional data.

This criterion plays a minor role in the confined aquifer settings due to the small surface area associated with artificial recharge wells and associated piping.

Waterlogging and Nonbeneficial Use

This criterion considers the potential for shallow water table conditions, both near a potential recharge area as well as down-gradient of the area, which could promote the growth of undesirable vegetation such as tamarisk and lead to nonbeneficial water consumption. Gates (2006) recently estimated that nonbeneficial consumption of water in the Arkansas Valley can account for the loss of approximately 50,000 acre-feet per year. The shallow water table conditions could also lead to waterlogging of soils, creation of undesirable wetlands, and flooding of basements. The potential for these concerns was evaluated using the depth to water table maps. The maximum depth to which this criterion was estimated to have any impact was 30 feet below ground surface, which is the approximate depth to which tamarisk is capable of extending its roots. This criterion applies mainly to alluvial systems. Underground water storage in the confined aquifers is expected to have minimal effects regarding this criterion.

2.1.3 Implementation Considerations

The following four criteria concern issues beyond geologic and environmental factors. They are related to the relative ease or difficulty of implementing a recharge operation within one of the identified subregions.

Land Ownership and Land Use

This criterion examines general land use, including the location of urban, agricultural, native and range lands, public vs. private land ownership and the location of inaccessible lands (such as military reserves). A key assumption is that recharge projects will be more easily sited on accessible public lands and non-urban lands and so higher scores were assigned to areas with more of these types of lands. Land ownership and land use are available from the USGS (2001). Public lands considered to be publicly accessible, and therefore potentially amenable to recharge projects, include those lands managed by the following federal or state agencies:

- Bureau of Land Management
- Bureau of Reclamation
- U.S. Forest Service
- U.S. Fish and Wildlife Service
- Colorado Division of Wildlife
- State Land Board

In contrast, public lands that were considered to not be publicly accessible and therefore not available for recharge projects are managed by the following federal agencies:

- Department of Defense
- Department of Energy
- Federal Aviation Administration
- Bureau of Indian Affairs
- National Park Service
- Department of Commerce

Proximity to Existing Infrastructure

The presence of water conveyance structures and other infrastructure is an important consideration affecting the cost and overall feasibility of an underground water storage project. This criterion considers the proximity of major ditches and pipelines on the basis that existing water conveyance structures will improve the suitability of an area and reduce cost to deliver water for recharge activities. Areas where suitable infrastructure is located within five miles received the highest scores. Maps from the Colorado Division of Water Resources, the USGS National Hydrography Database (USGS, 2006b) and various municipalities were used to identify key conveyance structures.

Proximity to Demand

This criterion concerns the distance from a potential underground water storage location to areas where unmet water demands have been identified. Projects are more likely to be implemented in locations where demand is highest. Projected unmet municipal and industrial (M&I) and agricultural demands for the year 2030 are used for this criterion; these unmet demand figures were obtained from the CWCB's Statewide Water Supply Initiative report (CDM, 2004). The scoring did not distinguish between M&I and agricultural demands.

Cost

This criterion considers anticipated facility construction costs for potential underground water storage projects. Cost associated with water treatment is not included in this criterion due to the site-specific nature of the water to be used for recharge. For the unconfined aquifer areas (both alluvial and bedrock), the primary cost discriminator is likely to be land acquisition for spreading basins, and away from metropolitan areas land costs will generally be relatively low. For the confined bedrock aquifers, the depth to the aquifer and the presence of existing high-capacity wells are key factors in comparing the relative cost of implementing projects. Projects located in unconfined aquifers are likely to be lower in cost than for confined aquifers since construction costs for spreading basins are relatively small. However, in situations where bedrock wells and associated infrastructure already exist, the construction-related cost for bedrock recharge would be only for retrofitting existing wells.

2.2 Data Collection and Analysis

Data used in this analysis were obtained from published sources, agencies, and universities performing studies in the relevant areas, and from technical experts with local experience. The primary sources of data are published reports by the United States Geological Survey (USGS), the Colorado Geological Survey (CGS), and the Colorado Water Conservation Board (CWCB). Key sources of information relied on for this study include the CGS Groundwater Atlas of Colorado (Topper et al., 2003), the CGS Artificial Recharge of Ground Water in Colorado – A Statewide Assessment (Topper et al., 2004), the CWCB Statewide Water Supply Initiative (CDM, 2004) and the CWCB South Platte Decision Support System groundwater technical memoranda. The latter study includes a comprehensive database and analysis of the available groundwater-related data in the South Platte River alluvial aquifers and Denver Basin bedrock aquifers and was relied on for the hydrogeologic criteria in those regions.

Data sources are listed in Section 6 and are also cited on maps where they are used. Information relied upon are generally from interpreted data reports rather than raw data from individual wells or sample locations. If available, data from existing Geographic Information System (GIS) data sets were used. If unavailable in GIS format, maps from reports were digitized and imported into GIS. The results of the data collection and analysis are presented in Section 3. That section provides a series of maps and related discussion for each of the evaluation criteria for the areas considered in the study.

2.3 Subregion Evaluation and Ranking

In order to evaluate and compare potential underground water storage areas, a set of quantitative measures were developed for each of the evaluation criteria described in Section 2.1. These measures were employed to rank potential areas for underground water storage. For the purposes of analysis, the study area was divided into four major aquifer regions, based primarily on aquifer types and locations, which were then subdivided into multiple subregions or areas. The ranking measures use the technical data presented in Section 3 as the basis to assign a score to each subregion for each of the ten evaluation criteria. The criteria received weighting factors based on their relative importance to the study's objectives. Then a total score was calculated for each area evaluated, resulting in relative rankings for comparing the potential recharge areas. The remainder of this section describes the area ranking process in more detail.

2.3.1 Areas Evaluated

The major aquifers in the South Platte and Arkansas River Basins were broken into the following regions and subregions for the purposes of this study. The subregions were defined based on drainage basins, hydrogeologic characteristics, and to a lesser extent on the locations of major roads and irrigation ditches that cross the aquifer regions. The subregions are numbered within each region for ease of evaluation and not in terms of their order of importance.

South Platte River Basin Alluvial Aquifer Region

1. South Platte River – Denver Metro
2. South Platte River - Metro to Greeley
3. Cache la Poudre River Basin
4. Upper Beebe Draw and Upper Box Elder Creek
5. Lower Beebe Draw and Lower Box Elder Creek
6. South Platte River - Greeley to Fort Morgan
7. Upper Lost Creek
8. Lower Lost Creek
9. Upper Kiowa Creek
10. Lower Kiowa Creek
11. Upper Bijou Creek
12. Lower Bijou Creek
13. Badger Creek and Beaver Creek
14. South Platte River - Fort Morgan to Balzac
15. South Platte River - Balzac to State Line
16. South Platte River - South Park

Arkansas River Basin Alluvial Aquifer Region

1. Arkansas River - Pueblo to Apishapa River
2. Arkansas River - Crowley Area
3. Arkansas River - Apishapa River to John Martin Reservoir
4. Arkansas River - John Martin Reservoir to Lamar
5. Arkansas River - Lamar to State Line
6. Upper Black Squirrel Creek
7. Upper Big Sandy Creek
8. Fountain Creek
9. Wet Mountain Valley
10. Arkansas River - Buena Vista to Salida

Denver Basin Bedrock Aquifer Region

1. Dawson Unconfined Aquifer - West
2. Dawson Unconfined Aquifer - East
3. Denver Confined Aquifer - West
4. Denver Confined Aquifer - East
5. Denver Unconfined Aquifer - West
6. Denver Unconfined Aquifer - East
7. Arapahoe Confined Aquifer - Northwest
8. Arapahoe Confined Aquifer - Southwest
9. Arapahoe Confined Aquifer - East
10. Arapahoe Unconfined Aquifer - West
11. Arapahoe Unconfined Aquifer - East
12. Laramie-Fox Hills Aquifer Confined - West
13. Laramie-Fox Hills Aquifer Confined - East
14. Laramie-Fox Hills Unconfined Aquifer - West
15. Laramie-Fox Hills Unconfined Aquifer - East

Dakota and Ogallala Aquifer Region

1. Dakota-Cheyenne Aquifer
2. Ogallala Aquifer - North
3. Ogallala Aquifer - South

2.3.2 Scoring Measures

The subregions used to investigate the potential for underground water storage in the South Platte and Arkansas River Basins were evaluated using the hydrogeologic, environmental and implementation considerations described in Section 2.1. These evaluation criteria were defined by quantitative measures that allowed each subregion to be scored and ranked, based on the technical findings presented in Section 3.

The quantitative measures used to score and rank each of the subregions described above are presented in Table 5. This table lists each evaluation criterion along with a brief description. The table also lists the quantitative measures for high, medium, and low scores. Where possible, the intent of the scoring measures was to evaluate alluvial and bedrock aquifers on the same basis. However, in four cases the evaluation criteria could not be evaluated using the same measures. These evaluation criteria are listed with separate descriptions for unconfined and confined aquifers. The dual definitions for criterion 1 (available storage capacity) reflect the difference in how water is stored in confined and unconfined aquifers. Criteria 2 (hydrogeologic suitability), 3 (residence time) and 10 (implementation costs) also have separate scoring measures for unconfined and confined aquifers due to the physical differences between the aquifer types.

To aid in the comparison of study areas within a given region, separate ranking tables were developed for the South Platte River Basin Alluvial Aquifer Region, the Arkansas River Basin Alluvial Aquifer Region, and for all of the bedrock aquifers areas in both basins, as shown in Tables 6 through 8. These tables use the scoring measures from Table 5 to score each subregion on a 1-to-10 scale for each evaluation criteria. The scores represent the degree to which each subregion meets the quantitative measures provided by the scoring measures, with a score of ten indicating the subregion best meets the criterion. Individual characteristics of a given area were evaluated as being "high," "medium," or "low" and then assigned a more refined number within those categories using engineering judgment and feedback from basin experts and stakeholders. Although the subregions have been ranked on separate tables according to study region and alluvial vs. bedrock aquifer setting, the scores for all subregions have been assigned on the same scale to allow subregions to be compared to each other. These comparisons, however, should take into consideration the differences in some of the evaluation criteria and their scoring measures, especially those for unconfined and confined aquifers.

The evaluation criteria shown in Table 1 and described in Section 2.1 cover a wide range of considerations for underground water storage, and they are not necessarily equal in importance. Weighting factors were chosen for this evaluation after much interaction with members of the study team. These were applied to each of the criteria before calculating total scores for each subregion. The weighting factors appear directly below the criteria listed at the top of Tables 6 through 8 and range from 0.5 to 2. It should be emphasized that using different values for the weighting factors can give significantly different results in the scoring. Values were chosen that were deemed to best reflect the relative importance of each of the criteria; however, there are other interpretations that may be more appropriate for a specific area.

The result of the weighting factors was that the three categories of evaluation criteria, hydrogeologic, environmental, and implementation considerations, received 45%, 15%, and 40%, respectively, of the overall score determined for a given area. The hydrogeologic considerations (criteria 1-3) received the highest weighting because of the reliable hydrogeologic data available for most of the study area, and because suitable hydrogeologic conditions are key factors for evaluating suitable underground water storage locations.

The environmental considerations (criteria 4-6) received lower weighting factors relative to the other two categories. This is largely because there are many environmental aspects that are dependent on conditions at a site-specific scale. For example, within any of the areas that include mapped habitat for threatened and endangered (T&E) species, implementation of a given project could have impacts ranging from significant to none at all, depending on where the project is sited. It is also conceivable that improvement of T&E habitat may be among the goals of an underground storage project and could be accomplished by siting a recharge pond in a location favorable to a given T&E species. The low weighting factors for these criteria also reflect the limited data available and the desire to not put too much emphasis on sparse data.

The implementation considerations received relatively high weighting factors, because these include key considerations affecting whether a project would be undertaken. Even so, relevant criteria for a potential underground water storage project are likely to be dependent on site-specific factors. Areas were evaluated with respect to land ownership on the basis that accessible public and range lands in rural districts are more favorable locations. However, it is conceivable that siting of a project on private land could be a favorable alternative due to the nature of the project, or that siting a recharge pond in an urban area could be favorable due to fulfillment of multiple purposes such as esthetic, recreational, and stormwater management needs.

