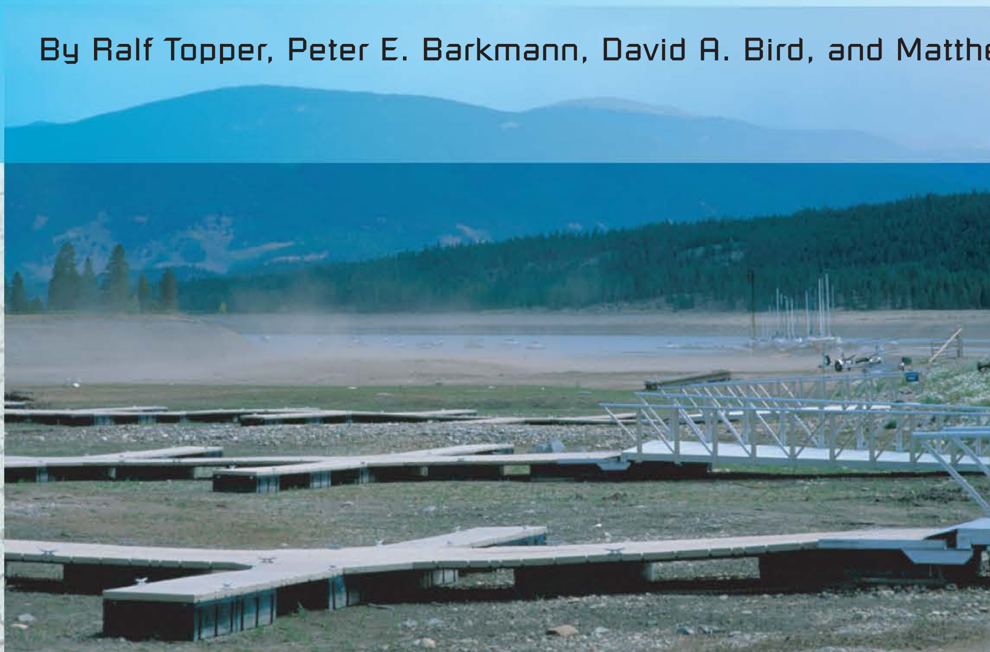
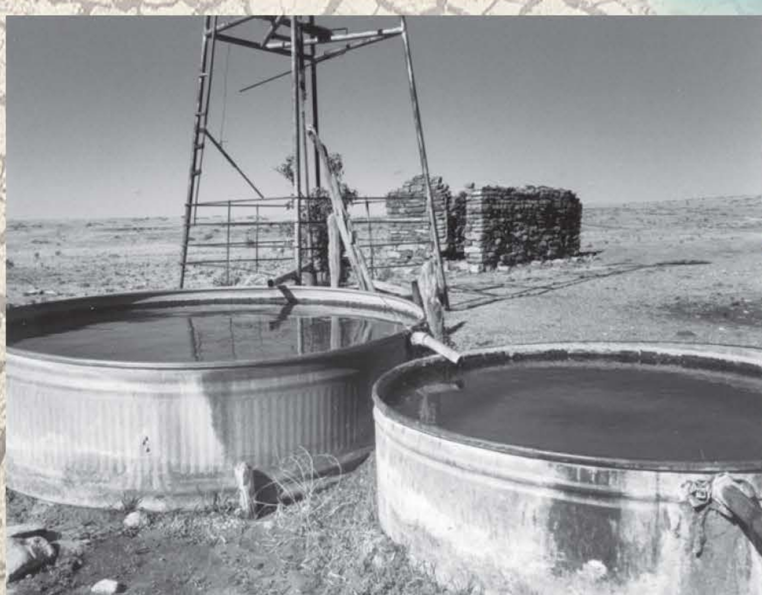
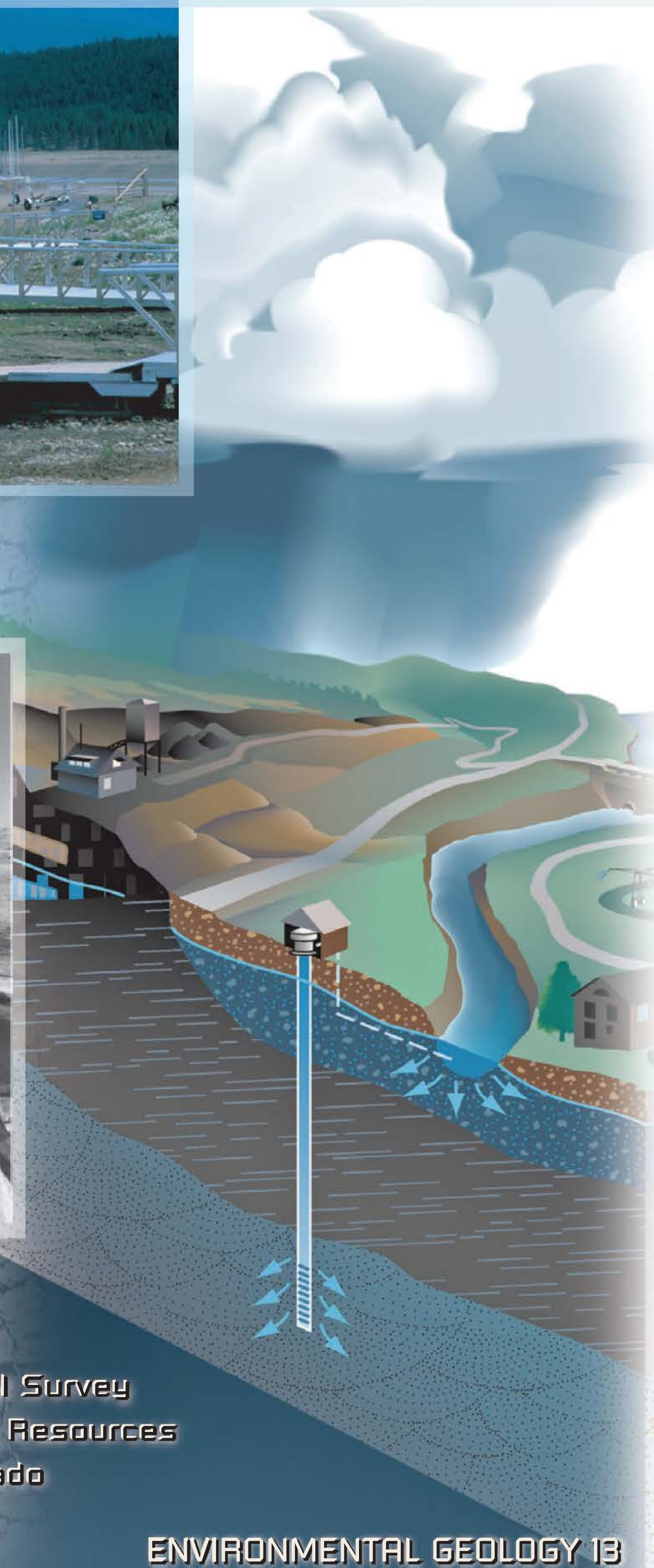
ARTIFICIAL RECHARGE OF GROUND WATER IN COLORADO *—A Statewide Assessment*

By Ralf Topper, Peter E. Barkmann, David A. Bird, and Matthew A. Sares







Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
2004

ENVIRONMENTAL GEOLOGY 13

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– *A Statewide Assessment*

Environmental Geology 13

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Colorado Geological Survey
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FOREWORD

This report, *Artificial Recharge of Ground Water in Colorado – A Statewide Assessment*, was requested by the Executive Director of the Department of Natural Resources in June 2003 to assess the underground water storage options potentially available in our state. The study was a special assignment for the Colorado Geological Survey — information and recommendations were requested within six months of the study's commencement.

The urgency of the request came in response to several years of lower than average precipitation, culminating in the extraordinary drought conditions of 2002. The drought highlighted the need for additional water storage to help Colorado store available water from rivers originating in the state. With a growing population and substantial agricultural production, underground storage of water through artificial recharge could provide an important water storage option for the future of Colorado.

Funding for this project was provided by the Colorado Geological Survey's portion of the Colorado Department of Natural Resources Severance Tax Operational Fund. Severance taxes are derived from the production of gas, oil, coal, and minerals.

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ACKNOWLEDGMENTS

Many people played important roles in the preparation and production of this report. From the Colorado Geological Survey, Jim Cappa, Chris Carroll, Sean Gaffney, and Karen Morgan all helped with literature review and data collection for aquifer and non-aquifer (mining) underground water storage options. Beth Widmann created the database to capture data for the inventory of Colorado, national, and international artificial recharge sites. Betty Fox and Brenda Hannu assisted with documentation of references. Jason Wilson and Larry Scott assisted with preparation of figures and facilitated the production of the document.

Elizabeth Moll and Matthew Grizzell assisted in the voluminous literature search necessary for a study of this scope. We thank the reviewers of this publication: Hal Simpson and Glenn Graham of the Division of Water Resources; Rod Kuharich, Dan McAuliffe, Randy Seaholm, and Ted Kowalski of the Colorado Water Conservation Board; Frank McNultyand Dawn Taylor Owens of the DNR Executive Director's Office; and Russell George Executive Director of the Department of Natural Resources. Discussions with Ivan Johnson, Courtney Hemenway and Vince Matthews were very helpful in our initial scoping process. We also acknowledge Ron Cattany's direction as the acting Director of the Colorado Geological Survey during the production of this report.

Cover: Dillon Reservoir from Frisco marina during the summer of 2002, a year of extreme drought in Colorado. Photo credit: Brad Odekirk.

Cover design and photo of ground water well in Baca County by Larry Scott, Colorado Geological Survey.

Executive Summary

Throughout the Centennial State's history, its semi-arid climate, periodic multi-year drought cycles, and the needs of its growing population have all conspired to highlight the need for water storage. Once again, recent drought and increasing water demands of a growing population have made Coloradans critically aware of the need for additional water storage. Surface-water reservoirs have been the primary means of storing water to meet Colorado's needs, but due to site logistics, regulatory requirements, and public opinion, building large new reservoirs has become more complicated, requiring years of planning and ever-increasing construction costs. An alternative means of increasing water storage capacity is to store water underground in aquifers and voids.

The extreme drought conditions experienced in 2002 solidified the value of ground water as part of an overall water management strategy. In 2003, the director of the Colorado Department of Natural Resources requested that the Colorado Geological Survey conduct a statewide assessment study of artificial recharge potential. This study assessed the opportunities for using artificial recharge to meet water storage needs statewide, focusing primarily on the hydrogeologic properties of aquifers and other underground storage options. The American Society of Civil Engineers has recently identified six phases of planning that are typically needed to develop, operate, and maintain a project for artificial recharge of ground water. This study parallels this process, but represents only the beginning physical data collection and technology assessment stages of the initial phase.

Artificial recharge (AR) is defined as any engineered system designed to introduce water to, and store water in, underlying aquifers. This report discusses several aspects important to the understanding of artificial recharge potential in Colorado, including

- the design objectives for implementing artificial recharge;
- the various artificial recharge technologies available;
- the current application of artificial recharge in other states and countries;
- the present practice of artificial recharge in Colorado; and
- the physical suitability of various aquifers, abandoned mines, and caves to store water.

The objectives of most AR applications fall into one, or a combination, of the following categories:

- ***Manage water supply***, including short-term water supply regulation, seasonal storage, long-term storage (drought mitigation), emergency supply, and conjunctive use;
- ***Meet legal obligations,*** such as providing augmentation water, supplementing downstream water rights, or facilitating compliance with interstate agreements;
- ***Manage/mitigate water quality*** through the improvement of surface- or ground-water quality or treated wastewater disposal;
- ***Restore/protect aquifers*** by restoring ground-water levels, limiting aquifer compaction and surface subsidence resulting from excessive ground-water withdrawals, or mitigating saltwater intrusion;
- ***Protection of the environment*** by maintaining wetland hydrology, enhancing endangered species habitat, or controlling the migration of ground-water contamination.

Artificial recharge technologies are broadly grouped according to whether water is recharged at the surface or underground, and then by whether water is recharged into the unsaturated zone or directly into the saturated zone of the aquifer.

- ***Surface infiltration*** is the impoundment of water at the ground surface for the purpose of infiltration to the underlying near-surface, unconfined aquifer.
- ***Subsurface infiltration*** is the application of water below the ground surface for infiltration to the underlying unconfined aquifer.
- ***Direct injection*** differs from infiltration systems by recharging water directly into the saturated zone of the aquifer.
- ***Aquifer storage and recovery (ASR) wells*** are wells through which water is injected into aquifer *storage* during times of low demand and high surface-water supply and subsequently *recovered* by pumping at a later date when demand exceeds surface supply.
- ***Modification of natural recharge*** involves man-made changes to the land surface or hydrogeologic conditions to increase the amount of recharge from natural and local sources.
- ***Underground (non-aquifer) water storage*** technologies apply to storage and retrieval of water in natural or manmade voids in the subsurface, such as abandoned mines or natural caverns.

The selection of a particular technology requires detailed site investigation and depends on the hydrogeologic setting of the target aquifer, land availability and uses, and the project objectives.

Artificial recharge is being used in at least 32 states in the U.S. and at least 26 countries worldwide. The methods used span the entire spectrum of known technologies, but the dominant methods are injection wells and infiltration basins. The larger scale projects are generally located in drier areas of the U.S. (i.e., the west and southwest), or areas in which the growing population has overtaxed the available water supply (e.g., California, Florida, New Jersey, New York).

An inventory of artificial recharge projects within Colorado identified 19 active operations including

- ***augmentation*** in the lower South Platte River basin,
- ***seasonal*** storage as part of conjunctive use of ground water and surface water in the San Luis Valley,
- ***direct*** injection by two water districts in the Denver Basin, and
- ***regulation*** of water supply and water quality at several smaller municipal water systems.

The occurrence and distribution of Colorado's water resources are inherently linked to the state's geography and underlying geology. As a result of Colorado's complex geology, a multitude of aquifers in various areas of the state are suitable for artificial recharge projects. The geologic units containing these aquifers can be broadly classified as unconsolidated sediments, poorly consolidated sediments, or consolidated rock. The amount of storage available in an aquifer is dependent upon the aquifer's (1) storage coefficient (storage ability), (2) areal extent, and (3) freeboard (amount the water level could rise above present water level). In general, unconfined aquifers have smaller areal extent, tens of feet of freeboard, and a high storage coefficient. Confined aquifers, on the other hand, often have a large areal extent and hundreds of feet of available freeboard, but a very low storage coefficient.

A weighted ranking system was established to evaluate the key physical properties of the state's 16 highest-potential unconsolidated aquifers and 29 highest-potential consolidated aquifers. Hydrogeologic parameters taken into account in the "aquifer ranking value" include *areal extent, depth, saturated thickness, head freeboard, storage coefficient, and hydraulic conductivity*. In addition to calculating a final ranking for the aquifer, the quality of the input data was also assessed. The alluvial deposits of the South Platte River, its tributary Bijou Creek, and the Arkansas River are the top three ranked unconsolidated aquifers. The High Plains Aquifer, Dakota-Cheyenne Group of southeast Colorado, and the Denver Basin aquifers are the top three ranked consolidated bedrock aquifers.

The evaluation of the available storage capacity in Colorado's highest-potential aquifers was guided by the desire to find opportunities to develop large-scale artificial recharge projects, i.e. defined as having storage capacity in excess of 100,000 acre-feet. Thirteen of the 16 primary unconsolidated rock aquifers have sufficient storage capacity to accommodate a large-scale project. In aggregate, the lower South Platte River alluvium and the San Luis Valley alluvium have the capacity to store in excess of one million acre-feet. All but two of the 26 primary consolidated rock aquifers have sufficient storage capacity available to meet the 100,000 acre-feet criterion. Because of their large areal extent and head freeboard, the majority of these aquifers can store millions of acre-feet of water.

Three types of non-aquifer underground water storage possibilities were assessed statewide: abandoned coal mines, abandoned metal mines, and caves. Storage of water in abandoned underground coal mines is not a new concept, but has only recently been tried in Colorado, most notably by the City of Arvada at the former Leyden coal mine. Overall, the estimated storage capacities of non-aquifer alternatives are much smaller than those of aquifers. An estimated 55,000 acre-feet of underground water storage is available for artificial recharge in inactive coal mines, statewide. Major technical challenges to water storage projects in coal mines include maintaining hydraulic control of stored water, poor water quality (high salinity), and mine subsidence. The potential water storage volumes for abandoned metal mines and natural cave systems are much smaller than for coal mines. Metal mines and natural caves are not a viable option for water storage because of their limited storage capacity, water quality issues, leakage of stored water, and land ownership issues.

Artificial recharge projects can increase the total amount of stored ground water in a very specific and calculated fashion. In addition, indirect or passive methods of ground-water recharge such as vegetation control, storm-water retention basins, and leaky ditches are non-specific in application, but can significantly increase overall ground-water storage. Similar to water conservation measures, some changes in legislation and water facility design and engineering, combined with passive recharge structures, would benefit both ground-water and surface-water resources.

This study assesses the best aquifers in Colorado for their artificial recharge potential of ground water based primarily on their hydrogeological suitability. Implementation of an AR project must also consider several other factors, including (1) project objectives; (2) site-specific hydrogeologic conditions; (3) source water availability; (4) water law and water rights; (5) available land surface area and compatible land-use activities; (6) governing water-management districts or entities; (7) facility design criteria; (8) capital costs to construct; (9) operation and maintenance costs; and (10) general storage efficiency, recovery, and deliverability.

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"It is no secret in Colorado that 2002 saw the worst drought in our state in recorded history. In many areas, it was the third consecutive dry year, and it stressed the water supply capabilities of many water providers and users. The value of reservoir water and ground water was clearly realized, and we all recognize that additional storage would have reduced the impact of the drought."

Hal Simpson, State Engineer
--Division of Water Resources
2002 Annual Report

I. Introduction - Statement of Problem

Colorado experienced the worst drought in recorded history in 2002 and is currently in the fifth consecutive year of the driest five-year period in a century of record keeping (Stein, 2004). Colorado has been subject to recurring multiple-year drought cycles through history (McKee and others, 2000). Even during times of normal precipitation, Colorado's relatively low precipitation rate (statewide average of approximately 16 inches per year) combined with high evaporative losses (statewide average of approximately 81 percent) result in a water balance deficit over most of the state, with the exception of the higher mountainous regions (Topper and others, 2003). The opening quote by Hal Simpson stresses the importance of ground water within the state's overall water management, and indicates a need for additional storage capacity. This storage capacity can take the form of surface-water reservoirs or underground water storage.

The impacts of the current drought cycle on the state's agriculture, water supply systems, industry, citizens, and natural resources have been substantial and measurable. Colorado's accelerated population growth has also placed increasing demands on its limited water resources. Periods of drought highlight this resource limitation and raise serious concerns about the sustainability of our state's water resources. Surface-water reservoirs have been the primary means of storing water to meet Colorado's needs. This study looks at an alternative means of increasing water storage capacity by storing water underground in aquifers and voids.

Scope and Objectives

This study is a statewide assessment of the potential for artificial recharge of ground water in Colorado. *Artificial recharge* is defined as any engineered or designed system that puts water on or in the ground for the purpose of infiltration and subsequent migration into underlying aquifers. The study focuses on the location, geology, and physical ability of various aquifers within Colorado to store additional water supplies. In addition, other unconventional means of *underground water storage* through the use of abandoned coal mines, metal mines, and caves are assessed.

This study discusses several aspects important to the understanding of artificial recharge potential in Colorado, including

- the various artificial recharge technologies available;
- the application of artificial recharge in other states and countries;
- the present practice of artificial recharge in Colorado; and
- the physical suitability of various aquifers, abandoned mines, and caves to store water.

The suitability of an aquifer to store water is not the only consideration involved in a successful artificial recharge project. Two other factors are crucial: available water supply for recharge and a supportive legal policy. This report does *not* address either water supply or legal structure in a comprehensive manner, but does touch on these factors because they bear on the implementation of any potential artificial recharge project. The Colorado Water Conservation Board is in the midst (2003-04) of the *Statewide Water Supply Initiative*, a study that will help address both of these factors.

Artificial recharge is most commonly implemented on a local basis, primarily by individual water districts. Development of an artificial recharge project can take years to accomplish between the initial concept and full-scale implementation. The process requires interdisciplinary data gathering and research to determine applicability and design criteria. The American Society of Civil Engineers (ASCE) recently established a set of standard guidelines to develop, operate, and maintain a project for artificial recharge of ground water (ASCE, 2001). The phased progression as outlined by ASCE is as follows:

Phase I—Preliminary activities:

- Data collection and organization, resource evaluation (including identification of source water alternatives), alternative site evaluation, and preliminary studies; and
- Conceptual plan development, environmental assessment, and public involvement

Phase II—Field investigation and test program
Phase III—Design:

- Preliminary design, public involvement, engineering reports; and
- Final design, draft final report, public hearings, response to comments, and final report

Phase IV—Construction and start up
Phase V—Operation, maintenance, project review, and project modification
Phase VI—Closure

This study represents only the beginning of Phase I activities in this process. It includes data collection and organization, alternate site evaluation, and preliminary studies on a statewide basis. Not included in this investigation, yet an important part of Phase I, are evaluation of potential source-water supplies, development of a detailed conceptual plan, environmental assessments, and public involvement. These activities and additional data gathering are best done by local entities when a specific local project is identified. The results of this study provide the scientific background for the development of underground water storage in Colorado. It provides the foundation for the development of a conceptual plan, site-specific field investigation, and the construction of a pilot test program.

Background

Colorado is a semi-arid state with a rapidly growing population that is straining a limited water-resource base. Compounding the situation is the geographic imbalance of water supply with water demand. The greatest amount of precipitation, and hence the greatest runoff of surface water, occurs on the Western Slope of Colorado's Rocky Mountains, yet the greatest number of people live on the Eastern Slope of the Rockies. A second imbalance exists in the relative timing of supply and demand. The greatest supply falls in the late winter and spring, while the greatest demand occurs in the summer, well after the snowmelt runoff has peaked. These factors mandate careful management of the limited resource to provide a sustainable supply. In Colorado, management of the water resource has evolved into a complex system of water law, which attempts to allocate the limited resource fairly, and a complex infrastructure system to distribute the limited resource. The infrastructure system includes numerous water storage and diversion facilities, which include a series of trans-basin diversions that generally move water from west to east, across and under the Continental Divide.

Sustainable water management relies on the ability to store water. The traditional method of storing water has been to construct dams and develop reservoirs (**Fig I-1**). However, the high cost and long timeframes combined with adverse ecological, environmental, and socio-cultural impacts have hindered construction of new large reservoir projects in the west. In addition, surface reservoirs lose tremendous amounts of water to evaporation (especially in the semi-arid west), require expensive maintenance, accumulate sediment, have the potential of structural failure, are vulnerable to contamination whether accidental or by criminal acts, increase breeding areas for disease carrying insects, and interfere with river ecology. A viable alternative is the storage of water below ground in aquifers, which are natural reservoirs.

Ground water has long been an important water resource in parts of Colorado, particularly on the Eastern Slope where surface-water supplies are limited. In fact, many regions and communities are completely dependant on ground water for agricultural and municipal supplies. Much of the rapidly growing southern Denver metropolitan region is currently dependant on non-renewable ground water extracted from the Denver Basin aquifer system. As a result of the extensive development of ground water to meet a rapidly growing population, ground-water supplies are being depleted and water levels are declining. For example, water levels in the Denver Basin Arapahoe aquifer southeast of Denver are dropping at rates up to 30 feet per year (ft/yr) (DWR, 2000).

In addition to water supply, aquifer storage can be utilized as part of an overall water management strategy. This storage potential can be used in the short-term, season-to-season balancing act between natural supply and demand, or to provide a cushion for periods of drought. Referred to as conjunctive use, surface water is used as the primary source of water in periods of abundance, while ground water is reserved for times when surface water is limited. When necessary, natural ground-water recharge can be enhanced to take advantage of peak surface-water flows. Aquifers represent tremendous opportunities for underground storage of water with essentially zero evaporative losses.

Denver Basin Aquifer Recharge Demonstration Project well house A-6a.

The Frisco Marina on Dillon Reservoir during the summer 2002 drought.

Figure I-1. Construction of dams and the development of surface-water reservoirs has been the traditional means of storing water. An environmentally sensitive, low-cost, flexible alternative is to store water underground in aquifers.

Artificial recharge in some fashion has been used for centuries. During the last several hundred years, nomads in Turkmenistan have been collecting infrequent surface runoff into an infiltration pit located in sand dunes where the surface water recharges near-surface ground water. Ground water is then available for extraction from a series of hand-dug wells surrounding the pit even during dry periods (Pyne, 1995). A tribal community in western India has also been applying artificial recharge to enhance water supply and improve water quality obtained from a tank excavated in fine sand and clay (Pyne, 1995). Closer to home, California began practicing artificial recharge by routing storm runoff into infiltration (spreading) basins around the turn of the century. Interest in artificial recharge grew in California and New York during the 1930s as a way to conserve or enhance ground-water resources (Weeks, 2002).

In Colorado, the earliest documented application of artificial recharge began at Olds Reservoir in Weld County when local farmers took advantage of a leaky reservoir built several decades earlier. Surface water was diverted into the little used structure in order to maintain water levels in the underlying alluvial aquifer (Skinner, 1963). In 1959, the Colorado Agricultural Experiment Station (CAES) initiated a study of artificial and natural recharge in Colorado that was funded by the Forty-second Colorado General Assembly under Senate Bill No. 336. This study was initiated to consider artificial recharge in the following basins (CSU, 1960):

- South Platte River Basin
- Arkansas River Basin
- Colorado High Plains Ogallala formation
- San Luis Valley
- Denver Basin bedrock aquifers
- Dakota and Cheyenne sandstone
- Grand Junction Basin

A progress report was prepared in 1960 addressing artificial recharge at Olds Reservoir and Kiowa Creek (CSU, 1960).

Application of artificial recharge in Colorado blossomed in the 1980s following the drought of 1977 as farmers in the South Platte River Basin and the San Luis Valley realized that artificial recharge could be used to restore water levels in the near-surface aquifers as well as to manage timing of available surface-water supplies with high demands during crop growing seasons. Recently, artificial recharge is being developed in the Denver Basin by several municipal water districts for long-term storage. An in-depth discussion of artificial recharge projects in Colorado is presented in Section VI.

II. Definitions of Recharge

The original source of ground water is precipitation (rain, hail, or snow). *Natural recharge* occurs when precipitation percolates into the ground and reaches the water table. Natural recharge rates in Colorado are highly variable, with only 0-12 percent of precipitation contributing to recharge of long-term ground-water storage. *Enhanced recharge* has historically consisted of vegetation management, where deep-rooted, water-loving vegetation is replaced by shallow-rooted water-conserving vegetation or bare soil. Enhanced recharge can also be achieved by routing storm-water runoff from urban areas to designed infiltration facilities. *Induced recharge* is created by the pumping of alluvial wells adjacent to streams and rivers. Decreased water tables around the wells increase flow to the alluvial aquifer through the riverbed and stream banks. *Incidental recharge* is the unintentional recharge of ground water including return flows from septic-tank leach fields and deep percolation from irrigation. The reduction in evapotranspiration and increased runoff resulting from urbanization (more land surface covered by impermeable materials) may also be considered incidental recharge in circumstances where that water flows to natural surfaces or ephemeral streams. Various types of recharge and underground water storage are illustrated in **Figure II-1**.

Artificial recharge, aquifer storage and recovery, and underground water storage are terms that are central to the topics of this study. The definitions of these terms as used in this report are:

Artificial Recharge (AR): Engineered or designed systems that put water on, or in, the ground for the purpose of infiltration and subsequent migration to underlying aquifers to augment ground-water resources. (the term “artificial” implies a mechanism other than natural meteoric ground-water formation)

Aquifer Storage and Recovery (ASR): ASR is a type of artificial recharge that focuses on the use of injection/pumping well systems to inject water directly into the receiving aquifer for future recovery at the same location.

Underground Water Storage: The storage of water beneath the ground surface in large caverns, voids, or mines in which hydraulic control can be maintained.

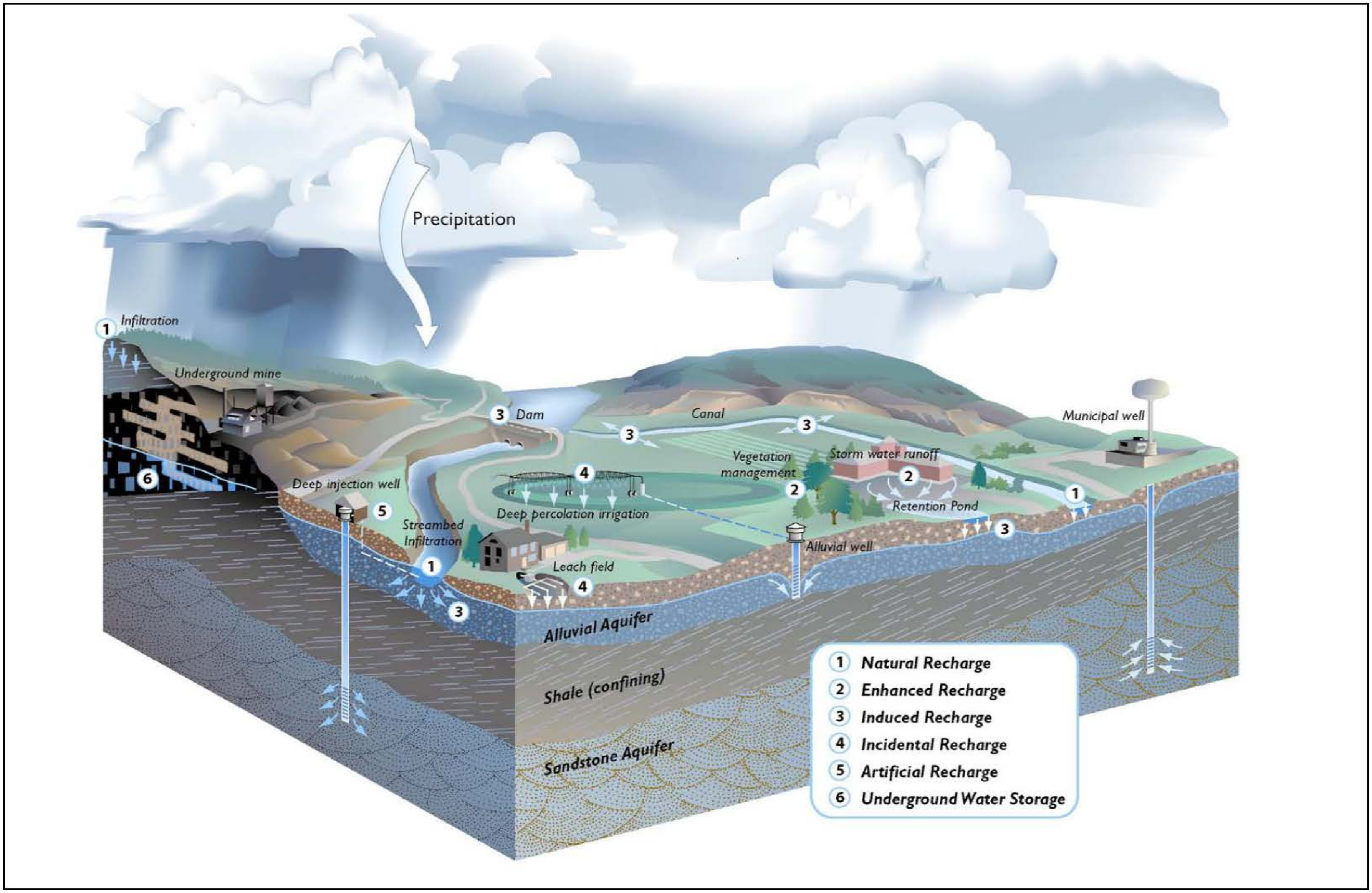


Figure II-1. Types of ground water recharge. Schematic block diagram illustrating examples of natural, enhanced, induced, and incidental recharge and water storage in man-made cavities.

III. Objectives of Artificial Recharge

Although the basic concept of AR is simple – purposefully filling void spaces in earth materials with water – the applications vary considerably depending on the objective. The applications are quite versatile given the many options of geologic environment, source of water, and intended use of the stored water. The intended use of the stored water is a primary consideration in the planning of AR facilities. The technology, location, design, permit requirements, and operation of an AR system are dependent upon the primary water management objective(s). Clearly defining the objectives of an AR project is a prerequisite to its initiation.

Most AR applications are for seasonal, long-term, or emergency storage of drinking water supplies. Recent interest in AR in Colorado evolved from several factors, including the 2002 drought, water supply security issues since 9/11/2001, limited ability to construct new surface-water reservoirs, the need for additional water supplies for new developments, documented declines in the potentiometric head of many aquifers, and legislative funding opportunities for new projects. In addition to storing water, AR projects can influence water quality, environmental impacts, water system operations and capital costs, ground-water levels, and agricultural water supplies.

The objectives of most AR applications fall into any one, or a combination of, the categories listed below and shown in **Figure III-1**. These categories have been compiled from literature and cover a wide spectrum of possible objectives, some of which may not apply to Colorado (e.g., mitigate saltwater intrusion). Furthermore, the categories listed below can overlap such that any given AR project may meet several objectives. For example, an AR application may be primarily designed for short-term, seasonal storage, but may also improve surface and/or ground-water quality. The potential for meeting multiple objectives demonstrates the versatility of AR.

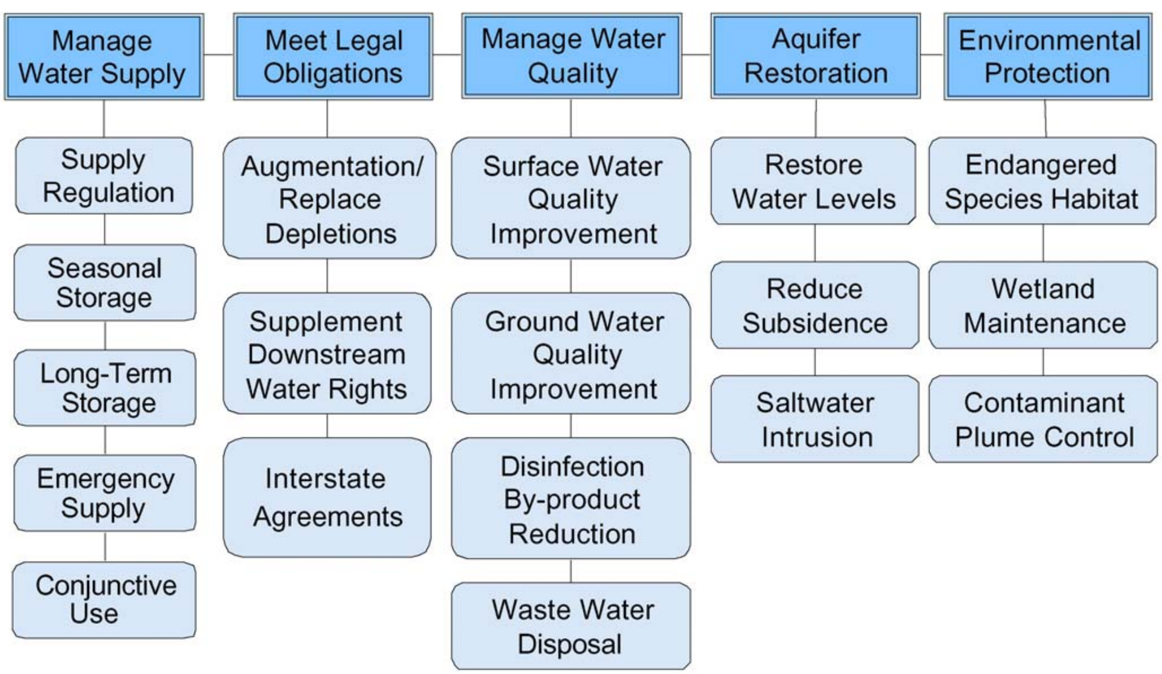


Figure III-1. Objectives of artificial recharge. Artificial recharge projects may meet one or more objectives including water supply management, meeting water delivery obligations, management of water quality, aquifer restoration, and environmental protection.

Manage Water Supply

AR is utilized as a component of water supply regardless of whether the water is used for municipal, agricultural, industrial, or other uses. The objectives can be further categorized as follows:

- *Water supply regulation* – Surface-water supplies are highly variable with discharge rates varying on a daily, weekly, monthly or seasonal basis. Ground-water availability is less variable and therefore, potentially more reliable as a water source. AR into an aquifer with subsequent extraction on a local basis evens out the variations of surface-water delivery systems.
- *Seasonal storage* – As a more advanced form of water supply regulation, water is recharged when surface-water supply is plentiful, and recovered later in the year when needed. **Figure III-2** illustrates the seasonal imbalance between springtime surface runoff supply and later water demand during the summer months. Seasonal storage can regulate water supply through the year.

