State of Oklahoma
OWRB
WATER RESOURCES BOARD
the water agency

Oklahoma Comprehensive Water Plan
Supplemental Report

Artificial Aquifer Recharge Issues & Recommendations

June 2010

This study was funded through an agreement with the Oklahoma Water Resources Board under its authority to update the Oklahoma Comprehensive Water Plan, the state's long-range water planning strategy. Results from this and other studies have been incorporated where appropriate in the OCWP's technical and policy considerations. The general goal of the 2012 OCWP Update is to ensure reliable water supplies for all Oklahomans through integrated and coordinated water resources planning and to provide information so that water providers, policy-makers, and water users can make informed decisions concerning the use and management of Oklahoma's water resources.

Oklahoma Comprehensive Water Plan
OCWP

Artificial Aquifer Recharge Issues and Recommendations

The following report was commissioned by the Oklahoma State Legislature in 2008 as a component of technical work performed under the 2012 Update of the Oklahoma Comprehensive Water Plan. This report presents the results of a technical workgroup study, supported by the Oklahoma Water Resources Board and CDM, to evaluate the potential for water supply augmentation through implementation of artificial aquifer recharge projects in Oklahoma. More specifically, this report presents recommended criteria for evaluating aquifer recharge project locations where most feasible throughout the state.

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Acronyms

AF	acre-feet
AFY	acre-feet per year
AR	artificial recharge
ASR	Aquifer Storage and Recovery
ASCE	American Society of Civil Engineers
AWI	American Water Institute
bgs	below ground surface
BOR	United States Bureau of Reclamation
CDM	Camp Dresser & McKee Inc.
DEM	digital elevation models
EPA	United States Environmental Protection Agency
GIS	geographic information system
gpm	gallons per minute
LSI	Langelier Saturation Indices
M&I	municipal and industrial
MCL	maximum contaminant level
NAS	National Academy of Sciences
NOAA	National Oceanographic and Atmospheric Agency
NSSL	National Severe Storms Laboratory
O&M	operations and maintenance
OCC	Oklahoma Corporation Commission
OCS	Oklahoma Climatological Survey
OCWP	Oklahoma Comprehensive Water Plan
ODEQ	Oklahoma Department of Environmental Quality
OGS	Oklahoma Geologic Survey
OU	University of Oklahoma
OWRB	Oklahoma Water Resources Board
PWS	public water supply
T&E	threatened and endangered
TDS	total dissolved solids
TM	Technical Memorandum
TSS	total suspended solids
USGS	United States Geologic Survey
WSTB	Water Science and Technology Board

Section 1
Introduction

The Oklahoma Water Resources Board (OWRB) is developing a major update to the Oklahoma Comprehensive Water Plan (OCWP). The Oklahoma Legislature passed Senate Bill 1410 (SB1410) in 2008, requiring OWRB to develop and implement criteria to prioritize potential locations throughout Oklahoma where artificial recharge (AR) demonstration projects may be most feasible.

The SB1410 work is divided into two phases. The goal of the Phase 1 investigation is to identify locations in both alluvial and bedrock aquifer settings that would be most suitable for AR demonstration projects to help meet future water supply challenges. Work under Phase 2 would implement the recommendations from Phase 1, including pilot project field demonstration(s) of AR.

Work for Phase 1 was authorized under a contract between Camp Dresser & McKee Inc. (CDM) and the OWRB and includes the following tasks:

- Task 1 - Develop Site Evaluation Methods
- Task 2 - Preliminary Screening of Potential Sites
- Task 3 - Evaluation of Potential Sites
- Task 4 - Reporting and Coordination

Task 1 includes the development of a set of criteria to be used to evaluate potential AR sites. A Technical Memorandum (TM) that described criteria selection was produced (CDM 2010) with feedback from the advisory work group. Section 2 of this report is a copy of that TM with minor revisions for incorporation into the final report.

A variety of sources were recommended to assist in criteria development, including the draft United States Bureau of Reclamation (BOR) Planning Framework for Artificial Recharge (BOR 2008), the National Academy of Sciences (NAS) Water Science and Technology Board's (WSTB) Prospects for Managed Underground Storage of Recoverable Water (WSTB 2008), the American Society of Civil Engineers' (ASCE) Managed Aquifer Recharge Standards (ASCE 2001), and previous regional assessments such as the Colorado Senate Bill 06-193 Underground Water Storage Study (CDM 2007).