The overall score for each subregion shown on the far right column on Tables 6 through 8 is the sum of each score multiplied by its weighting factor. The maximum possible score for a subregion is 100. As stated in Section 1.1 the feasibility of an underground water storage project depends greatly on a variety of site- and project-specific elements. The combination of elements unique to a given recharge site or project is difficult to address in a regional study such as this. As a result, there may be favorable underground water storage sites in all of the areas evaluated regardless of the overall area scores shown on Tables 6 through 8.

2.4 Stakeholder Meetings and Input from Basin Experts

Feedback and recommendations provided by basin experts has been a very important component of the project and has improved both the technical analyses and the evaluation of potential areas. Stakeholders and local technical experts from throughout the South Platte and Arkansas River Basins have been involved in the study through formal meetings, telephone conversations, individual questionnaires and email correspondence.

During the study data collection period, three meetings were held with each of the groundwater subcommittees from the Interbasin Compact Committee (IBCC) Roundtables representing the South Platte River Basin, the Metro Area, and the Arkansas River Basin. During these meetings the draft evaluation criteria, maps of technical findings, criteria weighting factors, and preliminary subregion rankings were presented, and stakeholder feedback was solicited. Local experts were also solicited for information and were provided questionnaires to facilitate compilation of their responses. In addition to those providing feedback via the questionnaires, informal feedback was provided by a number of experts who were contacted as a part of the study. Approximately 60 basin experts were involved in different aspects of this study.

The IBCC Roundtable groundwater committee members and other technical experts solicited for information are listed in Appendix B. A copy of the questionnaire provided to the basin experts is provided in Appendix C along with a summary of their responses. Many of the comments and suggestions provided by these individuals have been incorporated into this report.

Section 3
Technical Findings

Information and data collected from a variety of sources were used to characterize each potential underground water storage area (subregion) in terms of the hydrogeologic, environmental and implementation criteria described in Section 2.1. The sources of information included published reports, databases, and interviews with basin experts. The results of the data collection and analysis are presented in this section. These results were used to score each potential subregion using the scoring measures presented in Section 2.1. The site scoring is presented and discussed in Section 4.

To assist in the comparison of potential storage areas, the technical findings are grouped by the four geographic regions, listed below, and then for each evaluation criterion.

- South Platte River Basin Alluvial Aquifer Region
- Arkansas River Basin Alluvial Aquifer Region
- Denver Basin Bedrock Aquifer Region
- Dakota and Ogallala Bedrock Aquifer Region

The following sections present and discuss the technical data analyzed for these geographic areas for each of the ten evaluation criteria. The data have been analyzed and presented graphically in map format. Supporting technical data used to prepare some of the maps presented in the section are provided in Appendix D; these will be referred to as appropriate when discussing individual technical findings.

3.1 South Platte River Basin Alluvial Aquifer Region

The alluvial aquifer system of the South Platte River Basin has been subdivided into 16 areas or subregions for this evaluation, as defined in Section 2.3. Figure 4 shows a map depicting the location of the alluvial aquifer system within the watershed, the boundaries of Water Division 1, and the 16 subregions. Fifteen of these subregions are located east of the foothills. The alluvial aquifer along the mainstem of the South Platte River has been subdivided into five subregions, and key alluvial aquifers tributary to the South Platte River have been subdivided into ten additional subregions. The subregions were defined based on hydrogeologic characteristics and the location of major roads and irrigation canals. The 16th subregion includes the headwaters of the South Platte River in South Park. Each of the ten evaluation criteria are applied to each of these subregions.

3.1.1 Available Storage Capacity

The available storage capacity in the alluvial aquifer is the volume of unsaturated subsurface materials that could be used to store recharged water. The depth to the water table is an indicator of the available storage. Depth to water in the South Platte River alluvial aquifers is depicted in Figure 5. The depth to water in the figure is divided into ten- to twenty-feet increments and a color-fill is assigned to each depth increment as defined in the legend. Areas with a larger depth to water and thus a larger potential storage volume are shown in blue, representing depths greater than 30 feet. Areas with the largest depth to water shown in Figure 5, exceeding 50 feet over large areas, include the alluvial deposits of Upper Lost Creek (subregion 7), Lower Kiowa Creek (subregion 10), Upper and Lower Bijou Creek (subregions 11 and 12), and the South Platte River area near Fort Morgan (subregion 14). In contrast, most of the remaining alluvial deposits along the South Platte River, the Cache la Poudre River, and smaller tributaries have a depth to water less than 30 feet in most locations.

The available storage capacity was computed as both the total available volume in acre-feet and as the available volume per acre (acre-feet/acre) in each subregion, as shown in Table 2. The available storage volume on a per-acre basis may be the most useful way to characterize and compare subregions. Figure 6 shows the average available storage capacity for the areas within the South Platte River Basin Alluvial Aquifer Region, color-coded by available volumes on a per-acre basis, with blue indicating more available storage and warmer (yellow to red) colors representing less storage potential. Upper Lost Creek (subregion 7), Lower Kiowa Creek (10), Lower Bijou Creek (12) and the mainstem of the South Platte downstream of Fort Morgan (14) are the subregions showing the largest overall available storage capacity. The mathematical data used to develop the numbers presented in Table 2 are found in Appendix D.2.

The available storage capacity does not consider the upper ten feet of unsaturated materials. This is to minimize the potential for waterlogging, flooding of basements, flooding of septic system leach fields and other adverse effects due to a high water table. More detailed data and maps used to compute the depth to water table are presented in Appendix D.1

3.1.2 Hydrogeologic Suitability

For this analysis the hydraulic conductivity of the underlying saturated aquifer was used to evaluate the relative rate at which the subsurface materials could receive and transmit recharged water. Figure 7 presents a map summarizing the hydraulic conductivity values of the alluvial materials of the South Platte River and its tributaries. Most of the subregions have high to very high hydraulic conductivity values (greater than 250 feet per day), as suggested by the extent of green and blue color-fill presented. More detailed information on hydraulic conductivity values that were used to create this figure is presented in Appendix D.3, as developed in the CWCB's South Platte Decision Support System Task 43 (CDM, 2006a).

3.1.3 Residence Time

This criterion relates to the relative length of time a given volume of recharged water would be expected to stay underground before discharging to a nearby stream or other surface water body. To evaluate this criterion the 120-day and 480-day stream depletion factor (SDF) analyses developed by Hurr and others (Hurr et al., 1972) were used. A given SDF value represents the approximate distance from the river that recharged water would have a specified effect on the river within the number of days indicated. These SDF lines were adopted to represent relatively short and long residence times, respectively. The SDF lines are available for the mainstem of the South Platte River downstream of Denver. For other areas not covered by these maps, residence times were estimated based on aquifer properties, groundwater gradients, and the presence or absence of flowing streams. A map showing residence times defined by the 120- and 480-day SDF lines are shown in Figure 8. The tributaries entering the South Platte River from the south, including Box Elder, Lost, Kiowa, Bijou, Badger and Beaver Creeks, generally do not flow under normal conditions and so their nearest points of discharge is the mainstem of the South Platte River, resulting in relatively long travel times.

3.1.4 Water Quality

The water quality criterion relates primarily to the quality of water in the aquifer and the potential that its quality might adversely affect the quality of the recharged water. This criterion was evaluated based on maps of total dissolved solids (TDS) available for the aquifer and on water sampling results of individual wells obtained from various sources. Leaching of salts and metals is not a concern for this region. For the South Platte alluvial aquifer system, the concentration of TDS is generally representative of overall water quality. Figure 9 is a map of TDS for the mainstem of the South Platte River downstream of Denver. Values of TDS are in an intermediate range over most of the mapped area, but they get slightly larger in the downstream direction, indicating slowly degrading water quality. Water quality in the tributaries is somewhat better although sampling results are limited.

3.1.5 Habitat Concerns

Habitat concerns include potential impacts to habitat for threatened and endangered (T&E) species and potential impacts to wetlands. GIS coverages showing habitat of T&E species in the South Platte River Basin were obtained from the Colorado Division of Wildlife (DOW) and are shown in Figure 10. In some cases the habitat range of several of these species overlaps, such as along the Front Range where the Preble's meadow jumping mouse and bald eagle summer foraging grounds coexist. There are few mapped wetlands within the South Platte River Basin Alluvial Aquifer Region and those that exist are too small to appear at the scale of the map shown in Figure 10.

3.1.6 Waterlogging and Nonbeneficial Use

This criterion recognizes concerns that an elevated water table could have adverse effects such as waterlogging and increased water use by phreatophytes. The depth to water table map shown in Figure 4 was used to evaluate these concerns. Phreatophytes such as tamarisk have roots that can extend to 30 feet below ground surface, so areas shown in Figure 4 in yellow (depth to water of 10 to 30 feet below land surface) could be susceptible to increased nonbeneficial consumptive use. Most of the mainstem of the South Platte River, the Cache la Poudre River, the Beebe

Draw/Box Elder Creek, and the Lower Lost Creek subregions have a depth to water of less than 30 feet so the concern exists in these areas.

An additional concern is that underground water storage in upland terrace deposits could lead to waterlogging in bottomlands as the recharged water flows downgradient toward streams and causes the water table to rise too close to the land surface. This concern was considered on a regional scale in this study, but it should be examined more closely with site-specific investigations.

3.1.7 Land Use and Ownership

For the purposes of this analysis it is assumed that non-urban land uses and accessible publicly-owned lands will be more favorable for constructing aquifer recharge facilities. Figure 11 shows general land usage and land ownership within the South Platte River Basin. Most of the land is privately owned and is predominantly agricultural, indicated in green in Figure 11. Public lands are indicated in red in the figure and are assumed to be more accessible, while black indicates non-accessible public lands such as military reserves. The land use information was obtained from the USGS National Land Cover Dataset; it is current as of 2001 and represents the most recent information available. The Denver Metro region and Front Range urban corridor along Interstate 25 (subregions 1 and 2) include a large amount of urban land, but the remaining subregions consist mostly of agricultural, native or range lands. Subregions 8 (Lower Lost Creek) and 10 (Lower Kiowa Creek) contain relatively more publicly accessible lands than other areas.

3.1.8 Existing Infrastructure

The existing infrastructure criterion concerns the ability to convey water to and from a potential recharge location. The sources of water available for underground water storage are not considered in this study. However, for the purposes of this analysis, it is assumed that the existence of canals, ditches, pipelines and other infrastructure in a given area would make it more likely that one or more of them would have available capacity that could be used to convey water to a potential recharge location. Figure 12 shows the location of canal, ditches, pipelines and other infrastructure. In general there are a large number of canals and ditches near the mainstem of the South Platte River (subregions 1, 2, 6, 14 and 15), within the Cache la Poudre River drainage (subregion 3), and in the Beebe Draw/Box Elder tributary areas (subregions 4 and 5). In addition, a canal extends to the middle portion of the Upper Lost Creek area (subregion 7). Existing infrastructure mapped in the other areas is very limited.

3.1.9 Proximity to Areas with Demand

This criterion assumes that it will be more favorable to store water near the higher demand areas. Demand was estimated based on information included in the Statewide Water Supply Initiative study (CDM, 2004). Projected unmet agricultural, municipal, and industrial demands in the year 2030 were obtained from that report and summed by county. Figure 13 shows the projected unmet demands in the year 2030. Douglas County and the western portion of Adams County show large projected unmet municipal demands while Weld, Morgan, Logan, Larimer, and Boulder Counties show large projected unmet demands that are primarily agricultural. A listing of projected unmet demands is presented in Appendix D.4.

3.1.10 Cost

For the construction of a potential aquifer recharge facility, there will be a variety of site-specific costs that cannot be readily determined in a regional study. For the purpose of this study, the cost criterion for alluvial aquifer underground storage considers only the anticipated cost necessary to purchase land upon which a recharge facility would be constructed. In general it is assumed that land within or near urban areas will have a higher cost than would agricultural or native rangeland. The land use map presented in Figure 11 can be used to assess the relative land costs. As with the previous implementation criteria, the cost criterion should be considered as a more qualitative factor when comparing potential recharge areas.