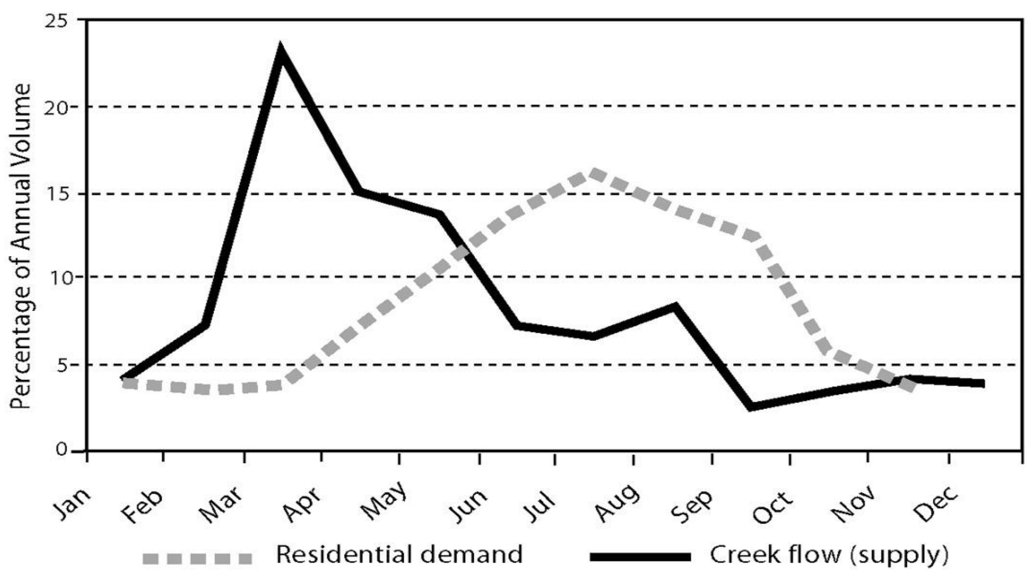
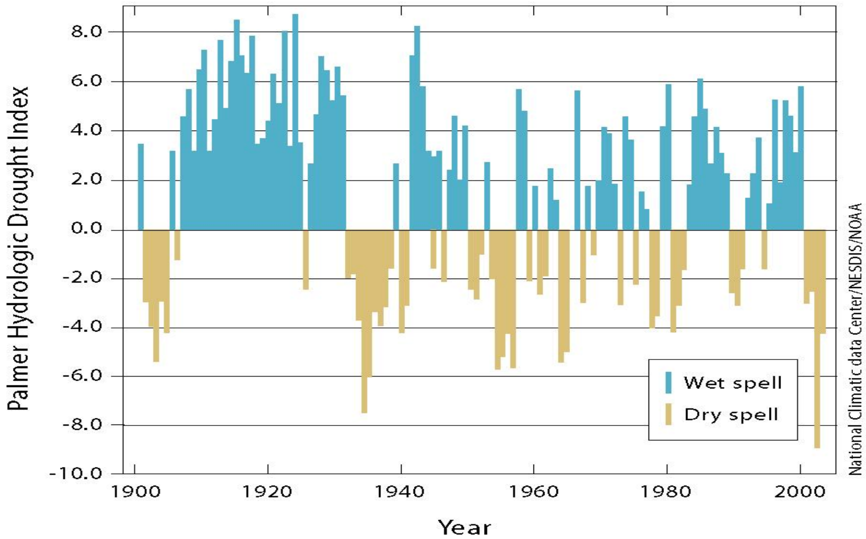


Figure III-2. Water supply and demand curves. Native water supply in the form of runoff typically peaks in the spring, yet demand doesn't peak until several months later when daily temperatures rise and water use, primarily for irrigation, increases. Water storage bridges the gap between the two peaks.

- *Long-term storage* – Water is stored, or "banked," during seasons or years of excess supply and is recovered during drought years. Drought is a part of the natural climatic cycle in Colorado. Periods of drought have been documented for the past century as shown in **Figure III-3**. The 2002 drought is estimated to have cost the Colorado economy over $1 billion (Byers, 2002).
- *Emergency supply* – Water is stored to provide a strategic reserve in response to warfare or natural disaster.
- *Conjunctive use* – This practice integrates the use of both surface and ground water to meet demands. When plentiful, surface water is the primary source while ground water is used when surface-water supplies dwindle. AR may or may not be used as a part of conjunctive use.



<u>Figure III-3.</u> Colorado Palmer hydrologic drought index graph. Colorado's weather cycles between wet periods (positive numbers, up) and dry periods (negative numbers, down) as shown in this drought index graph. The length of the negative bar for year 2002 illustrates the severity of the current drought cycle.

<u>Meet Legal Obligations</u>

A water user may be required to meet a number of legal obligations for release of water in order to hold a water right. These legal obligations generally fall into the following categories:

- *Augmentation* – This replaces depletions to surface-water or tributary ground-water systems. Within the priority system under which tributary ground water is administered in Colorado, it is possible to use water when a water right is out of priority, providing that the depletion to the surface-water source is offset with another source. AR can be used as part of an augmentation plan whereby water is recharged when there is excess water available. The location of the recharge is selected such that the travel time through the aquifer replaces the depletion to the stream at the time that the water is needed by the other holders of water rights. **Figure III-4** depicts how AR may be utilized to replace tributary depletions.
- *Supplementing downstream water rights* – AR can provide a supplemental source of baseflow to a stream to meet either consumptive or non-consumptive uses downstream such as maintaining minimum in-stream flow conditions. In a sense, this is a subset of serving as part of an augmentation plan, however, in this case the downstream needs include non-traditional, non-consumptive uses such as maintaining aquatic habitat or providing recreational opportunities.
- *Interstate agreements* –AR can be utilized for water storage to help manage surface-water resources in such a way that timing of flows may facilitate compliance with interstate agreements.

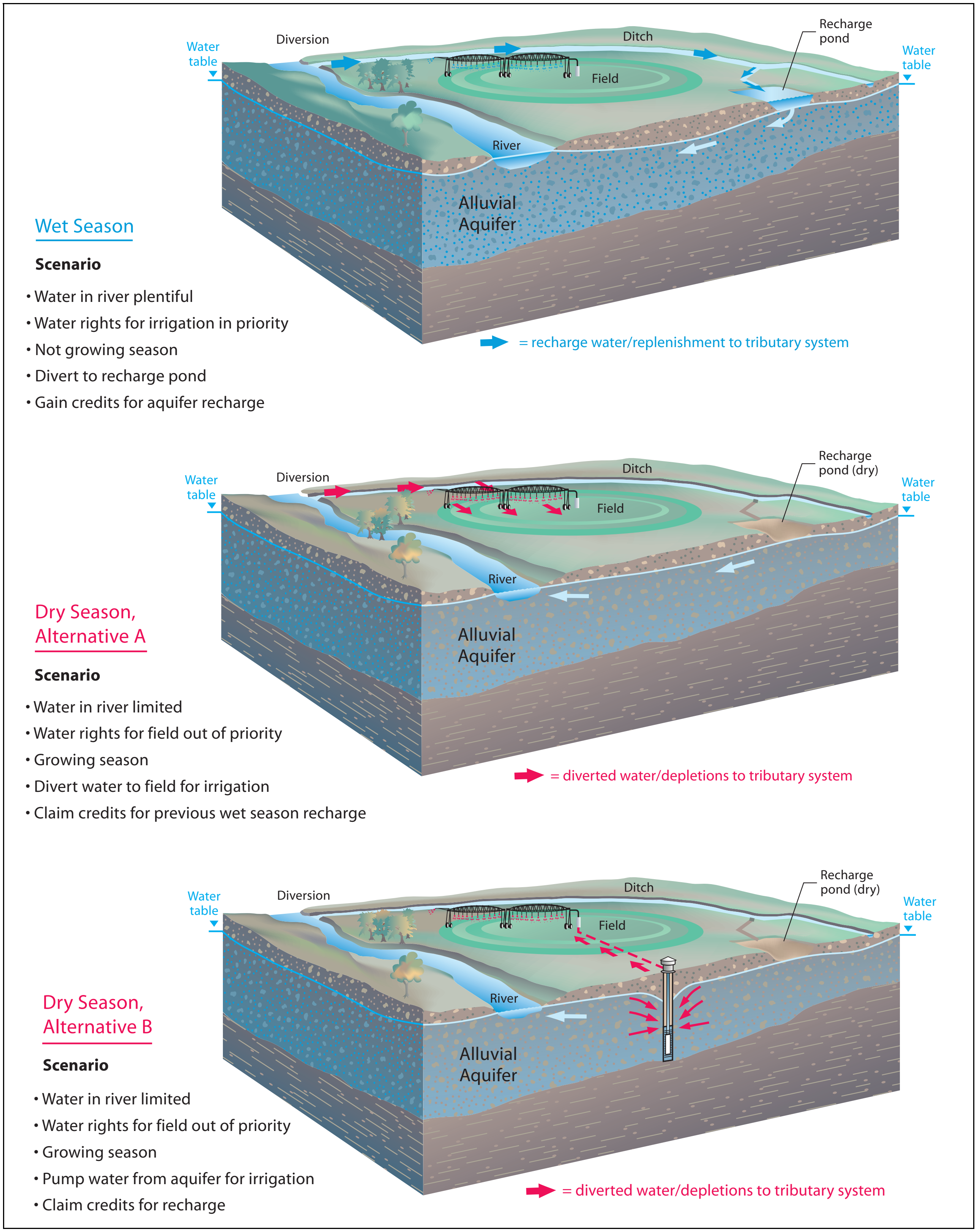


Figure III-4. Artificial recharge as augmentation for tributary ground water. During the wet season, water is diverted in-priority for artificial recharge (upper block diagram). Water continues to be diverted later in the dry season (Alternative A or B), this time for irrigation, even if the junior water rights are out of priority. Augmentation credits from the artificial recharge allow for continuing diversions.

Manage/Mitigate Water Quality

Physical, chemical, and biological processes in an aquifer have the potential for modifying water quality. AR can take advantage of these natural processes, through soil/aquifer treatment (**Figure III-5**), to improve water quality of the water supply in the following situations:

- *Improvement of surface-water quality* – AR can be used when surface water requires a level of treatment prior to utilization. Bacterial digestion and physical-chemical processes (geo-purification) in an aquifer can act as a natural treatment facility. Surface water may contain high levels of suspended or dissolved solids that must be removed before the water can be placed to beneficial use. AR mitigation is accomplished by capturing the runoff for recharge infiltration and geo-purification through an aquifer. The water is then recovered from the aquifer some distance away from the active channel through wells or infiltration galleries and put to beneficial use.

- *Improvement of ground-water quality* – AR can be used to improve ground-water quality. High quality surface water can be recharged to an aquifer where the ambient ground-water quality is impaired by naturally occurring dissolved solids, producing a lens of higher quality water. Recovered water is of higher quality than the ambient ground water.

- *Disinfection byproducts (DBP) reduction* – Chlorination of water can produce elevated concentrations of DBP's (trihalomethane compounds: chloroform, bromoform, dichlorobromomethane, and dibromochloromethane). Treated drinking water can be used as the source water for AR. Dilution and geo-purification in the aquifer will reduce the DBP concentrations in the recovered water.

- *Wastewater disposal* – In this situation, treated wastewater is allowed to infiltrate as an alternative to discharging to surface water. This option typically requires less treatment, therefore less expense for wastewater disposal.

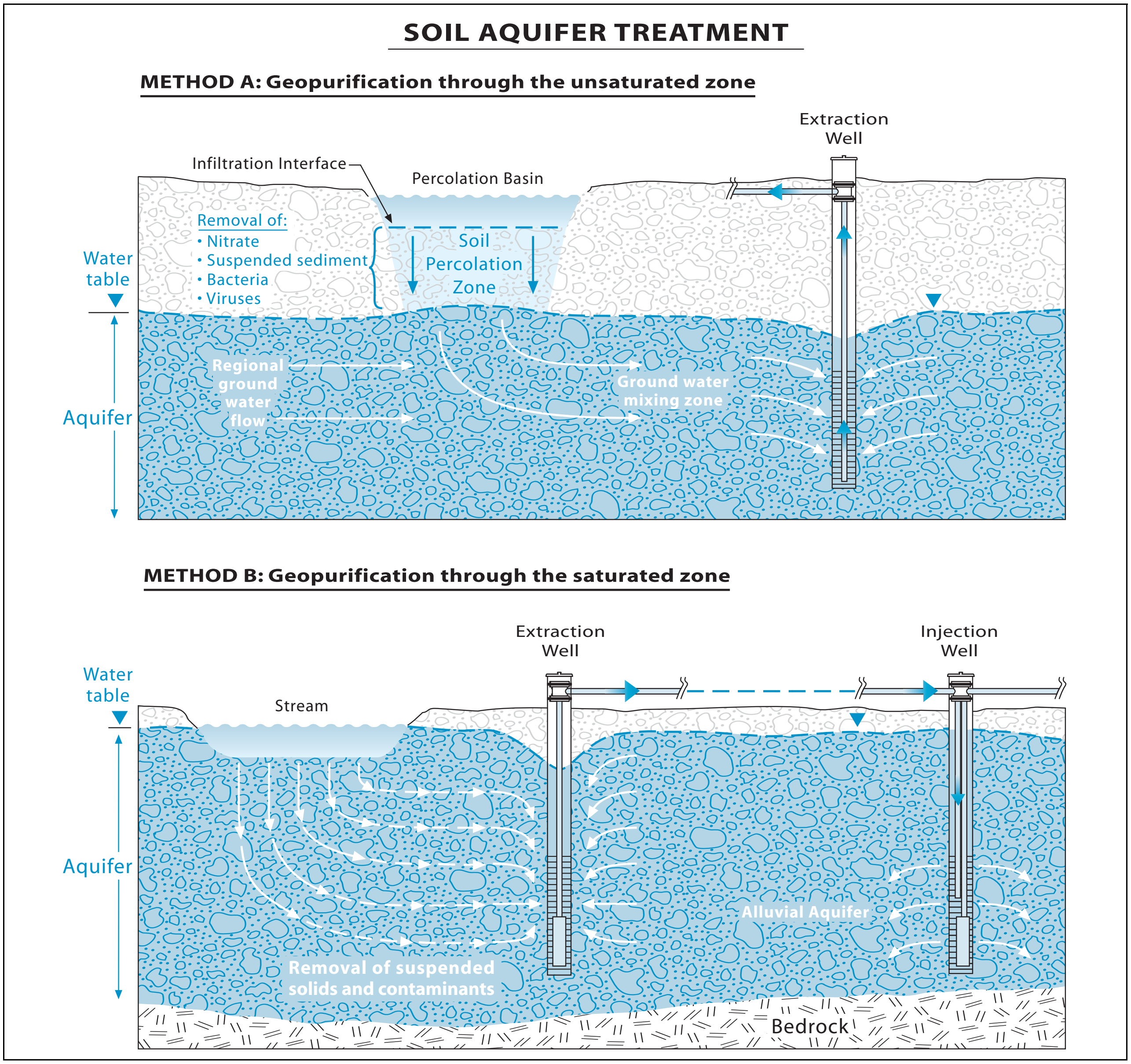


Figure III-5. **Schematic diagram illustrating two mechanisms of soil aquifer treatment. As water moves through the unsaturated or saturated portions of the subsurface, it is subjected to physical, chemical, and biological treatment process termed geopurification.**

Restore/Protect Aquifers

Unless mitigated, excessive ground-water extraction can decrease the usefulness of an aquifer over time due to water-level declines. AR can maintain the long-term viability of an aquifer:

- *Restoring ground-water levels* – Recharging more water than is recovered can reverse, or stabilize, water-level declines. The primary result of ground-water extraction at rates exceeding natural recharge is widespread water-level decline in the aquifer. AR can reverse or stabilize this trend. **Figure III-6a thru c** compares the hydrographs of an ASR well, observation well, and nearby production well in the Denver Basin where a regional water-level decline is evident. Frequent recharge cycles at the injection well offset the regional decline trend.

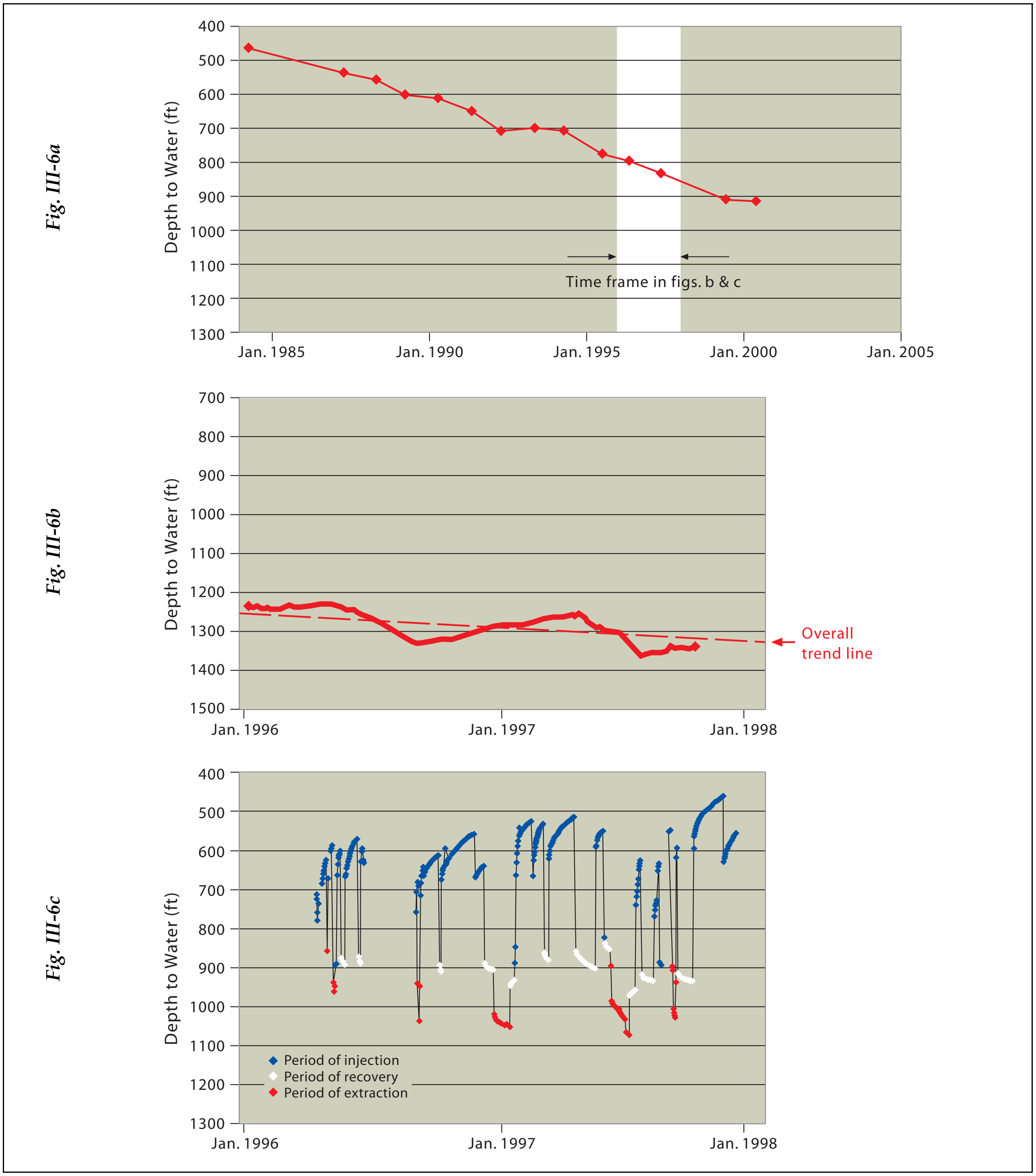


Figure III-6. Denver Basin hydrographs and ASR operation.

Fig. III-6a **A typical hydrograph from an Arapahoe Aquifer well in the Highlands Ranch area illustrate a regional water level decline of approximately 30 feet per year; over a 16-year period.**

Fig. III-6b A seasonal cycle overprints the regional trend, where water levels fall through the summer as the aquifer is stressed by pumping from nearby wells, and rise in the winter when nearby pumping decreases.

Fig. III-6c is from an active ASR well operated by the Centennial Water and Sanitation District that shows cycles of water injection (blue points), extraction (red points), and recovery (white points). A projection of the recovery cycles (white) suggests that, locally, the rate of water level decline is less than the regional rate, possibly due to the aquifer restoration benefit of artificial recharge.

- *Reducing subsidence* – Restoration of ground-water levels can reduce or mitigate subsidence that occurs due to water-level declines. Declining water levels can cause compaction within the aquifer and subsequent land subsidence at the surface.

- *Mitigating saltwater intrusion* – Injection of fresh water is commonly used to halt the advance of a saltwater intrusion front. Where saline or brackish water is present in a fresh water aquifer, withdrawal of fresh water through production wells can cause the saline water to encroach into the fresh water zone of that aquifer.

Protection of the Environment

As a water management tool, AR can also be used to benefit sensitive environments or mitigate environmental contamination as follows:

- *Protect endangered species habitat* – AR projects within tributary alluvial aquifers provide for recharge return flows that may be timed to augment stream flow during low-flow months, thereby maintaining minimum water levels to protect aquatic and terrestrial ecosystems.

- *Maintain wetland hydrology* – Maintenance of water levels through AR can help protect sensitive wetlands. Ground-water conditions are an integral factor in wetland viability and AR can be used to increase ground-water discharge rates to a wetland. AR can also help maintain a supply of water to a wetland throughout the season necessary to sustain plant and animal communities vital to the system.

- *Control migration of ground-water contamination* – Injection or recovery wells may be used to maintain hydraulic control in an aquifer threatened by movement of contamination plumes.

IV. Technologies for Artificial Recharge

AR technologies vary considerably, and their application depends on the hydrogeologic setting of the target aquifer and the objectives of the particular application. Hydrogeologic characteristics critical to determining an appropriate technology include (1) depth to the top of the aquifer; (2) depth to water; (3) the stratigraphic layering above and within the aquifer; and (4) the areal extent of the aquifer. These characteristics determine whether surface or subsurface techniques can be implemented. Other considerations influencing the choice of available technologies include surface topography and land uses. Aspects of the project objectives pertinent to selecting a technology include (1) the volume of water to be recharged, (2) the anticipated rate of recharge, (3) the ultimate fate of the water, and (4) the nature of the source water.

The technologies are broadly grouped according to whether water is recharged at the surface or underground and then by whether water is recharged into the unsaturated zone (vadose zone) or directly into the saturated zone of the aquifer. Recharge facilities at the surface can be very simple and can require minimal effort and cost to install and maintain. Conversely, recharge facilities underground usually require more sophisticated design and can be more costly. The following are brief descriptions of the technologies currently being used in AR projects.

Surface Infiltration

Surface infiltration is simply the impoundment of water at the ground surface to allow it to soak into the underlying near-surface, unconfined aquifer. Surface-infiltration recharge systems are suitable for unconfined aquifers where water levels are relatively shallow and impermeable layers are absent between the ground surface and the base of the aquifer. Receiving aquifers typically have relatively high transmissivities to accommodate lateral flow away from the recharge area and thus prevent the formation of high ground-water mounds.

Varying in shape from symmetrical ponds to long linear ditches, and in size from several acres to several hundred acres, surface infiltration design is highly dependant on surface conditions. Structures can be entirely constructed on flat land or can take advantage of natural topography. Surface infiltration systems may cover large areas, but can be relatively simple to construct. The structures can coexist with other uses such as recreation and wildlife habitat, but compatibility with adjoining land use is an important consideration. As in surface-water reservoirs, evaporative losses must be considered.

The general types of surface infiltration structures, illustrated in **Figure IV-1,** are described below.

- *Infiltration ponds and spreading basins* – Circular or rectilinear structures into which water is directed and allowed to infiltrate through the bottom. These may be constructed above grade or excavated below grade and often take advantage of existing excavations such as gravel pits or water storage reservoirs that naturally leak. Terminology typically refers to small structures as infiltration *ponds* or *basins* and larger scale structures as *spreading basins.*

- *Infiltration ditches* –Water is directed into linear structures and allowed to infiltrate through the bottom. Often, these take advantage of existing water conveyance ditches and canals that naturally leak. They can be adapted to topographic conditions that prohibit large infiltration ponds and basins.

- *Stream channels* – Water is directed to natural ephemeral or perennial streams . Dry stream channels may require little modification in situations where the channel morphology and highly permeable streambed material allow for rapid infiltration. This method may also involve construction of dams or low weirs across the channel to back the water up and increase the wetted surface area of the streambed or floodplain, providing a larger area for infiltration into the ground.

- *Playa lakes* –These ephemeral lakes are natural topographic depressions where water is directed for recharge. Surface modification may be required to increase lakebed permeability.

- *Land application* – This involves over-irrigation of fields at rates at which excess soil moisture infiltrates down to the underlying aquifer.

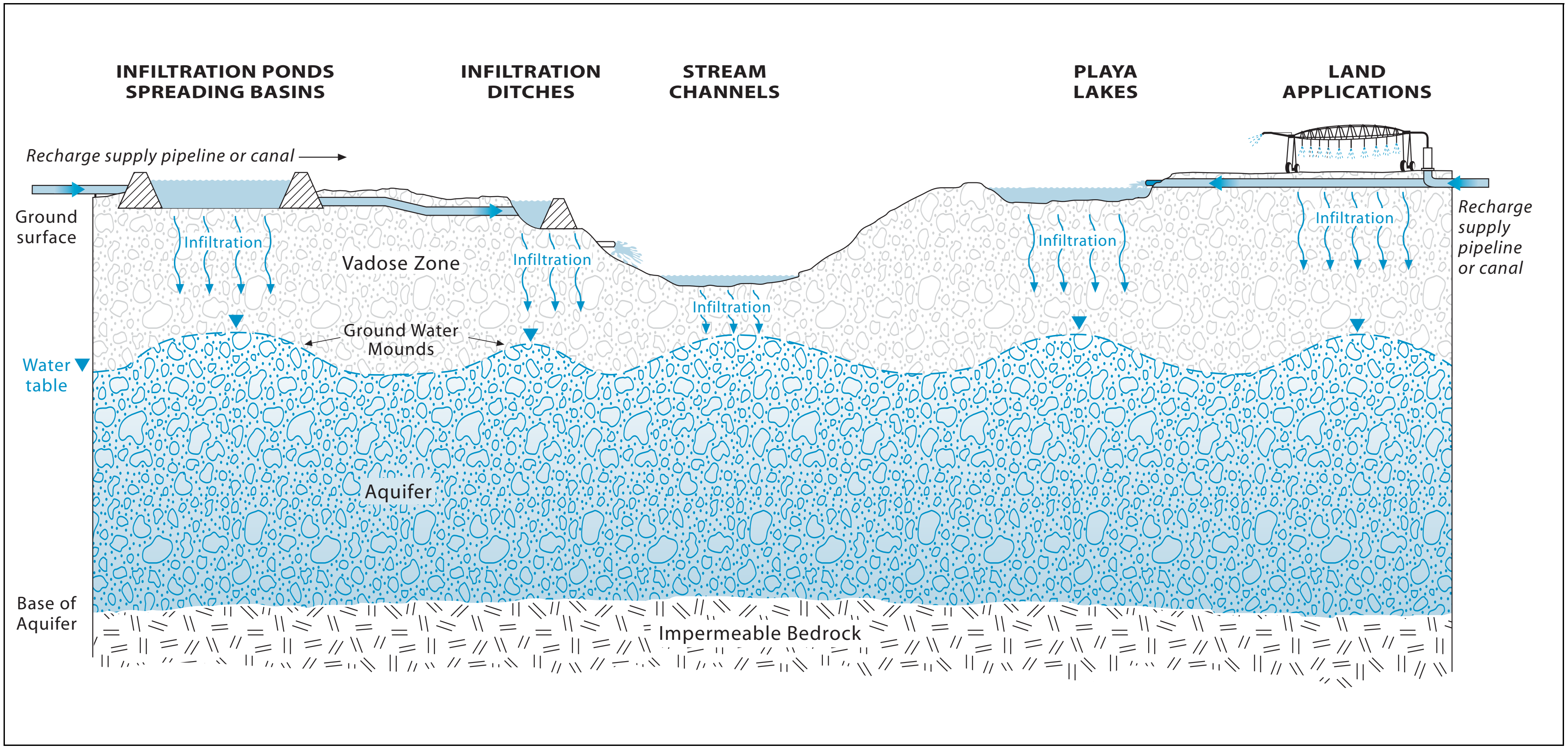


Figure IV-1. **Examples of surface infiltration technologies. Water for recharge is applied at the surface above an unconfined aquifer in man-made or natural depressions to infiltrate down to the underlying water table ultimately causing the water table to rise. This application requires high vertical permeabilities and the absence of impeding layers.**

Subsurface Infiltration

Subsurface infiltration is the application of water below ground surface for infiltration to the underlying unconfined aquifer. Subsurface infiltration recharge systems are utilized for unconfined aquifers where surface conditions, such as impermeable layers or incompatible land uses, preclude surface infiltration. These technologies reduce evaporation losses and can coexist with other land uses such as parking lots or recreational fields; however, they are more limited in size. The costs for installation and O&M can be much higher than for surface infiltration systems because these systems require more sophisticated design and installation procedures and have limited access for maintenance.

The general types of subsurface infiltration structures, illustrated in **Figure IV-2,** are described below.

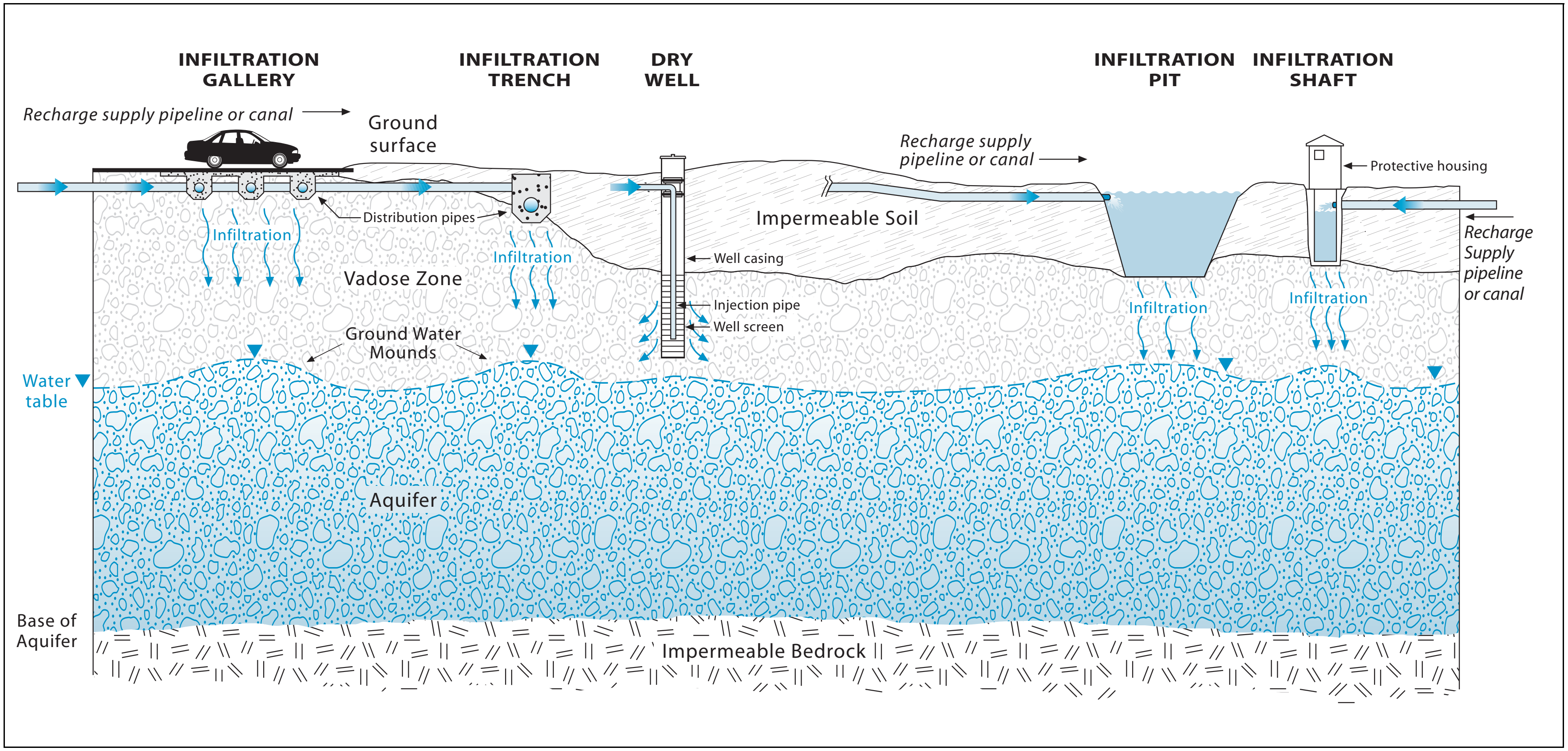
- *Infiltration trenches* –Excavated ditches are equipped with a perforated pipe embedded in gravel. Trenches are excavated through impermeable soils into the top of the aquifer. The land surface can be covered and contoured to accommodate other land uses such as play fields, parking lots, etc.

- *Infiltration galleries* – Similar to infiltration trenches, but these consist of arrays of multiple pipes.

- *Dry wells* –Wells that are installed above the water table in the unsaturated zone of the aquifer. These are often used where water levels are deep and shallow wells reduce costs as compared to completing a recharge well into the saturated zone of the aquifer.

- *Infiltration shafts* – Excavations are made through impermeable layers into the unsaturated zone of the aquifer. These are larger diameter than a dry well and may be cased or lined to maintain hole stability.

- *Infiltration pits* – Made similarly to an infiltration shaft but has a larger diameter. This method could be classified as surface infiltration except that the application is generally used to penetrate through soils of lower permeability.



<u>Figure IV-2.</u> Examples of subsurface infiltration technologies. Water for recharge is applied beneath the land surface but above an unconfined aquifer where conditions preclude surface infiltration techniques. This type of application can be utilized where surface, or near-surface, materials have low permeability or where other land uses are not compatible with surface infiltration facilities.

Direct Injection

Direct injection differs from infiltration systems by recharging water directly into the saturated zone of the confined or unconfined aquifer. Direct injection is accomplished through a well in situations where the target aquifer is deep, confined, or contains impermeable layers. Injection well design styles vary with hydrogeological conditions and operation modes. Operational modes also vary depending on project objectives. Wells may be used solely as injection wells with the water extracted at remote locations, or the wells can serve for both injection and extraction in an aquifer storage and recovery (ASR) application. The wells occupy very little land surface area and can be compatible with nearly any type of existing land use. The technology can also take advantage of existing water supply infrastructure, however, initial design, installation, and O&M can be costly relative to infiltration recharge systems. Source water must be of the highest quality and underground injection permitting is required. Since there is no evaporation, losses are limited to the small quantities of water pumped during routine well maintenance.