The criteria are intended to serve as an objective method to identify potential AR areas and consist of a set of quantitative metrics from which numeric scores can be assigned to each potential AR site. The criteria are focused on the Phase 1 goal of identifying areas within the state where demonstration projects may be most feasible. A project size of 1,000 acre-feet (AF) was used as the maximum for the pilot project. It was assumed that a recharge project would be able to divert water into underground storage for 3 months of the year. This corresponds to a maximum recharge rate of 2,500 gallons per minute (gpm) for 3 months. Agricultural needs were not considered for a pilot-project because such a project would likely benefit private individuals as opposed to a public project that benefits the broader public through a public entity such as a municipality or public water provider.

An irrigation based project would require a large amount of water with a likely lower cost-benefit ratio than a municipal provider. Additionally, the feasibility of a recharge project has been demonstrated in the Blaine aquifer for agricultural use by the OWRB. However, the implementation of a demonstration or full-scale project would be expected to benefit all users of the recharged aquifer in the general vicinity of the project, and additional demonstration or full-scale recharge projects could be implemented for agriculturally-dominated aquifers.

Site-specific considerations, such as land ownership, were not considered at this level. Variations on a given criteria will be developed for different aquifer settings such as unconfined and confined aquifers. Results from this study and additional insight gained from a Phase 2 pilot project can be used to meet longer-term needs, such as drought protection.

The OWRB has successfully demonstrated AR in the Blaine aquifer in southwest Oklahoma. The sites were in karst aquifers and utilized gravity flow infiltration and recharge methods. Sites in this area were not considered in this study since AR has already been demonstrated in that region.

Criteria were developed for both a preliminary screening and a more detailed ranking process. The purpose of the preliminary screening was to eliminate many areas from further consideration based on relatively simple application of a small number of the criteria. All sites not eliminated through the preliminary screening would likely be suitable for an AR demonstration project. The more detailed ranking process identified the most feasible of the suitable sites identified through the preliminary screening. Figure 1 represents this process graphically.

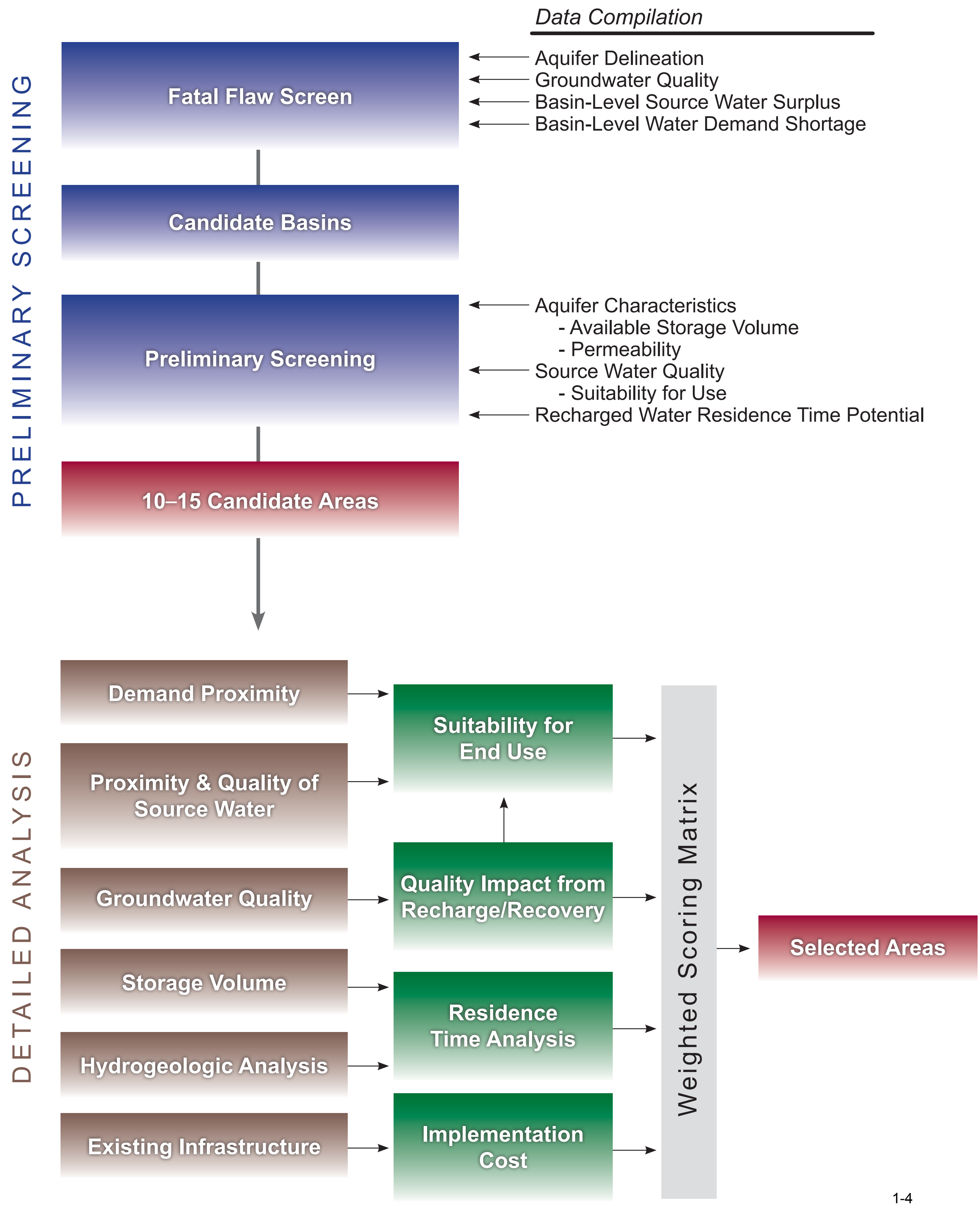
The preliminary screening was divided into a fatal flaw analysis and a threshold analysis. The fatal flaw analysis applies a limited set of criteria that, if the necessary characteristics are not present, would eliminate regions or aquifers from any further analysis. The fatal flaw screening criteria were developed to be able to use readily available information and relatively simple analyses of data. The threshold level screening was used to eliminate additional aquifers or areas from further consideration based on several key factors, and thus will expedite the more detailed analysis of remaining areas. The preliminary screening was performed by Wayne Kellogg with the American Water Institute (AWI) (2009) based on criteria outlined in Section 2 of this report. A summary of the conclusions from the preliminary screening is presented in Section 3 of this report. Through the detailed ranking, the entire suite of criteria and criteria weightings were applied to each remaining suitable site, resulting in a score for each site that identified the most feasible AR sites for the field demonstration projects.