3.2 Arkansas River Basin Alluvial Aquifer Region

The alluvial aquifer system of the Arkansas River Basin has been subdivided into ten subregions for the purposes of this evaluation, as defined in Section 2.3. Figure 14 shows a map depicting the extent of the alluvial aquifers within the Arkansas River watershed, the boundaries of Water Division 2, and the ten subregions. Seven of these subregions are located east of the foothills. The alluvial aquifer along the mainstem of the Arkansas River has been subdivided into four subregions and key alluvial aquifers tributary to the Arkansas River have been subdivided into four additional subregions. The subregions were defined based on hydrogeologic characteristics. The other two subregions are west of the mountain front in the Wet Mountain Valley and along the upper Arkansas River near Buena Vista. Each of the ten evaluation criteria were applied to each of these subregions. The criteria described below are explained in Section 2.1, Criteria Development.

3.2.1 Available Storage Capacity

The available storage capacity in the alluvial aquifer is the volume of unsaturated subsurface materials that could be used to store recharged water. The depth to the water table is an indicator of the available storage. Depth to water in the Arkansas River alluvial aquifers is depicted in Figure 15. The depth to water in the figure is divided into ten- to twenty-foot increments and a color-fill is assigned to each depth increment as defined in the legend. Areas with a larger depth to water and thus a larger potential storage volume are shown in blue, representing depths greater than 30 feet. Areas with the largest depth to water shown in Figure 15, exceeding 50 feet over large areas, include the alluvial deposits of the Upper Black Squirrel Creek Basin (subregion 6), Wet Mountain Valley (subregion 9), and the Buena Vista to Salida area (subregion 10). As noted in Section 2.1, the available storage considers only those portions of the aquifers where the depth to water is greater than 10 feet. The Wet Mountain Valley available storage is based on the area shown in the eastern portion of this subregion. Most of the remaining alluvial deposits along the lower Arkansas and smaller tributaries have a depth to water less than 30 feet in most locations. An exception to this is in the area north of the Arkansas River near the Kansas state line (subregion 5), where there are large available unsaturated volumes.

The available storage capacity was computed as both the total available volume in acre-feet and as the available volume per acre (acre-feet/acre) in each subregion, as shown in Table 3. The available storage volume on a per-acre basis may be the most useful way to characterize and compare subregions. Figure 16 shows the average available storage capacity for the areas within the Arkansas River Basin Alluvial Aquifer Region, color-coded by available volumes on a per-acre basis, with blue indicating more available storage and warmer (yellow to red) colors representing less storage potential. The Upper Black Squirrel and upper Arkansas subregions (6 and 10, respectively) show the largest overall available storage capacity. The data used to develop the available storage volumes as presented in Table 3 are found in Appendix D.2.

The available storage capacity does not consider the upper ten feet of unsaturated materials. This is to minimize the potential for waterlogging, flooding of basements, flooding of septic system leach fields and other adverse effects due to a high water table. More detailed data and maps used to compute the depth to water table are presented in Appendix D.1.

3.2.2 Hydrogeologic Suitability

For this analysis the hydraulic conductivity of the underlying saturated aquifer was used to evaluate the relative rate at which the subsurface materials could receive and transmit recharged water. Figure 17 presents a map summarizing the hydraulic conductivity values present in the alluvial materials of the Arkansas River and its tributaries. Most of the subregions have high hydraulic conductivity values, as suggested by the extent of green and blue color-fill presented. More detailed information for hydraulic conductivity values that were used to create this figure are presented in Appendix D.3.

3.2.3 Residence Time

This criterion relates to the relative length of time a given volume of recharged water would be expected to stay underground before discharging to a nearby stream or other surface water body. To evaluate this criterion for the Arkansas River Basin, the 120-day and 480-day stream depletion factor (SDF) analyses developed by Jenkins and Taylor (1972) were used for the lower Arkansas areas (subregions 1-5). A given SDF line represents the approximate distance from the river that recharged water would have a specified effect on the river within the number of days indicated. These SDF lines were adopted to represent relatively short and long residence times, respectively. For other areas not covered by these maps, residence times were estimated based on aquifer properties and groundwater gradients, and the presence or absence of flowing streams. A map showing residence defined by the 120- and 480-days SDF lines is shown in Figure 18.

Residence times approximated for the Wet Mountain Valley (area 9) and the Buena Vista to Salida area (area 10) were estimated to be very low due to steep groundwater gradients. The Upper Black Squirrel and Upper Big Sandy Creek subregions have long residence times since these creeks do not flow under normal conditions, and therefore recharged water would not readily return to these streams.

3.2.4 Water Quality

The water quality criterion relates primarily to the quality of water in the aquifer and the potential that its quality might adversely affect the quality of the recharged water. This criterion was evaluated based on maps of total dissolved solids (TDS) available for the aquifer and on water sampling results of individual wells obtained from various sources. For the Arkansas alluvial aquifer system, the concentration of TDS is generally representative of overall water quality. Figure 19 is a map of TDS for the mainstem of the Arkansas River downstream of Pueblo. TDS is low in the Buena Vista to Salida area (subregion 10) and in the Wet Mountain Valley (subregion 9). Values of TDS are high in most of the lower Arkansas River valley (subregions 1, 3 4 and 5), degrading in the downstream direction. Water quality in the tributaries is somewhat better, as indicated by lower TDS concentrations, although sampling results are limited.

In addition, it is known that naturally occurring selenium exists in the alluvial materials in the lower portions of the Arkansas River Basin and can leach into the alluvial aquifer when water is applied during irrigation (Gates et al., 2006). This could be a concern should artificial recharge projects be undertaken in selenium-rich areas.

3.2.5 Habitat Concerns

Habitat concerns include potential impacts to habitat for threatened and endangered (T&E) species and potential impacts to wetlands. GIS coverages showing habitat of T&E species in the Arkansas River Basin were obtained from the Colorado Division of Wildlife (DOW) and are shown in Figure 20. Generally none of the ranges of the listed species overlaps. In addition, there are a few areas of critical environmental concern in the areas evaluated. Areas of critical environmental concern (ACEC) are Bureau of Land Management lands defined as having important riparian corridors, threatened and endangered species habitat, cultural and archeological resources and unique scenic landscapes that the agency believes need special management attention. The Apishapa to John Martin area (subregion 3), John Martin to Lamar area (subregion 4), and Buena Vista to Salida area (subregion 10) include bald eagle winter range; the remaining areas do not appear to have any significant habitat concerns. There are few mapped wetlands within the Arkansas River Basin Alluvial Aquifer Region, and those that exist are too small to appear at the scale of the map shown in Figure 20.

3.2.6 Waterlogging and Nonbeneficial Use

This criterion recognizes concerns that an elevated water table could have adverse effects such as waterlogging and increased water use by phreatophytes. The depth to water table map shown in Figure 15 was used to evaluate these concerns.

Phreatophytes such as tamarisk have roots that can extend to 30 feet, so areas shown in Figure 15 in yellow (depth to water 10 to 30 feet below land surface) could be susceptible to increased nonbeneficial consumptive use. Most of the mainstem of the Arkansas River (subregions 1, 2, 3, 4, and 5) and the eastern side of the Upper Black Squirrel (subregion 6) have depths to water of less than 30 feet. Most portions of alluvial deposits in the Wet Mountain Valley (subregion 9) and Buena Vista to Salida area (subregion 10) have depths to groundwater in excess of 30 feet.

An additional concern is that underground water storage in upland terrace deposits could lead to waterlogging in bottomlands as the recharged water flows downgradient toward streams and causes the water table to rise too close to the land surface. Extensive drainage systems exist in portions of the Arkansas River Alluvial Aquifer Region to control high water table levels. Efforts have been underway for many years to lower the water table and thus salvage water lost to nonbeneficial evapotranspiration uses, and to reduce salinity. Attempts to lower the water table are not compatible with efforts to undertake aquifer recharge. This concern was considered on a regional scale in this study, but it should be examined more closely with any site-specific investigations.

3.2.7 Land Use and Ownership

For the purposes of this analysis it is assumed that non-urban land uses and accessible publicly-owned lands will be more favorable for constructing artificial recharge facilities. Figure 21 shows general land usage and land ownership within the Arkansas River Basin. Most of the land is privately owned and is predominantly agricultural, which is indicated in green in Figure 21. Public lands are indicated in red in the figure and are assumed to be more accessible while black indicates non-accessible lands such as military reserves. The land use information was obtained from the USGS National Land Cover Dataset; it is current as of 2001 and represents the most recent information available. The Interstate-25 corridor extending north from Pueblo (areas 1 and 8) includes urban lands, but the remaining areas consist mostly of agricultural and native or rangelands.

3.2.8 Existing Infrastructure

The existing infrastructure criterion concerns the ability to convey water to and from a potential recharge location. The sources of water available for underground water storage are not considered in this study. However, for the purposes of this analysis, it is assumed that the existence of canals, ditches, pipelines and other infrastructure in a given area would make it more likely that one or more of them would have available capacity that could be used to convey water to a potential recharge location. Figure 22 shows the location of canals, ditches, pipelines and other infrastructure. In general there are a large number of canals and ditches near the mainstem of the Arkansas River and in Fountain Creek (subregions 1, 2, 3, 4, 5, and 8). There are few canals in the Wet Mountain Valley or in the Upper Black Squirrel basin (subregion 6 and 9), but there is a moderately well-developed network in the Buena Vista to Salida area (subregion10). There are no canals mapped in the Upper Big Sandy area (subregion 7).

3.2.9 Proximity to Areas with Demand

This criterion assumes that it will be more favorable to store water near the higher demand areas. Demand was estimated based on information included in the Statewide Water Supply Initiative study (CDM, 2004). Projected unmet agricultural, municipal, and industrial demands in the year 2030 were obtained from that report and summed by county. Figure 23 shows the projected unmet demands in the year 2030. El Paso and Pueblo Counties show the largest projected unmet agricultural demands while Otero, Bent, and Prowers Counties also show large projected unmet demands that are primarily agricultural. A listing of projected unmet demands is presented in Appendix D.4.

3.2.10 Cost

For the construction of a potential aquifer recharge facility, there will be a variety of site-specific costs that cannot be readily determined in a regional study. For the purpose of this study, the cost criterion for alluvial aquifer underground storage considers only the anticipated cost necessary to purchase land upon which a recharge facility would be constructed. In general it is assumed that land within or near urban areas will have a higher cost than would agricultural or native rangeland. The land use map presented in Figure 21 can be used to assess the relative land costs. As with the previous implementation criteria, the cost criterion should be considered as a more qualitative factor when comparing potential recharge areas.

3.3 Denver Basin Bedrock Aquifer Region

The Denver Basin bedrock aquifer system is complex due to the presence of a layered series of four bedrock aquifers with both confined and unconfined conditions. Denver Basin aquifers have been subdivided into 15 areas for the purposes of this evaluation, as defined in Section 2.3. These subregions are presented in Figure 24. As can be seen in this figure, the majority of the Denver Basin aquifers are still in confined conditions. The subregion boundaries have been chosen so that eight of the subregions represent unconfined areas of the aquifers and the remaining seven represent portions of the bedrock aquifers that are confined. Each of the three lower aquifers have both confined and unconfined areas, while the uppermost (Dawson) aquifer has only unconfined conditions, The rationale for the subregion divisions comes from the physical differences between confined and unconfined aquifers and the general west to east trend of several hydrogeologic characteristics. Each of the ten evaluation criteria are applied to each of these 15 subregions. The criteria described below are explained in Section 2.1, Criteria Development. The term "depth to potentiometric surface" will be applied to both confined and unconfined aquifers in this section to describe the depth to the potentiometric surface or water table.

3.3.1 Available Storage Capacity

The depths to the potentiometric surface in each of the Denver Basin bedrock aquifers are depicted in Figure 25. The available aquifer storage capacity, on an acre-foot per acre basis, is presented in Figure 26. Available storage volumes calculated for each subregion within the Denver Basin Bedrock Aquifer Region are presented in Table 4. The concept of how available storage was estimated for the confined aquifer areas is described in Section 2.1.