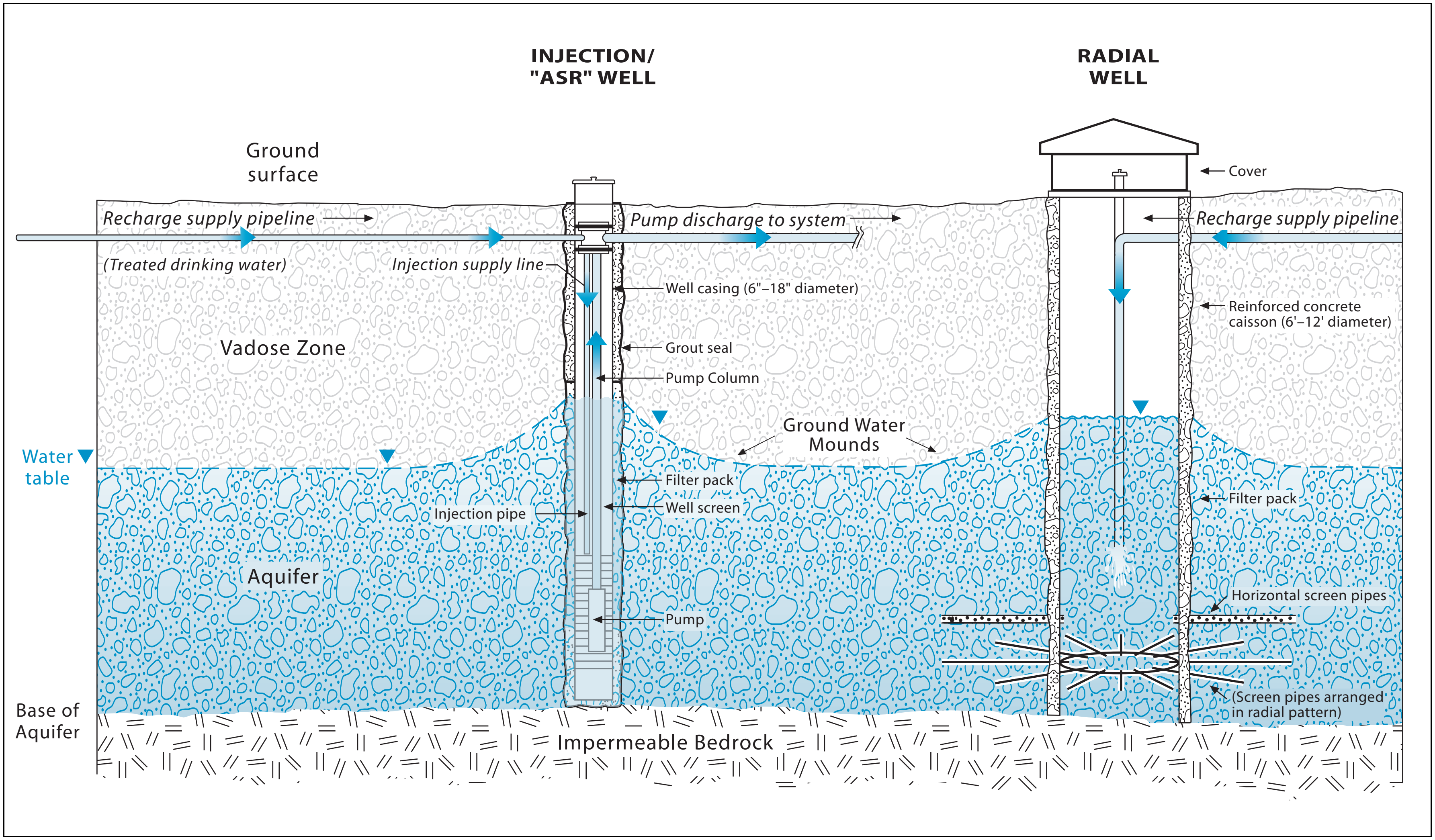
Injection well applications, shown in **Figure IV-3** for an unconfined aquifer and **IV-4** for a confined aquifer, are described below.

- *Injection well* – A well is completed in the saturated portion of an aquifer whether it be unconfined or confined. Water is injected into the well casing through an injection pipe, and the resulting head buildup causes the recharge water to flow out of the well screens into the surrounding aquifer.

- *ASR well* – ASR wells function as dual-purpose wells in which recharge and recovery from the aquifer occurs within a single well boring. Water is injected for *storage* to be *recovered* at a later date, hence the term aquifer storage and recovery (ASR) well. Injection may be through a separate injection pipe, or through the pump column equipped with a special down-hole flow control valve. Installed well pumps not only enable recovery of stored water, but also allow periodic cycling to redevelop the wells, thus maintaining their injection capacity. ASR wells have proven to be cost-effective, and can be readily implemented within existing water utility facilities using well fields.

- *Radial well* – This is a large-diameter, cased borehole installed into the saturated zone of an aquifer with screened pipes extending horizontally away from the casing some distance into the aquifer. These installations potentially increase the surface area open to the aquifer as well as the radius of influence of a well allowing higher injection or extraction rates than a traditional well.

- *Horizontal/directional well* – This technology is relatively unproven for water supply applications. A well is installed such that it approaches a horizontal orientation at depth. The technology allows for longer screened intervals and, in theory, higher well yields than a traditional vertical well installation, particularly in thinly bedded aquifers.



<u>Figure IV-3.</u> **Direct injection in an unconfined aquifer. Water for recharge is injected through a well directly into the saturated aquifer raising the water table in a conical mound around the well. The well can also be used for recovery of the injected water as an ASR well. Injection can use a dedicated injection pipe or the pump column equipped with a down-hole flow control valve. A radial well increases the radius of influence of the well through a series of horizontal feeder screened pipes arranged in a radial pattern around the well.**

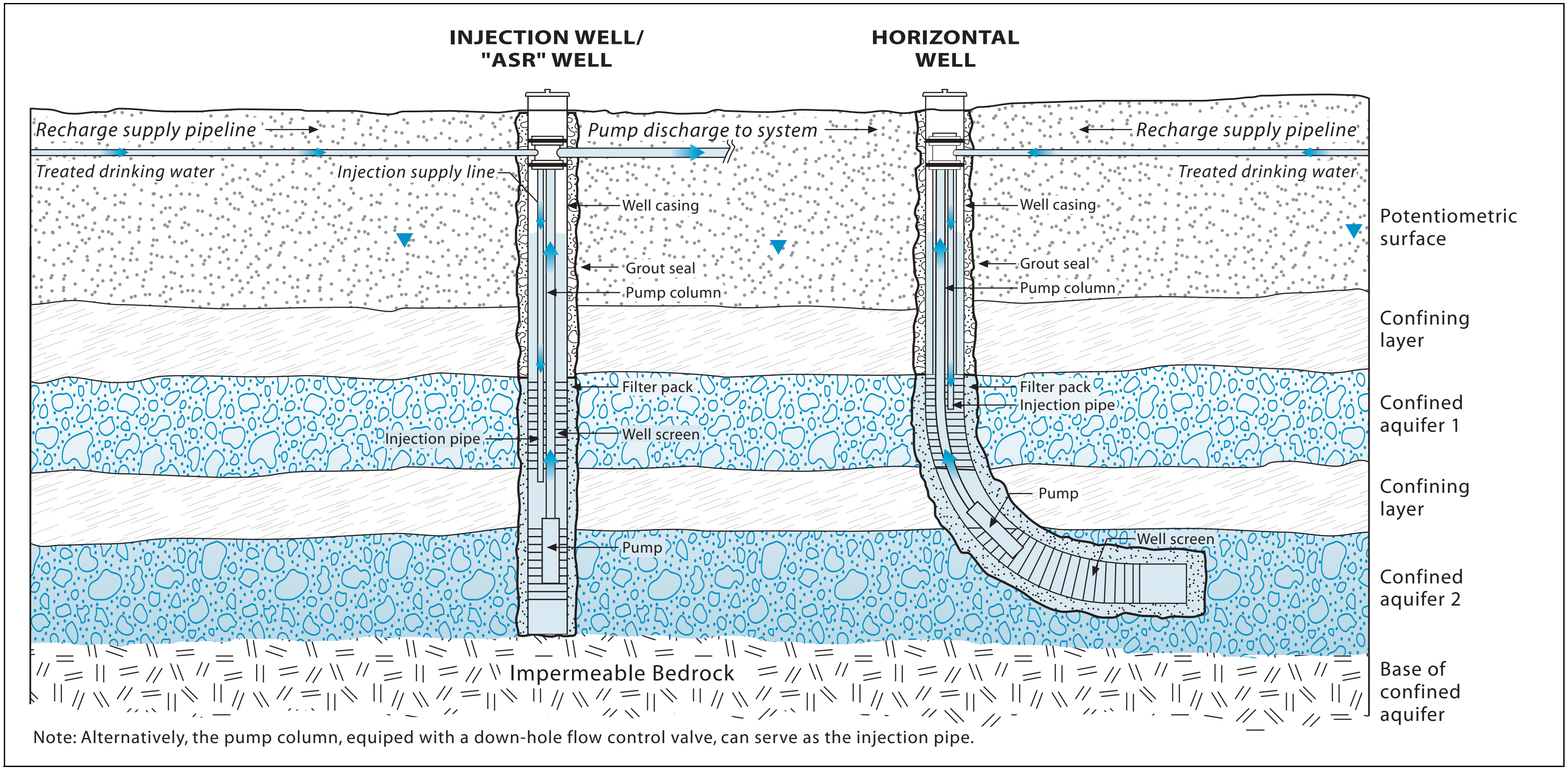


Figure IV-4. **Direct injection in a confined aquifer. Water for recharge is injected through a well directly into a confined aquifer raising the potentiometric surface around the well. The well can also be used for recovery of the injected water as an ASR well. Injection can use a dedicated injection pipe or the pump column equipped with a down-hole flow control valve. A horizontal well increases the area of the well open to the aquifer and can potentially increase well yields and/or injection rates.**

Modification of Natural Recharge

In addition to artificially recharging ground water with imported source water, natural recharge from a local source can be increased by *enhanced, induced, or incidental* means. Figure II-1 illustrates these various types of recharge. The natural outflow of ground water through an alluvial aquifer can also be modified to increase ground water in storage by installing ground-water dams in an aquifer.

- *Enhanced recharge* is commonly done through vegetation management, where deep-rooted water-loving vegetation is replaced by shallow-rooted water-conserving vegetation or bare soil. Enhanced recharge can also be achieved by routing storm-water runoff from urban areas to designed infiltration facilities.

- *Induced recharge* is created by pumping alluvial wells adjacent to streams and rivers. Increased gradients produced by pumping enhance flow through the streambed and banks.

- *Incidental recharge* –is the unintentional recharge of ground-water resources through leaks from water and wastewater storage and distribution structures; sewage disposal by septic-tank leach fields; and deep percolation from irrigation. The reduction in evapotranspiration and increased runoff resulting from urbanization (more land surface covered by impermeable materials) may also be considered incidental recharge where that water flows to native surfaces or ephemeral streams.

- *Ground-water dams* are structures that intercept or obstruct the natural flow of ground water in shallow alluvial aquifers. Ground-water dams are constructed by digging a trench down to bedrock across a valley and backfilling with low permeability materials.

Underground Water Storage Options

Underground water storage options include natural or manmade voids in the subsurface, such as abandoned mines or natural caverns. A critical aspect of underground water storage is being able to maintain hydraulic control of the injected water. Nationally, coal mines are currently being utilized for water storage with most of the active projects located in the Central Appalachia Coal Basin. Successful water storage deployment in coal mines is very dependent upon the hydrogeologic characteristics of the mine environment and surrounding host rock, and geochemical interactions that influence water quality. The city of Arvada is currently utilizing the abandoned mine workings at Leyden for underground water storage by direct injection. Other abandoned coal mines along the Front Range may also be suitable for storage purposes.

Inactive underground metal mines throughout Colorado may also represent potential water storage sites. Initial considerations in using inactive metal mines concern potential water quality degradation due to chemical reactions with host rock. Hydraulic control is also a significant consideration, as most metal-mining districts are in steep, mountainous terrain deeply dissected by streams. Significant costs would be incurred to seal the mines to maintain hydraulic control of injected water.

Like abandoned mines, natural cave systems consist of subsurface void space that may be suitable for underground water storage. Colorado contains a few hundred caves scattered throughout the mountainous western part of the state. Like mines, the ability to maintain hydraulic control of injected water in carbonate cave systems presents an engineering hurdle. Land ownership, environmental issues, and access to the cave systems are also critical considerations.

General AR Technology Design Considerations

Each type of AR technology comes with its own set of efficiency considerations, advantages, and disadvantages, as well as potential benefits that must be considered to make an informed system design. Considerations include (1) project objectives, (2) hydrogeologic conditions of the site, (3) source water considerations, (4) available land surface area and land-use patterns, (5) capital cost to construct, (6) operation and maintenance (O&M) costs, and (7) general storage efficiency issues such as evaporation losses. **Table IV-1** lists advantages and limitations of each technology and provides examples of applications in Colorado.

One of the most compelling advantages of incorporating AR in a water management plan is adaptability. AR can be installed in a phased manner that can translate to vastly reduced costs. Design can be modified as phases progress based on experience, advances in technology, and changes in objectives. This is in sharp contrast to many surface-water storage facilities that may need to be constructed for full capacity at completion.

Additional benefits of using AR as part of a water supply utility include the following:

- *Maximizing use of infrastructure during periods of low demand* – Water treatment and distribution systems are designed to meet peak demands. During periods of low demand, which often correspond to periods of high supply of the natural water resource, these infrastructure facilities are underutilized. The infrastructure can be utilized during periods of low demand to implement AR.

- *Enhance well-field production* – Implementation of AR and restoration of ground-water levels allows wells to produce at higher rates during peak demand months. The injection and recovery cycles in ASR wells can even increase well development for greater well efficiency.

- *System capital cost deferral* – Implementation of AR produces more efficient use of existing water system treatment and conveyance capacity throughout the year and life of the facility, which means that expansion of water facilities can be deferred and downsized with substantial cost savings.

- *Maintain distribution system pressure* – Recovery of stored water in conjunction with small elevated or ground storage tanks can alleviate seasonal low pressure issues during peak demand months.

- *Commercial/industrial temperature control* – Seasonal source water temperature variability can be mitigated by recovering and blending AR water to meet process temperature control requirements such as fish hatcheries or industrial cooling.

Table IV-1. Comparisons of Artificial Recharge Technologies

Technology	Description	Active Colorado Examples	Advantages	Limitations	Aquifer Suitability
Surface Infiltration (General comments apply to all technologies within this category)			• Initial low capital cost • Maintenance can be simple and low cost • Low O&M costs • Can use untreated surface water • Can co-exist with recreation use or wildlife habitat	• Require near-surface aquifer • Require permeable soil profile/high vertical permeability • Require frequent maintenance to prevent clogging • Evaporation losses can be high • Vulnerable to surface contamination • May be incompatible with nearby land uses	• Unconfined aquifers with surface exposure • Alluvium • Semi-consolidated sediments at outcrop • Highly fractured bedrock
➢ Infiltration Ponds and Basins, ➢ Spreading Basins	Engineered off-channel structures (rectilinear)	San Luis Valley	• Can adapt former gravel pits/quarries	• Can require large tracts of land	
➢ Leaky Ponds and Reservoirs	Allow existing structure to leak	Olds Reservoir	• Take advantage of existing structure	• Very site specific	
➢ Infiltration Ditches ➢ Ditch/Furrow	Engineered off-channel structures (linear)	None	• Adapt to irregular topography	• Very site specific	
➢ Leaky Ditches	Allow existing structure to leak	South Platte River Basin	• Take advantage of existing structure	• Very site specific	
➢ Dry Stream Channels	Divert flow into the natural channel of an ephemeral stream	Bijou Creek	• Take advantage of natural topographic feature	• Very site specific • Environmental concerns	
➢ Playa Lakes	Use natural depressions that catch water in wet cycles	Akron playa experiment	• Take advantage of natural topographic feature	• Very site specific • Require soil modification to break-up/remove native low permeability soils.	
➢ Land Application	Surface irrigation at rates that exceed crop consumptive use	None	• Combine with agricultural or recreational land use • Generate revenue from crops or recreational fees	• Require large tracts of land	

Table IV-1. Comparisons of Artificial Recharge Technologies (Cont'd)

Technology	Description	Active Colorado Examples	Advantages	Limitations	Aquifer Suitability
Subsurface Infiltration (General comments apply to all technologies within this category)			• Can be used where surface layers of low permeability preclude surface infiltration • Can co-exist with other surface urban uses such as parking lots and recreation facilities • Minimize evaporation losses	• Higher initial capital costs • Limited aerial extent • Difficult to clean/maintain • Dependent upon near-surface geology	• Unconfined aquifers • Alluvium • Semi-consolidated sediments at outcrop • Highly fractured bedrock
➢ Infiltration Trenches	Perforated pipe embedded in a gravel-filled ditch	None	• Compatible with urban land uses		
➢ Infiltration Galleries	Similar to trenches except in arrays	None	• Can cover larger areas		
➢ Dry Wells	Wells completed above the water table	None	• Can be used where space is limited		
➢ Infiltration Pits/Shafts	Large diameter bore or excavation to penetrate near-surface low permeability soils	None			

Table IV-1. Comparisons of Artificial Recharge Technologies (Cont'd)

Technology	Description	Active Colorado Examples	Advantages	Limitations	Aquifer Suitability
Direct Injection (General comments apply to all technologies within this category)			• Work where vertical permeability is limited • Occupy small surface areas • Can fit in with most land-use patterns • Can utilize existing water supply infrastructure	• Require pre-treatment to drinking water standards • Require tight control over source water quality • High capital costs, when existing infrastructure is not available • High energy requirements, high O & M costs • Require frequent pumping to remove clogging • Contamination from recharge would be difficult to remediate	• Unconfined aquifers with limited surface exposure • Confined aquifers • Deep alluvium • Sedimentary bedrock aquifers
➢ Injection Wells/ ASR Wells	Wells that are either used solely for injecting water (injection wells) or both injection and recovery (ASR wells)	Centennial Water District	• Can be used for deep aquifers • Low capital costs, when existing infrastructure is available		• All of above • Abandoned mines • Karst, caverns
➢ Radial Collection Wells (Raney Well)	Large diameter collector well with horizontal radial bores	None	• High infiltration rates from a single point	• High initial capital costs	• Unconsolidated aquifers
➢ Horizontal Wells	Small diameter well that deviates from vertical to horizontal with depth	None	• High infiltration rates from a single point	• High initial capital costs • Un-proven technology	• All of above

Table IV-1. Comparisons of Artificial Recharge Technologies (Cont'd)

Technology	Description	Active Colorado Examples	Advantages	Limitations	Aquifer Suitability
Other					
Detention Dams, Dikes and Weirs	Engineered structures in the channel of a stream to catch natural flow and enhance natural recharge	Indian Hills	• Low O & M costs	• Very site specific • Environmental concerns	• Unconfined aquifers with surface exposure • Alluvium • Semi-consolidated sediments at outcrop • Highly fractured bedrock
Ground-Water Dams	Structures in the aquifer that intercept or obstruct natural ground-water flow		• Do not necessarily require outside source of water • Low O & M costs • Low evaporation losses	• Site specific and limited to shallow aquifers with small cross-sectional areas. • High construction costs for larger, deeper aquifers.	• Unconfined aquifers with surface exposure • Alluvium
Adits/Shafts/Natural Openings	Allow water to flow into cavern or mine using open shaft	Leyden Coal Mine	• High recharge rates	• Vulnerability to contamination • Site specific	• Abandoned coal and metal mines, caverns • Karst • Caverns

V. Selected National and International Artificial Recharge Applications

Artificial recharge (AR) is being used in at least 32 states in the U.S. (**Figure V-1**) and at least 26 countries worldwide (**Figure V-2**). Methods used span the entire spectrum of known technologies, but the dominant methods are injection wells and infiltration basins. Currently, more than 60 aquifer storage and recovery (ASR) sites are in operation around the U.S. These projects range from a single well to networks of 30 wells, with recovery capacities ranging from 500,000 gallons per day from single wells to 100 million gallons per day (mgd) from well fields (Tampa Water Dept., 2003). The larger scale projects are generally located in drier areas of the U.S. (i.e., the west and southwest), or areas in which the growing population has overtaxed the available water supply (e.g., California, Florida, New Jersey, New York). The following section provides brief descriptions of some of the higher profile projects in the U.S. and around the globe.

NATIONAL PROJECTS

High Plains Aquifer System

The High Plains Aquifer system forms one of the largest and most important ground-water resources in the United States, supplying agriculture as well as municipal water providers in the states of South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, Texas, and New Mexico. Comprised of late Tertiary sediments, the aquifer covers approximately 156,000 square miles and includes a number of recognized geologic units. The Pliocene Ogallala Formation is the most widespread and commonly recognized geologic unit within the High Plains Aquifer and consists of quartz-rich sand, silt and gravel in varying degrees of consolidation.

Withdrawal of ground water from the Ogallala on a large-scale basis began in the 1930s predominantly for agricultural purposes (Robertson, 2003). By the 1980s, about 16 million acres, more than 20 percent of the nation's irrigated land, were watered from the Ogallala Aquifer (Longenbaugh and others, 1984). Municipal and industrial use occurs to a lesser degree. High salinity often makes the resource undesirable for drinking water. The aggressive ground-water withdrawal has caused a decline in the water table, producing concerns that the resource might be locally depleted in a few decades.

Among the many recharge projects undertaken in the High Plains within the Ogallala Aquifer have been: the Holcomb Irrigation Farm operated by Kansas State University; the investigation in Wet Walnut Creek Valley in Rush County, Kansas; tests in Scott County, Kansas conducted by USGS and Western Kansas Groundwater Management District No.1 (Gillespie and Slagle, 1972; Gillespie and others, 1977; Stullken, 1988). In Texas, the USGS has partnered with Texas Tech on recharge projects near Lubbock and Wolfforth, and has worked with the Agricultural Research Service on projects near Hereford and in Hale County (Brown and Keys, 1985). In Nebraska, which contains the largest area underlain by the Ogallala, the Upper Big Blue Natural Resources District, with funding from the U.S. Bureau of Reclamation, conducted a recharge project near York in the southeastern part of the state (Western States Water Council, 1998).

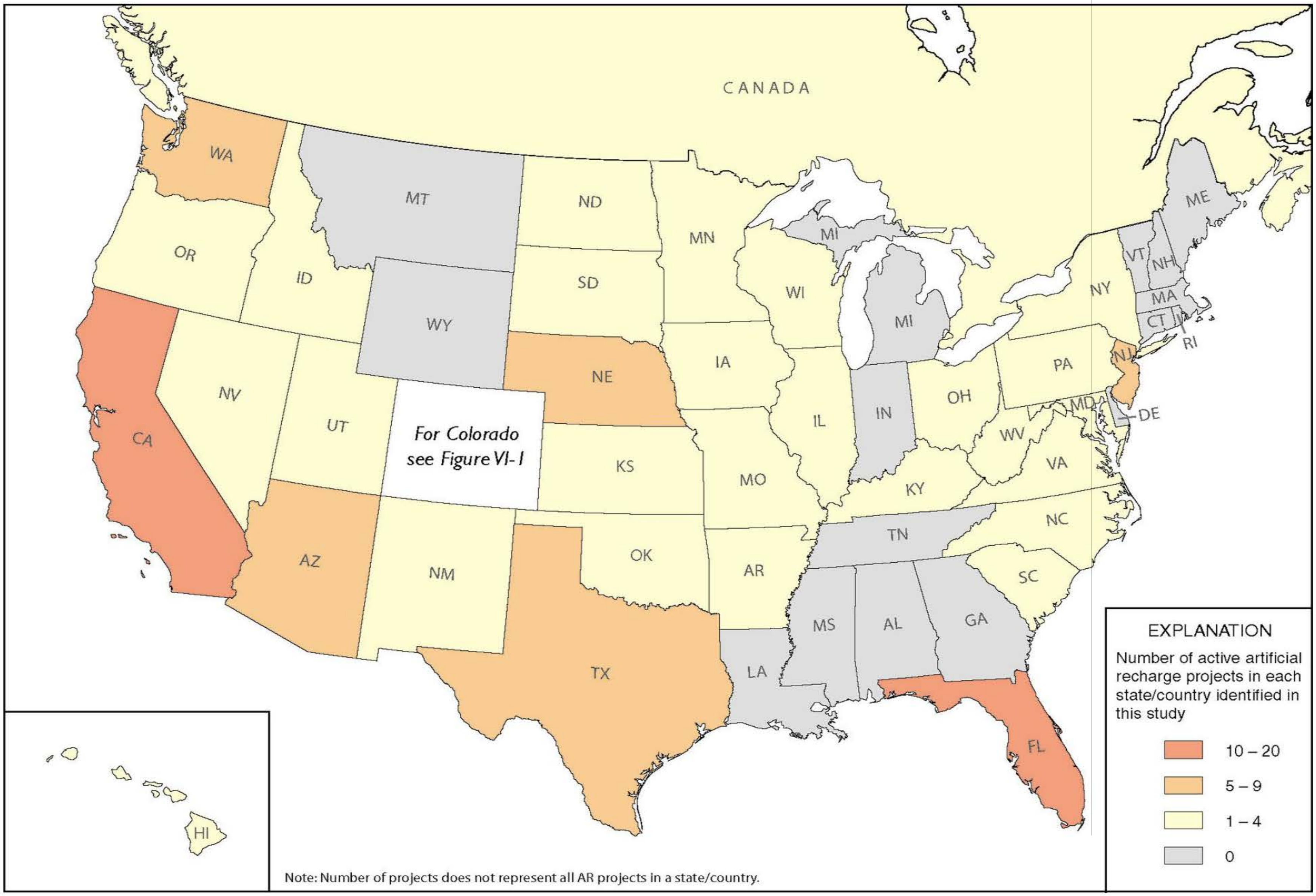
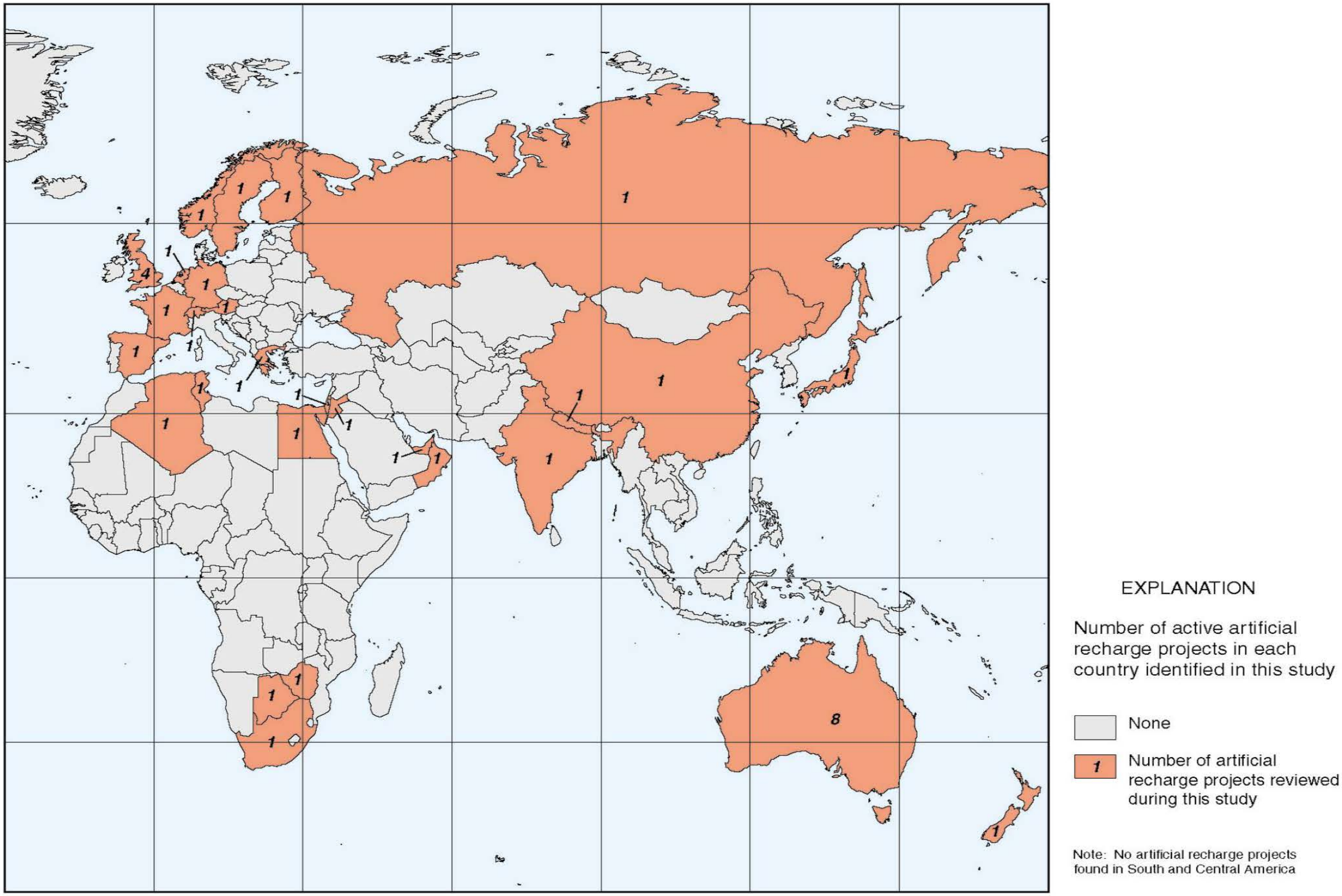


Figure V-1. Artificial recharge is being implemented in at least 32 states in the U.S. and in Canada.



<u>Figure V-2.</u> At a minimum, 26 countries worldwide use artificial recharge with injection wells and infiltration basins dominating the technology.

California

The AR of ground water in California dates back to the late 1800s (Calif. Dept. of Water Resources, 2003). Recharge of alluvial aquifers with storm water runoff through use of spreading basins began in the early 1900s, and was a widespread practice by the 1930s (Weeks, 2002). The original California Water Plan, completed by the Department of Water Resources in 1957, contained provisions for importation of water from northern California and storage in the southern California subsurface through AR.

Central Coast Hydrologic Region

Although several large aquifer recharge projects have been implemented as water supply projects, many smaller projects were implemented to mitigate saltwater intrusion and land subsidence. Several reservoirs including Hernandez, Twitchell, Lake San Antonio, and Lake Nacimiento are operated primarily for the purpose of ground water recharge.

South Coast Hydrologic Region

At present, approximately 2 million acre-feet (ac-ft) per year of potable water used in Southern California are imported from the Colorado River and from sources in the eastern Sierra Nevada Mountains and Northern California. Though reservoirs are the primary storage mechanism, management objectives include recharge of ground-water basins from the outflow of some reservoirs to maintain streamflow over a longer period of time and thus provide for increased recharge of ground water through streambed infiltration. Recharge is also used to maintain seawater intrusion barriers along the Los Angeles and Orange County sections of the coastal plain.

Tulare Lake Hydrologic Region (Southern Central Valley)

The cities of Fresno, Bakersfield and Visalia have ground-water recharge programs to ensure that ground water will continue to be a viable water supply in the future. Extensive ground-water recharge programs are also in place in the south valley, especially Kern County, where water districts have recharged several million acre-feet since the early 1950s for future use and transfer through water-banking programs (Balch and Jans, 1957).

South Lahontan Hydrologic Region (Owens Valley and Mojave Desert)

Conjunctive use of surface water and ground water is practiced in the more heavily pumped basins. Some of the water imported from Northern California by the State Water Project is used to recharge ground water in the Mojave River Valley basins.

Colorado River Hydrologic Region

Conjunctive use of surface water and ground water is a long-standing practice in the region. The concept of utilizing ground-water basins in this sparsely populated region for storing water that is available during periods of drought is getting much attention. By example, the Hayfield Ground Water Storage Project, consisting of 390 acres of spreading basins and 40 extraction wells, will eventually store 800,000 acre-feet of Colorado River Aqueduct water and will yield 150,000 acre-feet annually.

Arizona

Municipalities and special districts manage most of the recharge projects in Arizona with some projects partially managed and/or funded by the Bureau of Reclamation. Recharge is focused on unconsolidated to semi-consolidated basin-fill aquifers. The primary recharge objectives include stabilizing ground-water levels to reduce subsidence impacts and to store Arizona's excess Colorado River allotment. Recharge occurs primarily by injection and infiltration, with volumes ranging from approximately 3500 to 200,000 ac-ft per year.

The Granite Reef Underground Storage Project (GRUSP) has used four infiltration basins to recharge 194,000 ac-ft per year since 1994. The source water is conveyed via the Central Arizona Project Aqueduct. The Vidler Recharge Project, slated to become operational this year, proposes to recharge 100,000 ac-ft per year of Central Arizona Project water. The city of Tucson artificially recharges a small quantity of treated wastewater and uses it for irrigation.

Florida

Florida has 13 operating ASR projects using a total of 43 injection wells, most of which are located in the southern half of the state (ASR Forum, 2004). In the Orlando area, a relatively impervious surface geologic formation retards natural recharge to the underlying limestone. Due to the lack of adequate surface drainage, a network of wells were drilled into the limestone in the 1940s to act as surface drains thereby recharging the underlying aquifer (Unklesbay and Cooper, 1946). Over 400 such wells are located in the Orlando area (German and Bradner, 1988).

Kansas

Since 1997, 5 percent of Wichita's water needs, over 3,000 acre-feet, have been met by an AR project administered by the Equus Beds Groundwater Management District (Ziegler and Ross, 2002; Sophocleous and Buchanan, 2003). Treated source water from the Little Arkansas River is piped and transferred to wells, ponds, and other structures where it recharges the Equus Beds portion of the High Plains Aquifer, an important source of drinking water for the city of Wichita and other cities, and a source of water for irrigation and domestic use in central Kansas. The project also keeps the water table high enough to prevent a salt plume (originating from the briny Arkansas River) from migrating into the Wichita water-supply well-field. While the project is still in its initial stages, it seems to have been successful in artificially moving water from a surface source (the Little Arkansas River) into the Equus Beds portion of the High Plains Aquifer. The quality of ground water has remained mostly unchanged over the life of the project.

Nebraska

Ground-water resources in Nebraska occur in alluvial aquifers associated with the Platte River and its tributaries, and in the High Plains Aquifer. Concerns with declining water levels and deterioration in water quality, due primarily to agricultural fertilizers, have prompted AR pilot studies in several locations in Nebraska. In 1978, the USGS investigated recharging an alluvial aquifer tributary to the Platte River in south-central Nebraska in order to restore water levels. Recharge of alluvial aquifers has also been investigated by the Nebraska Water Resources Center with USGS support at Platte River and at Aurora by the Old West Regional Council. Aurora is in the Big Blue River basin in southeast Nebraska. At York, the Upper Big Blue Natural Resources District took part in the US Bureau of Reclamation's High Plains States Groundwater Demonstration Project with a pilot study recharging the Ogallala aquifer. There has also been use of an injection well completed in the Dakota sandstone at Lincoln for storage using water pumped from the alluvial aquifer. It is not clear from the literature whether there are any ongoing AR applications at this time in Nebraska.

New Jersey

The state of New Jersey has nine relatively new ASR projects (ASR Forum, 2004). The nation's first ASR well, operating since the late 1960s, is located at the Wildwood site and is now part of a system of four wells. New Jersey utilizes ASR to augment municipal water supplies during periods of high demand.

New York

AR has been practiced on Long Island since the 1930s. To help replenish the aquifer, as well as reduce urban flooding and control saltwater intrusion, more than 3,000 recharge basins dispose of storm runoff at an average rate of about 150 million gallons per day. Initially, many of these basins were abandoned gravel pits, but since 1936 urban planners require developers to construct recharge basins with new developments. Practically all basins are unlined excavations in the upper glacial deposits and have areas from less than 0.1 to more than 30 acres (Alley and others, 1999).

Nevada

The Southern Nevada Water Authority has been using ASR to augment water supply since 1988, and is currently cycling 60,000 to 72,000 ac-ft per year. The program was also designed to partially abate a severe ground subsidence problem that has existed in the Las Vegas Valley because of excessive ground-water withdrawal over the past several decades.

Texas

Projects in Texas primarily conduct AR into unconsolidated to semi-consolidated basin-fill aquifers. Municipalities appear to be the primary operators of recharge projects with the primary objectives being disposal of treated wastewater and storage of excess seasonal surface-water resources. Injection is the dominant recharge method being used and volumes range from 33 to 12,000 ac-ft per year. Several small ASR projects are scattered around Texas, including El Paso, Kerrville, and San Antonio.

INTERNATIONAL PROJECTS

The use of AR internationally is concentrated within developed countries in Europe, the Middle East, and in the South Pacific. A representation of the international recharge projects reviewed for this study is presented in figure V-2. A brief discussion of some of the more significant international projects follows.

Australia

The literature documents several small ASR projects scattered around Australia. At the Andrews Farm project, passively treated storm water is injected into a brackish aquifer to improve water quality for irrigation (UNEP, 2004). At the Burdekin River Delta project, about 50 gallons per minute (gpm) of water is pumped from Burdekin River to a distribution network of natural and artificial channels for surface infiltration. The system is the primary water source for the highest yielding sugarcane farm in Australia. In the town of Clayton, one ASR well injects storm water into a limestone aquifer (Gerges and others, 1998). An AR system using 6 infiltration ponds recharges aquifers supplying the town of Newman and iron mining operations of Mt. Newman Mining Co (Foo and others, 1989).

England

The North London Artificial Recharge Scheme provides up to 46,000 ac-ft per year to the London area. Surplus surface water from the river Thames and Lee is treated and recharged into the Chalk aquifer beneath London (Ramsay, 2002). In dry summers, the stored water is pumped from the aquifers, treated once again and then distributed. The Chalk aquifer was heavily depleted in the early half of the 20th century, but due to a combination of ASR and declining industrial water usage, ground-water levels beneath London are actually rising at the rate of 2.5 m/yr, currently threatening tunnels and building foundations (Oldershaw, 2002).