Through the course of the work group meetings, comments and questions surfaced regarding the definition of the word 'site' for this project. A site is defined differently for the different phases of the project. In the preliminary screening, a site refers to a larger region of approximately a township (6 miles by 6 miles) that generally identifies a favorable portion of an aquifer and associated surface water basin. The boundaries of a preliminary screening site are not set and in some instances were expanded or moved in the detailed analysis. The maps presented in the detailed analysis appendices use the term recharge region, referring to the preliminary screening township-sized site. Within each recharge region, there is at least one recharge area of approximately 1 square mile and can be referred to as a site in the detailed analysis. Smaller design-level sites were not identified as part of this phase of the pilot project and are anticipated for Phase 2. References to site-specific criteria that were excluded from this phase of the project refer to the smaller scale design-level site size.

CDM would like to acknowledge the many organizations that provided invaluable data and technical input through the work group meetings for this project.

- Oklahoma Water Resources Board (OWRB)
- Oklahoma Geologic Survey (OGS)
- United States Geologic Survey (USGS)
- American Water Institute (AWI)
- Chickasaw Nation
- United States Bureau of Reclamation (BOR)
- Oklahoma Corporation Commission (OCC)
- United States Environmental Protection Agency (EPA)
- Oklahoma Department of Environmental Quality (ODEQ)
- University of Oklahoma (OU)
- Oklahoma Climatological Survey (OCS)
- National Oceanographic and Atmospheric Agency, National Severe Storms Laboratory (NOAA, NSSL)
- Oklahoma Conservation Commission (OCC)
- State Senator Susan Paddack

FIGURE 1:
Screening Process



Section 2
Site Evaluation Methods and Criteria

2.1 Potential Screening Criteria

Several previous studies have identified important criteria to consider for AR projects (CDM 2007; ASCE 2001; BOR 2008; NAS WSTB 2008). Table 1 lists the criteria that were considered for each of the studies and provides brief descriptions of each; more detailed descriptions follow the table. During previous meetings of the OWRB work group (December 8, 2008; January 21, 2009), several criteria were discussed as being most important to this study. Criteria that were used in other studies were also considered for inclusion for this project. It should be noted that there can be overlap between several of these criteria (e.g., source water availability could be limited by poor source water quality rather than physical availability).