Areas with a greater depth to the potentiometric surface and thus a larger potential storage volume are shown in green and blue with the greatest depths depicted by dark blue in Figure 25. Areas with the greatest depths to the potentiometric surface include the confined portions of the Denver, Arapahoe, and the Laramie-Fox Hills Aquifers (subregions 3, 4, 7, 8, 9, 12, and parts of 13). A portion of the Dawson West area (subregion 1) is mapped as having greater than a depth of 250 feet to the potentiometric surface. The unconfined areas of the Dawson Denver, Arapahoe, and Laramie-Fox Hills Aquifers (subregions 1, 2, 5, 6, 10, 11, 14, and 15) have less available storage, with large areas with less than 250 ft of unsaturated thickness. The availability of data in much of the eastern unsaturated areas is minimal, resulting in more uncertainty concerning actual field conditions.

The unconfined portions of these aquifers generally have the highest storage capacity on a per-acre basis. The total available and per-acre storage volumes for the Denver Basin Bedrock Aquifer Region are presented in Table 4. The subregions with the highest available aquifer storage per unit area are the Dawson West (subregion 1), Dawson East (subregion 2), Arapahoe Unconfined West (subregion 10), Laramie-Fox Hills Unconfined West (subregion 14), and the Denver Unconfined West (subregion 5), as shown graphically in Figure 26. The lowest available storage capacities are generally in areas located in the eastern half of the Denver Basin. More detailed data and maps used to compute the depth to water table are presented in Appendix D.1. The data used to develop the available storage volumes are found in Appendix D.2.

3.3.2 Hydrogeologic Suitability

As described in Section 2.1, the aquifer transmissivity (T) is used as the basis for evaluating the hydrogeologic suitability of the bedrock aquifers. Figure 27 presents a map summarizing the T values present in the Denver Basin bedrock aquifers. This map groups values into ranges as shown in the legend, with blue representing the values greater than 900 ft2/day. The highest T values are found in Douglas County south of the Denver Metro area, in both the Dawson Unconfined West (subregion 1) and the Arapahoe Confined North (subregion 7) areas, with the Dawson Unconfined East area (subregion 2) exhibiting moderate T values. More detailed data regarding individual T values used to create this figure are presented in Appendix D.3.

3.3.3 Residence Time

This criterion relates to the relative length of time a given volume of recharged water would be expected to stay underground before discharging to a nearby stream or other surface water body. The residence time was determined to be very long for the confined aquifers due to their low groundwater flow rates and deeper underground physical setting. To evaluate this criterion for the unconfined portions of these bedrock aquifers, the relative distance to overlying alluvial systems was used. A map showing the unconfined areas and accompanying overlying alluvial systems is shown in Figure 28. The Dawson Unconfined West and East areas (subregions 1 and 2) have the least area overlain by alluvial aquifers, and areas such as the Denver Unconfined East and West (subregions 5 and 6) and the Arapahoe Unconfined East and West (subregions 10 and 11) have among the highest portions of overlying alluvium.

3.3.4 Water Quality

The water quality criterion relates primarily to the quality of water in the aquifer and the potential that its quality might adversely affect the quality of the recharged water. This criterion was evaluated based on available maps of total dissolved solids (TDS) for the bedrock aquifers. Figure 29 presents maps of TDS for the Denver Basin bedrock aquifers. Values of TDS are generally low in the Dawson West and East areas (subregions 1 and 2) and in the confined portions of the underlying Denver and Arapahoe Aquifers (subregions 3, 4, 7, 8, and 9). TDS concentrations are highest in the Laramie-Fox Hills Aquifer (subregions 12 and 13) and in the unconfined portions of all remaining aquifers (Figure 29).

3.3.5 Habitat Concerns

Habitat concerns include potential impacts to habitat for threatened and endangered (T&E) species and potential impacts to wetlands. GIS coverages showing habitat of T&E species in the Denver Basin Bedrock Aquifer Region were obtained from the Colorado Division of Wildlife (DOW) and are shown in Figure 30. Due to the minimal surface area required for construction of deep well injection facilities, all of the confined aquifer areas have been shown on the figure without T&E species habitat. Ranges of the listed species overlap in unconfined areas such as the Dawson West (subregion 1), Denver Unconfined West (subregion 5), and Laramie-Fox Hills Unconfined West (subregion 14); therefore, construction of facilities in these areas may have a greater chance of impacting T&E species.

3.3.6 Waterlogging and Nonbeneficial Use

This criterion recognizes concerns that an elevated water table could have adverse effects such as waterlogging and increased water use by phreatophytes. The depth to potentiometric surface map shown in Figure 25 was used to evaluate these concerns. Phreatophytes such as tamarisk have roots that can extend to 30 feet below ground surface, so areas shown in Figure 25 in yellow (depth to water of 10 to 30 feet below land surface) could be susceptible to increased nonbeneficial consumptive use. The available data and mapping suggest that there are few areas within the unconfined portions of the Denver Basin bedrock areas that would be susceptible to waterlogging and increasing nonbeneficial use.

An additional concern for the unconfined portions of these aquifers is that underground water storage in upland deposits could lead to waterlogging in bottomlands as the recharged water flows downgradient toward streams and causes the water table to rise too close to the land surface. This concern was considered on a regional scale in this study, but it should be examined more closely with site-specific studies.

3.3.7 Land Use and Ownership

For the purposes of this analysis it is assumed that non-urban land uses and accessible publicly-owned lands will be more favorable for constructing artificial recharge facilities. However, the surface area required for well injection recharge projects, if existing wells are not available, is minimal and is not considered a significant factor for the confined aquifers. Figure 31 shows general land usage and land ownership within the Denver Basin Bedrock Aquifer Region. The land use information was obtained from the USGS National Land Cover Dataset; it is current as of 2001 and represents the most recent information available. Most of the land is privately owned. The northern portions of the Denver Basin bedrock areas are predominantly agricultural, indicated in green, while the southern portion is predominantly range land, indicated in yellow. Accessible public lands are indicated in red and non-accessible public lands such as military reserves are indicated in black. All of the unconfined aquifers in the eastern portion of the Denver Basin are overlain by agricultural or range land, which is assumed to be easily accessible for project implementation. The Denver Unconfined West area (subregion 5) and Arapahoe Unconfined West area (subregion 10) are both overlain by a relatively high proportion of urban land with lesser portions of inaccessible public lands.

3.3.8 Existing Infrastructure

The existing infrastructure criterion concerns the ability to convey water to and from a potential recharge location. The presence of existing high-capacity wells to recharge the confined portions of these bedrock aquifers is a very important consideration to implementing an aquifer recharge program. Wells are considered under the Cost criterion. The sources of water available for underground water storage are not considered in this study. However, for the purposes of this analysis, it is assumed that the existence of canals, ditches, pipelines and other infrastructure in a given area would make it more likely that one or more of them would have available capacity that could be used to convey water to a potential recharge location in either the confined or unconfined portions of these bedrock aquifers. Figure 32 shows the location of canals, ditches, pipelines and other infrastructure. In general there are a large number of canals and ditches in the northwestern part of the Denver Basin Bedrock Aquifer Region (subregions 5, 7, 10, and 14). There are very few ditches, canals, or pipelines in the southern and eastern portions of the region.

3.3.9 Proximity to Areas with Demand

This criterion assumes that it will be more favorable to store water near the higher demand areas. Demand was estimated based on information included in the Statewide Water Supply Initiative study (CDM, 2004). Projected unmet agricultural, municipal, and industrial demands in the year 2030 were obtained from that report and summed by county. Figure 33 shows the projected unmet demands in the year 2030. Douglas, Weld, and western Adams Counties show the largest projected unmet demands, while the City and County of Denver, eastern Arapahoe, Elbert and eastern El Paso Counties show the lowest projected unmet demand. A listing of projected unmet demands is presented in Appendix D.4.

3.3.10 Cost

For the construction of a potential aquifer recharge facility, there will be a variety of site-specific costs that cannot be readily determined in a regional study. For the purpose of this study, the cost criteria for construction of underground storage facilities recharging unconfined aquifers considers only the anticipated cost necessary to purchase land upon which a recharge facility would be constructed. Land requirements of deep well injection projects recharging confined aquifers are anticipated to be minimal. However, the cost of drilling new wells into such aquifers could be substantial depending on the depth required, so depth to the aquifer is utilized to help characterize this criterion. Costs to retrofit existing wells are generally less than $50,000 per well (Hemenway, 2007); therefore, the locations of existing high capacity wells are also considered.

The western portions of the Denver Basin Bedrock Aquifer Region can be seen in Figure 34 to have a large number of existing wells that are permitted to pump more than 50 gpm. The eastern portion of this region has a very low number of wells mapped; however, this may be an under-representation of the number of wells in this part of the area. The eastern portion of the Denver Basin is administered by the State according to the Designated Basin rules, and the database for this category of wells is not as complete. Figure 34 also shows the depth to the top of each aquifer. The unconfined portions of the aquifers are at land surface in most locations. The depth to the confined portions of these aquifers is commonly in excess of 500 to 1,000 feet.

In general it is assumed that land within or near urban areas will have a higher cost than agricultural land or rangeland. The land use map presented in Figure 31 can be used to assess the relative land costs. The cost criterion should be considered in a more qualitative manner when comparing potential recharge areas, because the site-specific conditions associated with a given aquifer recharge site could cause its implementation costs to vary widely from other potential sites in the same area. It is also worth noting that recharging the confined bedrock aquifers would raise the potentiometric surface and thereby reduce pumping costs in those areas.

3.4 Dakota and Ogallala Bedrock Aquifer Region

The Dakota-Cheyenne (referred to herein as the Dakota) and Ogallala (High Plains) Aquifers are located at the southern and eastern extents of the study area, respectively. For the purpose of this study, only the portion of the Dakota Aquifer in the southern part of the Arkansas River Basin is being considered due to the significant depth of this aquifer to the north. These aquifers have been subdivided into three areas for the purposes of this evaluation: the Dakota, Ogallala North, and Ogallala South. The resulting subregions are presented in Figure 35, where they are listed as subregions 16, 17, and 18 of the combined bedrock aquifer subregions. The

Ogallala Aquifer is unconfined and the Dakota Aquifer has areas of both confined and unconfined conditions. Each of the ten evaluation criteria have been applied to each of these three subregions. The criteria described below are explained in Section 2.1, Site Criteria Development. The term "depth to potentiometric surface" will be applied to both confined and unconfined portions of the Dakota Aquifer to describe the depth to the potentiometric surface or water table.

3.4.1 Available Storage Capacity

The depths to the potentiometric surface in the Dakota and Ogallala Aquifers are depicted in Figure 36. The available aquifer storage capacity, on an acre-foot per acre basis, is presented in Figure 37. Available storage volumes calculated for the Dakota and Ogallala Aquifer subregions are presented in Table 4. The concept of how available storage was estimated for the confined aquifer areas is described in Section 2.1.

Areas with a greater depth to the potentiometric surface and thus a larger potential storage volume are shown in dark blue in Figure 36. Areas with the greatest depths to the potentiometric surface include the confined portions of the Dakota Aquifer (subregion 16), with depths greater than 50 feet in most locations.

The unconfined portions of the aquifers generally have a higher storage capacity on a per-acre basis than the confined portions of the aquifers. The total available and per-acre storage volumes for the Dakota and Ogallala areas are presented in Table 4. The areas with the highest available aquifer storage per unit area are the Ogallala North and South subregions (17 and 18). More detailed data and maps used to compute the depth to water table are presented in Appendix D.1. The data used to develop the available storage volumes are presented in Appendix D.2.

3.4.2 Hydrogeologic Suitability

As described in Section 2.1, the aquifer transmissivity (T) is as the basis for evaluating the hydrogeologic suitability of the bedrock aquifers. Figure 38 presents a map summarizing the T values in the Dakota and Ogallala Aquifers. The highest T values are found in the Ogallala Aquifer (subregions 17 and 18), with values in excess of 4000 ft2/day. The Dakota Aquifer T values are in the 100 to 300 ft2/day range. More detailed information used to create this figure is presented in Appendix D.3.