Germany

Bank filtration and ground-water recharge have been used for treatment of drinking water for more than a hundred years in Germany (Jekel and Heinzmann, 2003). Approximately 15 percent of drinking water in Germany is derived through the bank filtration method of AR (Schöttler, 1996). Seventy percent of Berlin's drinking water comes from ground water that originated from surface waters, either by bank filtration or AR (Jekel and Heinzmann, 2003). Artificial recharge is commonly used in Germany to purify water, in combination with chemical treatment techniques.

Israel

In Israel, approximately 70 percent of the national wastewater is reclaimed for use in irrigation. The Dan Reclamation projects in the Tel Aviv area, plus several other projects, artificially recharge over 200,000 ac-ft per year of treated wastewater into an aquifer for later agricultural withdrawals. The wastewater effluent is first treated and then injected into the ground for soil aquifer treatment. The system also helps prevent seawater intrusion (Oron, 2002).

Netherlands

Various forms of AR have been operating in the Netherlands since 1957. About 5 percent of the country's drinking water is Rhine bank infiltrate, and 14 percent is pretreated surface water from the Rhine and Meuse Rivers that is artificially recharged in 25 recharge basins within dune areas (Stuyfzand and Kooiman, 1996; Schijven and others, 1999). Recharge to spreading basins accounts for around 120,000 ac-ft per year. A deep well infiltration plant also operates in the dune area, west of Amsterdam (Stakelbeek and others, 1996). In this system pre-treated surface water is injected into semi-confined aquifers at greater depths (50-100 meters).

Sweden

Approximately 25 percent of Sweden's public water supply is derived from artificially recharged ground water (Sundlöf and Kronqvist, 1992). Most AR recharge plants in Sweden are located in glaciofluvial deposits. Sweden's first artificial ground-water recharge system was developed in the 1890s by J.G. Richert in Gothenburg utilizing recharge through an old gravel-pit (Gudmundson, 1971).

VI. Inventory of Artificial Recharge Projects in Colorado

In 1990, the Western States Water Council reported that there were over 150 existing AR facilities operated by municipalities, ditch companies, water supply districts, and other public agencies in Colorado (WSWC, 1990). The CGS used this as a benchmark for conducting an inventory of current AR facilities for this investigation. The results of the inventory have confirmed that there are more than 150 individual recharge sites in Colorado, if not many more. However, many of the individual sites that make up this impressive number should be considered parts of larger AR systems, as will be described for the lower South Platte River basin and San Luis Valley.

The compilation of an inventory of AR projects in Colorado consisted of conducting a thorough literature search of geologic and water-resource publications as well as interviewing personnel in a number of state agencies and local water entities. Personnel from the following entities were interviewed:

- *Division of Water Resources (DWR)* – including technical staff at the main office in Denver, each of the seven division engineers, and select district commissioners;

- *Water Conservancy Districts* – established to construct, pay for, and operate water projects in a number of regions in the state; and

- *Water providers* – individual water providers identified during the literature search or other interviews.

Water rights tabulations were researched (at the DWR) for water rights that include recharge as a decreed beneficial use. Using water rights alone as an indication of AR can be misleading, since that right may not have been exercised. Water rights listings did, however, provide a good source of leads for subsequent interviews.

The intent of this inventory is to understand the current extent of AR application in Colorado. AR projects identified in the inventory are divided into two categories: 1) recharge operations that are currently active, and 2) projects that are currently inactive, whether they be one-time pilot studies, operations that have since been terminated, or proposed projects that are only in the initial planning stages.

Active Recharge Operations

Currently, the application of AR in Colorado is somewhat limited in scope and geographical distribution due primarily to a lack of incentives to implement AR, which may include a paucity of source water. **Table VI-1** lists the active AR projects in Colorado, identified by this inventory, with their locations shown in **Figure VI-1**. In locations where AR has been recognized as a useful tool in water management and a water source has been present, the applications have evolved to meet a number of objectives.

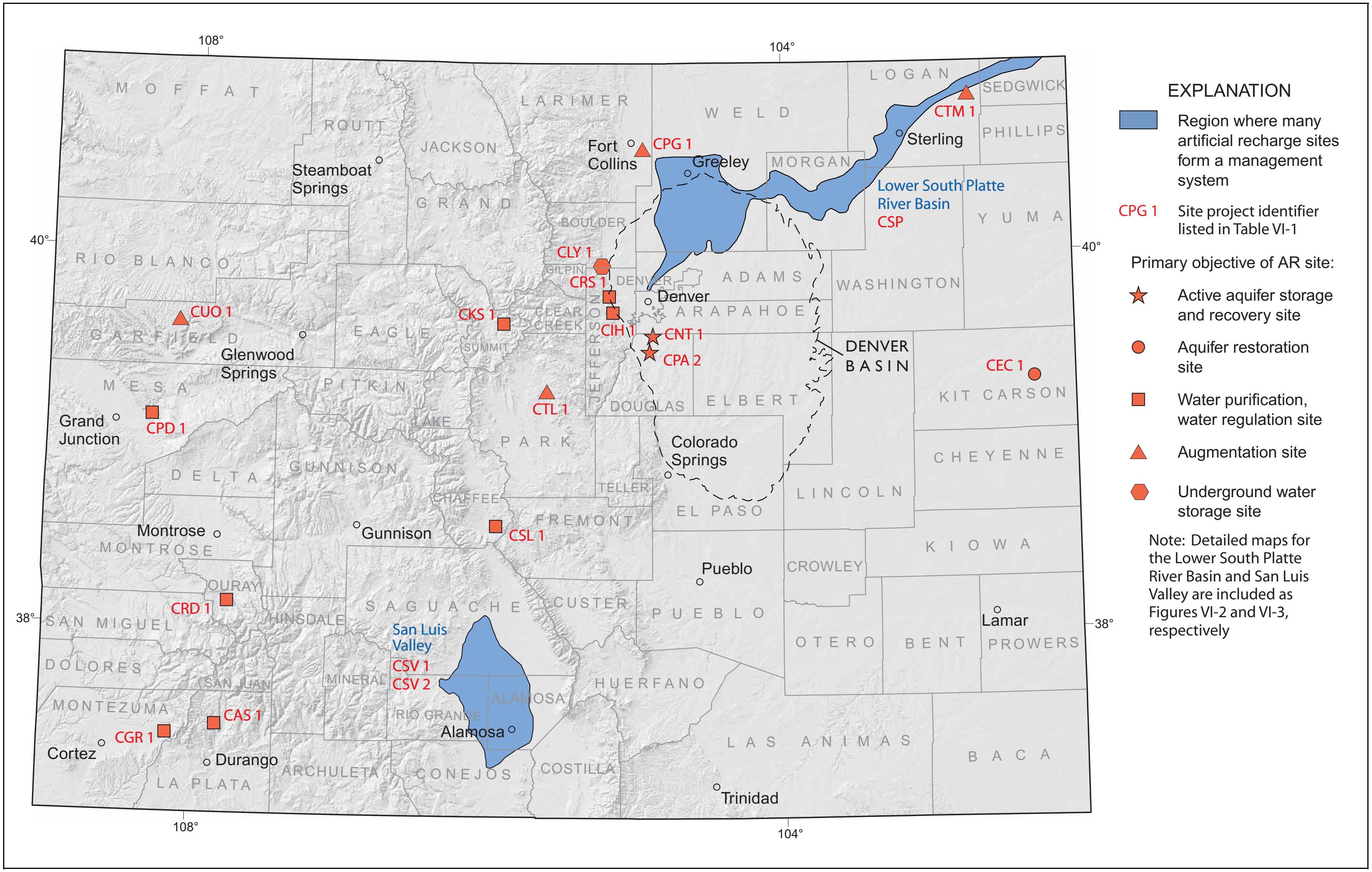


Figure VI-1. This map shows the locations of 16 individual sites and two regions identified in the inventory (Table VI-1) where artificial recharge is currently being implemented in Colorado.

This inventory has identified 19 active AR operations within the state (Table VI-1). The actual number of specific points of recharge is much higher. For purposes of this inventory, AR projects within common management regions such as the San Luis Valley and lower South Platte River basin are treated as single operations because the objectives, technologies, and operations within the regions are similar. Furthermore, the many individual sites within the two regions are poorly documented and, therefore, difficult to inventory in detail.

Recharge volumes for all of the individual sites are not readily available. However, recharge volumes have been obtained for AR operations in the Denver Basin, decreed ditch companies in the San Luis Valley, and lower South Platte River basin. Total recharge volumes for these operations over the period of 1992 through 2002 are listed in **Table VI-2**. As shown, the annual recharge volumes range from just over 65,200 acre-feet (ac-ft) in 1992 to a high approaching 285,000 ac-ft in 1995. The total volume of water recharged by these operations alone for that period is approximately 2.4 million ac-ft. The statewide total is likely to be somewhat higher taking into account the individual sites for which records could not be obtained.

The following discussion will first address regional AR activity in the lower South Platte River basin and San Luis Valley, both areas where many individual AR sites create large AR systems. Next will be a brief discussion of emerging application of ASR technology in the Denver Basin. Lastly, there are a number of relatively small AR operations at other locations in the state that meet various objectives.

Table VI-1. Active Artificial Recharge Sites in Colorado

ID	Site	Operator	Basin/Aquifer System	Initial Operation	Objective					Technology			
					Water Storage	Legal Obligations	Water Quality	Aquifer Restoration	Environmental	Surface Infiltration	Subsurface Infiltration	Direct Injection	Shaft/tunnel
CAS 1	Animas Springs	Individual owners of small capacity wells	Animas River	Unknown	X					X			
CPG 1	Cache le Poudre Gravel Pits	Gravel quarry operators	Cache la Poudre	Unknown		X				X			
CPA 2	Castle Pines	Castle Pines Metropolitan District	Denver Basin / Arapahoe Aquifer	1998	X			X				X	
CNT 1	Centennial Denver Basin ASR	Centennial Water District	Denver Basin / Arapahoe, Denver, Laramie-Fox Hills Aquifers	1992	X			X				X	
CRS 1	Clear Creek Recharge Ponds	Coors Brewing Company	Clear Creek Alluvium	~ 1988		X	X			X			
CEC 1	Eastern Colorado	Plains Ground Water Management District	High Plains / Ogallala	1971				X		X			
CGR 1	Gold Run Ditch	Individual owners of small capacity wells	East Fork Mancos River	Unknown	X					X			
CIH 1	Indian Hills	Indian Hills Water District	Turkey Creek	1963-	X		X			X			
CLY 1	Leyden Coal Mine	City of Arvada	Boulder Creek	2003-	X							X	

Table VI-1. Active Artificial Recharge Sites in Colorado (Cont'd)

ID	Site	Operator	Basin/Aquifer System	Initial Operation	Objective					Technology			
					Water Storage	Legal Obligations	Water Quality	Aquifer Restoration	Environmental	Surface Infiltration	Subsurface Infiltration	Direct Injection	Shaft/tunnel
CPD 1	Palisade Public Water	Palisade Public Works	Colorado River	Prior to 1963	X		X		X	X			
CUO 1	Parachute Gravel Pits	Union Oil	Parachute Creek	Unknown		X				X			
CRD 1	Ridgway Public Water	Town of Ridgway	Gunnison	Prior to 1963	X		X		X	X			
CSL 1	Salida Public Water	Salida Public Works	South Arkansas	Prior to 1963	X		X		X	X			
CSV 1	San Luis Valley Closed Basin Irrigation Management	Five ditch companies: Billings, Farmers Union, Prairie l, Rio Grande, and San Luis Valley.	San Luis Valley	Approx. 1977	X	X		X		X			
CSV 2	San Luis Valley Rio Grande Water Users	Six ditch Companies: Centennial, Empire, Farmers Union, Monte Vista, Prairie, Rio Grande Canals	San Luis Valley	1980	X	X	X	X		X			
CKS 1	Snake River Recharge	Keystone Resorts	Snake River	Unknown	X			X		X			
CSP	South Platte Irrigation Management	Twenty-seven ditches companies, at least 79 sites	South Platte River Basin	1939	X	X		X		X			
CTM 1	Tamarack Wildlife Area	Colorado Division of Wildlife	South Platte River Basin	1979	X	X			X	X			
CTL 1	Tarryall Recharge	Centennial Water District	Tarryall Creek	Unknown		X				X			

Table VI-2.
Recharge Volumes for the Denver Basin, San Luis Valley, and the Lower South Platte River Basin
(in acre feet)

Water Year	Denver Basin						San Luis Valley 4)						South Platte Basin 5)			Total Colorado
	Castle Pines ASR 1)	Centennial ASR 2)			DB Aquifer Recharge Demo. Project 3)	Total Denver Basin	San Luis Valley, Closed Basin				San Luis Valley, RGWUA	Total San Luis Valley	South Platte Irrigation	Tamarack Ranch	Total South Platte Basin	
		Denver	Arapahoe	Laramie-Fox Hills			W-3980	W-3979 Confined	W-3979 Unconfined	Total W-3979 & W-3980						
1992			79		143	**222**	22,773	18,648	65,267	106,688	14,334	**121,022**	80,634		**80,634**	**201,878**
1993			5		300	**305**	41,923	24,550	85,926	152,399	10,729	**163,128**	80,472		**80,472**	**243,905**
1994			70		310	**380**	39,497	20,084	70,294	129,875	10,299	**140,174**	68,995		**68,995**	**209,549**
1995			186		328	**514**	51,275	29,300	102,551	183,126	11,741	**194,867**	89,508		**89,508**	**284,889**
1996			652		201	**853**	22,615	14,547	50,914	88,076	19,955	**108,031**	90,571		**90,571**	**199,455**
1997		24	1,166			**1,190**	58,409	22,555	78,944	159,908	13,340	**173,248**	96,734		**96,734**	**271,172**
1998	153	86	1,168			**1,407**	19,634	20,134	70,468	110,236	0	**110,236**	102,888		**102,888**	**214,530**
1999	71	62	663			**796**	57,459	27,389	95,860	180,708	19,236	**199,944**	116,584		**116,584**	**317,325**
2000	11	215	803			**1,029**	17,823	12,088	42,309	72,220	5,162	**77,382**	78,946		**78,946**	**157,357**
2001	10	227	549			**786**	42,332	No Report	No Report	42,332	7,452	**49,784**	148,548	2,140	**150,688**	**201,257**
2002	0	68	197	111		**376**	0	No Report	No Report	0	5,906	**5,906**	55,471	3,424	**58,895**	**65,177**
Total	**245**	**682**	**5,538**	**111**	**1,283**	**7,858**	**373,740**	**189,295**	**662,533**	**1,225,568**	**118,153**	**1,343,721**	**1,009,351**	**5,564**	**1,014,915**	**2,366,494**

Notes:
1) Source: Jehn Water Consultants, unpub data, August 2003
2) Source: Rick Mcloud, unpub data, August 2003
3) Source: Halepaska, J.C. and Assoc, 1997
4) Source: Steve Vandiver, unpub data, October 2003
5) Source: Jim Hall, unpub data, October 2003

Lower South Platte River Basin

Associated with the South Platte River and its tributaries are Pleistocene alluvial and eolian deposits covering an area of over 4,000 square miles **(Figure VI-2)**. These deposits form a vital aquifer in what is referred to as the lower South Platte River basin (LSPRB), which extends from the foothills of the Rocky Mountains east to the state's border with Nebraska. The same geographic region also hosts more than 60 percent of Colorado's population and a thriving agricultural economy that rely on both surface water from the South Platte River and ground water from the underlying alluvial aquifer for crop irrigation, municipal supplies, and industrial uses. A complex system of water distribution canals and ditches has evolved since the late 19^{th} century to distribute that water while several diversion and reservoir projects have been constructed to import and store more than 1.5 million ac-ft of water.

The alluvial aquifer is estimated to hold as much as 8.3 million ac-ft of water, and over 3,200 wells tapping the alluvial aquifer extract as much as 0.6 million ac-ft per year (Topper and others, 2003). Furthermore, wells in this alluvium can yield up to 3,000 gpm (CWCB, South Platte River Basin fact sheet).

AR is being used extensively throughout the LSPRB as part of a number of augmentation plans and substitute supply plans. Most of the alluvial wells have original water rights that are junior to the majority of the surface-water diversions. The augmentation and substitute supply plans that incorporate AR allow those junior rights to continue to pump ground water, and therefore to continue to irrigate their crops, even when their original water rights are out-of-priority. This application of AR relies on lagged replacement of water to the mainstem of the affected river. Water from ditches, and to a lesser extent from wells, is recharged through infiltration ponds, dry streambeds, leaky reservoirs, and leaky ditches. When possible, distances between point of recharge and the river are selected to time the replacement to the river when natural flows are generally low. Recharge site selection utilizes stream depletion factors (SDFs) that have been calculated and mapped for the entire reach of the LSPRB by the USGS (Hurr and others, 1972a, 1972b, 1972c, 1972d, 1972e, 1972f).

Although the primary objective of AR in the LSPRB is to meet legal obligations, there is also a component of water storage involved. Many of these recharge projects allow greater utilization of the agricultural water in the LSPRB, so that water is available during high demand times (April-October). These projects also promote aquifer restoration by mitigating decreasing water levels. In fact, the original application of AR in the LSPRB at Olds Reservoir (COR-1 in Figure VI-2) in 1939 was done with the objective of restoring declining water levels (Skinner, 1963). Water levels in the aquifer had decreased by up to 36 feet as of 1970, prior to widespread application of AR (Topper, and others, 2003). Since that time the rate of water-level decline has appeared to decrease, much of which may be attributable to increased use of AR.

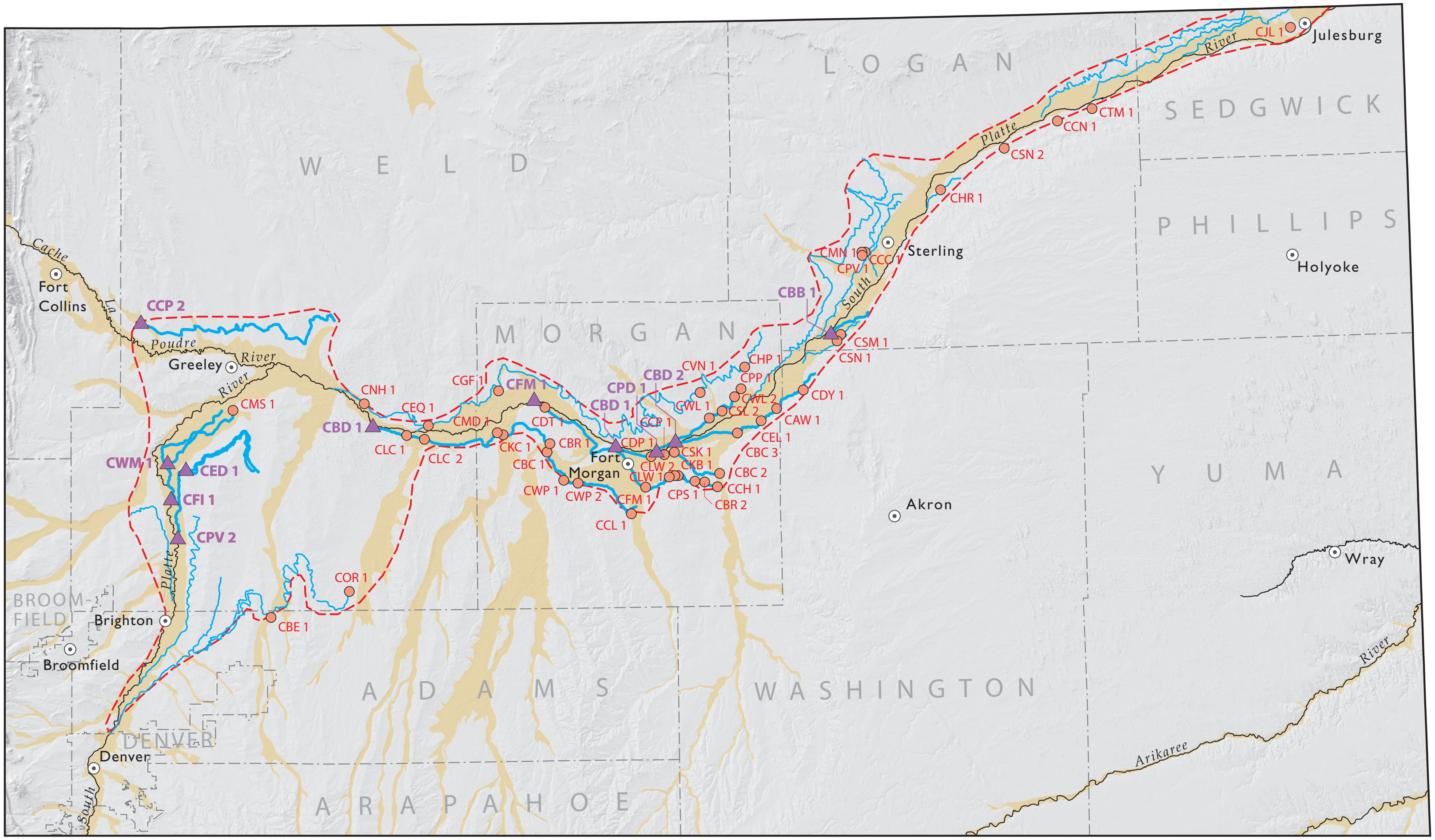
Artificial recharge in the LSPRB has been an active part of ground-water management since the 1940s, when Olds Reservoir was first utilized, although recharge incidental to agricultural land-use had occurred prior to that. Leaky irrigation ditches and reservoirs have been unofficially recharging the aquifer since they were first constructed. Most of the AR projects in the LSPRB were initiated in the late 1970s to mid 1980s. The actual number of individual AR sites currently active in the LSPRB is difficult to tally. New sites are being added while others are taken out of service (R.V. Stroud, pers. com., 2003), and the number is always changing. Furthermore, most individual sites have not been documented in the literature outside of individual court decrees and substitute supply plans.

Warner and others (1994) described 54 individual sites, identified in Figure VI –2**,** operated by 17 organizations and individual farmers. The organizations cited by Warner that operate recharge sites include

- Central Colorado Water Conservancy District,
- Henry Lyn Irrigation Company,
- Ground-Water Appropriators of the South Platte (GASP),
- Bijou Irrigation Company,
- Fort Morgan Reservoir and Irrigation Company,
- Pioneer Water and Irrigation Company,
- Upper Platte and Beaver Canal Company,
- Lower Platte and Beaver Canal Company, and
- Riverside Irrigation Company.

Artificial recharge as augmentation along the LSPRB is being implemented in Water Districts 1, 2 and 64, all within Division I. Records from DWR Division 1 indicate that, as of September 2003, there are 27 ditches along which AR is being implemented (shown in Figure VI -2), and that there are 79 designated recharge locations (Jim Hall, oral commun. and unpublished data, 2003). The water rights database lists 118 water rights for Water Districts 1, 2, and 64 that include AR as a beneficial use. Since 1992, annual recharge totals along the LSPRB have ranged between 58,900 to 150,700 ac-ft per year and over 1.0 million ac-ft have been recharged as part of augmentation to the tributary system.

The Colorado Division of Wildlife (DOW) owns and operates the Tamarack Ranch State Wildlife Area on the south side of the South Platte River in Logan County (CTM-1 in Figure VI-2). In cooperation with the Colorado Water Conservation Board and a coalition of water users, AR is being implemented at Tamarack Ranch as part of an augmentation plan that allowsthe DOW to divert water to maintain wildlife habitat (Watt, 2003a). The Tamarack AR project is also a main component of the State of Colorado proposal for a recovery program for endangered species in Nebraska. Recharge ponds are filled by discharge from wells completed near the South Platte River. This site is listed as a separate site in the inventory since wildlife habitat maintenance is the primary objective of the ranch, although the operation of AR at the ranch for augmentation is similar to AR operations throughout the LSPRB. It is also significant that the recharge basins utilized at Tamarack are located in the sand hills formed on eolian deposits that overlie the alluvium south of the valley.



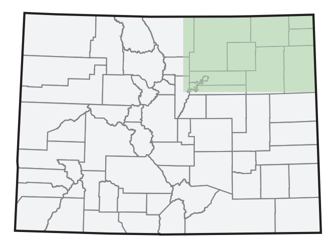


Figure VI-2. Artificial recharge sites in the South Platte River Basin. This map illustrates the individual sites in the Lower South Platte River basin region that include infiltration ponds, dry streambeds, leaky reservoirs, and leaky ditches identified in the literature where artificial recharge is used for augmentation. The heavy dashed outline shows the approximate area where the alluvium and surface deposits hydraulically connected with the alluvium are influenced by recharge.

San Luis Valley

The San Luis Valley is an intermontane basin in south-central Colorado that covers approximately 3,200 square miles within five counties **(Figure VI-3)**. Although this high mountain desert has an average annual precipitation of only eight-to-ten inches per year, it is also home to a thriving agricultural community second only to that in the lower South Platte River basin. Historically, croplands covering 617,000 acres were irrigated using surface water diverted from rivers emerging from the San Juan Mountains on the west and the Sangre de Cristo Mountains on the east. The valley relies on a vast network of distribution canals and laterals to distribute the surface water across the flat valley floor with over 2 million ac-ft of water per year diverted for irrigation (Topper and others, 2003).

In the 1950s and 1960s farmers began to rely more heavily on ground water for irrigation both in response to drought and improvements in sprinkler technology. Currently, the vast majority of irrigation is done with center-pivot sprinklers driven by well water. The principal unconsolidated aquifers in the San Luis Valley are referred to as the upper unconfined aquifer and the lower confined aquifer of the late Cenozoic Alamosa formation (Topper and others, 2003). Reported aquifer transmissivity values reach as high as 225,000 gallons per day per foot (gal/day/ft) and well yields can be as high as 3,000 gpm, giving the unconfined aquifer optimum characteristics for large-scale irrigation exploitation. As of the 21st century, approximately 0.8 million ac-ft of ground water per year are withdrawn for irrigation (CWCB, 2003).

With the increased reliance on ground water for irrigation, water levels in the unconfined aquifer began to decline rapidly. During the period from 1969 to 1980 areas in the valley experienced declines of up to 40 feet (Topper and others, 2003). In the late 1970s and early 1980s the water community in the San Luis Valley realized that AR could help maintain water levels in the unconfined aquifer and, thus, AR became a tool for managing surface and ground-water resources (Allan Davies, oral commun., 2003). Since that time, farmers and ditch companies have been converting surface-water rights to include AR as a beneficial use so that recharged water could be used for diversion at a later date using wells.

The combined surface- and ground-water resource has evolved into a large-scale conjunctive-use system, and the primary objective for recharge is to regulate supply through the irrigation season. In effect, the unconsolidated aquifer is utilized as a large storage reservoir allowing farmers to continue to irrigate, even during times of low surface-water flow. The water in storage in the unconfined aquifer also provided a cushion for the 2002 drought. Farmers were able to irrigate during the summer of 2002 even though there was very little surface flow.

There are hundreds of individual recharge sites in the valley and the number continues to grow (Allan Davies, oral commun., 2003). Many of the AR sites are excavated pits in the corners of land grid quarter-sections that are difficult to irrigate with the center-pivots. Water is directed from the canals to the pits for recharge. Artificial recharge is also accomplished through leaky ditches and canals with many canals and laterals actually maintained to enhance leakage. As a check of the balance between well usage and recharge, the Rio Grande Water Conservancy District monitors water levels in the valley. Results of this monitoring indicate that the management system appears to be very effective (Steve Vandiver, oral commun., 2003).

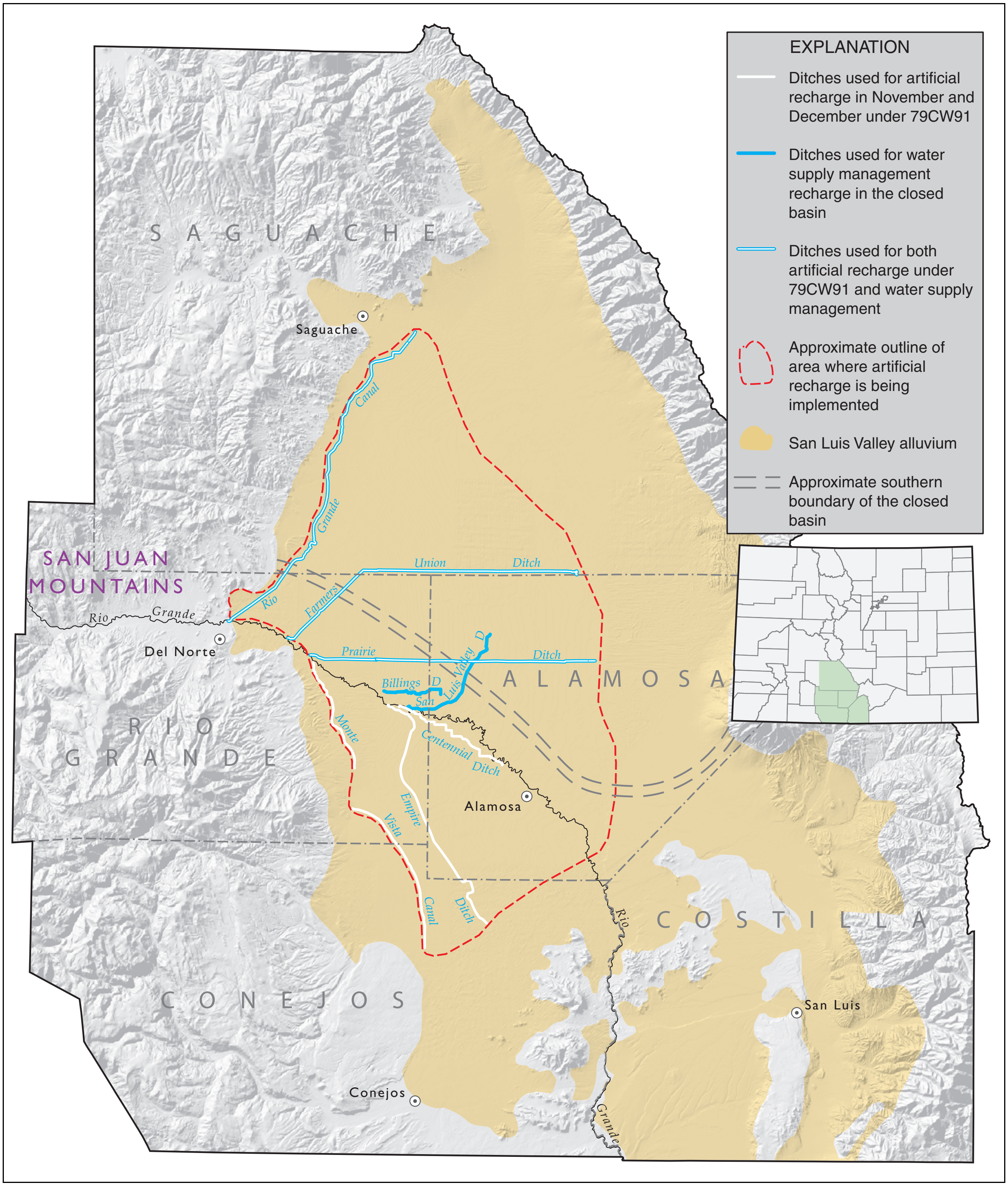


Figure VI-3. **Artificial Recharge in the San Luis Valley. Artificial recharge in the San Luis Valley is being implemented to manage water supply for irrigation from the Rio Grande River. In the Closed Basin, north of the double dashed gray line, water is recharged during spring when runoff is high through many infiltration pits and leaky ditches, allowing pumping for irrigation throughout the summer growing season even when river flow is low. South of the Closed Basin, water is recharged through leaky ditches in November and December to offset depletions to the Rio Grande caused by pumping during the summer growing season.**

The northern end of the valley, where there is no external drainage of surface water, is referred to as the "Closed Basin." A ground-water divide separates the Closed Basin from the alluvial aquifer underlying the Rio Grande and, for water management purposes, ground water in the Closed Basin is not considered to be in hydraulic connection to the surface flow of the Rio Grande. This separation has affected how irrigators in the Closed Basin use their water. In this area, surface water is imported from the Rio Grande for irrigation and recharged via five principle ditches shown in Figure VI-3.

Water is recharged at many individual sites throughout the irrigation season, with cumulative rates averaging over 120,000 ac-ft per year when water is available from the canals. The farmers then pump from wells as needed while the individual ditch companies maintain an account of recharge and pumping totals (Steve Vandiver, oral commun., 2003). The accounting system in the San Luis Valley is much simpler than that in the South Platte River Basin since it is held that pumping ground water from within the Closed Basin does not cause depletions to the Rio Grande and the ground-water usage is not administered with augmentation plans.

In addition to the conjunctive use within the Closed Basin, water is also recharged during the winter by the Rio Grande Water Users Association (RGWUA) using six principal ditches over a larger area covering the west central portion of the valley that includes the Closed Basin (Figure VI-3). Reported annual recharge totals have been as high as 20,000 ac-ft. Recharge by the RGWUA offsets depletions to the Rio Grande caused by pumping outside of the Closed Basin and thus allows pumping to continue when surface flow is low.

Denver Basin Aquifer Storage and Recovery

The Denver Basin is a structural basin that encompasses much of the Denver and northern Colorado Springs metropolitan areas (Figure VI-1), home to almost 60 percent of Colorado's population. The administrative ground-water portion of the basin underlies a 6,700 square mile area and is subdivided into the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers. These aquifers consist of interbedded sandstone, conglomerate, shale, and claystone of Tertiary to Upper Cretaceous age. The basin is asymmetrical with the center just west of the town of Parker where the base of the Laramie-Fox Hills is approximately 3,000 feet deep. Water levels are quite variable depending on geographic location as well as well depth. However, much of the ground water in the basin is under confined conditions and is considered non-tributary. The most prolific aquifer is the Arapahoe, which has a stratigraphic thickness ranging between 400 and 700 feet and contains up to 400 feet of saturated sand and conglomerate. Transmissivities in the Arapahoe aquifer range between 500 and 5,000 gpd/ft with pumping rates in excess of 1,000 gpm common in the deepest part of the basin where there is sufficient available head above the top of the aquifer.

In 1987, Robson estimated that the Denver Basin aquifer system has a storage capacity of approximately 470 million ac-ft of water, however the actual amount of recoverable water may be closer to 200 million ac-ft due to physical and practical limitations (Topper and others, 2003). Still, this volume is a tremendous resource with over 1,000 times the volume of storage in Dillon Reservoir, Denver Water's largest surface reservoir. The DWR estimated that nearly 445,000 ac-ft of water were withdrawn from the Denver Basin aquifer system in the Denver metropolitan region in 1995, and the annual withdrawal has certainly increased since then.

While a withdrawal rate less than 500,000 ac-ft per year may represent a depletion of the resource of less than one half of one percent per year, the resource is considered non-renewable. Pressures to increase exploitation of the aquifer are mounting. The portion of the Denver metropolitan region covering western Arapahoe County and northeastern Douglas County relies most heavily on the Denver Basin aquifers. Water levels in the Arapahoe aquifer in this area have been declining up to 30 feet per year. At this rate of decline, water levels could drop to the top of the currently confined Arapahoe aquifer in ten years, or less. Furthermore, declining water levels result in greater pumping costs and decreasing well yields that ultimately result in higher costs to produce the water.

With the prospect of skyrocketing costs and rapidly increasing demand on this non-renewable resource, several districts in the Denver Metropolitan region have either completed pilot studies or have initiated ASR projects since the mid-1980s. Concurrently, the DWR has implemented a set of rules and regulations governing how ASR can be managed in the Denver Basin. These important regulations allow banking of water in place as well as banking of recharged water imported from other sources.

ASR pilot studies were first undertaken by Parker Water and Sanitation District (Parker WSD) and Willows Water District (Willows WD) in the mid-1980s (WSWC, 1998). Willows WD (CWW-1 in Figure VI-3) participated in the US Bureau of Reclamation High Plains States Groundwater Demonstration Program with the Denver Basin Aquifer Recharge Demonstration Project between 1990 and 1997 (Lytle, 2003b). Results of these pilot studies indicated that ASR was a viable technology in the basin. Parker WSD (CPW-1 in Figure VI-3) currently does not have a source of recharge water; however, ASR implementation is in the long-term plan for the district (Lytle, 2003a) once a surface-water supply is secured.

Full scale ASR implementation in the Denver Basin was first undertaken by Centennial Water and Sanitation District (Centennial WSD) in 1992 (Hemenway and Grundemann, 2002). The Centennial WSD supplies the vast Highlands Ranch community in Douglas County (CNT-1 in Figure VI-2) with water and operates a well field completed in the Denver, Arapahoe, and Laramie-Fox Hills aquifers. In addition, the district has tributary surface-water rights on the South Platte River system. Tributary water is drawn directly from the South Platte River and through alluvial wells. During periods of surplus tributary water, treated water from the South Platte system is injected in a series of ASR wells. ASR wells are equipped with down-hole control valves that allow both extraction and injection through the pump column.