Table 1. AR Project Criteria Identified by Various Entities Considered for Phase 1 Site Screening

			Source/Reference				
	Criteria	Criteria Description	SB1410 Meetings 1 & 2	Colorado SB06-193	BOR	NAS WSTB	ASCE
1	Proximity to Demand	Proximity of recharge project to areas with a demand, including seasonal demands	x	x	x	x	x
2	Source Water Proximity and Availability	Proximity to and availability of (consistent/seasonal/etc) source water	x		x	x	x
3	Source Water Quality	Suitable water quality of source water	x		x	x	x
4	Regulatory Concerns	Regulatory, water rights, or public involvement issues			x	x	x
5	Available Storage Capacity	Available capacity for recharge water storage in the aquifer	x	x	x	x	x
6	Hydrogeologic Suitability	Potential rate of aquifer recharge/conductivity	x	x	x	x	x
7	Residence Time	Duration recharged water is in aquifer		x	x	x	x
8	Groundwater Quality	Aquifer water quality	x	x	x	x	x
9	Effects on Groundwater Chemistry/Clogging	Potential for groundwater and recharge water to interact or for aquifer clogging			x	x	x
10	End Use	Drinking water, M&I, streamflow augmentation	x		x	x	x
11	Land Ownership/Land Use	Proportion of area with accessible public land		x	x	x	x
12	Proximity to Existing Infrastructure	Proximity of infrastructure (pipelines, ditches, etc)		x			x
13	Cost	Likely method of recharge and recovery and need to treat source water		x	x	x	x
14	Habitat Concerns	Presence of threatened and endangered species or wetlands		x	x	x	x

Table 1. AR Project Criteria Identified by Various Entities Considered for Phase 1 Site Screening

	Criteria	Criteria Description	Source/Reference				
			SB1410 Meetings 1 & 2	Colorado SB06-193	BOR	NAS WSTB	ASCE
15	Impacts to Nearby Streams	Potential to create gaining streams			x	x	
16	Waterlogging and Non-beneficial Use	Potential to create high water table/losses to vegetation or gaining streams		x	x	x	x
17	Existing Aquifer Use	Current use of the aquifer			x	x	x

Proximity to Demand

The proximity to the groundwater demand to be met by the AR project is an important consideration primarily from a cost perspective. Projects sited far from the demand location could require costly infrastructure to deliver the water to the demand location. Total annual demand as well as seasonal demands should be considered. For example, shortages may appear minimal on an annual basis, but an AR project may be beneficial where supplies are stressed by elevated seasonal demands. Projected unmet municipal and industrial (M&I), agricultural, and petroleum demands for the year 201 can be used for this criterion; the unmet demand data can be obtained from the OWRB's OCWP Gap Analysis (CDM 2009). Demand locations can further be identified in the detailed ranking through a demand density analysis using well permit information to show which areas within a given region have higher groundwater demand density. Demand projections for the year 206 can be used for siting future projects where demands are projected to increase significantly.

Source Water Proximity and Availability

The legal and physical availability of source water, and the distance to the AR site, is an important consideration from a project cost perspective. The proximity to source water will be generally measured in miles, but topographic data can be utilized to determine whether the AR site can be supplied by gravity flow, or if pumping would be required. Right-of-way concerns should also be considered, particularly in or through urban areas. The availability of source water is meant to provide an evaluation of the consistency of the source whether the source could be continuously utilized, seasonally, or only during periodic storm events. Climatic considerations in relation to amount of precipitation may also factor into this criterion.

Source Water Quality

Source water quality will be evaluated for general water quality parameters as data are available. Factors that should be considered include the presence of nutrients, high concentrations of effluent, high salinity or total dissolved solids (TDS), or any other common water quality parameter that could have a negative effect on the implementation of an AR project. Presence of negatively-impacting parameters could be mitigated through treatment prior to AR, but would lead to increased implementation costs and are therefore less desirable. Source water should not cause degradation of the native groundwater.

Regulatory Concerns

There are a variety of regulatory and political concerns that may affect the feasibility of AR projects. These include drinking water quality standards and public health concerns, water rights considerations, funding challenges, land ownership, permitting, and other regulatory requirements that may help or hinder specific locations. For this study, water rights with respect to source water will be considered to the extent possible, so as to avoid the assumption that source water is available from streams when the extraction would negatively impact senior water rights. Regulatory concerns that apply to all potential AR sites in the state regardless of location (e.g., funding and statewide regulatory requirements) will not be used in the ranking to prioritize sites since they would not differentiate any site over another.