3.4.3 Residence Time

This criterion relates to the relative length of time that a given volume of recharged water would be expected to stay underground before discharging to a nearby stream or other surface water body. The residence time was determined to be very long for the confined portions of the Dakota Aquifer due to slower groundwater flow rates and deeper underground physical setting. To evaluate this criterion for the unconfined portions of the Dakota Aquifer and for the Ogallala Aquifers, the relative distances to overlying alluvial systems were used and are shown in Figure 39. There are relatively few streams draining areas underlain by the Dakota and Ogallala Aquifers; therefore, these aquifers could potentially store water for long periods.

3.4.4 Water Quality

The water quality criterion relates primarily to the quality of water in the aquifer and the potential that its quality might adversely affect the quality of the recharged water. This criterion was evaluated based on available maps of total dissolved solids (TDS) for the aquifers. Figure 40 presents maps of TDS for the Dakota and Ogallala Aquifers. Water quality generally meets drinking water standards in the Ogallala North subregion, but the majority of the Ogallala South subregion exceeds standards (subregions 17 and 18, respectively). Water quality in the southeastern portion of the Dakota Aquifer (subregion 16) is generally below drinking water standards, although TDS concentrations increase to the west and north.

3.4.5 Habitat Concerns

Habitat concerns include potential impacts to habitat for threatened and endangered (T&E) species and potential impacts to wetlands. GIS coverages showing habitat of T&E species overlying the Dakota and Ogallala Aquifers were obtained from the Colorado Division of Wildlife (DOW) and are shown in Figure 41. Due to the minimal surface area required for construction of deep well injection facilities, the confined portions of the Dakota Aquifer are more favorable for this criterion. Generally, ranges of the listed species do not overlap and cover a very small percentage of the Dakota and Ogallala Aquifer subregions.

3.4.6 Waterlogging and Nonbeneficial Use

This criterion recognizes concerns that an elevated water table could have adverse effects such as waterlogging and increased water use by phreatophytes. The depth to potentiometric surface map shown in Figure 36 was used to evaluate these concerns. Phreatophytes such as tamarisk have roots that can extend to 30 feet below ground surface, so areas shown in Figure 36 in yellow (depth to water of 10 to 30 feet below land surface) could be susceptible to increased nonbeneficial consumptive use. This criterion is not considered to be applicable to the confined portions of the Dakota Aquifer. The Dakota and Ogallala Aquifer areas include significant portions with depths greater than 30 feet to the potentiometric surface.

An additional concern for the unconfined portions of these aquifers is that underground water storage in upland deposits could lead to waterlogging in bottomlands if the recharged water flowed downgradient toward existing streams and causes the water table to rise too close to the land surface. This concern was considered on a regional scale in this study, but it should be examined more closely with site-specific studies.

3.4.7 Land Use and Ownership

For the purposes of this analysis it is assumed that non-urban land uses and accessible publicly-owned lands will be more favorable for constructing aquifer recharge facilities. Figure 42 shows general land usage and land ownership overlying the Dakota and Ogallala Aquifer subregions. The land use information was obtained from the USGS National Land Cover Dataset; it is current as of 2001 and represents the most recent information available. The Dakota and Ogallala Bedrock Aquifer Region is overlain primarily by privately owned agricultural or range land and interspersed with public land that is assumed to be accessible for project implementation. Relatively significant areas covered by non-accessible public lands (military facilities) exist over the Dakota Aquifer in Pueblo County and about 25 miles northeast of Trinidad.

3.4.8 Existing Infrastructure

The existing infrastructure criterion concerns the ability to convey water to and from a potential recharge location. The presence of existing high-capacity wells to recharge the confined portions of these bedrock aquifers is a very important consideration to implementing an aquifer recharge program. Wells are considered under the Cost criterion. The sources of water available for underground water storage are not considered in this study. However, for the purposes of this analysis, it is assumed that the existence of canals, ditches, pipelines and other infrastructure in a given area would make it more likely that one or more of them would have available capacity that could be used to convey water to a potential recharge location. Figure 43 shows the location of canals, ditches, pipelines and other infrastructure. In general there are a significant number of canals and ditches along the South Platte and Arkansas Rivers, but these conveyance structures do not generally extend very far out of the alluvial valleys and to the highlands overlying the Ogallala Aquifer subregions. Very few canals and ditches overlie the Dakota Aquifer.

3.4.9 Proximity to Areas with Demand

This criterion assumes that it will be more favorable to store water near the higher demand areas. Demand was estimated based on information included in the Statewide Water Supply Initiative study (CDM, 2004). Projected unmet agricultural, municipal, and industrial demands in the year 2030 were obtained from that report and summed by county. Figure 44 shows the projected unmet demands in the year 2030. Overlying the Ogallala North subregion (area 17), only Washington County shows projected unmet demands greater than 1,000 acre-feet/year. The largest projected unmet demands are along the Arkansas River in Prowers, Bent, and Otero Counties. A detailed listing of projected unmet demands is presented in Appendix D.4.

3.4.10 Cost

For the construction of a potential aquifer recharge facility, there will be a variety of site-specific costs that cannot be readily determined in a regional study. For the purpose of this study, the cost criterion for construction of underground storage facilities recharging unconfined aquifers considers only the cost necessary to purchase land upon which a recharge facility would be constructed. It is assumed that the land cost in these areas would be relatively low. Land requirements of deep well injection projects recharging confined aquifers would be minimal. However, the cost of drilling new wells could be substantial depending on the depth required, so depth to each aquifer is presented to help characterize this criterion (Figure 45). Costs to retrofit existing wells are generally less than $50,000 per well (Hemenway, 2007); therefore, the locations of existing high capacity wells that could be used for artificial recharge are also considered.

The location of high-capacity wells are shown on Figure 45, based on information available from the State Engineer's Office. There are many wells present in the Ogallala Aquifer areas (subregions 17 and 18) and few wells present in the Dakota (subregion 16). The depth to the Dakota Aquifer exhibits a wide range as shown in Figure 45.

The cost criterion should be considered in a more qualitative manner when comparing potential recharge areas because the site-specific conditions associated with a given artificial recharge site could cause its costs to implement a project to vary widely.

Section 4

Scoring and Ranking of Potential Recharge Areas

This section presents the results of the scoring and ranking for each of the subregions considered. For the purposes of discussion the subregions are grouped by geographic location and aquifer type. This section concludes with a presentation and comparison of the areas receiving the highest ranking scores.

A total of 44 potential areas or subregions for underground water storage in the South Platte and Arkansas River Basins were evaluated using a series of criteria that include hydrogeologic, environmental and implementation considerations. These evaluation criteria were defined by quantitative measures that allowed each area to be scored and ranked, based on the technical findings presented in Section 3. The scoring measures are presented in Table 5 and discussed in Section 2.3. The scores are assigned on a relative basis, allowing comparison of subregions within and between the various aquifer regions.

It should be emphasized that the scoring and ranking is based on a subregional scale analysis in which the smallest areas evaluated are tens of square miles in area. The scale of this analysis does not take into account site-specific variations in the factors used for evaluation and may underestimate the feasibility of an underground water storage project in localized areas. In addition, the study does not consider a number of factors (including project scale and goals, sources of water, water rights, and water pre-treatment) that could affect the feasibility of an underground water storage project. Consequently, the scoring and ranking should be viewed as a guide to the relative merits of the subregions regarding their potential for underground water storage sites.

4.1 South Platte River Basin Alluvial Aquifer Region

The alluvial aquifers east of the foothills were divided into 15 areas with an additional area located in South Park in the headwaters of the South Platte River Basin. A map showing the location of these 16 areas is presented in Figure 4. Technical information relating to each of the evaluation criteria, presented in Figures 5 through 13 and discussed in Section 3.1, was the basis for assigning scores for each criterion. A listing of the scores for the South Platte River Basin Alluvial Aquifer Region areas is presented in Table 6.

4.1.1 Hydrogeologic Criteria

The subsurface materials of the alluvial aquifers within the South Platte River Basin provide a relatively large storage volume and are generally very permeable. These factors result in the individual areas receiving high scores for the storage availability and hydrogeologic suitability evaluation criteria (Table 6).

The permeable nature of the alluvial aquifer materials results in a high hydraulic conductivity and relatively rapid groundwater flow rates. The narrow width of the alluvial aquifer adjacent to the mainstem of the South Platte and Cache la Poudre Rivers plus the flowing reaches of tributaries to these rivers results in relatively short travel times for the areas within the mainstem alluvial system, giving those subregions (1, 2, 4, 6, 14 and 15) lower scores for the residence time criterion (Table 6). In contrast, areas consisting of alluvial tributaries located east and northeast of Denver (subregions 4, 5, 7-12, and 13) have longer residence times and higher scores for this criterion, because there is no flowing tributary stream in most locations.

4.1.2 Environmental Criteria

Water quality is generally fair along the mainstem of the South Platte River with some areas of poor quality associated with the effects of urbanization and agriculture. The quality decreases downstream, as suggested by the TDS map shown in Figure 9. Subregions 1-3, 6, 14 and 15 score in the medium to low range for this reason (Table 6). The upper parts of the tributary areas (subregions 7, 9, 11, 13, and 16) have water quality that is relatively good. Higher TDS values in the lower parts of these tributaries (subregions 8, 10, and 12) reduce those criterion scores into the medium range based on the scoring measures.

Most of the subregions are within the habitat range of at least one threatened and endangered (T&E) species (Figure 10) and so receive medium to low scores. Those areas that do not contain any critical habitat (subregions 11-13 and 16) received scores of 10 for this criterion. There are few wetlands indicated on the available maps within the South Platte River Basin so they were not a factor in the scoring for this criterion.

Waterlogging and nonbeneficial consumptive use could be a concern in areas where the depth to water table is less than 30 feet. A map showing the depth to groundwater is presented in Figure 5. Subregions 2-6, 15 and 16 received low to medium scores for this criterion due to the extensive areas with existing depth to water less than 30 feet (Table 6). The other subregions received a medium to high score because of the greater depth to water present in these areas. Waterlogging is expected to be a minor concern since areas with groundwater depths less than 10 feet below land surface were eliminated from consideration; however, this potential concern should be considered as part of any site-specific evaluation.

4.1.3 Implementation Criteria

Land use within the South Platte River Basin areas is primarily agricultural outside of the Denver Metro area (Figure 11). The Metro area (subregions 1) scored lowest, with areas in the Front Range urban corridor (subregions 2 and 3) also scoring relatively low due to their level of urbanization (Table 6). Areas with predominantly agricultural land use (subregions 4, 6, 7, 12, and 14) were assigned moderate scores, assuming land available for recharge facilities would be limited. Areas with a mix of agricultural land and range land (subregions 5, 9-11, and 15) scored higher, and those with predominantly native land (subregions 8, 13, and 16) scored the highest. There is relatively little public land within these subregions, so public vs. private land ownership did not influence the scoring.

Existing infrastructure is present throughout the areas near the mainstem of the South Platte River and its western tributaries but decreases to the east (Figure 12). As a result subregions 1-6, 14, and 15 scored high while subregions 9-13 received lower scores.

Projected unmet demand in 2030 (Figure 13) is high in the south Denver Metro area (subregion 1) and in the agriculturally-dominated areas east of Greeley (subregions 5, 6, 8, 10, 14, and 15; Table 6). These areas received the highest score for the demand criterion. Areas with a range of projected demand values received medium scores (subregions 4, 7, 10, 12, 13, and 16), while the remaining subregions have low projected demands.

Cost for land used to construct recharge facilities was assumed to be high in predominantly urban and urbanizing regions (subregions 1-6) and received low to medium scores (Table 6). The remaining areas received higher scores, with those farthest from urban areas and consisting predominantly of range land (subregions 8 and 13) receiving the highest scores.

4.2 Arkansas River Basin Alluvial Aquifer Region

The alluvial aquifers east of the foothills were divided into eight subregions with additional subregions located in the Wet Mountain Valley and along the upper Arkansas River between Buena Vista and Salida. A map showing the locations of these 10 subregions is presented in Figure 14. Technical information relating to each of the evaluation criteria, presented in Figures 15 through 23 and discussed in Section 3.2, was the basis for assigning scores for each of the criteria. A listing of the scoring measures for the Arkansas River Basin Alluvial Aquifer Region is presented in Table 7.