Castle Pines Metropolitan District (Castle Pines MD), which supplies water to the Castle Pines community in Douglas County (CPA-2 in Figure VI-2), began operating an ASR well in the Arapahoe aquifer in 1998 (Jehn, 2003). The source water is obtained from the district's not-non-tributary Denver aquifer wells and is treated prior to injection in the ASR well. The district also plans to install a tributary well field in the Plum Creek alluvium once an augmentation decree has been obtained that will provide additional source water.

Total recharge volumes for ASR in the Denver Basin for the period 1992 through 2002 are listed in Table VI-2. Annual recharge volumes range between 220 and 1,410 ac-ft. The total volume of recharge for the period is just under 8,000 ac-ft.

Other Colorado Recharge Operations

A number of smaller AR applications throughout the state are shown in Figure VI-1. These include sites where AR is used to modify water quality, provide short-term water volume regulation, and provide augmentation water. Moulder and others (1963) described eight community water systems that used AR to both pretreat surface-water quality and regulate unreliable surface-water volumes. These small AR applications capture surface water that is prone to detrimental water quality conditions, such as high turbidity during spring runoff or flooding, as well as highly variable flow rates. These sites consist of a surface diversion combined with some type of surface infiltration structure. Ground water is then withdrawn downgradient for use in the system.

In some instances, the AR application has been specifically designed as a pretreatment facility. For example, Salida (CSL-1 in Figure VI-2) diverts water from the South Arkansas River into two infiltration ponds. A horizontal perforated pipe beneath the ponds extracts the clarified water for use when river flow is low. Other applications are more accidental, taking advantage of leaky reservoirs. Although leaky reservoirs may not strictly meet the definition of AR, they are included in this inventory because of their previous citation in the literature (Moulder and others, 1963). An example of this type of application is at Ridgway (CRD-1 in Figure VI-2), where water is diverted into a reservoir that leaks. The town captures seepage from the drainage topographically below the reservoir. As described by Moulder, the seepage is of better quality and more reliable in quantity than the surface supply.

The eight systems described by Moulder and others (1963) are Salida, Indian Hills, Littleton, Nederland, Pagosa Springs, Palisade, Ridgway, and Wheatridge Mutual. These communities were contacted as part of this inventory to determine which still utilize AR. Those that continue to use AR as described by Moulder include Salida, Indian Hills, Palisade, and Ridgway (CSL-1, CIH-1, CPD-1, and CRD-1 in Figure VI-2). At the other locations modifications to the water supply systems, such as high-volume filtration units, have apparently replaced the AR applications.

In addition to the eight communities described by Moulder, this investigation identified other projects where AR was used for water-quality modification or water-supply regulation. These sites, also shown in Figure VI-1, include AR by Coors Brewing Company near Clear Creek in Jefferson County (CRS-1 in Figure VI-2), AR by Keystone Resorts near the Snake River in Summit County (CNT-1 in Figure VI-2), and AR at several small capacity wells near the Animas River in La Plata County (CAS-1 in Figure VI-2) as well as near the East Mancos River in Montezuma County (CGR-1 in Figure VI-2).

There are also several small-scale sites shown on Figure VI-1 (CUO-1, CPG-1, and CTC-1) where AR is used as part of augmentation plans. These consist primarily of gravel pit operations that use AR to replace ground water lost to evaporation. Lastly, the City of Arvada has started using the abandoned Leyden coal mine (CLY 1) as an underground water storage facility by injecting treated municipal water. This mine had previously been used as a gas storage facility, and is estimated to have a 3,000 ac-ft water capacity.

Inactive Artificial Recharge Operations

The inactive category includes projects that are still in the planning stages, pilot projects reported in the literature that have not led to full-scale AR implementation, as well as AR operations that have been terminated. These projects are listed in **Table VI-3** and are shown in **Figure VI-4**. The table includes the reasons for the inactive status. Many of these projects were one-time research projects that had no follow-up. Several of the community systems that were cited by Moulder and others (1963) as utilizing AR have since discontinued their operations; satisfying their objectives through facility upgrades.

AR operations that are in the planning stages include Parker WSD's Denver Basin ASR and the Cherokee Metropolitan District's (Cherokee MD) Upper Black Squirrel Creek AR project (CPW-1 and CBS-2 in Figure VI-4). Parker WSD has recently received approval for construction of the Reuter-Hess Reservoir that will provide a source of water for ASR in their Denver Basin aquifer wells. Once implemented, the Cherokee MD's operation in the Upper Black Squirrel Creek drainage will be the first AR application in Colorado to use treated wastewater as the source water for recharge.

Factors limiting implementation of AR in Colorado that were cited during the interviews conducted for this inventory include

- lack of source water,
- lack of a sponsor or operator to follow up after a pilot study,
- lack of funding, and
- concerns with the complex permitting process to initiate and continue to operate an AR project.

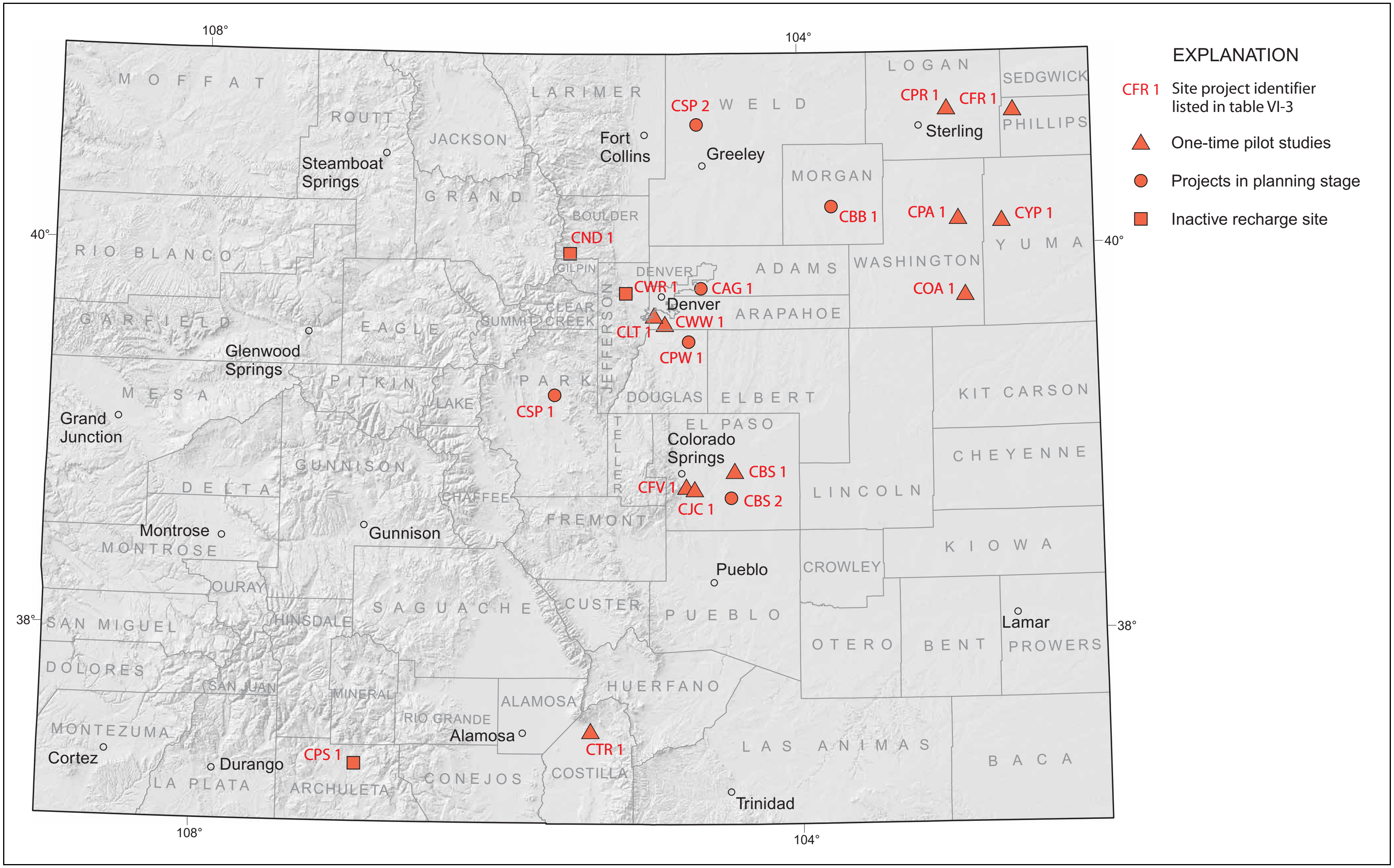


Figure VI-4. **Inactive artificial recharge projects in Colorado. This map illustrates locations identified in the inventory (Table VI-3) where artificial recharge has been utilized or tested in the past, but was discontinued for various reasons. It also shows sites where artificial recharge is currently in the planning stages.**

Table VI-3. Inactive Colorado Recharge Sites

ID	Site	Operator	Basin/Aquifer System	Dates of Operation	Reason For Termination	Objective					Technology			
						Water Storage	Legal Obligations	Water Quality	Aquifer Restoration	Environmental	Surface Infiltration	Subsurface Infiltration	Direct Injection	Shaft/tunnel
CPA 1	Akron Playa Experiment	Central Great Plains Experiment Station	High Plains / Ogallala	1964	One time research project				X		X			
COA 1	Arikaree Near Cope	Cope Soil Conservation District/CSU	High Plains / Ogallala	1964-1968	Pilot study, no funding to follow through. Onerous permitting issues.				X		X			
CAG 1	Aurora Gravel Pits	City of Aurora	South Platte Alluvium	—	Conceptual		X	X			X			
CBB 1	Badger-Beaver Creek AR	Badger-Beaver Creek Water Conservancy District	Badger DGWB	1978-1979	Pilot study, no funding to follow through				X					
CBS 2	Upper Black Squirrel / Cherokee	Cherokee Metro District	Upper Black Squirrel DGWB	2002-2003	Pilot Study In Progress		X	X			X			
CWW 1	Denver Basin Recharge Project	Willows Water District	Denver Basin/Arapahoe	1990-1997	US BuRec Funded Study	X							X	
CBS 1	Upper Black Squirrel / USGS	USGS	Upper Black Squirrel DGWB	1975	Funding for pilot study only				X		X			
CFV 1	Fountain Valley (Widefield Aquifer)	USGS	Fountain Creek Alluvium	1975	Funding for pilot study only				X		X			
CFR 1	Frenchman Creek Project	Frenchman Ecological Area Committee, CSU	High Plains / Ogallala	1974-1975	One time research project				X		X			
CJC 1	Jimmy Camp Valley	USGS	Jimmy Camp Alluvium	1975	Funding for pilot study only				X		X			

Table VI-3. Inactive Colorado Recharge Sites (Cont'd)

ID	Site	Operator	Basin/Aquifer System	Dates of Operation	Reason For Termination	Objective					Technology			
						Water Storage	Legal Obligations	Water Quality	Aquifer Restoration	Environmental	Surface Infiltration	Subsurface Infiltration	Direct Injection	Shaft/tunnel
CLT 1	Littleton		South Platte	-1963-	Buy water from Denver, quit using ground water			X			X			
CND1	Nederland Public Water	Town of Nederland Public Works	Boulder Creek	To mid-60s	Upgrade treatment plant, recharge not used anymore			X			X			
CPS1	Pagosa Springs Public Water	Pagosa Area Water and Sanitation	San Juan River	To mid-60s	Upgrade treatment plant, recharge not used anymore			X			X			
CPW 1	Parker Recharge Study	Parker Water and Sanitation	Denver Basin/Dawson	1984-1985	Pilot Study, need source water to continue	X							X	
CPR 1	Proctor Recharge Experiment	USGS/Lower South Platte Water Conservation Dist.	South Platte Basin	1979	Short-term study	X			X		X			
CTR 1	San Luis Valley Trinchera Project	Trinchera Ditch Company	San Luis Valley	1982	Ponds filled in with sediment		X		X		X			
CSP 1	South Park Conjunctive Use Project (SPCUP)	City of Aurora	South Park Formation	--	Conceptual	X					X			
CSP 2	South Platte Water Conservation Project	Northern Colorado Water Conservancy District	Cache la Poudre	--	Conceptual	X	X		X		X			
CWR 1	Wheatridge	Wheatridge Mutual	Clear Creek Alluvium	To mid-60s	Buy water from Denver, quit using ground water			X			X			
CYP 1	Yuma Recharge Pit	CSU	High Plains / Ogallala	1971	One-time research project				X		X			

VII. Statewide Potential for Artificial Recharge/Underground Water Storage

Colorado's Aquifer Systems

The occurrence and distribution of Colorado's water resources are inherently linked to the state's geography and underlying geology. Geologic units and hence, aquifers, consist of either unconsolidated sediments or consolidated rock. Ground water is simply water that fills the pore spaces between rock grains in sedimentary rocks or in crevices such as fractures and faults in crystalline rocks. A geologic unit's ability to store and transmit water is dependent not only on the amount of pore space (porosity) within the rock or sediment, but also on the size and degree of interconnection (permeability) of those openings. A geologic unit containing interconnected pore spaces or crevices that are filled or saturated with water is termed an aquifer. Not all rocks make good aquifers. In fact, some geologic units actually impede the flow of water, as their porosity and permeability are very low.

As a result of Colorado's complex geology, a multitude of aquifers in various areas of the state are suitable for AR projects. Colorado's principal aquifers are categorized into the following: (1) unconsolidated Quaternary-age alluvial aquifers associated with major river systems; (2) poorly consolidated or unconsolidated sediments such as valley-fill deposits; (3) consolidated sedimentary rock aquifers; and (4) volcanic and crystalline rock aquifers. Alluvial deposits associated with the state's major river systems consist of unconsolidated silt, sand, and gravel that have been deposited during recent geologic time by water transport. The statewide distribution of mapped modern, Quaternary-age alluvium is illustrated in **Figure VII-1**. As in other western states, the aquifers with the highest yields in Colorado are composed of unconsolidated sand and gravel deposits adjacent to major river systems. Wells completed in alluvial deposits can yield from hundreds to thousands of gallons per minute (gpm).

Unconsolidated to poorly consolidated sediments are largely derived from erosion of surrounding highlands. These sediments were deposited by wind, water, and gravity, and represent the accumulation of alluvial fans, landslide deposits, glacial drift, and eolian deposits. The principal aquifers of this type include the Ogallala Formation of the High Plains aquifer, and the valley-fill deposits of the San Luis and Wet Mountain Valleys. Valley-fill deposits have hydraulic characteristics similar to the alluvial aquifers, though with slightly lower permeability, and they can be hundreds of feet thick.

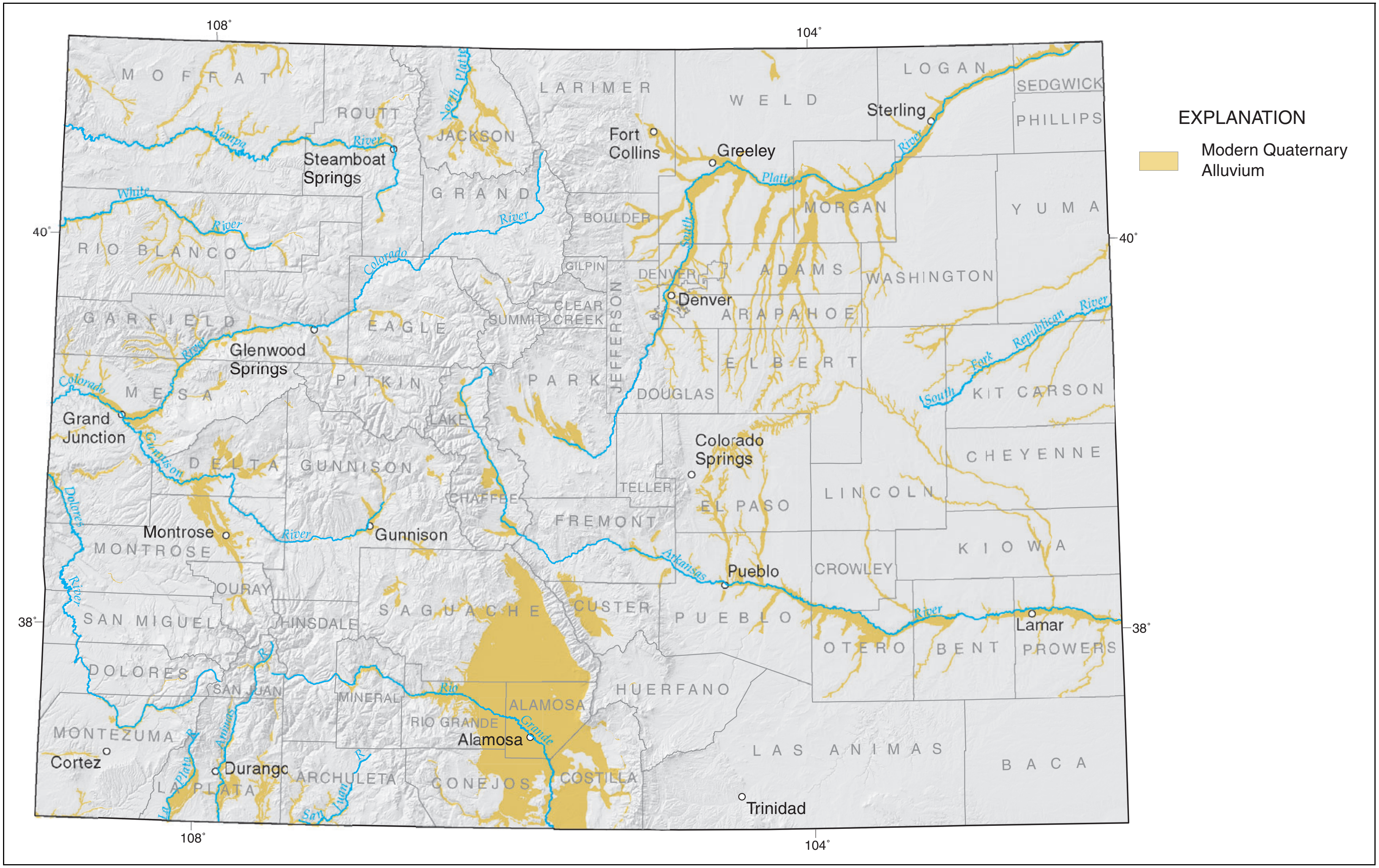


Figure VII-1. Modern, Quaternary age, alluvium composed of unconsolidated sand and gravel deposits adjacent to major river systems are among the most prolific aquifers in Colorado.

The sedimentary rocks of Colorado are either composed of fragments of pre-existing rocks (clastic) or formed by the precipitation of carbonate compounds associated with marine life. The names of the clastic sedimentary rocks are largely derived from the size of the fragments from which they are composed; these include siltstone, sandstone, and conglomerate. The common carbonate rocks are limestone and dolomite. Chemically precipitated carbonate rocks can have very low primary porosity and permeability, but secondary permeability is developed along bedding planes, fractures, and faults by dissolution and enlargement of these zones of weakness. Florida's carbonate aquifers produce tremendous amounts of ground water, and contain a number of "underground rivers" where a surface stream disappears and flows through caves. Colorado's carbonate aquifers are best developed in the Eagle Basin, where wells typically yield from 1 to 3,000 gpm. The topography over carbonate rocks, which is characterized by sinkholes, caverns, and lack of surface streams, is termed karst. AR possibilities in caves in carbonate rocks of Colorado are discussed later in this section.

The major sedimentary rock aquifers in Colorado consist predominantly of sandstones and limestones of varying ages. Many of these aquifers are located in structural basins that contain multiple geologic units and aquifers such as the Denver, Raton, San Juan, Paradox, Piceance, and Sand Wash Basins. Due to their convex structure and perimeter outcrop areas, these basins represent multiple aquifer systems and wells may penetrate several geologic units. The majority of sedimentary rock aquifers within the state's structural basins are under confined conditions. The hydraulic characteristics of these aquifers vary significantly with location and depth, with well yields from 50 to 1,500 gpm. Other sedimentary rock aquifers, such as the Cretaceous Dakota and Cheyenne sandstones and the High Plains aquifer, are relatively flat lying and are present throughout large portions of the state. The Dakota-Cheyenne aquifer is most prolific in the southeast portion of Colorado, yielding from 50 to 1,000 gpm, where the aquifer is at, or near, the surface. The High Plains aquifer has been used extensively for irrigation in eastern Colorado, with well yields averaging 300 gpm. The state's major structural basins and sedimentary rock aquifers are presented in **Figure VII-2**.

The aquifers that occupy the mountainous regions of Colorado include fractured crystalline-rock and volcanic rocks, valley-fill deposits, and intermontane park sequences. Fractured igneous and metamorphic rocks, as well as volcanic rocks, form the backbone of the states major mountain ranges and provide much of the domestic water supply in the mountainous regions. Well yields in these aquifers are typically only a few gallons per minute, and fracture porosities are less than one percent. The intermontane parks such as North and South Park, on the other hand, contain thousands of feet of sedimentary rocks that were not eroded during the uplift of the Rocky Mountains. The state's mountainous region aquifers are presented in **Figure VII-3**.

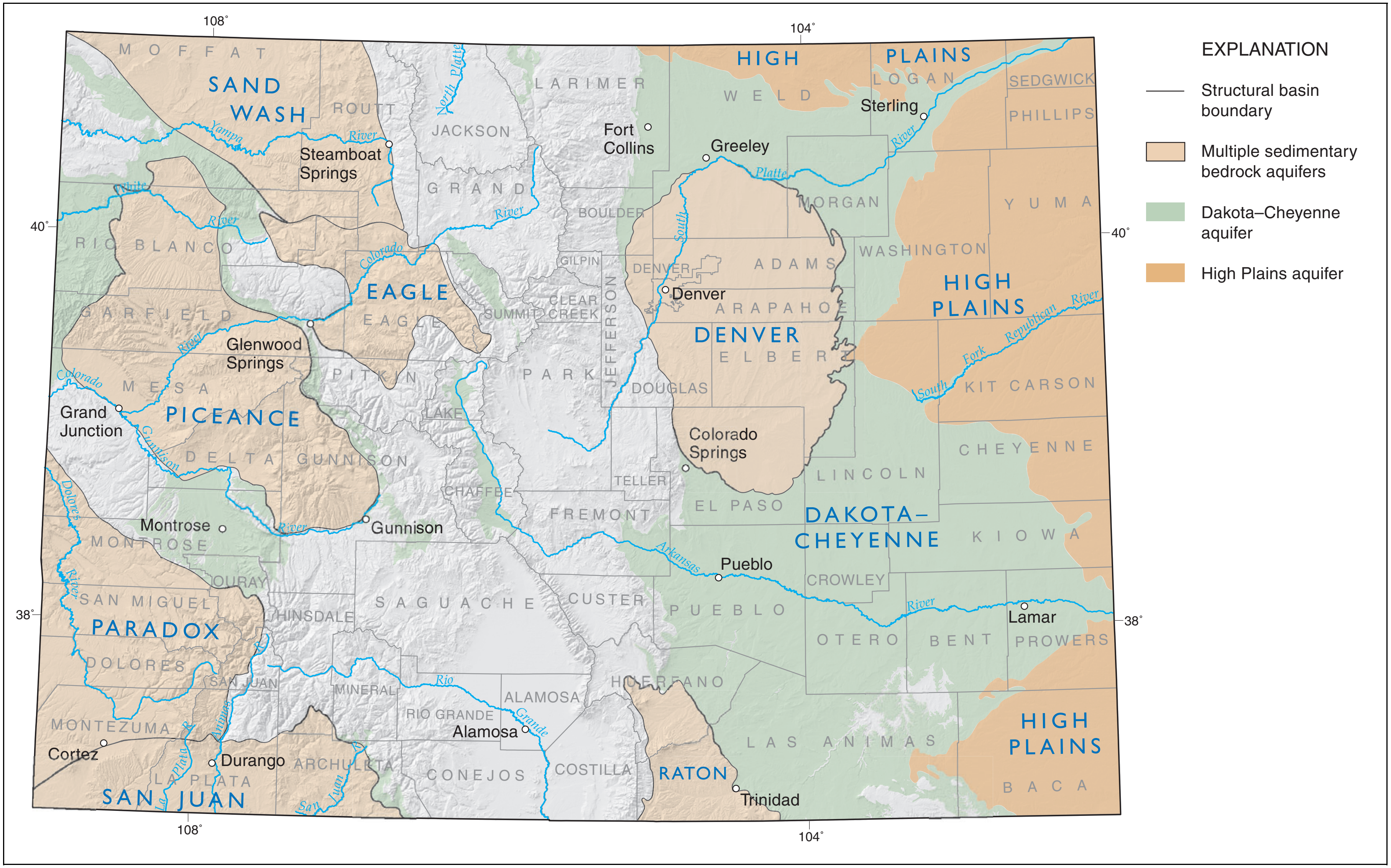


Figure VII-2. The major sedimentary rock aquifers in Colorado consist predominantly of sandstones and limestones. Many of these aquifers are located in structural basins that contain multiple geologic units/aquifers.

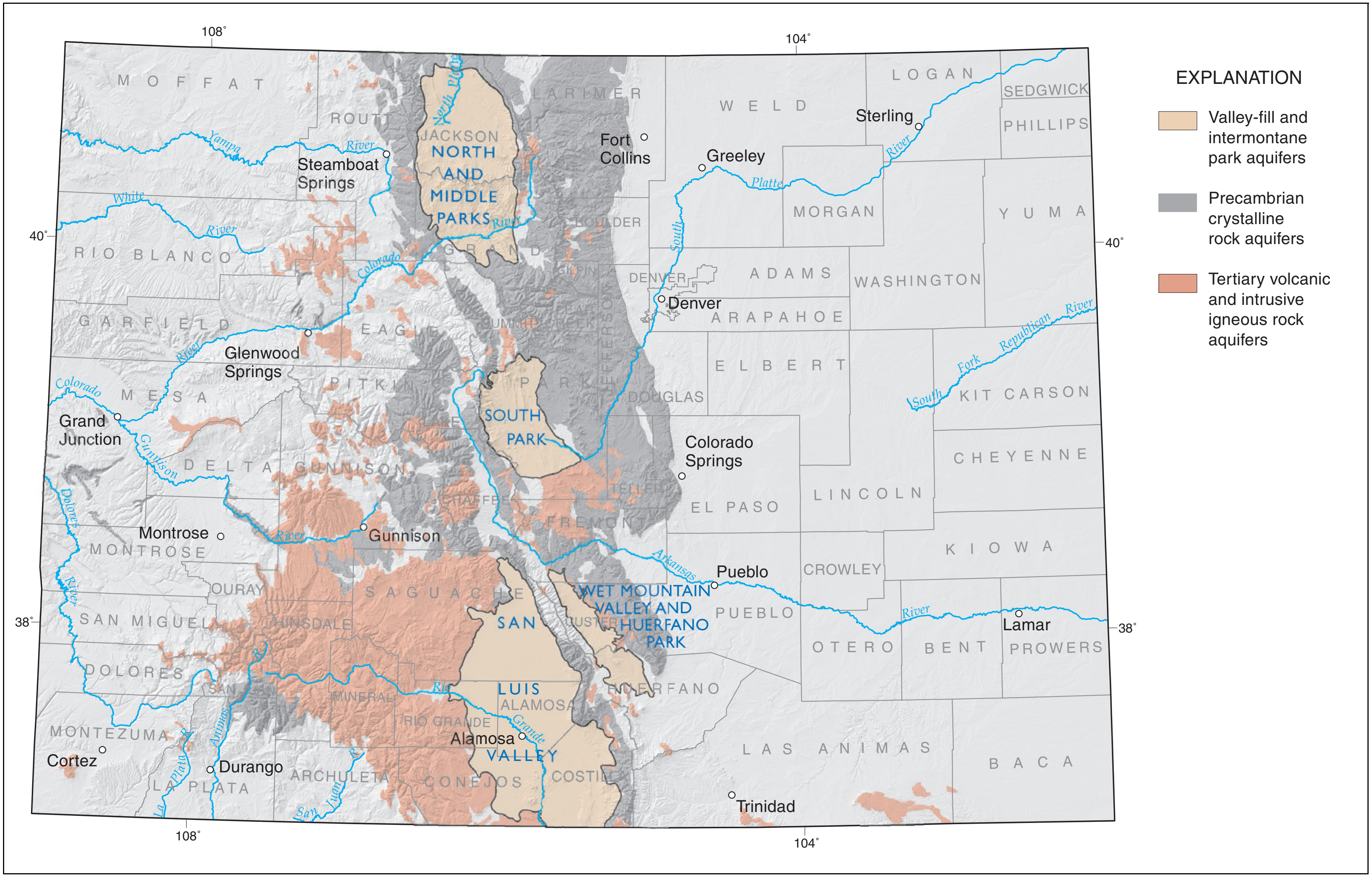


Figure VII-3. **The aquifers that occupy the mountainous regions of Colorado include fractured, crystalline-rock, volcanic rocks, valley-fill deposits, and intermontane park sedimentary sequences.**

Hydrogeologic Conditions Favorable for Recharge

Hydrogeologic studies are the critical element, and typically most time-consuming component of an AR feasibility assessment. Careful evaluation of an area's hydrology and geology can lead to the identification of aquifers suited for AR, available sources of recharge water, selection of treatment options, and application of recharge technologies. Aquifers are classified as either unconfined or confined. The top of the saturated interval, or water table, in an unconfined aquifer is at atmospheric pressure and is free to move up or down as water is added or withdrawn from the aquifer. Unconfined aquifers are recharged by deep percolation from the land surface or by streambed infiltration. The water in a confined aquifer is under pressure, as the aquifer is sandwiched between impermeable layers. The water level in a well completed in a confined aquifer rises above the physical top of the aquifer. Confined aquifers are recharged at their outcrop areas where the aquifer has become unconfined and by minor vertical leakage through the confining layers.

Aquifers provide two important functions: they transmit ground water from areas of recharge to areas of discharge, and they provide a storage medium for usable quantities of ground water. The means by which confined and unconfined aquifers yield water is also an important distinction. Unconfined aquifers yield water from storage by vertical drainage of water within the pore spaces. Injection or withdrawal of water in an unconfined aquifer results in a change of the saturated thickness of the aquifer. Confined aquifers yield water from storage from the compressibility of the mineral skeleton and the expansion of pore water. In the case of a confined aquifer, the saturated thickness remains constant.

When the water level of an aquifer changes, water will either be stored or expelled. The quantity of water that will either be stored or expelled per unit surface area per unit change in water level is defined as the storage coefficient. Because of the physical differences between confined and unconfined aquifers, the storage coefficient of an unconfined aquifer is orders of magnitude higher than that of a confined aquifer.

Significant quantities of water can only be stored when an aquifer is of suitable extent and thickness, and has sufficient porosity and permeability. The amount of volume in storage can be expressed as:

$$V_s = SA\Delta h$$

Where S is the aquifer's storage coefficient, A is the aquifer's area, and Δh is the change in water level or hydraulic head.

For AR considerations, the amount of water-level rise available within the aquifer is dependent upon the ambient or static water level. For example, if water levels in an alluvial aquifer are 10 feet below ground surface, the available head or freeboard may only be five feet without impacting surficial structures (i.e. flooding basements). These five feet of available head, however, may translate into a large storage volume if the areal extent of the aquifer is large. While an aquifer's area is an important factor in the evaluation, it must be considered in the context of the objectives of the proposed recharge project. The geographic extent of an aquifer is a primary factor in computing the amount of water in storage. Implementation of a recharge project, however, generally occurs on a local scale and depending upon recharge rates, far-field effects may not be realized for decades. As such, the impact of an individual recharge project may be dwarfed by the regional storage capacity present in large, extensive aquifers.

To put the concept of total storage capacity into perspective, consider a comparison between an equivalent sized confined and unconfined aquifer with 10 feet of available water storage above the ambient water level. Assuming an area of 100 square miles, a confined aquifer with a smaller storage coefficient of 0.0005 can store 160 acre-feet of water while an unconfined aquifer with a storage coefficient of 0.10 can store 32,000 acre-feet in the same volume. Clearly for a given volume or unit change in water level, an unconfined aquifer can store or yield significantly more water. In addition to the volume available for storage, the hydraulic characteristics of the aquifer will determine the rate at which water can be injected or extracted.

The physical properties that make rocks and sediments good aquifers are the key characteristics assessed in selecting an aquifer for AR. Excluding issues of water rights and recharge water sources, a hydrogeologic evaluation of a ground-water basin should consider:

- Surface topography
- Geologic structure and stratigraphy
- Surface soil and unsaturated zone characteristics
- Number and extent of aquifers
- Aquifer hydraulic characteristics (storage coefficient, hydraulic conductivity, saturated thickness, hydraulic gradient)
- Historic and current water levels
- Aquifer depth and unit thickness
- Water quality

Application of AR technologies is very dependent upon the depth to the top of the aquifer. In general, water-supply well depths rarely exceed 2,500 feet below ground surface. This is largely an economic consideration with deep wells incurring increased construction and operation expenses, as well as a water quality concern as aquifers generally become more saline with depth. Aquifers that are at or near the land surface are suitable candidates for surface and subsurface infiltration methods, while deep aquifers can only be recharged by direct injection. The characteristics of the overlying surficial soil and unsaturated zone materials (porosity, percolation rates, impeding layers, etc.) must also be considered for surface spreading and unsaturated zone recharge applications, because these properties determine the rate at which water will infiltrate the subsurface.

The head freeboard or amount of water level (potentiometric) rise available within the aquifer is dependent upon the ambient, or static, water level. An aquifer whose water level is at or near the surface does not have sufficient head freeboard to accommodate much additional storage. Since recharge produces a rise in water levels, project design must consider the impacts to surface structure, land use, potential sources of contamination, and increased surface-water discharge. Because water levels in unconfined aquifers vary seasonally, an understanding of the historic water levels is critical. The head freeboard, in combination with the area and storage coefficient, determines the amount of available additional storage an aquifer can handle. Deep confined aquifers may have hundreds of feet of available head freeboard, while shallow unconfined aquifers have only tens of feet.

Finally, the rate at which water is transmitted through the aquifer is dependent upon the aquifer's hydraulic conductivity and the hydraulic gradient. This parameter is strongly dependent upon the porosity and permeability of the material. Hydraulic conductivity is also a function of the fluid, with density and temperature affecting the viscosity of water. The hydraulic conductivity of earth materials varies by several orders of magnitude. Unconsolidated sand and gravel aquifers as well as cavernous carbonate rocks have values of 100 to 10,000 feet per day, while values in consolidated sandstone aquifers may range from 0.1 to 0.0001 feet per day. Thus for recharge project considerations, hydraulic conductivity represents the volume of water that will move through a unit area in a unit time under a unit hydraulic gradient. The hydraulic gradient is the driving force for ground-water movement. The timeframe and amount of water transmitted between an area of recharge and the area of discharge will be dependent upon the hydraulic conductivity and gradient of the aquifer.

Application of AR Technologies to Colorado Aquifers

Section III describes technologies used for AR and provides Colorado examples for each technology where identified in the AR inventory. This section describes which technology would be appropriate for each of the aquifer systems evaluated.

Table VII-1 lists the general aquifer systems in Colorado along with possible AR technologies that could be applied in those aquifer systems. Included are general considerations that should be addressed before any detailed evaluation of particular technologies can be made. Detailed design of an AR application is highly site specific and cannot be made until a proposed AR site has been thoroughly characterized; therefore, this section provides very general guidelines regarding applications of technologies to the aquifers.

Table VII-1.
Applicable Technologies for Colorado Aquifers

Aquifer System	Technology	Considerations
Unconsolidated Sedimentary Aquifers	• Surface Infiltration • Subsurface Infiltration • Direct Injection/ASR • Detention dams • Ground water dams	• Project objectives • Available land area and land-use • Presence/absence of impervious layers • Depth and aerial extent of aquifer
Consolidated Sedimentary Aquifers	• Surface Infiltration • Direct Injection/ASR	• Project objectives • Available land area and land-use • Stratigraphy • Outcrop characteristics
Fractured Bedrock Aquifers	• Surface Infiltration • Subsurface Infiltration	• Project objectives • Available land area and land-use • Outcrop characteristics
Carbonate Aquifers	• Natural Openings • Direct Injection/ASR	• Project objectives • Outcrop characteristics • Stratigraphy
Abandoned Mines	• Adits/Shafts • Direct Injection/ASR	• Project objectives • Mine characteristics

Non-Aquifer Geologic Storage Options

There are several types of unconventional, non-aquifer geologic storage options. This study considers these storage options as a specific type of AR, called *underground water storage*. Underground water storage is the storage of water beneath the ground surface in natural or human excavated voids such as mines or caves. Strictly speaking, caves are generally part of larger carbonate rock (limestone, dolomite) aquifers, but are treated separately here because of the potential for open void space that could be artificially recharged.