Available Storage Capacity

Available storage capacity describes the availability of additional storage volume within an aquifer. The available storage consists of the unsaturated zone of an unconfined aquifer and the ability to inject water under reasonable pressures into a confined aquifer while minimizing loss through confining beds or other discharge pathways. The available storage in a confined aquifer is dependent on the overburden pressure and existing potentiometric surface depth. Aquifer properties such as porosity, depth to water, and top of formation are important for quantifying the available storage capacity. The available storage per unit area is much higher in unconfined aquifers. Generally, storage is available in aquifers that have been pumped in excess of current recharge and can be identified by declining water levels. Storage capacity may be available in more heavily pumped areas of an aquifer, even if other areas within the aquifer do not share the same declining water level trends.

Hydrogeologic Suitability

Hydrogeologic suitability is the characterization of an aquifer's ability to transmit water (receive recharge or yield water). Characteristics such as hydraulic conductivity (K) and transmissivity (T) and storage coefficients (S, Sy) are important aspects to consider. Aquifer characteristics must be assessed for the ability of the aquifer to accept or produce water at a rate appropriate for the associated project source and demand. Different criteria are necessary for alluvial and bedrock aquifers since hydraulic properties vary widely between alluvium and bedrock.

Residence Time

Residence time quantifies length of time a recharged volume of water will remain in the aquifer and can be readily retrieved. The purpose of the AR project will play an important role in selecting an appropriate aquifer (e.g., short-term seasonal use could tolerate short residence time aquifers, but long-term drought protection would need multi-year residence times). In the Colorado SB06-193 study, alluvial aquifer residence times of 120 and 480 days were used. For the SB1410 study, similar increments would be utilized if the data are available, as these residence times represent the time for water to remain in storage for part of a growing season or for more than a year. If data are not available, estimates of residence times will be made based on aquifer properties, groundwater hydraulic gradients, and distance to discharge areas (e.g., nearby streams or aquifer outcrop areas).

For the unconfined portions of bedrock aquifers, the proximity of alluvial aquifers or other discharge areas and relative difference between water levels and discharge elevations can be used to evaluate this criterion. Maps showing the locations of alluvial aquifers and aquifer outcrop areas that overlie or are proximal to the unconfined portions of the bedrock aquifers could be used for the bedrock aquifer evaluation.

The residence time in the confined portions of bedrock aquifers is a function of the distance to potential discharge areas and can be significant (years to decades) for areas sufficiently distant from points of discharge.

Groundwater Quality

The water quality within the aquifer is important to consider; both for how it could impact the quality of the source recharged water and how it might be affected by it. Poor groundwater quality that degrades higher quality recharge water will potentially result in water unsuitable for its intended use or generate additional treatment costs when extracting for reuse. The potential to enhance the native aquifer water quality also exists under certain conditions (e.g., arsenic immobilization and dilution of TDS). The criterion also addresses the concern of degrading aquifer water quality by leaching of minerals naturally found in soils when recharge water is added. Locations where there is a high leaching potential (e.g., saline soils for spreading basins) could render that area unsuitable for aquifer recharge.

Effects on Groundwater Chemistry and Clogging

This criterion is concerned with the potential for source water and groundwater geochemical interactions. This could include interactions of source water with the aquifer matrix, as well as the potential for clogging aquifer pore spaces due to geochemical or biological interactions. Differences in water properties, such as pH or reduction/oxidation (redox) characteristics, could lead to dissolution of undesirable metals or minerals within the aquifer, or conversely, the immobilization of some elements or compounds. Detailed analysis of specific geochemical properties of the aquifers and source waters, including potential for clogging due to interaction, is more appropriate for evaluation of specific implementation locations rather than the more general investigation intended for Phase 1 of the study. However, simple comparisons of pH and redox conditions could be completed for this investigation, as data are available.

End Use

The requirements of the end user of AR recovered water will have an effect on the need for treatment of the recovered groundwater. Municipal, industrial, agricultural, petroleum industry, and power generation all have different requirements for treatment upon extraction. It is important to ensure that the water quality of the recovered groundwater is suitable for its intended use. Some aspects of this criterion can be addressed through source water and groundwater quality criteria.

Land Ownership/Land Use

This criterion examines general land use, including the location of urban, agricultural, native and range lands, public vs. private land ownership, and the location of inaccessible lands (such as military reserves). A key assumption is that recharge projects will be more easily sited on accessible public lands and non-urban lands. Land acquisition costs will play an important role in determining economic feasibility.

Proximity to Existing Infrastructure

The presence of water conveyance structures and other infrastructure is an important consideration affecting the cost and overall feasibility of an underground water storage project. This criterion considers the proximity of major ditches and pipelines on the basis that existing water conveyance structures will improve the suitability of an area and reduce cost to deliver water for recharge activities. This criterion should evaluate existing infrastructure that can be used to supply source water and/or deliver water to the demand. This criterion will likely not apply during the regional-level preliminary screening, but will become increasingly important as the size of potential sites decreases.