4.2.1 Hydrogeologic Criteria

The hydrogeologic setting varies significantly across the areas evaluated within the Arkansas River Basin. Subregions 1, 3, and 4 along the mainstem downstream of Pueblo have a relatively shallow depth to the water table (Figure 15) and score in the low to moderate range for the storage availability criterion, as shown in Figure 16 and presented in Table 7. The tributary areas to the mainstem (subregion 2 and the north side of subregion 5) have a greater volume of available storage and received moderate scores. In contrast, the areas west of the mountain front and in the Upper Black Squirrel Creek area (subregions 9, 10 and 6, respectively) have a greater depth to water resulting in high scores for storage availability. The Wet Mountain Valley (subregion 9) falls in this latter category due to the large available storage volume located on its eastern side.

The hydraulic conductivity of the alluvial aquifer is high in most of the areas within this basin. As a result, all subregions along the Arkansas River were assigned high scores as shown in Table 7, and the other subregions were assigned medium scores according to the scoring measures (Table 5).

As in the South Platte River Basin, subregions located near the mainstem of the Arkansas River have relatively low travel times back to the river due to the high hydraulic conductivity and short distance to the river (Figure 18). Those areas (subregions 1, 3-5, and 8-10) received low scores for the residence time criterion (Table 7). The Upper Black Squirrel and Upper Big Sandy areas (subregions 6 and 7) are distant from a receiving perennial stream and scored high for this criterion.

4.2.2 Environmental Criteria

Water quality is generally poor along the mainstem of the Arkansas River downstream of Pueblo, due to a combination of irrigated agriculture and natural soil conditions that leach undesirable minerals into the groundwater. The water quality decreases downstream (Figure 19), leading to low scores being assigned to subregions 1, 3, 4, and 5 (Table 7). Areas adjacent or tributary to the mainstem (subregions 2, 8) have somewhat better water quality and slightly higher scores reflect this. The mountain areas (subregions 9 and 10) have significantly better water quality and receive higher scores.

The habitat of T&E species appears to affect only a few of the areas within the Arkansas River drainage and the evaluation scores are generally high. Exceptions are subregions 6 and 8, which are completely contained within the habitat of one species (Figure 20). There are few wetlands indicated on the available maps for the Arkansas River Basin so they were not a factor in the scoring for this criterion.

Nonbeneficial consumptive use by phreatophytes and invasive species and waterlogging of soils is a significant concern in the areas along the mainstem downstream of Pueblo (Figure 15). Drainage systems in portions of this region control high water table levels, which is not compatible with efforts to undertake aquifer recharge. These areas and Fountain Creek (subregion 8) received low scores due to the shallow depth to the water table. In contrast, the Upper Black Squirrel and Buena Vista to Salida areas (subregions 6 and 10, respectively), scored high because of the greater depth to water (Table 7). The Crowley area (subregion 2), near the Kansas state line (subregion 5) and in the Wet Mountain Valley (subregion 9) appear to have small areas where nonbeneficial use and waterlogging concerns are possible and so received medium scores.

4.2.3 Implementation Criteria

Land use in the areas is primarily agricultural and range land in all but subregion 8, where urban and inaccessible public lands also exist; therefore, subregions 1-7 and 9-10 were assigned higher evaluation scores, and subregion 8 was assigned a low score due to its limited spatial extent and relatively high degree of urbanization. The variation in the higher scores is due to the amount of public land present in each area (Figure 21).

The Arkansas River valley has an extensive network of existing infrastructure (Figure 22), so subregions 1-5 and 8 received high scores. In addition, a pipeline exists in the Upper Black Squirrel Creek area (subregion 6), giving it a medium score. The other subregions (7, 9, and 10) have limited infrastructure, resulting in low scores (Table 7).

Projected unmet agricultural demands in 2030 in the Arkansas River valley (Figure 23) give the areas located there (subregions 1-5) high scores. Subregion 8 is near a projected unmet urban demand and also scored high. The Upper Black Squirrel and Upper Big Sandy are near areas of growing demand so received medium scores. The mountain subregions (9 and 10) have lower demand and received low scores (Table 7).

The cost criterion is based primarily on the estimated cost for land upon which an artificial recharge project might be constructed. Since all of the subregions except Fountain Creek (area 8) are located in agricultural and range land areas, the land cost is generally expected to be low; all of these subregions (except subregion 8) scored high for this criterion.

4.3 Bedrock Aquifers

The bedrock aquifers consist of the Denver Basin, the Dakota, and the Ogallala Aquifers. The bedrock aquifers were subdivided into 18 subregions. The Denver Basin Aquifers are subdivided first into the four constituent aquifers, then by whether that aquifer layer is confined or unconfined, and also by geographic location when warranted, for a total of 15 subregions. The Dakota Aquifer is treated as a single subregion, while the Ogallala Aquifer is divided into northern and southern subregions separated by the Arkansas River. Maps showing the location of these subregions are presented in Figures 24 and 35, respectively. Technical information relating to each of the evaluation criteria, presented in Figures 25 through 34 for the Denver Basin subregions, and Figures 35 through 44 for the Dakota/Ogallala subregions, and discussed in Sections 3.3 and 3.4, was the basis for assigning scores for each criterion. A listing of the ranking scores for all of the bedrock aquifer areas is presented in Table 8.

4.3.1 Hydrogeologic Criteria

The hydrogeologic setting varies significantly among the subregions of the bedrock aquifers. The Denver Basin unconfined areas (subregions 1, 2, 5, 6, 10, 11, 14, and 15) have more suitable aquifer hydraulic and storage characteristics than do the Denver Basin confined areas (subregions 3, 4, 7, 8, 9, 12, and 13). The Dakota Aquifer (subregion 16) also has confined and unconfined portions, but is treated as a confined aquifer due to the relatively limited unconfined portions. The Ogallala North and South areas are both unconfined (subregions 17 and 18).

The confined portions of the Denver Basin aquifers have significant depths to the potentiometric surface, but their much lower storage coefficient values (0.001 for all but the Denver confined areas, which were assigned a value of 0.0003) dictate that they have much lower storage potential per unit area than the unconfined portions of the aquifers. Therefore, the confined aquifer areas received lower scores for this criterion. The unconfined portions of the Denver Basin aquifers were assigned a storage coefficient value of 0.01, reflective of partially confined conditions in their lower portions, and received medium to high scores for this criterion, as shown in Figure 26 and presented in Table 8.

The aquifer transmissivity is by far highest in the Ogallala North and South areas (subregions 17 and 18). Among the remaining subregions, the uppermost three aquifers (Dawson, Denver, and Arapahoe) of the Denver Basin on the western side and the Dawson Unconfined East (subregions 1, 2, 3, 7, and 10) score intermediate to low, but still higher than the remaining bedrock aquifer subregions, as shown in Table 8.

Residence time was not a factor for the confined parts of the bedrock aquifers due to the generally low groundwater velocities in bedrock aquifers and the low likelihood of water discharging to streams within a period of several years, so confined subregions (3, 4, 7, 8, 9, 12, and 13) scored highest as shown in Table 8. Unconfined bedrock aquifer areas with relatively small portions overlain by alluvial aquifer systems (subregions 1, 2, 16, 17, and 18) received intermediate scores, while those with significant areas overlain by alluvial aquifer systems were estimated to have relatively long groundwater residence times to streams (subregions 5, 6, 10, 11, and 15), thereby earning the lowest scores. Table 8 provides the scoring for this criterion, and Figures 28 and 39 present the proximity to alluvial aquifer systems.

4.3.2 Environmental Criteria

Water quality is generally best in the Dawson Unconfined East area (subregion 2), followed by the Dawson Unconfined West area (subregion 1), several of the confined aquifer areas of the Denver Basin (subregions 1, 3, 4, and 8) and the Ogallala North and South areas (subregions 17 and 18). The unconfined areas in the Denver Basin, the confined Laramie-Fox Hills, and the Dakota areas ranked lowest for this criterion. Table 8 summarizes the evaluation scores, and Figures 29 and 40 present water quality parameters for the Denver Basin and the Dakota and Ogallala areas, respectively.

The habitat of T&E species affects only a few of the areas within the bedrock aquifers and the evaluation scores are generally high. Areas representing Denver Basin bedrock confined aquifers (subregions 3, 4, 7, 8, 9, 12, and 13) all scored highest due to the minimal land area required for construction of deep well injection facilities and the assumption that T&E species would not be impacted by this type of recharge. The Ogallala North and South areas (subregions 17 and 18) contain very little area with T&E species mapped. The remaining bedrock aquifer areas contain slightly more habitat, but construction of recharge facilities are not expected to be of significant impacts in these areas. Figures 30 and 41 present the extent of T&E species habitat mapped in the Denver Basin and the Dakota and Ogallala Aquifer areas, respectively.

Nonbeneficial consumptive use by phreatophytes and invasive species and waterlogging of soils is a significant concern at locations with less than approximately 30 feet to the underlying aquifer. This criterion does not apply to the confined areas of the bedrock aquifers (subregions 3, 4, 7, 8, 9, 12, 13, and 16) but is a minor concern in the unconfined bedrock areas. Figures 25 and 36 present the depth to the potentiometric surface in the Denver Basin and the Dakota and Ogallala Aquifer areas, respectively.

4.3.3 Implementation Criteria

Land use in the region includes a wide variety of land and ownership types. Areas farthest from urban land scored highest and include the Ogallala North and South areas (subregions 17 and 18), the Unconfined East, and Confined East Arapahoe and Laramie-Fox Hills areas (subregions 9, 11, 13, and 15). The heavily urban and agricultural portions of the Denver Unconfined East and West and the Arapahoe Unconfined West areas (subregions 5, 6, and 10) resulted in the lowest scores for this criterion. All other bedrock areas earned high scores. Small variations in scores in otherwise similar areas relate to the amount of public land present in each (Figures 31 and 42).

The bedrock aquifer areas have an extensive network of existing infrastructure near the rivers and in the metropolitan Front Range, causing subregions 5, 10, and 14 to receive high scores for this criterion. There is very little infrastructure in the eastern portion of the Denver Basin (subregions 2, 4, and 9; Figure 35) or in regions overlying the Ogallala and Dakota areas (subregions 16-18; Figure 43) so these subregions received low scores. Table 8 presents the rankings for this criterion in the bedrock areas.

Projected unmet municipal and industrial (M&I) and agricultural demands in 2030 for the Denver Basin and the Dakota and Ogallala Aquifer areas are presented in Figures 33 and 44, respectively. These figures show that the highest projected unmet demands occur in Douglas, eastern Adams, and Weld Counties, and adjacent to the South Platte and Arkansas Rivers. This distribution of projected unmet demand resulted in subregions 1, 3, 7, 8, 10, 12, and 14 receiving high scores. The Dakota and Ogallala North and South areas (subregions 16, 17, and 18) are farthest from high projected demand areas and received the lowest scores. The remaining areas received intermediate scores as shown in Table 8.

The cost criterion is based primarily on the estimated cost for land upon which an artificial recharge project might be constructed and the estimated depth of new wells that would be drilled for deep well injection projects. Land requirements are anticipated to be minimal for deep well injection projects but the cost of drilling new wells into such aquifers could be substantial depending on the depth required. For confined aquifers, the presence of existing wells to retrofit would decrease project costs; therefore, the existence of high-capacity wells that could be used for aquifer recharge is a very important consideration.

The western portions of all aquifers of the Denver Basin have a large number of wells that could potentially be retrofitted for aquifer recharge (Figure 34). The associated confined areas (subregions 2, 6, 7, and 11) are consequently given higher scores. In general it is assumed that land within or near urban areas will have a higher cost than would agricultural land or range land, so unconfined areas with more of these types of land (subregions 17 and 18) are scored higher and unconfined areas with more urban land are scored lower (subregions 5, 9, 12, and 13). The various land uses and types of ownership are shown on the map presented in Figure 31. The cost criterion should be considered in a more qualitative manner than other criterion when comparing potential areas.