Abandoned Coal Mines

A literature review was conducted of existing water storage and recovery projects in abandoned coal mines to evaluate the storage potential of this media in Colorado. Nationally, coal mines are currently being utilized for water storage with most of the active projects located in the Central Appalachia Coal Basin. In Central Appalachia, abandoned coal mines are being used to supply selected municipalities in West Virginia, Kentucky, and Ohio. All of these water-supply projects use mines that are naturally recharged rather than artificially injected.

Successful water storage deployment in coal mines is very dependent upon the hydrogeologic characteristics of the mine environment and surrounding host rock, and geochemical interactions that influence water quality. Roof collapse and associated surface subsidence represent additional safety and logistical concerns. The quantity of water available for extraction from abandoned underground coal mines is dependent on the mined-out void space and rate of natural ground water recharge into the mine. In the Appalachia region, many public water suppliers have experienced difficulties in obtaining dependable water supplies from coal mines because of erratic fluctuations in the quantity and chemical quality of the water (Ferrell, 1992). Coal mines respond differently to pumping and injection than do natural ground-water systems. Recharge rates vary according to local climatic conditions, proximity and elevation of adjacent stream courses, lithologic variations in the overlying rocks, the amount and depth of fracturing in those rocks, and the watershed area (thus, infiltration potential) draining into the mine. The Appalachia experience indicates that the total volume of stored water cannot be recovered. Mine configuration, roof collapse, and leakage from the mine limits the amount of stored water.

Colorado contains eight major coal regions **(Figure VII-4)**. In terms of abandoned coal mines, Colorado has over 1,700 locations (Carroll and Bauer, 2002); 1,430 of these are underground mines. They vary in size, but only 141 are considered large mines; that is, having produced more than 1 million tons of coal. These large mines, as well as hydraulically connected smaller mines, are considered the best candidates for significant underground water storage projects in Colorado.

Based on the distribution of the large mines, a total of eleven potential storage sites were identified for Colorado (Figure VII-4). More than 650 million tons of coal was produced from these sites (**Table VII-2**). To convert tons of coal produced to an equivalent mine volume in acre-feet, the following relationship was used:

Coal density (in tons/cu ft) x tons of coal produced / 43,560 cu ft / ac-ft

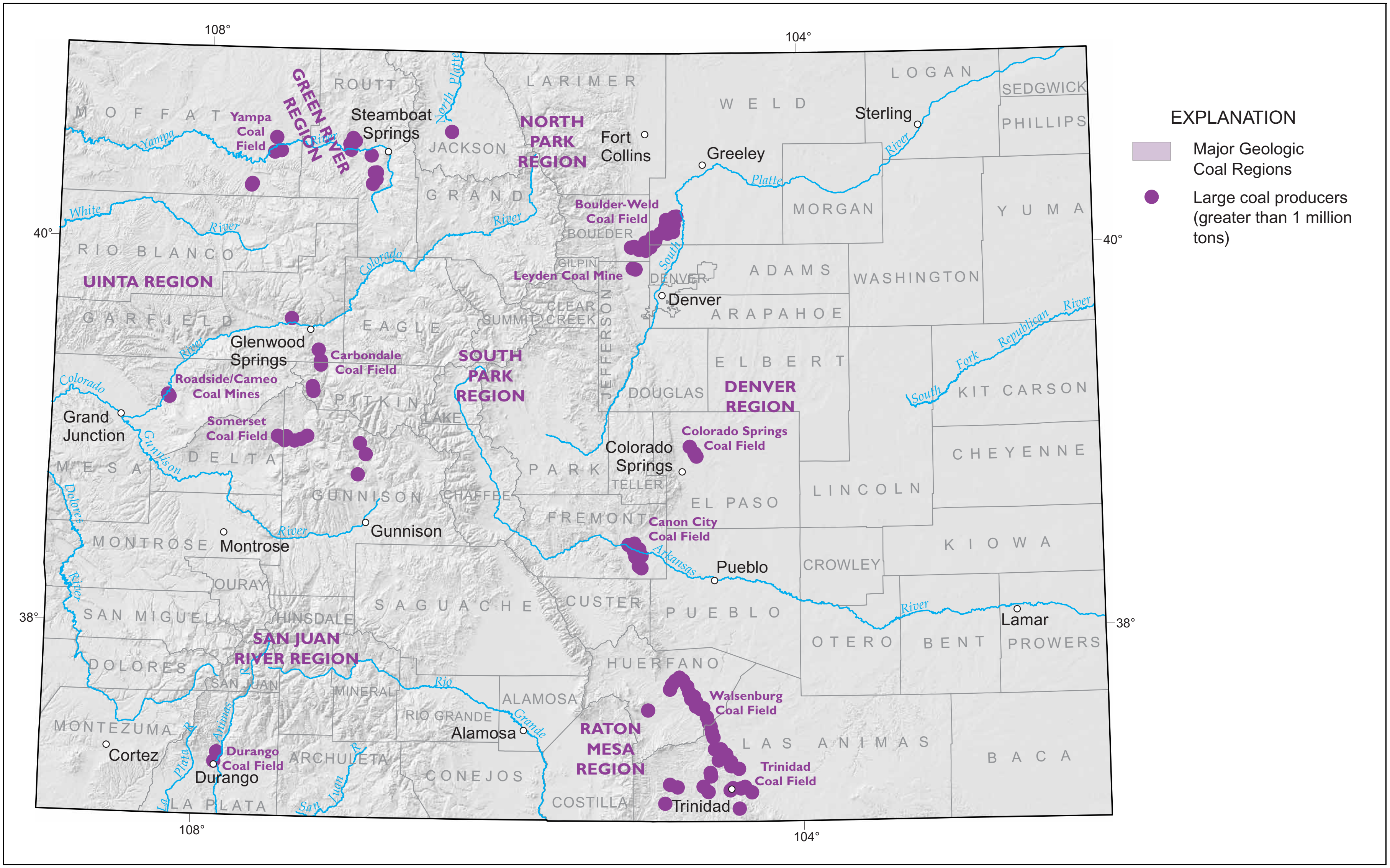


Figure VII-4. **Major Colorado coal regions with selected large abandoned underground mines. The 11 primary coal field or coal mine locations for underground water storage are identified. Potential capacities at these sites vary from 3,000 to 51,500 acre-feet (Table VII-2).**

In most cases, Colorado coal was produced by the room-and-pillar method, the preferred mining method prior to World War II. This type of mining is more suitable for underground water storage as the remaining void space in the mine may provide a substantial volume for water storage. Longwall mining, the method of large underground mining today, results in a larger area being mined but causes subsidence immediately behind the extraction panel. With this method, the void space remaining is completely transferred into subsidence of the overburden rock called the 'gob' zone, which may not provide water storage opportunities. To adjust mine volumes for subsidence and the associated reduction in storage volume (wet or dry), the calculated storage volume based on production was reduced by 50 percent.

Many abandoned mines are already full of water through natural recharge. In these cases, the existing mine water may be produced but there is no 'dry' volume available for incremental storage. Partially filled or dry mines provide greater opportunities for artificially storing water. For each of the storage sites listed in Table VII-2, an estimate of both the dry and wet storage volume was made. To achieve this, water-level data available from the Division of Water Resources were compared to overburden maps for mine areas such as Boulder/Weld coal field (Roberts and others, 2001). If these data were not available, mining companies and consultants were contacted for additional information.

In eastern Colorado, the primary storage sites are located along the eastern flank of the Rocky Mountains (Figure VII-4). Three storage sites were identified in the Denver Coal Region: Boulder/Weld, Leyden, and Colorado Springs. One storage site was assigned to the Cañon City Coal Region. Two storage sites were identified in the Raton Mesa Coal Region: Walsenburg, and Trinidad. Approximately 435 million tons of coal production is reported for eastern Colorado mines now abandoned. This yields an estimated 123,000 acre-feet of equivalent water volume available for storage. About 85 percent (104,000 acre-feet) of this volume has already been flooded by natural recharge, leaving only 19,000 acre-feet available for new ground-water storage. Most of the abandoned underground mines east of the Rocky Mountains are flooded by natural recharge.

In western Colorado the coal fields identified as possible storage candidates are the Somerset coal field, Durango coal field, Roadside/Cameo mines near Palisade, the Carbondale/Grand Hogback coal fields near Glenwood Springs, and the Yampa coal field (Figure VII-4). Approximately 230 million tons of coal production has been reported from western Colorado mines that are now abandoned. This yields an estimated 64,000 acre-feet of equivalent water volume available for storage. Unlike eastern Colorado where most abandoned mines are flooded, western Colorado mines are generally only partially flooded leaving approximately 36,000 acre-feet available for new ground-water storage.

In aggregate, abandoned coal mines in Colorado do not represent a significant storage volume compared to surface-water reservoirs. Locally, however, underground water storage does provide a viable, alternate water-management strategy to augment existing storage capacities. The success and difficulties encountered in Arvada's Leyden Coal Mine project will determine the extent of implementation of this storage concept.

Table VII-2. Estimated Water Storage for Abandoned Coal Mines in Colorado

Coal Region	Storage Site	County	Coal – Aquifer Interval	Coal Production (Million Tons)	Estimated Water Storage (acre-feet)					
					Unadjusted for Subsidence			Adjusted for Subsidence		
					Saturated	Dry	Total	Saturated	Dry	Total
Denver	Boulder/Weld	Boulder Weld	Laramie Fm Coals – Fox Hills Ss	109	53,000	9,000	62,000	26,500	4,500	31,000
	Leyden	Jefferson		6	1,000	2,300	3,300	900	2,100	3,000
	Colorado Springs	El Paso		14	5,400	2,600	8,000	2,700	1,300	4,000
Cañon City	Cañon City	Fremont	Vermejo Fm Coals – Trinidad Ss	46	25,800	0	25,800	12,900	0	12,900
Raton Mesa	Walsenburg	Huerfano	Vermejo/ Raton Fm Coals – Trinidad Ss	75	35,400	6,200	41,600	17,700	3,100	20,800
	Trinidad	Las Animas	Vermejo/ Raton Fm Coals – Trinidad Ss	185	87,500	15,400	102,900	43,800	7,700	51,500
Uinta	Somerset	Delta Gunnison	Lower B & D Coals	91	20,200	30,400	50,600	10,100	15,200	25,300
	Carbondale	Garfield	Lower A, C, & D Coals	36	5,000	14,900	19,900	2,500	7,500	10,000
	Roadside/Cameo	Mesa	Cameo Coals	24	10,700	2,600	13,300	5,300	1,400	6,700
San Juan River	Durango	La Plata	Menefee Fm	14	2,300	5,300	7,600	1,100	2,700	3,800
Green River	Yampa	Moffat Routt	Iles, Williams Fork	63	17,600	17,700	35,300	8,800	8,900	17,700
			TOTALS	**663**	**263,900**	**106,400**	**370,300**	**132,300**	**54,400**	**186,700**

Abandoned Metal Mines

Inactive underground metal-mining districts throughout Colorado were also investigated to determine their potential water storage capacities. Three evaluation criteria were used to identify potential underground water storage sites:

a) *Water quality considerations*
Many of Colorado's metal-mining districts contain sulfide mineralization in such abundance that water becomes acidic and contaminated with heavy metals within the mines. This is part of the reason that several former mining districts have been designated as EPA Superfund sites. Examples include the Leadville, Gilman (near Eagle), and Summitville mining districts. Yet, on the basis of a map showing metal-mine drainage hazards in Colorado (Plumlee and others, 1995), probable water quality characteristics within mining districts can be identified based on the ore type found there. Only mining districts determined to have minimal adverse effects on water quality were selected for further study. Twenty-five metal mining districts in the state were judged to potentially have good water quality, justifying further study.

b) *Volumetric considerations based on the total amount of ore production*
The 25 mining districts selected, based on favorable water quality characteristics, were assessed for their total amount of ore production. Several CGS and USGS sources were used for this research (Vanderwilt, 1947; Cappa, 1998; Lovering and Goddard, 1950; Beatty, Landis, and Thompson, 1990; Scarbrough, 2001; Cappa and Bartos, in press). In all of these districts, the estimated ore production is a combination of all of the mines that compose each district, which is commonly more than 10 individual mines. Because metal mines have never been required to publicly disclose mine production data, volumes, or detailed mine maps, only rough estimates of total ore production are available. For the same reason, detailed information regarding the maximum depths of the mines in the districts, the amount of ground-water inflow into the mines at various depths, water loss through fractured rock, amount of dewatering required during production (if any), and other information necessary for a comprehensive evaluation of each mining district's potential as a water storage site is commonly lacking from the public record.

c) *Water storage capacity considerations*
Based on the estimated tonnage of ore produced in each of the 25 metal mining districts with good to moderate water quality, the maximum potential water storage capacity of each district was calculated. Using a tonnage factor of 12.5 (12.5 cubic feet of rock per ton of ore), the volume of ore produced was estimated. An additional volume was separately added to account for the non-ore mining of development workings such as access tunnels, drifts, cross cuts, and shafts. A rough estimate of 50 percent of total ore production was used in this calculation of additional, non-ore volume. Therefore, the total volume of mine workings equals 1.5 times the volume of ore produced. Each mine in each district is different, of course, but as previously stated, detailed underground mine records are generally not available to the public. The ore volumes and non-ore volumes were added for each district, and the total volume was then converted to acre-feet. The volumes calculated by this method are considered to be maximum potential water storage volumes. Because of the limited data and highly variable characteristics of ground water in the mountainous terrain, and the

heterogeneous, fractured rocks that characterize most Colorado mining districts, no estimation was made of the water levels that certainly already exist in many of the abandoned mines in the state. Similarly, no estimate was made regarding the loss of volume that occurs due to collapsing of the mine workings.

The total calculated maximum storage capacities of all of the metal-mining districts in Colorado that can sustain good or moderate water quality is 22,220 acre-feet. Only 3 of the 25 mining districts were calculated to have more than 1,000 acre-feet of maximum potential water storage capacity. Only two other districts have maximum potential capacities of more than 100 acre-feet. The five metal-mining districts with the greatest maximum potential water storage capacities are listed in **Table VII-3** and shown on **Figure VII-5**.

Table VII-3. Metal mining districts with the greatest maximum water storage capacities

Mining District	County	Maximum Potential Water Storage
Cripple Creek district	Teller County	17,218 acre-feet *
Aspen district	Pitkin County	1,894 acre-feet
Alma (Buckskin/Mosquito) district	Park County	578 acre-feet
Silver Cliff/Westcliffe/Rosita district	Custer County	120 acre-feet
Granite	Lake	39 acre-feet

* Real storage volume is much lower due to the active Cresson Mine's removal of many old workings included in this calculation

The currently active open-pit mine at Cripple Creek was not included in the volume calculation. The open-pit mine is in the heart of the historic Cripple Creek mining district. Current mining activity often exposes the old underground workings to the open air, destroying their potential as underground water storage sites. Thus, the volume we have calculated for potential water storage in the Cripple Creek district is probably significantly higher than the actual capacity at this time.

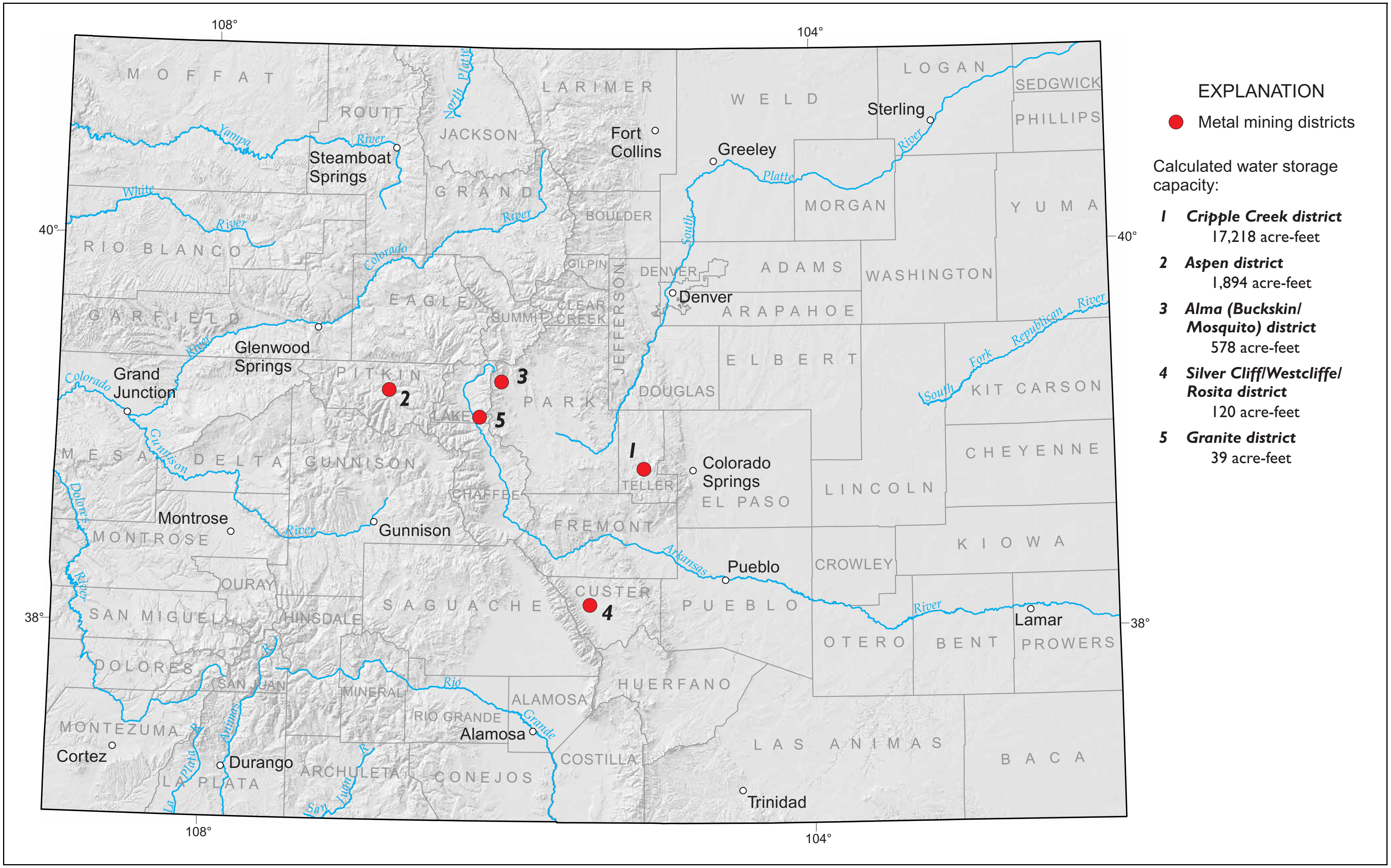


Figure VII-5. Selected major Colorado metal mining districts. Five primary metal mining districts for potential underground water storage were selected based on water quality and storage capacity considerations. Only districts with relatively low acid-mine-drainage potential were evaluated.

Additional Considerations

Significant costs would be incurred to seal the mines to maintain hydraulic control of injected water. Most metal-mining districts are in steep, mountainous terrain deeply dissected by streams. Mines in these areas are primarily accessed through adits (horizontal workings that intersect the land surface). Each mine of this type would need one or more engineered plugs, depending on the number of adits, to limit water drainage out of the workings. The cost of engineered plugging of an adit is site specific, but ranges from approximately $100,000 to $300,000 (Larry Perino, Sunnyside Mine, oral commun., 2003). Therefore, if normally more than 10 individual mines make up a mining district, construction costs to store the amount of water identified in Table VII-3 would be $1,000,000 at a minimum and possibly several times higher. Also, this cost does not include the infrastructure to bring source water to the site and to retrieve and distribute stored water.

Mine workings often intersect subsurface faults and fractures that commonly extend to the ground surface. These can serve as additional conduits to drain water out of the mine. In most situations, a metal (hardrock) mine will be a leaky storage vessel. Leakage of stored water from the mine will likely cause impacts outside of the project area that are difficult to predict.

Natural Caves

Like abandoned mines, natural cave systems represent subsurface void space that may be suitable for underground water storage. Colorado contains a few hundred caves scattered throughout the mountainous western part of the state (**Figure VII-6**). Many of Colorado's caves are found in the Mississippian Leadville Limestone, but they also occur in the Manitou, Fremont, Minturn, and Honaker Trail formations. Most of these caves are small with less than 100 feet of passage. However, there are concentrations of longer caves in the White River Plateau (Garfield County), Lime Creek Wilderness (Eagle County), Sangre de Cristo Mountains (Custer County), and in Williams Canyon (El Paso County). Colorado reportedly has only 12 caves with passages greater than one mile in length (Rhinehart, 2003). Of these, seven are on public land managed by the USDA Forest Service, one is within land managed by the Bureau of Land Management, and the other four are on privately-owned parcels.

Published information on caves and karst in Colorado is sparse, with only three books specifically written about caves in the state. The most comprehensive publication about caves is the quarterly journal *Rocky Mountain Caving*, edited by Richard Rhinehart. This journal provides historical, scientific, and anecdotal information on caves, but specifically avoids publication of cave locations. Because caves are fragile, non-renewable resources, people within the cave exploration and scientific communities have learned that secrecy is the best protection, and location information is closely guarded. Caves on public land became officially protected with the passage of the Federal Cave Protection Act of 1988. The purposes of this Act are to secure, protect, and preserve significant caves on Federal lands for the perpetual use, enjoyment, and benefit of all people, and to foster increased cooperation and exchange of information between governmental authorities and those who use caves located on federal lands for scientific, educational, or recreational purposes.

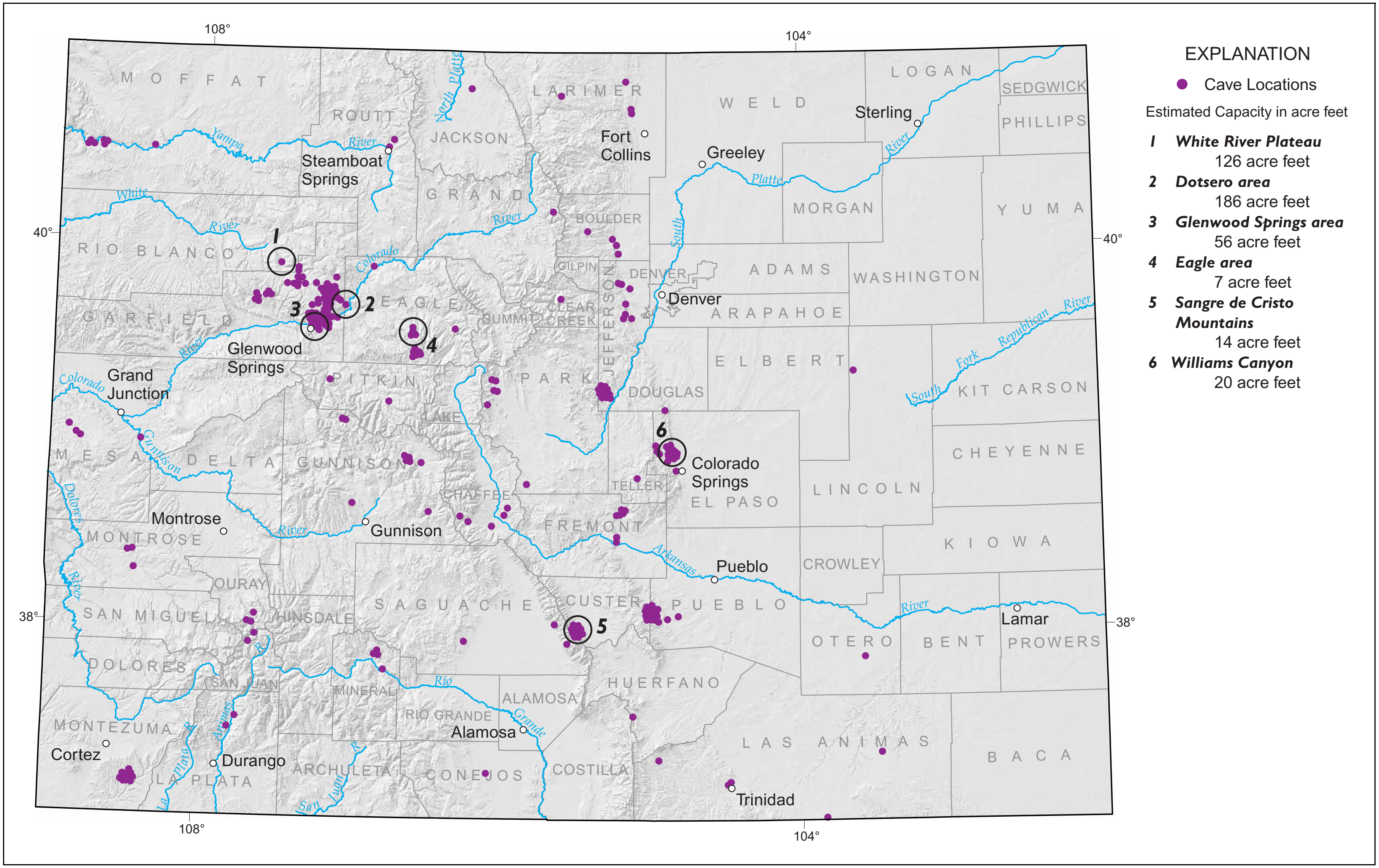


Figure VII-6. General location for large cave systems in Colorado. This map identifies the areas containing the 12 longest caves in the state. In some areas, several caves and their storage capacities are combined.

The 12 longest caves in the state were analyzed for their potential as water storage sites. These represent caves with greater than one mile of passage. Most Colorado caves do not contain permanent flowing streams. All of the known caves in the state are above the water table. Pertinent information and estimated water capacity storage volumes for the 12 largest caves in Colorado are presented in **Table VII-4**. The total maximum storage capacity of all known caves with more than one mile of passage is approximately 450 acre-feet. Eighty-six percent of this potential storage capacity is within caves on public land, and the remaining 63 acre-feet are in privately owned caves. Spring Cave in Rio Blanco County has the greatest storage capacity with 125.8 acre-feet.

The bedrock that contains the caves is faulted and jointed, with cave passages developing by selective solution enlargement of natural fractures. The predominance of joints, faults, and solution cavities that form these caves also indicates that caves would be a leaky storage medium. Because Colorado's caves are above the water table, stored water would either percolate to the water table or discharge in the form of springs and seeps. Limited storage capacity, leakage of stored water, land ownership issues, and associated regulatory protection eliminates this media from serious consideration for underground water storage.

Table VII-4. Parameters and Storage Volume of the Twelve Largest Caves in Colorado

Cave Name	County	Geologic Formation	Land Ownership	Depth (ft)	Length (ft)	Estimated Volume (sq ft)	Storage Volume (ac-ft)	Flowing Water?
Caves on Public Land								
Spring	Rio Blanco	Leadville	USFS	113	8,765	5,478,000	126	Y
Groaning	Garfield	Leadville	USFS	149	58,893	3,533,587	81	N
Twenty Pound Tick	Garfield	Leadville	BLM	469	5,702	2,851,200	65	Y
Hubbard's	Garfield	Leadville	USFS	50	6,442	2,415,600	55	N
Fixin'-to-die	Garfield	Leadville	USFS	266	21,648	1,082,400	25	N
Premonition	Garfield	Leadville	USFS	179	12,492	624,624	14	N
Spanish	Custer	Minturn	USFS	741	5,755	604,296	14	N
Fulford	Eagle	Leadville	USFS	253	5,306	286,524	7	Y
Subtotal, volume of caves on public land							**387**	
Caves on Private Land								
Glenwood (Fairy)	Garfield	Leadville	private	278	16,315	978,912	23	N
Cave of the Winds	El Paso	Leadville	private	294	11,141	891,264	20	N
Breezeway	El Paso	Leadville	private	?	6,853	548,275	13	N
Huccacove	El Paso	Leadville	private	230	5,291	317,434	7	N
Subtotal, volume of caves on private land							**63**	
Total volume, all caves with >1 mi passage							**450**	

General Considerations

While an understanding of the hydrogeologic conditions and appropriate technologies is paramount for consideration of an artificial recharge project, social and economic factors must also be considered. Several of these are discussed below.

Rural vs. Urban
The cost to extract and deliver water stored in the recharge project is a consideration in its proposed use. Urban areas, generally, can afford a higher cost for water than rural or agricultural areas. Therefore, some technologies may be cost effective for urban water supply, but not for agricultural water supply.

Large vs. Small Scale
The opportunity to store water in aquifers conducive to high-volume recharge, storage, and extraction can be attractive. Optimum storage locations may not coincide with areas where water is needed, thus requiring higher cost delivery systems. Small, targeted AR projects may be more effective in meeting local needs, and can be tailored to meet the water-supply needs in that area. A proliferation of smaller projects could store significant amounts of water in aggregate, meeting the same goal for water storage as a single large project.

Environmental
Because of its limited impact on the land surface, implementation of an AR project usually has fewer environmental issues to overcome than a comparable surface-water reservoir project. Nevertheless, environmental impacts must be assessed during the planning stages of a recharge project. This same process can be used to educate affected citizens of the benefits of this type of water storage.

Environmental protection benefits of AR into unconfined aquifers include protection of endangered species habitat and the maintenance, enhancement, or creation of wetlands. Wetlands consist of wet meadows, small vegetated pools in the alpine tundra, cattail marshes in some of the urban areas and areas of vegetation along rivers and streams. Wetlands are key components to a balanced natural environment that provide habitat, social, and environmental benefits. Wetlands help maintain hydrologic control by storing water during flood events, maintaining stream flow during dry periods, and recharging ground water. They are instrumental in improving water quality, and provide critical habitat for a diverse range of wildlife.

Wastewater for Recharge
A number of AR projects around the U.S. use treated wastewater for recharge. Technically, this practice has been applied successfully for over 30 years (U.S. Geological Survey, 1978). Municipal wastewater is a significant water source that is ideal for reuse in water short areas. In Western states governed by the prior-appropriation doctrine, this type of beneficial use may require a new water right. Unfortunately, public perception of the use of wastewater for additional water supply can be negative because of water quality concerns. This can be an obstacle to implementing this type of project. Public education about geopurification with the resulting good water quality (see Section III Manage/Mitigate Water Quality) and conservation benefits can usually overcome negative public sentiment.

Institutional Issues
Institutional constraints can be some of the biggest impediments to implementing effective AR or underground storage programs. Several factors can contribute to institutional difficulties, including

- lack of access to, or ownership of, source water;
- lack of access to, or ownership of, a suitable recharge site;
- higher priority water management programs that consistently limit the consideration of AR;
- institutional rules or bylaws that limit operational flexibility to include AR technologies; and
- a regulatory framework that limits implementation of the optimal AR method for a project or even prohibits the possibility of using AR.

Assessing these potential difficulties early in the project scoping process can lead to dialogue and resolution of issues, engendering greater support for the AR project.

Water Quality Considerations

Water quality is also a key consideration for both source and recovered waters. Quality issues are paramount in meeting anti-degradation regulations and drinking water standards. The quality of the source water also has an impact on recharge project operations and maintenance. Water quality considerations include (1) meeting the appropriate regulatory standards, (2) chemical characteristics that would result in undesirable water quality issues during or after recharge (e.g., algae formation, elevated suspended solids), and (3) chemical compatibility of recharge and ambient water to avoid undesirable consequences such as clogging of the well or aquifer, dissolution of aquifer materials, or increased corrosivity of recovered water.

The ultimate use proposed for the recharge water will dictate the regulatory standards that must be considered. Water to be used for potable purposes will likely have a more rigorous set of standards than water that will be used for irrigation, subsidence abatement, or other uses that do not involve direct human consumption. Pretreatment might have to be considered to bring the water quality up to regulatory standards before the water is recharged to the system.

Chemical interactions can occur between the recharge water and the ambient ground water, or between the recharge water and the aquifer mineral matrix. Chemical interactions can cause a variety of undesirable effects such as plugging. Plugging appears to be the most frequently reported problem in AR systems (Bouwer, 2002).

Surface waters of Colorado can exhibit significant variations in water quality as conditions change from times of snowmelt runoff to times of low-flow conditions or drought. In addition to seasonal changes, surface water typically is in a more chemically oxidized state than ground water, or may have significantly different concentrations of dissolved gases. Mixing waters of different chemical characteristics may lead to chemical reactions that cause mineral precipitation or dissolution. Additionally, conditions might be favorable for the formation of biologic communities in the recharge setting that did not previously exist before the AR process, such as formation of algae on infiltration systems.

If disinfection is required of recharge water, various water-quality issues could arise that will need to be addressed during design (Pyne, 1995). For example, the use of chlorine gas to treat water could result in a decrease in pH, with the possible consequence of increasing the corrosive properties of the water. Additional treatment to raise the pH might be required before the water is useable. The use of disinfection agents could result in the production of undesirable disinfection byproducts, for example chlorine producing trihalomethanes or haloacetic acid. A monitoring program may need to be implemented to assess the levels of disinfection byproducts.

VIII. Artificial Recharge Implementation Options

Aquifer Ranking

For economic and water quality considerations, water supply wells are generally less than 2,500 feet deep. As such, those geologic formations that lie at or near the surface also represent the primary aquifers. Because aquifers consist of rock or sediment within a geologic formation, the state's geologic complexity produces a variety of regional aquifers that may be tapped for beneficial uses.

Geologic units consist of either unconsolidated sediments or consolidated rock. This general distinction then forms the basis upon which to categorize Colorado's principal aquifers for assessment purposes. Unconsolidated, coarse-grained sediments, such as alluvial deposits, represent the more prolific aquifers. These deposits are geologically young, being of Quaternary age (1.8 million years or younger), and are considered tributary to the stream and river systems of the state. For the purposes of this assessment, all of the mapped, Quaternary-age alluvial deposits (Figure VII-1) have been included in the unconsolidated group. Since an aquifer's areal extent is one of the dominant parameters in determining its storage capacity, and we were looking for large storage-capacity aquifers, we have only evaluated alluvial deposits whose area exceeds 80 square miles in aggregate. The unconsolidated sedimentary aquifers meeting this area criterion were considered the priority unconsolidated, alluvial aquifers which are shown on **Figure VIII-1.**

Consolidation is the lithification of loose sediments to form a sedimentary rock. The sedimentary rocks of Colorado are either composed of fragments of pre-existing rock or formed by precipitation of minerals. The major sedimentary rock aquifers in Colorado consist predominantly of sandstones and limestones (Figure VII-2). The fractured, crystalline-rock aquifers, common in the mountainous regions of Colorado, were not evaluated in this assessment of recharge potential due to their low porosity and permeability. They should not be dismissed for potential local-scale projects in areas where these rock types dominate, but their hydraulic characteristics are not adequate for large-scale recharge considerations. For this assessment, sedimentary rock aquifers that are currently being tapped for water supplies and those with the potential to be used have been evaluated. As in the unconsolidated category, a minimum area criterion was established. For the consolidated aquifers this equated to 100 square miles. The locations of the priority consolidated, bedrock aquifers are presented on **Figure VIII-2**.