Cost

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

Habitat Concerns

The presence of habitat for federally designated threatened and endangered (T&E) species, or wetlands that could be adversely impacted by construction or operation of potential underground water storage projects should be considered for AR project siting. Depending on timing and operation of a recharge project, the impacts on habitat could be either positive or negative. For example, recharge ponds could provide beneficial waterfowl habitat in the fall and winter months, but may impact habitat for a T&E species. This criterion plays a minor role in the confined aquifer settings due to the small surface area associated with artificial recharge wells and associated piping. This criterion will likely not apply during the regional-level preliminary screening, but will become increasingly important as the size of potential sites decreases.

Impacts to Nearby Streams

This criterion includes the potential for an AR system to affect local streams through additional contribution to stream baseflow. This criterion is influenced by the type of aquifer (alluvial versus bedrock; bedrock aquifers would likely not affect streams unless it is an unconfined/outcrop area), as well as the general distance of the AR location to the stream.

Waterlogging and Non-beneficial Use

This criterion considers the potential for shallow water table conditions, both near a potential recharge area as well as downgradient of the area, which could promote the growth of undesirable vegetation such as tamarisk and lead to non-beneficial water consumption. The shallow water table conditions could also lead to waterlogging of soils, creation of undesirable wetlands, and flooding of basements. For the Colorado SB06-193 study, the maximum depth to which this criterion was estimated to have any impact was 30 feet below ground surface (bgs), which is the approximate depth to which tamarisk is capable of extending its roots. This criterion applies mainly to alluvial systems. Underground water storage in the bedrock aquifers is expected to have minimal potential to cause waterlogging or non-beneficial use. This criterion often overlaps with storage availability, as waterlogging due to the AR project can be considered an indication that there is no available storage or that hydrogeologic parameters are not suited for the scale of the project.

Existing Aquifer Use

Current aquifer use is a potential concern for selecting AR locations. The different source water qualities could affect the current aquifer use if a lesser-quality water is used for AR than what is currently present in the aquifer. Additionally, the operation of the AR facility could result in a fluctuating water table that would change the ability to use existing wells in the aquifer. This criterion may overlap with other concerns addressed in the groundwater and source water quality criteria.

Qualitative Factors

Other factors such as individual town or cities' desire to have the project in their area, overall public support or other non-quantitative factors may be considered in the final siting of the pilot project. Qualitative factors will likely only distinguish between otherwise equally feasible sites.

Selection of Criteria

Based on discussions at the OWRB work groups, previous regional studies and national guidelines and standards set forth by government and professional organizations, the following criteria are recommended for inclusion in the evaluation of potential AR locations. The criteria are organized by major category. Some criteria described above have been divided into multiple criteria as recommended in the work group meeting held September 22, 2009. Application of the selected criteria is discussed in detail in Section 3 of this document.

Demand

- Proximity to demand
- Frequency and seasonality of demand
- Demand density

Source Water

- Source water physical and legal availability and proximity to AR site
- Source water quality for non-degradation
- Regulatory challenges

Hydrogeologic Suitability

- Aquifer storage capacity (current utilization of aquifer / declining water levels)
- Aquifer conductivity, transmissivity, and storativity (K, T, S, Sy)
- Residence time/distance to discharge locations

Groundwater Quality

- Native groundwater quality for intended use
- Geochemical interaction with source water

Cost

- Recharge method
- Proximity and infrastructure considerations

Project Impact

- Qualitative ranking factors

The following criteria were not selected for this Phase of the siting study:

- **Habitat Concerns:** this criterion is more appropriate for site-specific implementation concerns (Phase 2 implementation). The nature of this investigation is to identify aquifers and surface water basins with favorable characteristics for the AR demonstration project. It is anticipated that critical habitat and wetlands would not comprise the entire selected area and specific sites could be identified for development of an AR facility within the scale of the investigation areas.

- **Waterlogging and Non-Beneficial Use:** this criterion can be addressed through the available storage capacity criterion. Alluvial aquifers will be the primary formations that could be influenced by this criterion, and thus the calculation of available storage will be modified to remove the subsurface zone that may be susceptible (approximately the upper 30 feet of subsurface).

- **Land Ownership/Use:** this criterion is more appropriate for site-specific implementation concerns. The nature of this investigation is to identify specific aquifers or portions of selected aquifers. Land ownership and use issues are appropriate for the site-specific selection process within the selected region.