4.4 Highest Ranking Recharge Areas

The 44 subregions were scored and ranked as shown on Tables 6 through 8. As a means to compare alluvial and bedrock areas in the South Platte and Arkansas River Basins, the highest-ranking subregions in each category are presented below. Their overall scores are listed in parentheses, out of a maximum possible score of 100. The top five areas in each of the South Platte and Arkansas alluvial regions are listed, while the top six areas are listed for the combined bedrock aquifer regions, because the 5th and 6th areas received the same score.

South Platte River Basin Alluvial Aquifers

- Lower Lost Creek (77)
- Upper Lost Creek (76)
- Lower Kiowa Creek (74)
- South Platte - Fort Morgan Area (73)
- Lower Beebe Draw/Box Elder Creek (72)

Arkansas River Basin Alluvial Aquifers

- Upper Black Squirrel Creek (71)
- Arkansas - Crowley Area (69)
- Arkansas – Lamar to State Line (68)
- Arkansas - Buena Vista to Salida (65)
- Fountain Creek (65)

Bedrock Aquifers

- Dawson Unconfined West (74)
- Arapahoe Confined Northwest (72)
- Ogallala North (70)
- Arapahoe Confined Southwest (68)
- Arapahoe Unconfined West (67)
- Ogallala South (67)

The focus of this study has been on determining locations with suitable hydrogeologic characteristics for underground water storage. The above subregions were scored and ranked highest largely due to their significant storage capacity, hydrogeologic suitability, and anticipated residence time criteria. These are the hydrogeologic criteria, which together received 45% of the weighting in the subregion scoring. As a result the alluvial subregions generally scored better than the bedrock subregions. Among the bedrock areas, the differences in hydraulic characteristics between unconfined and confined portions of the aquifers played a large role in the overall scores, leading to the highest bedrock subregion scores being in unconfined portions of bedrock aquifers.

Most of the scores for these areas are relatively close together, as presented in Tables 6 through 8. This may be a result of the regional nature of this study where the localized variation that exists for many of the criteria tended to be smoothed or averaged over a subregion. The similarity in scores also suggests that many of the areas considered in this report are worthy of further study on a more detailed level.

It should be emphasized that several factors could change the scores for a potential recharge project within a given subregion, including site-specific characteristics for any of the evaluation criteria, as well as the modification of weighting factors depending upon their relative significance at specific locations. Additionally, factors not considered in this study (including sources of water, water rights, water treatment requirements and partnering) could play an even larger role in determining the feasibility of a given site for underground water storage.

Section 5
Summary, Conclusions, and Recommendations

This section provides a brief review of the methods of evaluation and the results for the investigation of potential underground water storage areas in the South Platte and Arkansas River Basins, and closes with a set of recommendations that resulted from this study.

This evaluation of underground water storage areas in the South Platte and Arkansas River Basins has shown that a number of areas for potential underground water storage exist in both basins, in both alluvial and bedrock aquifer settings. Even on a subregion basis, available underground storage capacities are on the order of tens to hundreds of thousands of acre-feet in most areas.

5.1 Summary and Conclusions

As directed by Colorado State Senate Bill 06-193, the Colorado Water Conservation Board (CWCB) has prepared this study of potential underground water storage areas in the South Platte and Arkansas River Basins, including the alluvial aquifers underlying these river systems, the Denver Basin bedrock aquifers and the Ogallala and Dakota-Cheyenne bedrock aquifer systems.

Underground water storage is accomplished by recharging aquifers. It offers many benefits for Colorado's water resources management including reduction of evaporation losses, minimal environmental effects, lower capital costs, and potential water quality benefits. Aquifer recharge can be implemented at a variety of scales using approaches ranging from infiltration beneath irrigation ditches or shallow spreading basins to deep well injection. In many cases water may be available for recharge on a short-term basis, such as during high streamflows due to storm events or snowmelt runoff. Temporary surface storage of peak flows would increase the amount of water available for recharge in these circumstances.

Aquifer recharge has been a water management strategy in the South Platte River Basin for decades. There are now over 80 active aquifer recharge projects recharging over two million acre-feet of water to the underlying aquifer system, much of this for augmentation for well pumping. Underground water storage has been and will continue to be a significant water management tool in Colorado's future, especially considering growing social and environmental concerns associated with construction of traditional surface storage facilities.

The alluvial and bedrock aquifers in eastern Colorado were subdivided into 44 areas for detailed analysis. This evaluation was a natural next step beyond the larger-scale statewide artificial recharge study prepared by the CGS (Topper et al., 2004), which provided an essential starting point. Even with this higher level of detail, the current study should still be considered a regional-scale analysis focused on identifying broad geographic areas that appear suitable for underground water storage.

The study was undertaken by developing evaluation criteria, collecting and analyzing data relevant to each criterion, and then scoring each area using quantitative measures of each criterion. Over 50 technical experts and stakeholders from throughout the region provided input during the course of the study on the evaluation criteria, the data sources, the scoring and ranking process, and a draft of the findings. The insights and knowledge offered by these individuals are greatly appreciated and improved the study.

The areas were evaluated using a series of ten criteria that include hydrogeologic, environmental and implementation considerations. The hydrogeologic criteria were weighted the highest since the physical properties of an aquifer to store water were considered the most important from a regional perspective. Criteria that were not considered in this study include the sources of water to be used, water rights and the regulatory framework governing underground water storage, the quality and treatment requirements of the water to be recharged, the potential need for temporary surface storage in conjunction with a recharge facility, and the potential for partnerships among water management agencies to develop, support and finance specific projects. Any of these issues along with individual characteristics of a potential underground water storage site could cause them to be viewed more or less favorably than presented for a particular area in this report. Every potential underground water storage site will have advantages and disadvantages that must be thoroughly evaluated prior to construction of aquifer recharge facilities.

The areas were scored and ranked on a scale of 1 to 10 (with 10 being most favorable) for each criterion. Each of the criteria was weighted from 0.5 to 2 to reflect the relative importance of each at the regional scale of investigation.

There are significant portions of the South Platte and Arkansas River Alluvial Regions that are acceptable for underground water storage. Aquifer recharge in the Denver Basin and Dakota bedrock aquifers is feasible by using injection wells in their confined areas and spreading basins in their unconfined areas. Large volumes of unsaturated aquifer materials exist in the Ogallala Formation. The highest-scoring areas in the South Platte River Basin, Arkansas River Basin and for all bedrock aquifers are as follows. The locations of the areas are shown in Figures 4, 14, 24, and 35.

South Platte River Basin Alluvial Aquifers

- Lower Lost Creek
- Upper Lost Creek
- Lower Kiowa Creek
- South Platte - Fort Morgan Area
- Lower Beebe Draw/Box Elder Creek

Arkansas River Basin Alluvial Aquifers

- Upper Black Squirrel Creek
- Arkansas - Crowley Area
- Arkansas – Lamar to State Line
- Arkansas - Buena Vista to Salida
- Fountain Creek

Bedrock Aquifers

- Dawson Unconfined West
- Arapahoe Confined Northwest
- Ogallala North
- Arapahoe Confined Southwest
- Arapahoe Unconfined West
- Ogallala South

Many of the subregions received scores that are relatively close together. This may be a result of the regional nature of this study and suggests that many of the areas considered in this report are worthy of further study on a more detailed level. The Upper and Lower Lost Creek, Lower Kiowa Creek, Lower Beebe Draw/Box Elder Creek, Upper Black Squirrel, Fountain Creek, and Arkansas - Crowley areas are all located off the mainstem of the South Platte and Arkansas Rivers. Their scores reflect greater available storage capacities and longer residence times than areas adjacent to these rivers.

Of note is that two of the Denver Basin confined aquifer areas scored in the top tier, even though they were assigned a relatively low storage coefficient and hydrogeologic characteristics. This points to their suitable characteristics for almost all of the other criteria and in part explains why there are several artificial recharge projects operating in these aquifers. It is reasonable to expect that recharge projects would be successful in other Denver Basin bedrock aquifer areas, because they also possess desirable characteristics for the implementation and environmental criteria.

This study has focused on underground water storage in natural aquifer settings. It is understood that engineered structures such as slurry walls could be used to isolate portions of an aquifer making them more favorable for water storage. However, the use of such engineered structures could have a significant effect on neighboring water rights. This legal issue would need to be addressed in the early stages of such a project.

5.2 Recommendations

The following bulleted items are recommendations based on the evaluation of potential recharge areas in/from this study:

- The key recommendation from this study is that some of the areas evaluated should be investigated further at a much smaller and more detailed scale. Although the relative scoring of the areas should be used as one of the tools in selecting these sites, other issues not included this study, such as potential stakeholder involvement and available sources of water, may be the deciding factors.
- Follow-up investigations should refine what is known about the hydrogeologic, environmental and implementation considerations of selected areas. These may include limited field activities such as test borings, infiltration tests, aquifer sampling and pilot testing, and should focus on implementation considerations such as evaluation of existing infrastructure, potential partnering arrangements, water rights issues, and possible environmental concerns.
- Areas scoring lower in this study should not be excluded from further consideration for siting underground water storage projects. This is due to site- and project-specific factors affecting the feasibility of a given project that cannot be examined in a regional-scale study such as this one.

As mentioned previously, some of the steps involved in moving forward on investigating potential recharge sites include factors not evaluated in this study. Some of the more prominent factors include potential legal concerns with storing water underground, mainly in alluvial aquifers, establishing partnerships of stakeholders, obtaining water supplies for recharging, and obtaining funding for the potential projects.

At this time there are no rules and regulations regarding withdrawal of stored water from alluvial aquifers. This could be a concern for the implementation of underground water storage projects in certain areas, although several projects have been implemented through the water court process in the absence of rules and regulations. Currently, rules exist only for implementing underground water storage projects in the non-designated portions of the Denver Basin bedrock aquifers. The State Legislature, in conjunction with the Colorado Division of Water Resources and interested parties, should consider a dialog on developing rules and regulations for underground water storage in aquifers throughout the State. Developing a regulatory framework could resolve uncertainties regarding water rights issues regarding underground water storage.

Although this study has evaluated numerous areas that are favorable for aquifer recharge projects, the success of a potential project will most likely require local interest and cooperation. These stakeholder partnerships are best identified through means such as the Statewide Water Supply Initiative Technical Roundtables and Interbasin Compact Committee (IBCC) Basin Roundtables. Through these cooperative efforts, there is also more likelihood of obtaining water rights and water supplies for recharging potential aquifer sites.

Funding for potential aquifer recharge projects is possible through several avenues associated with the Colorado Water Conservation Board (CWCB). The CWCB administers the Water Supply Reserve Account, which was created by SB06-179. Funding requests from this account may be made through the IBCC Basin Roundtable for the basin in which the activity would occur. In addition, limited funds are available through the non-reimbursable grants from CWCB's Severance Tax Trust Fund Operational Account and the Construction Fund, and low-interest loans are available through the Water Project Loan Program. More information on these funding mechanisms can be found at CWCB's web page: cwcb.state.co.us.

Section 6
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Table 1 Evaluation Criteria

Evaluation Criteria	**Criteria Description**
Hydrogeologic Considerations	
1. Aquifer storage capacity	Available void space in the unsaturated soils or storage capacity in the aquifer
2. Hydrogeologic suitability	Ability of aquifer to quickly transmit recharged or extracted recharged water
3. Residence time	Duration that recharged water remains in the aquifer
Environmental Considerations	
4. Water quality	Aquifer water quality with respect to State standards, soil leaching potential
5. Habitat concerns	Presence of threatened and endangered species habitat; effect on wetlands
6. Waterlogging and nonbeneficial use	Potential to create high water table and increased ET by phreatophytes
Implementation Considerations	
7. Land ownership and land use considerations	Proportion of area in accessible public, non-urban land
8. Existing infrastructure	Proximity of infrastructure (pipelines, ditches, etc.) and available capacity
9. Proximity to areas with demand	Recharge areas nearby to areas of projected unmet demand in 2030
10. Implementation costs	Relative costs for construction of recharge facilities

Table 2 Available Storage Capacity – South Platte River Basin Alluvial Aquifer Region

Subregion Number	Subregion Name	Available Storage Capacity (acre-feet)	Available Storage Capacity (acre-feet/acre)
1	SP – Denver Metro	353,000	3.0
2	SP – Metro to Greeley	169,000	1.7
3	Cache la Poudre River	291,000	1.8
4	Upper Beebe/Box Elder	268,000	3.5
5	Lower Beebe/Box Elder	61,000	2.5
6	SP – Greeley to Ft. Morgan	94,000	1.4
7	Upper Lost Creek	1,260,000	10.6
8	Lower Lost Creek	157,000	5.7
9	Upper Kiowa Creek	234,000	5.0
10	Lower Kiowa Creek	806,000	9.5
11	Upper Bijou Creek	466,000	7.4
12	Lower Bijou Creek	1,067,000	8.5
13	Badger/Beaver Creek	311,000	4.4
14	SP – Ft. Morgan Area	968,000	8.5
15	SP - Balzac to State Line	890,000	4.8
16	SP – South Park	899,000	1.2

Note: 'SP' denotes areas along mainstem of South Platte River
SP - South Park data from Topper et al., 2004.