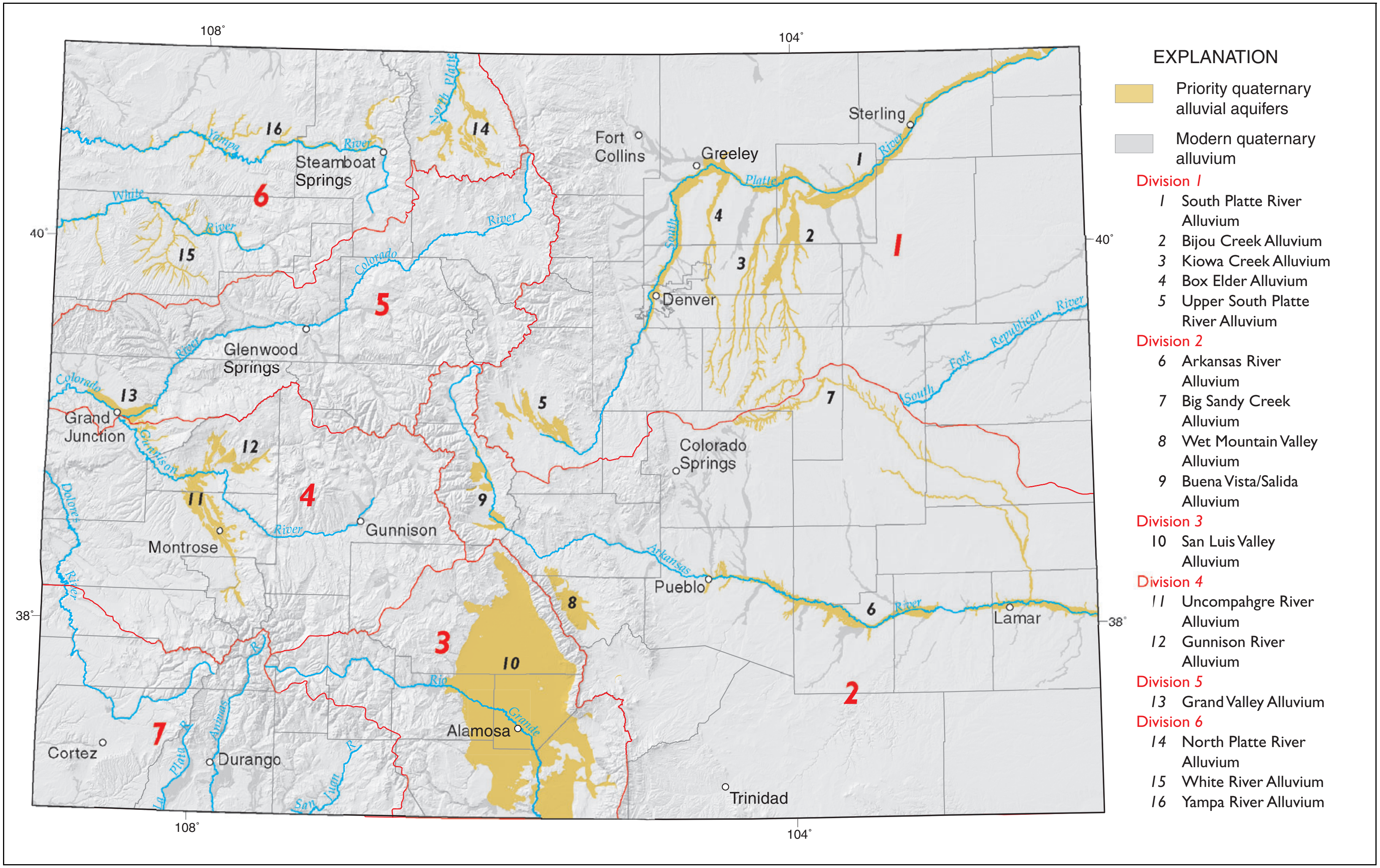


Figure VIII-1. **Sixteen preferred areas of Quaternary-age unconsolidated deposits were identified as priority candidates for artificial recharge implementation.**

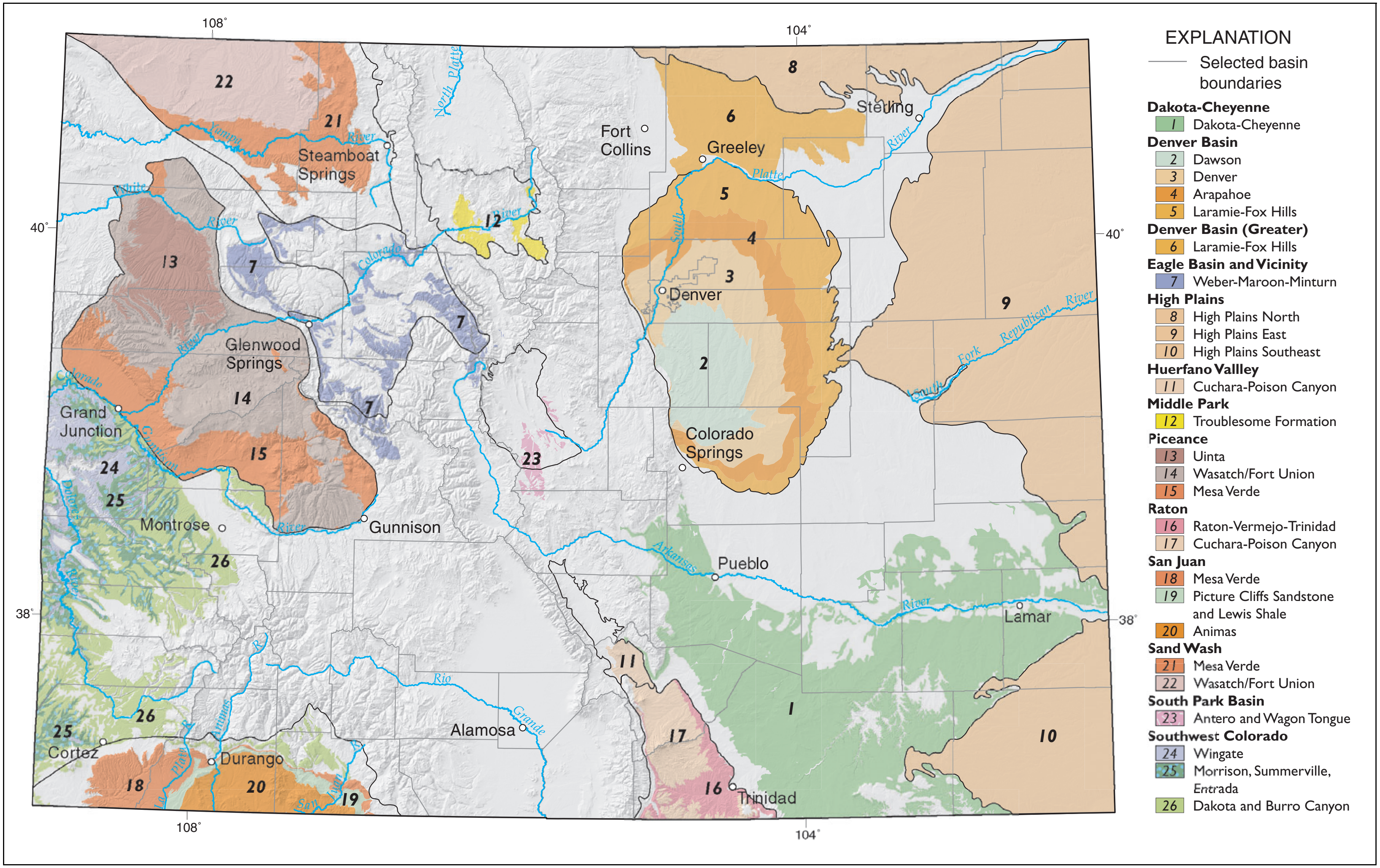


Figure VIII-2. Twenty-nine consolidated-rock aquifers, throughout the state, were identified as priority candidates for artificial recharge implementation.

Both consolidated sedimentary rock aquifers and unconsolidated sediment aquifers were ranked based on the parameters identified in the previous Section VII. That section discussed the relationship and importance of those hydrogeologic conditions or parameters paramount for AR implementation. These include

- areal extent,
- depth to top of formation,
- saturated thickness,
- head freeboard,
- storage coefficient, and
- hydraulic conductivity.

Based on the published data, a value range was established for each of these physical parameters. The various ranges were then assigned a weighted rank that considered not only the importance of that particular parameter as applied to AR potential but also the actual value of the parameter within the published range.

In addition to calculating a final ranking for the aquifer, the quality of the input data was assessed. Published, field-derived, hydrogeologic parameter data were used where available. For aquifers having little or no published data, standard reference values for hydrogeologic parameters based on geology were used. Therefore, a quality indicator value was calculated to provide a gauge upon which to assess the quality of the results. The quality of the input data must be considered as well as the project objectives when interpreting these aquifer rankings.

This weighting and ranking scheme was implemented as an Excel spreadsheet and copies of both the unconsolidated and consolidated spreadsheets are attached as **Appendices B and C**, respectively. The objective of this analysis was to identify those aquifers within the state with hydrogeologic characteristics favorable for large-scale AR implementation. This ranking is based solely on scientific and engineering parameters of the aquifers. It does not include factors such as source water, water transport infrastructure, construction economics, legal constraints, and other important considerations.

In addition to assigning a ranking and quality value to each of the aquifers evaluated, the storage capacity was also calculated. For the unconsolidated alluvial aquifers, the storage capacity was expressed as the number of acre-feet of storage per surface acre, the total available recharge storage capacity, and the total aggregate storage capacity of the aquifer. The results of this aquifer ranking analysis for the 16 priority unconsolidated, alluvial aquifers are summarized in **Table VIII-1**. Two alluvial deposits of the South Platte River and one on the Arkansas River are the top three ranked aquifers. All of the aquifers listed in Table VIII-1 are viable candidates for implementation of AR projects.

Table VIII-2 summarizes the results of the aquifer ranking analysis for the 29 priority consolidated, bedrock aquifers that met the selection criterion. In addition to the ranking and data quality values, the storage capacity per acre and potential available additional storage capacity for recharge are listed. Because these bedrock aquifers are partially confined and partially unconfined, the total storage capacity of the aquifer was not calculated due to the differing storage coefficients. As in the unconsolidated alluvial aquifers, the ranking value is a function of the aquifer characteristics only and not dependent upon the storage capacity. The per-acre storage capacity may be a more important factor in selecting an aquifer for implementation of an AR project, but the project objectives and preferred technology will guide the aquifer selection process. An aquifer's site-specific transmissivity will be the limiting factor in pumping and injection rates for artificial recharge. This limitation would most likely require a well field. Surface storage or other means of capturing high-runoff flows is often necessary to provide a continual source of water to the well field.

The consolidated, bedrock aquifers listed in Table VIII-2 are within near-surface geologic formations that are either currently being put to beneficial uses or have the potential to be used for water supply. The High Plains Aquifer, Dakota-Cheyenne Group of southeast Colorado, and the Denver Basin aquifers are the top three ranked aquifers in this category. Many of these aquifers are located within structural basins, and as such they dip into the subsurface towards the centers of the basins. Because of the structural dip of these units, portions of the aquifers may be too deep to economically implement recharge projects over their entire extent. The available storage calculation did not account for the inclination of these units, thus the calculated available storage values may represent the maximum potential.

TABLE VIII-1.
SUMMARY RANKING OF UNCONSOLIDATED ALLUVIAL AQUIFERS

Basin or Area	Aquifer	Ranking Value	Quality Value	Storage (ac-ft)		
				Per Acre	Total (thousands)	Available (thousands)
Lower South Platte River	South Platte River Alluvium	132	20	6.0	4,650	2,320
Lower South Platte River	Bijou Creek Alluvium	128	17	5.3	2,790	810
Lower Arkansas River	Arkansas River Alluvium	118	18	2.3	4,010	500
San Luis Valley	Quaternary Alluvium	113	18	2.3	15,550	3,890
Uncompahgre River	Uncompahgre River Alluvium	96	17	3.0	1,530	305
Lower South Platte River	Kiowa Creek Alluvium	92	16	5.3	920	405
North Park	North Platte River Alluvium	91	17	4.5	1,530	380
Gunnison River	Gunnison River Alluvium	88	18	2.3	1,175	220
Lower Arkansas River	Big Sandy Creek Alluvium	87	17	4.5	1,130	425
White River	White River Alluvium	81	18	1.5	805	110
Wet Mountain Valley	Quaternary Alluvium	77	16	1.5	1,240	125
Upper Arkansas River	Buena Vista/Salida Alluvium	77	15	2.3	660	125
Yampa River	Yampa River Alluvium	73	17	1.5	685	115
Lower South Platte River	Box Elder Alluvium	71	17	1.5	310	80
South Park	Upper South Platte River Alluvium	59	16	1.2	270	90
Colorado River	Grand Valley Alluvium	48	16	1.5	395	80

TABLE VIII-2.
SUMMARY RANKING OF CONSOLIDATED BEDROCK AQUIFERS

Basin or Area	Aquifer	Ranking Value	Quality Value	Storage (ac-ft) *	
				Per Acre	Available (thousands)
High Plains Aquifer	High Plains – East	169	19	15.0	95,290
High Plains Aquifer	High Plains – Southeast	162	20	15.0	28,530
High Plains Aquifer	High Plains – North	143	19	4.0	4,570
Denver Basin	Dawson	109	19	6.0	5,010
SE Colorado	Dakota-Cheyenne Group	105	19	0.3	1,280
Sand Wash Basin	Wasatch-Fort Union	94	15	0.3	320
Denver Basin	Laramie-Fox Hills	92	20	0.3	1,285
Denver Basin	Arapahoe	92	19	0.2	590
Middle Park	Troublesome Formation	91	16	7.5	1,025
Raton Basin	Cuchara-Poison Canyon	77	18	1.0	465
Sand Wash Basin	Mesa Verde	70	16	2.0	1,885
Greater Denver Basin	Laramie-Fox Hills	67	15	4.5	5,045
Piceance Basin	Mesa Verde	66	14	2.0	2,865
Eagle Basin & Vicinity	Weber-Maroon-Minturn	62	14	1.0	730
Piceance Basin	Uinta Formation	60	14	7.5	5,015
Denver Basin	Denver	55	19	0.1	155
SW Colorado	Morrison-Summerville-Entrada	55	14	0.8	735
Raton Basin	Raton-Vermejo-Trinidad	54	18	5.0	4,035
South Park	Antero-Wagontongue	51	13	3.8	370
SW Colorado	Wingate	50	12	3.8	1,810
SW Colorado	Dakota-Burro Canyon	48	14	0.8	1,340
North Park	Coalmont	46	18	0.0	20
North Park	North Park Formation	45	13	1.3	85
San Juan Basin	Mesa Verde	45	13	0.5	600
Huerfano Park	Huerfano Formation	40	13	2.0	160
San Juan Basin	Animas Formation	40	13	0.5	265
Huerfano Park	Cuchara-Poison Canyon	38	12	7.5	720
San Juan Basin	Pictured Cliffs	35	12	0.5	350
Piceance Basin	Wasatch-Fort Union	33	13	0.1	310

* Total storage capacity was not calculated due to variable storage coefficients (confined vs. unconfined).

Description of Possible Projects

The evaluation and ranking of unconsolidated sediments and consolidated bedrock aquifers was conducted based on the hydrogeologic properties of only those aquifers that were determined in this study to be physically capable of receiving, storing, and transmitting the desired quantities of artificially recharged water. Implementation of an AR project must also consider

- project objectives,
- site-specific hydrogeologic conditions,
- source-water availability,
- water rights and applicable water law,
- available land surface area and compatible land-use activities,
- governing water management districts or water providing entities,
- facility design criteria,
- capital costs to construct,
- operation and maintenance (O&M) costs, and
- storage efficiency and deliverability.

It was not the intent of this study to recommend specific AR projects in specific areas. Rather, the conclusions and recommendations of this evaluation provide guidance to the future implementation of possible AR projects of all scales and an awareness of some of the issues and considerations that need to be addressed.

The technology, location, design, permit requirements, and operation of an AR project are dependent upon the primary water management objective(s). The objectives of most AR applications fall into one, or a combination of, the categories discussed in Section III. The primary objective of most water managers is to provide for additional storage such that seasonal, long-term, and emergency demands may be met. Using storage as the primary criterion, large AR projects might be those with the capability of storing in excess of 100,000 acre-feet, while small projects may provide for less than 10,000 acre-feet of storage.

The ability to store large volumes of water underground through a large-scale water storage project is dependent upon the storage capacity of the aquifer, the land ownership or management, available source water, regulatory and legal issues, and available funds to construct the project. Both the unconsolidated sediments and the consolidated bedrock aquifers contain sufficient storage capacity to accommodate an additional 100,000 acre-feet of water. Thirteen of the 16 primary unconsolidated alluvial aquifers listed in Table VIII-1 have sufficient storage capacity to accommodate a large-scale project. In aggregate, the lower South Platte River alluvium and the San Luis Valley alluvium have the capacity to store in excess of one million acre-feet. All but two of the 26 primary consolidated rock aquifers listed in Table VIII-2 have sufficient storage capacity available to meet the 100,000 acre-feet criterion. Because of their large areal extent and head freeboard, the majority of these aquifers can store millions of acre-feet of water.

Large-scale AR projects, however, require accessibility to or ownership of large tracts of land. These types of projects can best be implemented through a consortium or cooperative agreement between water management agencies or districts and owners of large land holdings. Since the federal government is such a large landowner in Colorado, a consortium between federal and state land-management agencies would be an ideal platform to spearhead a large-scale demonstration project. With its emphasis on water management and history of developing projects to address the West's water management needs, the Bureau of Reclamation would be a key federal agency. Potential unconsolidated alluvial aquifers for consideration of such a project in eastern Colorado include the alluvium of the South Platte and Arkansas Rivers. Good candidates in central Colorado include alluvium of the North Platte River, Upper Arkansas River, and the San Luis Valley. On the west slope the alluvium of the Gunnison and Uncompahgre Rivers have excellent storage potential. Alluvial aquifers within the tributary reaches of the river mainstems provide a longer storage-retention time, constricted areas for recharge and withdrawal opportunities, rural land use settings, and good potential for seasonal and flood water capture. Areas with consolidated bedrock aquifers that contain good candidates for large-scale AR projects include the High Plains aquifer area, southeast Colorado, Denver Basin, Raton Basin, and the Piceance Basin.

Smaller scale AR projects are those that can be implemented by local water management districts or communities. Since available surface acreage is probably limited, aquifers with high per-acre storage capacities would be good candidates. For the unconsolidated aquifers of Table VIII-1 the top candidates include the alluvium of the following: the South Platte River and its tributaries; the North Platte River; the tributaries of the Arkansas River; and the Uncompahgre River. For the consolidated aquifers of Table VIII-2, good recharge candidates can be found within the High Plains, Middle Park, Piceance Basin, Huerfano Park, Denver Basin, and Raton Basin. As a result of Colorado's complex geologic history and geography, a multitude of aquifers are available for small-scale AR projects.

Colorado's consolidated and unconsolidated aquifers are not limited by existing AR technologies. The technologies are broadly classified according to whether water is recharged at the surface or underground, and subsequently by whether water is recharged into the unsaturated zone (vadose zone) or directly into the saturated zone of the aquifer. Recharge facilities at the surface can be very simple and have minimal effort and cost required to install and maintain. Conversely, recharge facilities underground usually require more sophisticated design and infrastructure and can be more costly. In a recent presentation on underground water storage techniques, James Jehn (President of Jehn Water Consultants) cited a range of capital costs for ground-water storage from $500 per acre-foot for retrofitted water supply wells to $1,500 per acre-foot for wells dedicated to recharge and recovery (Jehn, 2003).

Relative to surface-water reservoirs, start-up times for AR projects are short and the scale of the project can be easily altered to meet water management objectives. AR projects can be constructed in stages paced to meet demand and can be easily changed as they evolve to reflect changing conditions. The cost of ground-water storage is also substantially less than surface-water storage. Surface storage or other means of capturing high-runoff flows may still be necessary, however, to provide source water at a reasonable flow rate and quality needed for recharge.

Institutional Changes

AR projects can increase the total amount of ground water in storage in a very specific and calculated fashion. Enhanced, induced, and incidental recharges are non-specific in application, but can significantly increase overall ground-water storage. Similar to water conservation measures, some changes in current water law and standard practices in our society concerning overall water management combined with passive recharge structures would benefit both ground-water and surface-water resources. As with any diversion of water for beneficial use, AR projects are subject to the requirements and conditions of Colorado water law.

In urban areas, the historical natural recharge processes have been altered due to construction of impermeable surfaces (asphalt, concrete, buildings, etc.). Ground-water recharge can be enhanced through the use of engineered, leaky storm-water detention ponds, where water is allowed to percolate into the subsurface. Currently, storm-water retention is required in urban areas primarily for water quality and flood prevention purposes. Many retention systems collect surface runoff allowing suspended sediment to settle out, and later release the captured water directly to surface water through storm sewers. Ground-water storage would be enhanced if this captured water were allowed to percolate into the subsurface as opposed to discharging directly to surface water, while still maintaining water quality and flood prevention protection.

Subsurface storm-water collection chambers such as those currently being installed in Boston, Massachusetts offer lower installation costs, superior design flexibility, and enhanced performance as compared to traditional storm-water collection systems. Similar concepts are being implemented in Virginia where patches of trees combined with engineered underground recharge systems represent a "bioretention unit" meant to catch and filter storm-water runoff loaded with pollutants such as automotive fluids. If allowed by water law, individuals can capture roof runoff and route this water to "rain gardens" that consist of an engineered layered substrate with a topsoil layer for growing plants. This type of "garden" induces infiltration and significantly reduces the rapid evaporation and uptake by lawn grasses that prevent water from infiltrating to the ground. Educating planners, developers, and the public on alternate recharge systems can result in designs that replenish dwindling ground-water supplies significantly through enhanced recharge techniques.

One potentially significant area of enhanced recharge is the management of hydrophilic, or water-loving vegetation. In urban areas, over 50 percent of the water supply is used for irrigation; therefore, reducing the amount of water used for lawn irrigation can result in substantial change to urban water requirements. Bluegrass lawns need around 30 inches of water per year to thrive. With a statewide average annual precipitation rate of 16 inches per year, hydrophilic vegetation simply taxes the existing water resources. Incentives to homeowners and developers to limit grass lawn areas and increase native or xeric vegetation would lead to considerably lower water demand in urban areas and increased natural recharge. In November 2003, the town of Centennial passed a law prohibiting the *requirement* of bluegrass lawns in any subdivision or development. This is a step in the right direction, as it allows landowners to voluntarily reduce their water consumption and allows more infiltration of precipitation.

Vegetation management is also important outside urban areas. GovernorBill Owens signed Executive Order D-002-03 to assist in efforts to remove tamarisk and control their growth along waterways in Colorado. Tamarisk trees draw their moisture by putting roots down to the ground-water table, drawing that water up through the plant and transpiring it to the atmosphere. Ground water is consumed in massive quantities and ground-water discharge to streams is diminished. Tamarisk now consumes an estimated 170,000 acre-feet of water per year more than native vegetation would use in the same habitat area. If unchecked, this number could increase to almost 600,000 acre-feet per year by 2053 (Tamarisk Coalition, 2003). Ongoing diligence in removal of these non-native trees and replacement with native xeric grasses would enhance recharge and improve ground-water storage.

Forest canopy management in watershed areas is another form of vegetation management that is being considered. Forest cover is the optimum cover on the landscape in terms of protecting water yield and water quality (Peterson, 2003). The density of that cover, however, can dramatically affect the amount of precipitation that reaches the ground surface to infiltrate or runoff. Forests cover over 35,000 square miles of Colorado (MacDonald and Stednick, 2003). Thinning and selective clear-cutting are vegetation management options that reduce the amount of evapotranspiration within the watershed and increase recharge to both surface- and ground-water resources. Forestry projects favoring water management are an ideal fit with other forestry initiatives already started or in development stages, such as wildfire mitigation.

IX. Conclusions and Recommendations

As Colorado is currently in the fifth consecutive year of the driest five-year period in a century of record keeping, management of long-term water supplies has become a topic of considerable discussion from the average citizen to legislators at the Capitol. The value of reservoir water and ground water and the need for additional storage capacity has been a consistent theme in presentations by the State Engineer. While storage of peak flows in surface-water reservoirs has been the dominant historical water management policy, numerous environmental, social, and economic factors hinder the construction of large dams today. An alternative means of increasing water storage capacity is by storing water underground through artificial recharge. Artificial recharge systems can provide greater flexibility to changing water demands and economic environments.

To explore this alternate strategy, the Executive Director of the Colorado Department of Natural Resources requested that the Colorado Geological Survey conduct a statewide assessment of the artificial recharge potential of Colorado's aquifers. This study assessed the opportunities for using artificial recharge to meet water storage needs statewide focusing primarily on the hydrogeologic properties of aquifers and other underground storage options. The American Society of Civil Engineers has recently identified six phases of planning that are typically needed to develop, operate, and maintain a project for artificial recharge of ground water. This study represents only the beginning data collection and technology assessment stages of the initial phase in this process.

Artificial recharge (AR) is defined as any engineered system designed to introduce water to, and store water in, underlying aquifers. This report discusses several aspects important to the understanding of artificial recharge potential in Colorado, including

- the design objectives for implementing artificial recharge;
- the various artificial recharge technologies available;
- the current application of artificial recharge in other states and countries;
- the present practice of artificial recharge in Colorado; and
- the physical suitability of various aquifers, abandoned mines, and caves to store water.

Based on the research and investigations of this report, the following conclusions are offered:

- Artificial recharge (AR) is a viable technique for storing water underground in many parts of Colorado.
    - Favorable hydrogeologic conditions have been identified in unconsolidated sediments and consolidated bedrock aquifers throughout Colorado.
    - A weighted ranking system was established to evaluate the key physical properties of 16 priority unconsolidated, alluvial aquifers and 29 priority consolidated, bedrock aquifers.
    - The top three ranked unconsolidated aquifers lie within alluvial deposits of the South Platte and Arkansas drainage basins.
    - The High Plains Aquifer, Dakota-Cheyenne Group of southeast Colorado, and the Denver Basin aquifers are the top three ranked consolidated bedrock aquifers.

- Both aquifer types contain several candidates that can accommodate development of large-scale artificial recharge projects, i.e. those having storage capacities in excess of 100,000 acre-feet.
- This study has identified five main objectives in implementing an artificial recharge project. These include (1) management of the water supply, (2) meeting in-state legal obligations and complying with interstate agreements, (3) management or mitigation of water quality, (4) restoration or protection of the aquifer, and (5) protection of the environment.
- Water-management objectives determine the location, design, permit requirements, and operation of any AR system. Clearly defined objectives are required before beginning any detailed site selection, site evaluation, or system design efforts.
- A variety of technologies exist to implement artificial recharge, and are applicable in Colorado including surface and subsurface infiltration, direct injection, aquifer storage and recovery wells, modification of natural recharge, and non-aquifer geologic storage.
- Colorado currently has 19 active AR operations including operations in the South Platte River Valley, San Luis Valley, and the Denver Basin.
- Artificial recharge is being used in at least 32 states in the U.S. and at least 26 countries worldwide.
- Three types of non-aquifer underground water storage possibilities were assessed statewide: abandoned coal mines, abandoned metal mines, and caves. Water storage in abandoned coal mines potentially provides local, small-volume water storage opportunities. Abandoned metal mines and natural caves are not recommended for underground water storage because of their relatively small volume of storage complicated by difficulties in maintaining hydraulic control, environmental, and regulatory issues.
- Supply versus demand issues will identify those areas in Colorado that would benefit most from recharge project implementation.

Artificial recharge and underground water storage is an efficient, cost-effective tool for water-resource management. Artificial recharge projects can increase the total ground water in storage in a very specific and calculated fashion. The need to capture excess water during high runoff as a source of recharge water supply is still a necessity for many artificial recharge projects. In addition to site-specific projects, encouraging applications that enhance or induce additional recharge, as well as acknowledging the contributions of incidental recharge, can increase overall ground-water storage tangibly and significantly.

Implementation of an artificial recharge project must also involve several other aspects, concepts, and processes. Considerations include (1) project objectives, (2) site-specific hydrogeologic conditions, (3) source water availability, (4) water law and water rights, (5) available land surface area and compatible land-use activities, (6) governing water-management districts or water providing entities, (7) facility design criteria, (8) capital costs to construct, (9) operation and maintenance costs, and (10) general storage efficiency, recovery, and deliverability considerations. Integration of these concepts with the findings of this study produces the following recommendations:

- Move forward with evaluation of AR as a water storage option in Colorado. Several steps must be taken toward implementation prior to identification of site-specific pilot projects.
- Identify agencies that would implement new AR projects and define roles:
  - Existing water providers/districts
  - Existing Conservation/Conservancy Districts
  - Create a new Authority?
  - State Role?
  - Federal Role?
- Prepare and promulgate the legal framework for AR statewide. Currently, there are regulations governing AR only in the Denver Basin. Elsewhere in the state AR is being implemented under augmentation plans.
- Define the objectives for potential AR projects. Objectives may include any or a combination of the following: manage water supply (storage), meet legal obligations, manage water quality, restore or protect aquifers, and protect the environment.
- Identify source water for AR projects, whether large-scale or small-scale. Available surface water, ground water, and reclaimed or recycled water should be considered.
- Identify a project site location. Address land ownership and access issues.
- Research potential partnerships with federal agencies and federal funding opportunities.

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APPENDIX A

Inventory of Artificial Recharge Projects in Colorado

Inventory of Artificial Recharge Projects in Colorado

Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Akron Playa CO	CPA1	Conceptual	1964	Central Great Plains Experiment Station	Washington	High Plains Aquifer	Unconsolidated alluvial aquifer	Playa	Precipitation	Aquifer restoration.
Allyn Wind CO	CAW1	Active	1978+	Lower Platte and Beaver Canal Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in leaky pond	South Platte diversions.	Augmentation, aquifer restoration.
Animas Springs, CO	CAS1	Active	Unknown+	Individual small well operators	La Plata	Unknown	Unknown	Surface infiltration	Animas River diversion	Water supply management/ aquifer restoration
Arikaree, CO	COA1	Conceptual	1964-68	CSU Civil Engineering, COPE Soil Conservation Dist	Washington	Quaternary alluvium/HighPlains Aquifer	Unconsolidated alluvial aquifer	Surface infiltration, water spreading in stream channel.	Surface water when run-off present	Aquifer restoration
Aurora CO gravel pits	CAG1	Conceptual	2009?	City of Aurora	Denver/Arapahoe	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in spreading basins	Treated effluent	Augmentation/ water storage
Badger Creek CO	CFM1	Active	1979+	Ft. Morgan Reservoir and Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration into creek bed	South Platte River diversions	Augmentation
Badger-Beaver Creeks AR Project CO	CBB1	Conceptual	1978-1979	Badger/Beaver Creek WCD and USGS?	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration into dry creek beds	South Platte River diversions	Aquifer restoration
Beaver Creek (South Ditch) CO	CBC2	Active	1984+	Upper Platte and Beaver Canal Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration , leaky ditch	South Platte River diversions	Augmentation
Beaver Creek (Creekbed) CO	CBC3	Active	1984+	Upper Platte and Beaver Canal Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in creek bed	South Platte River diversions	Augmentation
Bijou #2 Reservoir CO	CBR1	Active	1981+	Bijou Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in Leaky Reservoir	South Platte River diversions	Augmentation

Inventory of Artificial Recharge Projects in Colorado (Continued)

Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Bijou Creek CO	CBC1	Active	1986+	Bijou Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in creek bed	South Platte River diversions	Augmentation
Bijou Ditch CO	CBD1	Active	1983+	Bijou Irrigation Company	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in leaky ditch	South Platte River diversions	Augmentation
Bolinger Pond CO	CBR2	Active	1979+	Ft Morgan Reservoir and Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in leaky pond	South Platte River diversions	Augmentation
Box Elder Creek CO	CBE1	Active	1980+	Central Colorado Water Conservancy District	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration into dry creek bed	Surface	Augmentation/aquifer restoration
Cache la Poudre Gravel Pits	CPG1	Active	Unknown+	LaFarge Aggregate	Larimer	Cache la Poudre Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, pond	Cache la Poudre diversions	Augmentation
Castle Pines Arapahoe ASR CO	CPA2	Active	2/98+	Castle Pines Metro District	Douglas	Arapahoe	Semi-consolidated basin fill aquifer	ASR injection well	Surface/ East Plum Creek	Long-term storage, conjunctive use.
Centennial Water Dist./ Laramie-Fox Hills ASR CO	CNT3	Active	2003+	Centennial Water District	Douglas	Laramie-Fox Hills	Consolidated sedimentary aquifer	ASR injection wells	Treated Surface	Long-term storage, conjunctive use.
Centennial Water District /Denver ASR CO	CNT1	Active	1997+	Centennial Water District	Douglas	Denver Aquifer	Semi-consolidated basin fill aquifer	ASR injection wells	Treated surface	Long-term storage, conjunctive use.
Centennial Water District/ Arapahoe ASR CO	CNT2	Active	1992+	Centennial Water District	Douglas	Arapahoe Aquifer	Semi-consolidated basin fill aquifer	ASR injection wells	Treated surface	Long-term storage, conjunctive use.
Charles Henry Pond CO	CCH1	Active	1986+	Ft. Morgan Reservoir & Irrigation Co.	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in leaky pond	South Platte River diversions	Augmentation

Inventory of Artificial Recharge Projects in Colorado (Continued)

Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Chase Lateral Pond CO	CCL1	Active	1983+	Bijou Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in leaky pond	South Platte River diversions	Augmentation
Clark Pond CO	CCP1	Active	1992+	Upper Platte and Beaver Canal Co.	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in leaky pond	South Platte River diversions	Augmentation
Clear Creek Recharge Ponds	CRS1	Active	1988+	Coors Brewing Company	Jefferson	Clear Creek Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, pond	Clear Creek diversions	Augmentation/ water quality management
Condon Recharge Site CO	CCN1	Active	1981+	Mr. Bill Condon (Prop owner)	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Spreading basin	groundwater	Augmentation
Country Club Hills Pond CO	CCC1	Active	1980+	Anderson & Vandemoer	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in a leaky pond	South Platte River diversions	Augmentation
Daily Pond CO	CDY1	Active	1986+	Lower Platte and Beaver Canal Co.	Washington	South Platte River Alluvium	Unconsolidated alluvial aquifer	S+I54urface infiltration in leaky pond	South Platte River diversions	Augmentation
Degenhart Pond CO	CDP1	Active	1992+	Upper Platte and Beaver Canal Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration in leaky pond	South Platte River diversions	Augmentation
Denver Basin Aquifer Recharge Project CO	CWW1	Non Active	1990-1997	Willows Water District/US Burec/Denver Water	Arapahoe	Arapahoe Aquifer	Semi-consolidated basin fill aquifer	ASR Well/Injection	Surface (Denver Water)	Evaluate feasibility of water storage using ASR
DT Ranch Pond CO	CDT1	Active	1991-1992	Ft. Morgan Res & Irrigation Company	Morgan	Ssouth Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through a leaky pond	South Platte River diversions	Augmentation
Eastern Colorado Plains Recharge CO	CEC1	Active	1969+	Plains Ground Water Management District	Kit Carson	High Plains Aquifer	Unconsolidated alluvial aquifer	Surface infiltration, ponds in stream-bed	Surface runoff	Aquifer restoration

Inventory of Artificial Recharge Projects in Colorado (Continued)

Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Emmerson Lake/Seaman Pond CO	CEL1	Active	1981+	Lower Platte and Beaver Canal Company	Washington	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through leaky pond	South Platte River diversions	Augmentation
Equus Ponds CO	CEQ1	Active	1986+	Riverside Irrigation Company	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through leaky ponds	South Platte River diversions	Augmentation
Evans 2 - Platte Valley Ditch CO	CED1	Non Active	1984	Central Colo Water Cons. Dist. & Evans Ditch Co.	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through leaky ditch	South Platte River diversions	Augmentation
Farmers Independant Ditch CO	CFI1	Active	1986+	Cent. CO Water Cons. Dist./ Farmers Ind. Dit. Co.	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through leaky ditch	South Platte River diversions	Augmentation
Fort Morgan Canal CO	CFM2	Active	1979+	Ft . Morgan Reservoir & Irrigation Co.	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through a leaky ditch	South Platte River diversions	Augmentation
Fountain Valley/Widefield Aquifer CO	CFV1	Conceptual	1975	El Paso County Water Association/USGS	El Paso	Widefield Aquifer	Unconsolidated alluvial aquifer	Surface infiltration through pits	Fountain Creek	Test for aquifer restoration
Frenchman Creek CO	CFR1	Conceptual	1974-75	Frenchman Ecological Area Committee, CSU	Phillips	High Plains Aquifer	Unconsolidated alluvial aquifer	Surface infiltration basins	Surface	Aquifer restoration test
Gold Run Ditch	CGR1	Active	Unknown	Individual small capacity well owners	Montezuma	Unknown	Unknown	Surface infiltration	East Fork Mancos River	Water supply management/ aquifer restoration
Goodrich Farms Ponds CO	CGF1	Active	1983+	Riverside Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltrations through leaky ponds	South Platte River diversions	Augmentation
Headly Property Ponds CO	CHP1	Active	1982+	Riverside Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through leaky ponds	South Platte River diversions	Augmentation

Inventory of Artificial Recharge Projects in Colorado (Continued)

Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Hessler Recharge Sites CO	CBB2	Active	1980-1991	R. Hessler & Davis Brothers Ditch Co.	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through leaky ponds and a leaky ditch	South Platte River diversions	Augmentation
Home Ranch of Wyoming Pond CO	CHR1	Active	1979+	George Faris	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through leaky pond	South Platte River diversions	Augmentation
Indian Hills CO	CIH1	Non Active	-1963 to 1970s?	Indian Hill Water District	Jefferson	Precambrian gneiss/Parmalee Gulch alluvium	fractured crystalline aquifer	Enhanced recharge through catch basin	Surface water	Maintain water levels
Jimmy Camp Valley CO	CJC1	Conceptual	August to November 1975	El Paso County Water Association/USGS	El Paso	Jimmy Camp Valley Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, ponds	Nearby well or water main	Determine AR potential of aquifer.
Julesburg, CO	CJL1	Active	1991+	Lower South Platte Water Conservency District	Sedgwick	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, spreading basins	South Platte River diversions	Augmentation
Keith Bath Pond CO	CKB1	Active	1986+	Ft. Morgan Reservoir & Irrigation Co.	Morgan	Sout Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Kiowa Creek CO	CKC1	Active	1981+	Central Colo Water Conserv District/Bijou Irr Co	Morgan	South Platte Alluvium	Unconsolidated alluvial aquifer	Infiltration Ponds	South Platte River diversions	Augmentation
Leyden Coal Mines CO	CLY1	Active	2004	City of Arvada	Jefferson	Non-aquifer	Unconsolidated alluvial aquifer	Injection Wells	Treated municipal water	Long-term water storage
Littleton CO	CLT1	Non Active	-1963-	Local water utility	Arapahoe	South Platte River Alluvium	Unconsolidated alluvial aquifer	Infiltration ponds	South Platte	Water quality/supply moderation

Inventory of Artificial Recharge Projects in Colorado (Continued)

Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Lost Creek East CO	CLC2	Active	1985+	Bijou Irrigation Co.	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	Aouth Platte River diversions	Augmentation
Lost Creek West CO	CLC1	Active	1985+	Bijou Irrigation Co.	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Lower Platte and Beaver Ditch CO	CBD3	Active	1986+	Lower Platte and Beaver Canal Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky ditch	South Platte River diversions	Augmentation
Lundock East Pond CO	CLW2	Active	1986+	Ft. Morgan Reservoir & Irrigation Co	Morgan	South Platte river Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Lundock West Pond CO	CLW1	Active	1986+	Ft. Morgan Reservoir & Irrigation Co	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Miller Site Pond CO	CMS1	Active	1988+	Central Colorado Water Conservancy District	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, pond	South Platte River diversions	Augmentation
Milliron Draw CO	CMD1	Active	1986+	Central Colorado Water Conservancy District	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration ponds	South Platte River diversions	Augmentation
Monahan Pond CO	CMN1	Active	1979+	Rex Monahan	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
National Hog Farm CO	CNH1	Conceptual	---	Riverside Irrigation/National Hog Farm	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration	South Platte River diversions	Augmentation
Nederland Public Water CO	CND1	Non Active	to mid-1960s	Town of Nederland	Boulder	Quaternary alluvium	Unconsolidated alluvial aquifer	Surface infiltration, pond	Surface water	Increase availability to wells and filtration

Inventory of Artificial Recharge Projects in Colorado (Continued)
Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
New Cache la Poudre CO	CCP2	Conceptual	1988-1989	Central CO Water Conservancy Dist	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration through leaky ditch and creek bed.	Diversions from Cache la Poudre River	Augmentation
North Ditch CO	CBD2	Active	1983+	Upper Platte & Beaver Canal Co.		South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky ditch	South Platte River diversions	Augmentation
Olds Reservoir CO	COR1	Active	1939+	Henry Lyn Irrigation Company	Weld	Prospect Valley Aquifer	Unconsolidated alluvial aquifer	Leaky Reservoir Infiltration	South Platte River diversions	Augmentation
Pagosa Springs Public Water CO	CPS1	Non Active	to mid-1960	Pagosa Springs Public Works	Archuleta	San Juan River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, ponds	San Juan River	Supply regulation/water quality improvement
Palisade Public Water CO	CPD1	Active	pre-1963+	Palisade Public Works	Mesa	Fractured basalt	Fractured basalt aquifer	Leaky reservoir	Snow melt	Supply regulation/water quality improvement
Parachute Gravel Pits	CUO1	Active	Unknown+	Union Oil	Garfield	Quaternary alluvium	Unconsolidated alluvial aquifer	Surface infiltration, pond	Surface water	Augmentation
Parker Water and San. CO	CPW1	Conceptual	Late 1980s	Parker Water and Sanitation District	Douglas	Denver Basin Bedrock aquifers	Unconsolidated alluvial aquifer	ASR wells	Tributary ground water/surface water	Long-term storage
Peterson-Pioneer Ditch CO	CPP1	Active	1982+	Pioneer Water and Irrigation Co.	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky ditch	South Plate River diversions	Augmentation
Pioneer Ditch CO	CPD1	Active	1982+	Pioneer Water and Irrigation Co.	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky ditch	South Platte River Diversions	Augmentation
Pivonka Pond CO	CPV1	Non Active	1979-1980	John Pivonka	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Susrface infiltration, leaky pond	South Platte River diversions	Augmentation

Inventory of Artificial Recharge Projects in Colorado (Continued)

Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Platte Valley Irrigation CO	CPV2	Active	1984+	Cent. CO Water Cons. Dist,/Platte Val. Irrig. Co.	Weld	South Platte Alluvium	Unconsolidated alluvial aquifer	Surface Infiltration thru leaky ditch	South Platte River diversions	Augmentation
Proctor Recharge Experiment CO	CPR1	Conceptual	1979	USGS/Lower S Platte Water Cons. District	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, spreading basin	Well water	Aquifer restoration/mound migration study
Public Service Pond CO	CPS1	Active	1985+	Ft. Morgan Reservoir & Irrigation Co.	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Ridgway Public Water CO	CRD1	Active	1963+	Town of Ridgway	Montrose	Sedimentary bedrock	consolidated sedimentary aquifer	Infiltration basin/leaky lake	Beaver Creek	Regulate supply/maintain water quality
Salida Public Water Supply CO	CSL1	Active	1963+	Salida Public Works	Chaffee	Arkansas River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, ponds, infiltration galleries	South Arkansas River	Increase availability to wells and filtration
San Luis Valley Trinchera CO	CTR1	Non Active	2/82 to 4/82	Trinchera Irrigation Co. and Rio Grande Water Cons	Costilla	SLV Unconfined and Confined Aquifers	Unconsolidated alluvial aquifer	Surface infiltration, recharge basin	Diverted surface water	Aquifer restoration demonstration project
San Luis Valley Closed Basin Water Management	CSV1	Active	1977+	Five ditch companies	Alamosa, Rio Grande, Saguache	SLV Unconfined and Confined Aquifers	Unconsolidated alluvial aquifer	Surface infiltration, ponds, leaky ditches	Rio Grande River diversions	Water supply management
San Luis Valley Rio Grande Water Users Recharge	CSV2	Active	1980+	San Luis Valley Rio Grande Water Users Association	Alamosa, Conejos, Rio Grande, Saguache	SLV Unconfined and Confined Aquifers	Unconsolidated alluvial aquifer	Surface infiltration leaky ditches	Rio Grande River diversions	Water supply management/ augmentation
Sand Hill Ditch (South Platte Ditch) CO	CSN1	Active	1978+	South Platte Ditch Co. (GASP, Colo DWR, CSU)	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky irrigation ditches/pond	South Platte River diversions	Augmentation, aquifer restoration
Smart Ponds, CO	CSM1	Active	1988+	Carson Smart	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky ponds	South Platte River diversions	Augmentation

Inventory of Artificial Recharge Projects in Colorado (Continued)
Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Snake River Recharge	CKS1	Active	Unknown+	Keystone Resorts	Summit	Unknown	Unknown	Surface infiltration	Snake River diversions	Manage water supply/ aquifer restoration
Snyder Lake CO	CSL2	Non Active	1982-1987	Pioneer Water & Irrigation Co.	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
South Platte River Augmentation	CSP	Active	1970s+	Multiple entities	Lower South Platte River Basin	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration	South Platte River diversions	Augmentation
South Park Conjunctive Use Project CO	CSP1	Conceptual	--	City of Aurora	Park	South Park Formation	Semi-consolidated basin fill aquifer	Surface infiltration	surplus surface water	Long-term storage
South Platte Water Conservation Project CO	CSP2	Conceptual	---	Northern Colorado Water Conservancy District	Weld	Quaternary alluvium	Unconsolidated alluvial aquifer	Surface infiltration	Surface	Aquifer restoration
State Kembel Ditch CO	CSK1	Active	1984+	Upper Platte & Beaver Canal Co.	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky ditch	South Platte River diversions	Augmentation
Tamarack Ranch CO	CTM1	Active	1979+	CDWR, CDOW, NCWCD, CSU	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, recharge ponds	South Platte alluvial wells	Wildlife habitat, augmentation
Tarrayall Recharge	CTL1	Active	Unknown+	City of Aurora	Park	Quaternary alluvium	Unconsolidated alluvial aquifer	Surface infiltration	Tarryall Creek diversions	Augmentation
Upper Black Squirrel Creek Basin AR Tests CO	CBS1	Conceptual	Sep-Nov 1975	El Paso County Water Association/USGS	El Paso	Upper Black Squirrel Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, ponds	Nearby well or water main	Aquifer restoration, long-term storage
Upper Black Squirrel Creek/Cherokee MD CO	CBS2	Conceptual	2002	Cherokee Met Dist/ Woodman Hills M.D./Meridian Ra	El Paso	Upper Black Squirrel Quaternary Alluvium	Unconsolidated alluvial aquifer	Infiltration Pond	Treated Municipal Wastewater	Increase Ground Water Pumping Capacity/ aquifer restoration

Inventory of Artificial Recharge Projects in Colorado (Continued)
Sorted Alphanumerically by Project Name

Project Name	Alpha ID	Status	Dates	Operator	County	Aquifer	Type	Technology	Source Water	Objectives
Vancil Reservoir CO	CVN1	Conceptual	-1994-	Riverside Irrigation District	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky reservoir	South Platte River diversions	Augmentation
Weimer Pond CO	CWP2	Active	1985+	Bijou Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Weingardt Pond CO	CWP1	Active	1983+	Bijou Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Western Mutual Ditch CO	CWM1	Active	1987+	Central Colorado Water Conservancy District	Weld	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky ditch	South Platte River diversions	Augmentation
Wheatridge Mutual CO	CWR1	Non Active	pre 1963- mid 1960s	Wheatridge Mutual	Jefferson	Quaternary Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, ponds	Surface (Clear Creek)	Regulate water supply/ water quality management
Wilhem (Sonnenberg) Pond CO	CSN2	Active	1980+	Painted Rock Development/Wilhem Co.	Logan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky ponds	South Platte River diversions	Augmentation
Woodward East Lake CO	CWL2	Active	1982+	Pioneer Water & Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Woodward West Lake CO	CWL1	Active	1982+	Pioneer Water & Irrigation Company	Morgan	South Platte River Alluvium	Unconsolidated alluvial aquifer	Surface infiltration, leaky pond	South Platte River diversions	Augmentation
Yuma Recharge Pit CO	CYP1	Non Active	1971	Colo State University	Yuma	High Plains Aquifer	Unconsolidated alluvial aquifer	Surface infiltration, tailwater pits	Local runoff	Aquifer restoration

APPENDIX B

Unconsolidated Aquifer Ranking/Decision Matrix Worksheets

(Aquifers listed in order by ranking value as in table VIII-1)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name:	Lower South Platte River	**Potential Storage Capacity, ac-ft per acre**	6.0
Aquifer Name:	South Platte River Alluvium	**Storage Capactiy, total (ac-ft)**	4.65E+06
Aquifer Type :	Alluvium	**Storage Capactiy, available (ac-ft)**	2.32E+06

(alluvium, colluvium, valley-fill,etc.)

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	605	605	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	40-100	60	<20	1	20-40	2	40-80	4	80-160	8	>160	10	4
Head Freeboard (ft)	10-40	30	<5	1	5-10	2	10-20	4	20-30	8	>30	15	4
Storage Coefficient (%)	20-25	0.2	<10	1	10-15	5	15-20	10	20-25	25	>25	50	2
Hydraulic Conductivity (ft/day)	100-2,000		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	3

poor=1, fair=2, good=3, excellent=4

Quality Indicator
19 Total

Final Ranking 132 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: South Platte River Basin
Aquifer Name: Bijou Creek Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 5.3
Storage Capactiy, total (ac-ft) 2.79E+06
Storage Capactiy, available (ac-ft) 8.13E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	242	242	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	40-140	120	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	25-55	35	<5	1	5-10	2	10-20	4	20-30	8	>30	15	3
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	100-1,000		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2

Quality Indicator
17 Total

Final Ranking 128 (summation of parameter rankings)

Version 5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Lower Arkansas River
Aquifer Name: Arkansas River Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre	2.3
Storage Capactiy, total (ac-ft)	4.01E+06
Storage Capactiy, available (ac-ft)	5.01E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	348	348	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	100-200	120	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	5-30	15	<5	1	5-10	2	10-20	4	20-30	8	>30	15	3
Storage Coefficient (%)	5-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	70-1,200	600	<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	3

Quality Indicator
18 Total

Final Ranking 118 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: San Luis Valley
Aquifer Name: Quaternary Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre	2.3
Storage Capactiy, total (ac-ft)	1.56E+07
Storage Capactiy, available (ac-ft)	3.89E+06

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ranl	Value Range	Weighted Ranl	Value Range	Weighted Ranl	Value Range	Weighted Ranl	Value Range	Weighted Ranl	Quality of Data
Aerial Extent (sq. miles)	2700	2700	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	<5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	3
Unit Thickness (ft)	40-100	60	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	10-20	15	<5	1	5-10	2	10-20	4	20-30	8	>30	15	2
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	85-3685	700	<1	1	1-10	5	10-100	10	100-1,00	25	>1,000	50	3

poor=1, fair=2, good=3, excellent=4

Quality Indicator
18 Total

Final Ranking 113 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Uncompahgre River
Aquifer Name: Uncompahgre River Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 3.0
Storage Capactiy, total (ac-ft) 1.53E+06
Storage Capactiy, available (ac-ft) 3.05E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	159	159	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	20-160	100	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	10-40	20	<5	1	5-10	2	10-20	4	20-30	8	>30	15	3
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	100-500		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2

poor=1, fair=2, good=3, excellent=4

Quality Indicator
17 Total

Final Ranking 96 (summation of parameter rankings)

Version 5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name:	South Platte River Basin	**Potential Storage Capacity, ac-ft per acre**	5.3
Aquifer Name:	Kiowa Creek Alluvium	**Storage Capactiy, total (ac-ft)**	9.22E+05
Aquifer Type :	Alluvium	**Storage Capactiy, available (ac-ft)**	4.03E+05
(alluvium, colluvium, valley-fill,etc.)			

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data	poor=1, fair=2, good=3, excellent=4
Aerial Extent (sq. miles)	120	120	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4	
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2	
Unit Thickness (ft)	40-120	80	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3	
Head Freeboard (ft)	25-55	35	<5	1	5-10	2	10-20	4	20-30	8	>30	15	2	
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3	
Hydraulic Conductivity (ft/day)	100-750		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2	
													Quality Indicator	
													16	Total

Final Ranking 92 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: North Park
Aquifer Name: North Platte River Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 4.5
Storage Capactiy, total (ac-ft) 1.53E+06
Storage Capactiy, available (ac-ft) 3.83E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	133	133	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	5-10		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	20-160	120	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	20-40	30	<5	1	5-10	2	10-20	4	20-30	8	>30	15	3
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	100-500		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2

Quality Indicator
17 Total

Final Ranking 91 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Gunnison River
Aquifer Name: Gunnison River Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 2.3
Storage Capactiy, total (ac-ft) 1.18E+06
Storage Capactiy, available (ac-ft) 2.20E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	153	153	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	20-100	80	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	5-30	15	<5	1	5-10	2	10-20	4	20-30	8	>30	15	3
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	100-500		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	3

Quality Indicator
18 Total

Final Ranking 88 (summation of parameter rankings)

Version 5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name:	Arkansas River Basin	**Potential Storage Capacity, ac-ft per acre**	4.5
Aquifer Name:	Big Sandy Creek Alluvium	**Storage Capactiy, total (ac-ft)**	1.13E+06
Aquifer Type :	Alluvium	**Storage Capactiy, available (ac-ft)**	4.23E+05
(alluvium, colluvium, valley-fill,etc.)			

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Dat
Aerial Extent (sq. miles)	147	147	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	20-100	80	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	20-40	30	<5	1	5-10	2	10-20	4	20-30	8	>30	15	3
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	100-500		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2

poor=1, fair=2, good=3, excellent=4

Quality Indicator
17 Total

Final Ranking 87 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: White River Basin
Aquifer Name: White River Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 1.5
Storage Capactiy, total (ac-ft) 8.06E+05
Storage Capactiy, available (ac-ft) 1.08E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	112	112	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	5-10		<5	20	5-10	15	10-25	10	25-50	3	>50	1	3
Unit Thickness (ft)	20-140	75	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	10-20	10	<5	1	5-10	2	10-20	4	20-30	8	>30	15	2
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	50-1,550		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	3

Quality Indicator
18 Total

Final Ranking 81 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Wet Mountain Valley
Aquifer Name: Quaternary Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 1.5
Storage Capactiy, total (ac-ft) 1.24E+06
Storage Capactiy, available (ac-ft) 1.24E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	129	129	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	<5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	3
Unit Thickness (ft)	100	100	<20	1	20-40	2	40-80	4	80-160	8	>160	10	2
Head Freeboard (ft)	10	10	<5	1	5-10	2	10-20	4	20-30	8	>30	15	2
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	50		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2

poor=1, fair=2, good=3, excellent=4

Quality Indicator
16 Total

Final Ranking 77 (summation of parameter rankings)

Version 5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Upper Arkansas River Basin
Aquifer Name: Buena Vista/Salida Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre	2.3
Storage Capactiy, total (ac-ft)	6.60E+05
Storage Capactiy, available (ac-ft)	1.24E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	86	86	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	60-100	80	<20	1	20-40	2	40-80	4	80-160	8	>160	10	2
Head Freeboard (ft)	10-20	15	<5	1	5-10	2	10-20	4	20-30	8	>30	15	2
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	10-500		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2

poor=1, fair=2, good=3, excellent=4

Quality Indicator
15 Total

Final Ranking 77 (summation of parameter rankings)

Version 5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Yampa River Basin
Aquifer Name: Yampa River Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 1.5
Storage Capactiy, total (ac-ft) 6.85E+05
Storage Capactiy, available (ac-ft) 1.14E+05

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	119	119	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	10-100	60	<20	1	20-40	2	40-80	4	80-160	8	>160	10	2
Head Freeboard (ft)	0-40	10	<5	1	5-10	2	10-20	4	20-30	8	>30	15	3
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	2-30		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	3

Quality Indicator
17 Total

Final Ranking 73 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: South Platte River Basin
Aquifer Name: Box Elder Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 1.5
Storage Capactiy, total (ac-ft) 3.11E+05
Storage Capactiy, available (ac-ft) 7.78E+04

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	81	81	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	0-5		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	20-60	40	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	10-20	10	<5	1	5-10	2	10-20	4	20-30	8	>30	15	2
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	110-630		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	3

Quality Indicator
17 Total

Final Ranking 71 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: South Park
Aquifer Name: Upper South Platte River Alluvium
Aquifer Type : Alluvium/colluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 1.2
Storage Capactiy, total (ac-ft) 2.70E+05
Storage Capactiy, available (ac-ft) 8.99E+04

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	117	117	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	5-10		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	10-40	30	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	10-15	10	<5	1	5-10	2	10-20	4	20-30	8	>30	15	2
Storage Coefficient (%)	10-15	0.12	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	50-300		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2

poor=1, fair=2, good=3, excellent=4

Quality Indicator
16 Total

Final Ranking 59 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

UNCONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Colorado River Basin
Aquifer Name: Grand Valley Alluvium
Aquifer Type : Alluvium
(alluvium, colluvium, valley-fill,etc.)

Potential Storage Capacity, ac-ft per acre 1.5
Storage Capactiy, total (ac-ft) 3.94E+05
Storage Capactiy, available (ac-ft) 7.87E+04

PHYSICAL PARAMETER	Actual Value or Range	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	82	82	< 50	1	50-75	5	75-100	10	100-200	25	>200	50	4
Depth to Formation Top (ft)	10-15		<5	20	5-10	15	10-25	10	25-50	3	>50	1	2
Unit Thickness (ft)	25-60	50	<20	1	20-40	2	40-80	4	80-160	8	>160	10	3
Head Freeboard (ft)	10-15	10	<5	1	5-10	2	10-20	4	20-30	8	>30	15	2
Storage Coefficient (%)	10-20	0.15	<10	1	10-15	5	15-20	10	20-25	25	>25	50	3
Hydraulic Conductivity (ft/day)	50-1,000		<1	1	1-10	5	10-100	10	100-1,000	25	>1,000	50	2

Quality Indicator
16 Total

Final Ranking 48 (summation of parameter rankings)

APPENDIX C

Consolidated Aquifer Ranking/Decision Matrix Worksheets

(Aquifers listed in order by ranking value as in table VIII-2)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: High Plains Aquifer
Aquifer Name: High Plains - East
Aquifer Type : Semi-consolidated silt, sand, & gravel
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 20.0

Storage Capacity, available (ac-ft) 1.27E+08

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data
Aerial Extent (sq. miles)	9,926	9,926	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	25-350	150	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	25-200	100	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	25-300	100	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.10-0.25	0.2	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			3
Hydraulic Conductivity (ft/day)	50-150	100	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	4

Quality of Data: poor=1, fair=2, good=3, excellent=4

Quality Indicator
19 Total

Final Ranking 169 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: High Plains Aquifer
Aquifer Name: High Plains - Southeast
Aquifer Type : Semi-consolidated silt, sand, & gravel
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 22.5

Storage Capacity, available (ac-ft) 4.28E+07

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	2,972	2,972	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-50		<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	0-50	50	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	100-200	150	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.10-0.20	0.15	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			4
Hydraulic Conductivity (ft/day)	25-100	75	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	4

poor=1, fair=2, good=3, excellent=4

Quality Indicator
20 Total

Final Ranking 162 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: High Plains Aquifer
Aquifer Name: High Plains - North
Aquifer Type : Semi-consolidated silt, sand, & gravel
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 4.0

Storage Capacity, available (ac-ft) 4.57E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data
Aerial Extent (sq. miles)	1,785	1,785	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-50	35	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2
Saturated Thickness (ft)	50-150	50	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	25-100	50	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.05-0.15	0.08	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			4
Hydraulic Conductivity (ft/day)	10-80	25	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	4

poor=1, fair=2, good=3, excellent=4

Quality Indicator
19 Total

Final Ranking 143 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: SE Colorado
Aquifer Name: Dakota-Cheyenne Group
Aquifer Type : Sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.3

Storage Capacity, available (ac-ft) 1.28E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data	poor=1, fair=2, good=3, excellent=4
Aerial Extent (sq. miles)	7,989	7,989	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4	
Depth to Formation Top (ft)	0-1,000		<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3	
Saturated Thickness (ft)	50-150	100	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3	
Head Freeboard (ft)	250-1,000	500	<50	1	50-100	2	100-300	6	300-750	15	>750	30	3	
Storage Coefficient	0001-0.001	0.0005	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			3	
Hydraulic Conductivity (ft/day)	0.2-2.0	1	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3	

Quality Indicator
19 Total

Final Ranking 105 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Denver Basin
Aquifer Name: Dawson
Aquifer Type : Sandstone + conglomerate
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 6.0

Storage Capactiy, available (ac-ft) 5.01E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	1,305	1305	< 500	1	500-1,000		1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-25	15	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	0-400	250	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	20-100	30	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.15-0.25	0.2	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			4
Hydraulic Conductivity (ft/day)	0.27-2.6	1.4	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

poor=1, fair=2, good=3, excellent=4

Quality Indicator
19 Total

Final Ranking 104 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Denver
Aquifer Name: Laramie-Fox Hills
Aquifer Type : Sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.6

Storage Capacity, available (ac-ft) 2.57E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data
Aerial Extent (sq. miles)	6,702	6,702	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-2400	1200	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	0-250	125	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	4
Head Freeboard (ft)	400-1000	600	<50	1	50-100	2	100-300	6	300-750	15	>750	30	3
Storage Coefficient	0.0004-0.20	0.001	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			3
Hydraulic Conductivity (ft/day)	0.5-3.5	2	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

Quality of Data: poor=1, fair=2, good=3, excellent=4

Quality Indicator
20 Total

Final Ranking 96 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Sand Wash Basin
Aquifer Name: Wasatch/Fort Union
Aquifer Type : Sandstone & siltstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.3

Storage Capacity, available (ac-ft) 3.20E+05

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data
Aerial Extent (sq. miles)	1,997	1,997	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	50-3000		<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	250-1000	500	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	100-500	250	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.0001-1	0.001	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.02-900		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

Quality of Data: poor=1, fair=2, good=3, excellent=4

Quality Indicator
15 Total

Final Ranking 94 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Raton Basin
Aquifer Name: Cuchara-Poison Canyon
Aquifer Type : Shale & sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per ac 15.0

Storage Capacity, available (ac-ft) 7.01E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	730	730	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-50		<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	0-2500	1000	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	50-150	100	<50	1	50-100	2	100-300	6	300-750	15	>750	30	3
Storage Coefficient	0.10-0.20	0.15	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			2
Hydraulic Conductivity (ft/day)	0.06-2.4		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	4

poor=1, fair=2, good=3, excellent=4

Quality Indicator
18 Total

Final Ranking 92 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Middle Park
Aquifer Name: Troublesome Formation
Aquifer Type : Siltstone, sandstone, tuffaceous
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 7.5

Storage Capacity, available (ac-ft) 1.03E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	214	214	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-50	25	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	0-800	400	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	50-100	75	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.05-0.1	0.1	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			2
Hydraulic Conductivity (ft/day)	1.5-4.0		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	2

poor=1, fair=2, good=3, excellent=4

Quality Indicator
16 Total

Final Ranking 91 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Piceance Basin
Aquifer Name: Mesa Verde
Aquifer Type : Sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 50.0

Storage Capacity, available (ac-ft) 2.27E+08

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	7,100	7,100	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	50->1000	500	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2
Saturated Thickness (ft)	500-2000	750	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	1000-2000	1000	<50	1	50-100	2	100-300	6	300-750	15	>750	30	1
Storage Coefficient	0.01-0.1	0.05	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.001-0.01		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

poor=1, fair=2, good=3, excellent=4

Quality Indicator
14 Total

Final Ranking 90 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Sand Wash Basin
Aquifer Name: Mesa Verde
Aquifer Type : Sandstone & shale
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 50.0

Storage Capacity, available (ac-ft) 1.11E+08

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data	poor=1, fair=2, good=3, excellent=4
Aerial Extent (sq. miles)	3,468	3,468	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4	
Depth to Formation Top (ft)	50->1000		<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3	
Saturated Thickness (ft)	1000-2000	1000	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3	
Head Freeboard (ft)	500-1000	500	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2	
Storage Coefficient	0.01-0.1	0.1	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1	
Hydraulic Conductivity (ft/day)	0.01-1	0.1	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3	

Quality Indicator
16 Total

Final Ranking 75 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Raton Basin
Aquifer Name: Raton-Vermejo-Trinidad
Aquifer Type : Siltstone & sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per ac 15.0

Storage Capacity, available (ac-ft) 1.21E+07

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	1,261	1,261	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-2500		<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	100-300	200	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	50-200	100	<50	1	50-100	2	100-300	6	300-750	15	>750	30	3
Storage Coefficient	0.10-0.20	0.15	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			2
Hydraulic Conductivity (ft/day)	0.02-0.61		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

poor=1, fair=2, good=3, excellent=4

Quality Indicator
18 Total

Final Ranking 69 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Greater Denver Basin
Aquifer Name: Laramie-Fox Hills
Aquifer Type : Sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 4.5

Storage Capacity, available (ac-ft) 5.05E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data	poor=1, fair=2, good=3, excellent=4
Aerial Extent (sq. miles)	1,752	1,752	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4	
Depth to Formation Top (ft)	10-50	25	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2	
Saturated Thickness (ft)	0-200	100	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3	
Head Freeboard (ft)	10-50	30	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2	
Storage Coefficient	0.10-0.20	0.15	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			2	
Hydraulic Conductivity (ft/day)	0.5-3.0	1	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	2	

Quality Indicator
15 Total

Final Ranking 67 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Denver
Aquifer Name: Denver
Aquifer Type : Sandstone & siltstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 12.0

Storage Capactiy, available (ac-ft) 2.45E+07

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	3,190	3,190	< 500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-1200	250	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated thickness (ft)	0-350	250	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	4
Head Freeboard (ft)	100-200	150	<50	1	50-100	2	100-300	6	300-750	15	>750	30	3
Storage Coefficient	0.002-0.17	0.08	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			2
Hydraulic Conductivity (ft/day)	0.1-1	0.5	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

poor=1, fair=2, good=3, excellent=4

Quality Indicator
19 Total

Final Ranking 64 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Eagle Basin Vicinity
Aquifer Name: Weber-Maroon- Minturn
Aquifer Type : Sandstone & limestone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 1.0

Storage Capacity, available (ac-ft) 7.31E+05

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data
Aerial Extent (sq. miles)	1,142	1,142	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-50		<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	400-1000	500	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	50-200	100	<50	1	50-100	2	100-300	6	300-750	15	>750	30	1
Storage Coefficient	0.001-0.1	0.01	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	.0001-2.0		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

Quality of Data: poor=1, fair=2, good=3, excellent=4

Quality Indicator
14 Total

Final Ranking 62 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Denver
Aquifer Name: Arapahoe
Aquifer Type : Sandstone & silstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 20.0

Storage Capacity, available (ac-ft) 5.90E+07

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	4,612	4,612	< 500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	800-2200	1200	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	0-400	275	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	200-800	400	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.005-.25	0.05	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			3
Hydraulic Conductivity (ft/day)	0.17-1.7	0.85	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	4

Quality Indicator
19 Total

Final Ranking 61 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Piceance Basin
Aquifer Name: Upper Piceance Basin Aquifer - Uinta Formati
Aquifer Type : silty sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 7.5

Storage Capacity, available (ac-ft) 5.02E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	1,045	1,045	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-50		<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3
Saturated Thickness (ft)	0-500	250	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	50-100	75	<50	1	50-100	2	100-300	6	300-750	15	>750	30	1
Storage Coefficient	0.01-0.1	0.1	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.2-1.2		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

poor=1,
fair=2,
good=3,
excellent=4

Quality Indicator
14 Total

Final Ranking 60 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: SW Colorado
Aquifer Name: Morrison/Summerville/Entrada
Aquifer Type : Sandstone interbedded with shale
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.8

Storage Capacity, available (ac-ft) 7.37E+05

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data	poor=1, fair=2, good=3, excellent=4
Aerial Extent (sq. miles)	1,536	1,536	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4	
Depth to Formation Top (ft)	0-100	50	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3	
Saturated Thickness (ft)	200-300	250	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2	
Head Freeboard (ft)	50-100	75	<50	1	50-100	2	100-300	6	300-750	15	>750	30	1	
Storage Coefficient	0.001-0.1	0.01	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1	
Hydraulic Conductivity (ft/day)	0.01-2.7		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3	

Quality Indicator
14 Total

Final Ranking 55 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: South Park
Aquifer Name: Antero/Wagontongue Formation
Aquifer Type : Sanstone, conglomerate, w/ volcanics
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 3.8

Storage Capacity, available (ac-ft) 3.70E+05

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data	poor=1, fair=2, good=3, excellent=4
Aerial Extent (sq. miles)	154	154	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4	
Depth to Formation Top (ft)	0-50	25	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	3	
Saturated Thickness (ft)	100-500	250	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2	
Head Freeboard (ft)	50-100	75	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2	
Storage Coefficient	0.01-0.1	0.05	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1	
Hydraulic Conductivity (ft/day)	0.1-10		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	1	

Quality Indicator
13 Total

Final Ranking 51 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: SW Colorado
Aquifer Name: Wingate
Aquifer Type : Sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 3.8

Storage Capacity, available (ac-ft) 1.81E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	754	754	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	50-100	75	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2
Saturated Thickness (ft)	0-400	200	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	50-100	75	<50	1	50-100	2	100-300	6	300-750	15	>750	30	1
Storage Coefficient	0.01-0.1	0.05	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.02-2.0		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	2

poor=1,
fair=2,
good=3,
excellent=4

Quality Indicator
12 Total

Final Ranking 50 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: SW Colorado
Aquifer Name: Dakota/Burro Canyon
Aquifer Type : Sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.8

Storage Capacity, available (ac-ft) 1.34E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data
Aerial Extent (sq. miles)	2,790	2,790	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-800	200	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2
Saturated Thickness (ft)	0-400	150	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	3
Head Freeboard (ft)	50-100	75	<50	1	50-100	2	100-300	6	300-750	15	>750	30	1
Storage Coefficient	0.001-0.1	0.01	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.09-3.3		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

Quality of Data: poor=1, fair=2, good=3, excellent=4

Quality Indicator
14 Total

Final Ranking 48 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Huerfano Park
Aquifer Name: Cuchara-Poison Canyon
Aquifer Type : Sandstone & siltstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 25.0

Storage Capacity, available (ac-ft) 2.40E+06

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data
Aerial Extent (sq. miles)	150	150	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-2000	1000	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2
Saturated Thickness (ft)	400	400	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	100-1000	500	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.01-0.1	0.05	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.06-1.5	1	<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	1

Quality of Data: poor=1, fair=2, good=3, excellent=4

Quality Indicator
12 Total

Final Ranking 47 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: San Juan Basin
Aquifer Name: Mesa Verde
Aquifer Type : Sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.5

Storage Capacity, available (ac-ft) 5.99E+05

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data	poor=1, fair=2, good=3, excellent=4
Aerial Extent (sq. miles)	1,872	1,872	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4	
Depth to Formation Top (ft)	0->1000	100	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2	
Saturated Thickness (ft)	50-350	150	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2	
Head Freeboard (ft)	20-150	50	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2	
Storage Coefficient	0.001-0.1	0.01	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1	
Hydraulic Conductivity (ft/day)	0.001-0.02		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	2	

Quality Indicator
13 Total

Final Ranking 45 (summation of parameter rankings)

5/6/2004

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: San Juan Basin
Aquifer Name: Animas Formation
Aquifer Type : Tuffaceous sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.5

Storage Capacity, available (ac-ft) 2.65E+05

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	829	829	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0->1000	100	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2
Saturated Thickness (ft)	200-800	500	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	20-150	50	<50	1	50-100	2	100-300	6	300-750	15	>750	30	2
Storage Coefficient	0.001-0.1	0.01	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.001-0.1		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	2

Quality Indicator
13 Total

Final Ranking 40 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: San Juan Basin
Aquifer Name: Pictured Cliffs
Aquifer Type : Sandstone
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.5

Storage Capacity, available (ac-ft) 3.49E+05

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Value Range	Weighted Rank	Quality of Data (poor=1, fair=2, good=3, excellent=4)
Aerial Extent (sq. miles)	1,090	1,090	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0->1000	100	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2
Saturated Thickness (ft)	0-300	150	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	20-150	50	<50	1	50-100	2	100-300	6	300-750	15	>750	30	1
Storage Coefficient	0.001-0.1	0.01	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.0001-.01		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	2

Quality Indicator
12 Total

Final Ranking 35 (summation of parameter rankings)

ARTIFICIAL RECHARGE
Conventional Aquifer Ranking

CONSOLIDATED SEDIMENTARY DEPOSITS

Basin or Area Name: Pieceance Basin
Aquifer Name: Wasatch/Fort Union
Aquifer Type : Sandstone & shale
(sandstone, siltstone, limestone, etc.)

Potential Storage Capacity (ac-ft), per acre 0.1

Storage Capacity, available (ac-ft) 3.12E+05

PHYSICAL PARAMETER	Actual Value	Value for Calculation	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Value Range	Weighted Ran	Quality of Data
Aerial Extent (sq. miles)	4,873	4,873	<500	1	500-1,000	5	1,000-3,000	10	3,000-5,000	15	>5,000	20	4
Depth to Formation Top (ft)	0-3000	1500	<100	20	100-500	15	500-1,000	10	1,000-2,000	3	>2,000	1	2
Saturated Thickness (ft)	50-250	100	<100	1	100-250	3	250-500	8	500-1,000	15	>1,000	30	2
Head Freeboard (ft)	100-500	100	<50	1	50-100	2	100-300	6	300-750	15	>750	30	1
Storage Coefficient	0001-0.001	0.001	<0.001	1	0.001-0.01	5	0.01-0.1	10	>0.1	25			1
Hydraulic Conductivity (ft/day)	0.001-0.01		<0.001	1	0.001-0.01	5	0.01-1.0	10	1-10	50	>10	100	3

poor=1, fair=2, good=3, excellent=4

Quality Indicator
13 Total

Final Ranking 33 (summation of parameter rankings)