- **Effects on Neighboring Streams:** this criterion shares common principles with the residence time criterion, and thus will not be evaluated separately.

- **Existing Aquifer Use:** this criterion shares common principles with the groundwater and source water quality, and effects on groundwater geochemistry criteria. Additionally, the operational issues associated with the demonstration AR facility would not be anticipated to produce excessive drawdown that would result in a loss of groundwater supply to current users.

- **End Use:** this criterion shares common principles with the groundwater quality and source water quality criteria and, and thus will not be evaluated separately

2.2 Application of Selected Criteria

As shown in Figure 1, potential AR demonstration project sites will go through a preliminary screening and a detailed ranking. The preliminary screening consists of a fatal flaw analysis and a threshold screening. Not all of the criteria identified in the previous section will be used in preliminary screening, but all are considered in the detailed ranking. This section describes the preliminary screening from the detailed analysis. In the detailed ranking analysis, the criteria will be weighted based on relative importance to determining the feasibility of the demonstration project.

Table 2 presents the criteria selected for the fatal flaw, threshold screening, and detailed ranking. These criteria were selected based on the recommendations of previous discussions within the SB1410 work group as well the recommended criteria from the Colorado SB06-193 study and the BOR report.

Table 2. Screening Levels and Criteria Weighting Factors

Category	Criteria	Screening Level		
		Fatal Flaw	Threshold	Detailed
Demand	Frequency	x	x	x
	Proximity	x	x	x
	Density			x
Source Water	Proximity	x	x	x
	Availability		x	x
	Quality for Non-Degradation		x	x
	Regulatory Challenges		x	x
Hydrogeologic Suitability	Available Storage Volume and Ability to Meet Local Demand		x	x
	Transmissivity		x	x
	Residence Time/Distance to Discharge		x	x
Groundwater Quality	Native Quality	x	x	x
	Geochemical Interactions with Source Water			x
Cost	Recharge Method (Capital and O&M)			x
Project Impact	Qualitative Considerations			x

The SB1410 work groups, the Colorado study, and the BOR report identified storage capacity, hydrogeologic suitability (transmissivity), and proximity to demand as having a high importance in evaluating AR locations. The SB1410 and the BOR report both identified source water quality and proximity/availability as important criteria. Several criteria were utilized in the Colorado SB06-193 study and/or recommended in the BOR report, but were not discussed in initial SB1410 work group meetings. These criteria include residence time, implementation costs, and effects on groundwater chemistry. Residence time and proximity to infrastructure were included as moderately-weighted criteria in the Colorado SB06-193 study. Residence time was highly weighted in the BOR report (included within the hydrogeologic considerations). All other criteria not included in the OWRB work group discussions received low weights in the SB06-193 study or were not included as weighted criteria in the BOR report.

Fatal Flaw Criteria

The fatal flaw analysis is the initial level of investigation intended to screen out several areas in the state located over aquifers based on relatively simple application of four criteria: annual or seasonal demand frequency; proximity of the AR site to demand; proximity of the AR site to a recharge source; and groundwater quality (based on TDS). This level of analysis is completed to answer a yes-or-no type question for each region under consideration for the AR demonstration project. At this level of analysis, the regions will likely consist of a surface water basin, groundwater aquifer, or combination as appropriate. The proximity criteria will be analyzed for each surface water basin, using the gap analysis tool for the OCWP to help assess demand and source data and geographic information system (GIS) mapping for physical distances. The water quality criterion will be analyzed for each major and minor aquifer within the State of Oklahoma as well as noting areas within each aquifer that may have poorer water quality. Failure at any one of the fatal flaw criteria indicates that a demonstration project at the potential AR site is most likely not feasible. Thus, any basin or aquifer that does not meet the recommendation for all fatal flaw analyses will be removed from further consideration. The portions of the surface water basins and groundwater aquifers that overlap (or are within close proximity) and produce a favorable response for all fatal flaw criteria will be retained for the threshold level analysis.

- Demand Frequency: Based on the discussion during the September 22, 2009 work group meeting, candidate recharge areas should have significant groundwater development and seasonal variability in the demand. Because Phase 2 is a pilot project, the work group concluded that the most appropriate demand to be met would be a seasonal demand, as the short-term effect of the pilot project would be seen. In the event that a long-term demand (such as storage for drought mitigation) were selected, it could be many years before the effect of the storage project would be observed. Thus, during fatal flaw analysis, only regions with short-term (seasonal) demands will be selected for further consideration.