Table 3 Available Storage Capacity – Arkansas River Basin Alluvial Aquifer Region

Subregion Number	Subregion	Available Storage Capacity (acre-feet)	Available Storage Capacity (acre-feet/acre)
1	Ark - Pueblo to Apishapa	14,000	0.6
2	Ark - Crowley Area	39,000	1.6
3	Ark - Apishapa to John Martin	30,000	0.6
4	Ark - John Martin to Lamar	36,000	1.2
5	Ark - Lamar to State Line	101,000	1.9
6	Upper Black Squirrel Creek	510,000	8.3
7	Upper Big Sandy Creek	11,000	1.2
8	Fountain Creek	45,000	6.7
9	Wet Mountain Valley	338,000	7.3
10	Ark - Buena Vista to Salida	2,074,000	25.0

Note: 'Ark' denotes areas along mainstem of Arkansas River

Table 4 Available Storage Capacity – Denver Basin and Dakota/Ogallala Bedrock Aquifer Regions

Subregion Number	Subregion Name	Available Storage Capacity (acre-feet)	Available Storage Capacity (acre-feet/acre)
1	Dawson Unconfined West	1,169,000	2.73
2	Dawson Unconfined East	520,000	1.89
3	Denver Confined West	87,000	0.19
4	Denver Confined East	60,000	0.15
5	Denver Unconfined West	387,000	1.30
6	Denver Unconfined East	770,000	1.21
7	Arapahoe Confined Northwest	511,000	0.75
8	Arapahoe Confined Southwest	204,000	1.05
9	Arapahoe Confined East	690,000	0.57
10	Arapahoe Unconfined West	324,000	1.70
11	Arapahoe Unconfined East	324,000	1.17
12	Laramie-Fox Hills Confined West	900,000	0.75
13	Laramie-Fox Hills Confined East	1,059,000	0.45
14	Laramie-Fox Hills Unconfined West	122,000	1.33
15	Laramie-Fox Hills Unconfined East	85,000	0.57
16	Dakota-Cheyenne Aquifer	5,238,000	0.51
17	Ogallala - North	89,412,000	12.1
18	Ogallala - South	31,178,000	15.9

Table 5 Scoring Measures

Evaluation Criteria	Criteria Description	Scoring Measures		
		High	Medium	Low
		10 9 8	7 6 5 4	3 2 1
Hydrogeologic considerations				
1. Aquifer storage capacity	Available capacity for recharge	> 2 AF/Ac	0.25 - 2 AF/Ac	< 0.25 AF/Ac
2. Hydrogeologic suitability	Potential rate of aquifer recharge;			
• Unconfined aquifers	- Estimated from aquifer K values	> 250 ft/day	50 - 250 ft/day	< 50 ft/day
• Confined aquifers	- Estimated from aquifer T values	> 900 ft^2/day	300 – 900 ft^2/day	< 300 ft^2/day
3. Residence time				
• Unconfined aquifers	Duration recharged water is in aquifer	> 1 year	4 months – 1 year	< 4 months
• Confined aquifers	Subcrop proximity to alluvial aquifers	> 3 miles	1 – 3 miles	< 1 mile
Environmental considerations				
4. Water quality	Aquifer water quality with respect to State standards, soil leaching potential	No standards exceeded; minimal leaching potential	Limited areas where standards exceeded; minor leaching pot.	Large areas where standards exceeded; strong leaching pot.
5. Habitat concerns	Presence of threatened and endangered species habitat; effect on wetlands	Minor area of T&E habitat; no effect on wetlands	Some T&E habitat; some wetlands affected	Much T&E habitat; wetlands affected
6. Waterlogging and non-beneficial use	Potential to create high water table & increased ET by phreatophytes	Low concerns for waterlogging effects	Medium concerns for waterlogging effects	High concerns for waterlogging effects
Implementation considerations				
7. Land ownership and land use considerations	Proportion of area with accessible public land, multiple jurisdictions	Many areas of public and non-urban land	Some areas of public and non-urban land	Mostly private and/or urban land
8. Existing infrastructure	Proximity of infrastructure (pipelines, ditches, etc.) and available capacity	Suitable infrastructure < 5 miles from area	Suitable infrastructure 5-20 miles from area	Suitable infrastructure >20 miles from area
9. Proximity to areas with demand	Recharge areas nearby to areas of projected unmet demand in 2030	Near areas with demands > 10,000 AF/yr	Near areas with demands of 5,000 – 10,000 AF/yr	Near areas with demands < 5,000 AF/yr
10. Implementation costs				
• Unconfined aquifers	Relative land costs for construction	Low cost	Medium cost	High cost
• Confined aquifers	Depth to aquifer and proximity to existing high capacity wells	< 250 ft; many wells in area	250 - 1,000 ft; few wells in area	> 1000 ft; no wells in area

Note: Criteria 2, 3 and 10 have separate definitions and scoring measures for unconfined and confined aquifers

Table 6 Scoring of Potential Underground Storage Areas
South Platte River Alluvial Aquifer Region

		Evaluation Criteria (Weighting Factor in bold)										
		Storage Availability	Hydrogeo. Suitability	Residence Time	Water Quality	Habitat Concerns	Nonbeneficial Use	Land Ownership/Use	Existing Infrastructure	Proximity to Demand	Costs	**Overall**
Area No.	Subregion	**2**	**1.5**	**1**	**0.5**	**0.5**	**0.5**	**0.5**	**1**	**2**	**0.5**	**Score**
8	Lower Lost Creek	9	8	9	6	6	7	7	4	8	9	**77**
7	Upper Lost Creek	10	8	10	5	6	9	6	5	6	8	**76**
10	Lower Kiowa Creek	10	8	9	5	6	8	7	2	7	8	**74**
14	SP - Ft. Morgan Area	9	7	4	3	6	8	6	9	8	8	**73**
5	Lower Beebe/Box Elder Ck	7	8	8	3	5	4	7	10	8	5	**72**
1	SP - Denver Metro	8	9	4	5	4	7	1	9	9	3	**71**
12	Lower Bijou Creek	10	6	8	5	10	8	6	1	7	8	**71**
15	SP - Balzac to State Line	8	9	3	3	3	6	7	10	7	8	**70**
4	Upper Beebe/Box Elder Ck	8	9	6	4	5	5	6	10	6	4	**70**
13	Badger/Beaver Creek	8	7	7	4	10	7	8	1	7	9	**68**
6	SP - Greeley to Ft. Morgan	6	8	5	3	3	6	6	9	9	4	**67**
2	SP - Metro to Greeley	7	8	5	4	3	5	4	9	8	4	**66**
3	Poudre River	7	9	4	4	3	4	4	9	8	4	**66**
9	Upper Kiowa Creek	9	8	10	6	6	7	7	3	3	8	**66**
11	Upper Bijou Creek	9	6	10	6	10	7	7	1	3	8	**63**
16	SP - South Park	7	8	7	7	10	6	8	6	2	8	**63**

Note: Rankings based on scoring measures in Table 5

Ranking is on a 1-to-10 scale with 10 being the highest score

'SP' denotes areas along the mainstem of the South Platte River

Table 7 Scoring of Potential Underground Storage Areas
Arkansas River Alluvial Aquifer Region

		Evaluation Criteria (Weighting Factor in bold)										
		Storage Availability	Hydrogeo. Suitability	Residence Time	Water Quality	Habitat Concerns	Nonbeneficial Use	Land Ownership/ Use	Existing Infrastructure	Proximity to Demand	Costs	**Overall**
Area No.	Subregion	**2**	**1.5**	**1**	**0.5**	**0.5**	**0.5**	**0.5**	**1**	**2**	**0.5**	**Score**
6	Upper Black Squirrel Creek	9	6	9	9	6	8	7	6	5	7	**71**
2	Ark - Crowley Area	6	7	7	1	10	6	7	9	7	8	**69**
5	Ark - Lamar to State Line	7	8	3	1	10	2	7	9	8	8	**68**
10	Ark - Buena Vista to Salida	10	9	1	10	3	9	8	7	2	8	**65**
8	Fountain Creek	9	6	3	7	6	1	2	9	8	3	**65**
3	Ark - Apishapa to John Martin	4	8	3	1	7	3	7	9	9	8	**63**
4	Ark - John Martin to Lamar	5	8	3	1	5	2	7	9	8	8	**62**
1	Ark - Pueblo to Apishapa	5	8	3	2	8	4	5	7	8	7	**61**
9	Wet Mountain Valley	9	7	3	7	9	7	8	4	2	8	**59**
7	Upper Big Sandy Creek	4	6	9	7	9	3	9	5	4	8	**57**

Note: Rankings based on scoring measures in Table 5

Ranking is on a 1-to-10 scale with 10 being the highest score

'Ark' denotes areas along the mainstem of the Arkansas River

Table 8 Scoring of Potential Underground Storage Areas
Denver Basin and Dakota/Ogallala Bedrock Aquifer Regions

		Evaluation Criteria (Weighting Factor in bold)										
Area No.	Subregion	Storage Availability	Hydrogeo. Suitability	Residence Time	Water Quality	Habitat Concerns	Nonbeneficial Use	Land Ownership/ Use	Existing Infrastructure	Proximity to Demand	Costs	**Overall Score**
		2	**1.5**	**1**	**0.5**	**0.5**	**0.5**	**0.5**	**1**	**2**	**0.5**	
1	Dawson Unconfined West	8	6	8	8	7	10	9	3	9	5	**74**
7	Arapahoe Confined Northwest	5	5	10	6	10	10	8	7	8	8	**72**
17	Ogallala - North	10	10	8	7	9	9	10	1	2	9	**70**
8	Arapahoe Confined Southwest	6	3	10	8	10	10	8	4	8	6	**68**
10	Arapahoe Unconfined West	7	3	4	4	7	8	6	9	10	6	**67**
18	Ogallala - South	10	10	8	5	9	9	10	1	1	9	**67**
2	Dawson Unconfined East	7	4	8	9	7	9	9	1	7	7	**64**
12	LFH Confined West	5	2	10	5	10	10	9	5	8	2	**62**
3	Denver Confined West	3	2	10	7	10	10	9	6	8	5	**62**
14	LFH Unconfined West	6	1	2	4	7	7	8	9	10	7	**61**
9	Arapahoe Confined East	4	3	10	5	10	10	10	1	6	4	**55**
5	Denver Unconfined West	6	1	3	5	7	9	5	9	6	3	**52**
13	LFH Confined East	4	2	10	6	10	10	10	2	5	2	**52**
11	Arapahoe Unconfined East	6	3	4	4	8	8	10	2	5	7	**51**
4	Denver Confined East	2	1	10	8	10	10	9	1	5	5	**48**
6	Denver Unconfined East	6	1	4	5	7	9	7	2	5	7	**47**
15	LFH Unconfined East	4	1	3	3	8	8	10	2	7	8	**47**
16	Dakota-Cheyenne	4	1	6	6	7	8	9	2	3	5	**41**

Note: Rankings based on scoring measures in Table 5
Ranking is on a 1-to-10 scale with 10 being the highest score
'LFH' denotes areas in the Laramie-Fox Hills aquifer