- **Proximity to Demand:** For the fatal flaw analysis, the demand center should be within a set distance from the proposed AR site. Areas where no seasonally based demand exists should be screened from further consideration for the demonstration project.

- **Proximity of Source Water:** For the fatal flaw analysis, the proximity of source water to potential AR site should be less than a set distance. Alternatively, existing infrastructure, such as pipelines or ditches, may be able to provide an adequate source if they are present within the same radius. Only proposed AR sites with source water within the set distance will be considered for the demonstration project.

- **Groundwater Quality:** For the fatal flaw analysis, any groundwater aquifer or portion of the aquifer at the proposed AR site that has a TDS concentration above a specified limit will be excluded from further consideration due to the limited uses this water might have.

Threshold Screening Criteria

The threshold level of analysis is the second part of the preliminary screening and will be completed for each potential AR site that passes through the fatal flaw analysis. The purpose of the threshold screening is to further narrow the number of sites that will undergo the detailed ranking by applying several of the identified criteria in a relatively simple manner. The threshold screening is more involved than the fatal flaw analysis in that a value of high (good), moderate (fair), or low (poor) is assigned to the criteria. Those sites that have a low (poor) ranking will be eliminated from further consideration, and those sites that have the most moderate (fair) rankings may also be eliminated, depending on the final rankings of the potential sites. The goal of the threshold screening is to reduce the number of potential sites for the detailed analysis to 10 to 15 sites.

The criteria used in the fatal flaw analysis are used again in the threshold screening, but will be ranked as high (good), moderate (fair) or low (poor) rather than a simple yes/no type answer. In addition, the source water quality, regulatory issues, and hydrogeologic characteristics (available volume, transmissivity, and residence time) will also be ranked.

- **Source Water Quality for Aquifer Non-Degradation:** Threshold analysis should initially rank sites based on TDS concentrations, with a tiered ranking for high, moderate, and low quality. If other water quality data are available to make reasonable comparisons across the state, those data should be utilized as well.

- **Source Water Availability:** The water available to the AR project should be sufficient to meet the demand, and could include various sources, such as precipitation capture systems or streamflow. Water rights are further evaluated within the regulatory challenges criterion to ensure legal availability.

- **Regulatory Challenges:** Many regulatory concerns will need to be addressed for any AR project, regardless of location. Some regulatory challenges, such as water rights, and their influence on source water availability, will be addressed in the source water proximity and availability criteria. Others regulatory challenges related to water quality are encompassed in water quality criteria. The SB1410 work group indicated that regulatory concerns are very important and should be highlighted.

- **Storage Availability:** For the threshold evaluation, the available aquifer storage capacity should at a minimum meet the demand volume, which will result in a moderate score. Aquifers that more than meet the demand gap size should receive a high score. Additional consideration should be given to the possibility that injection or recharge of water could displace existing groundwater, resulting in no net storage gain. Small aquifer storage availability volume should not result in a lower score if the available storage could meet a nearby demand gap. Storage availability should allow for water to recharge without causing waterlogging or non-beneficial use by phreatophytes.

- **Transmissivity (T):** For the threshold evaluation, a tiered ranking should be established based on the range of transmissivities encountered for both alluvial and bedrock aquifers across the state. Lower T values could severely hinder the effectiveness of an AR project. Hydraulic conductivity (K) may be considered as a surrogate for T if the saturated thickness of the aquifer is unknown.

- **Residence Time/Distance to Discharge:** For the threshold evaluation, the residence time can be approximated by the distance to discharge points (e.g. streams, outcrops or bedrock aquifer contact with alluvial aquifers). Generally a longer residence time will ensure that water stored at the potential AR site would be available for extraction at a later date and should be ranked higher. More detailed estimates of residence times based on local groundwater gradients and comparisons to the time required based on the demand pattern are more appropriate for the detailed ranking and will be avoided in the threshold screening. Consideration should also be made that water injected into the AR project does not simply displace water from the aquifer, but adds to the total aquifer storage.

Detailed Ranking

The detailed ranking will be performed on the best 10 to 15 potential AR sites from the threshold screening stage of the preliminary screening and will apply each criteria on a more detailed and quantitative basis than was done through the preliminary screening. Each criterion will be scored on a one to five scale, with five being most favorable and one being unfavorable. Scores will be assigned based on a detailed analysis of existing data and professional judgment. The score will then be multiplied by a weighting factor that represents the relative importance of each criterion. Once each criterion score is multiplied by the weighting factor, the results are summed to generate a single potential AR site score. Higher scores indicated AR sites that are more feasible than lower scoring sites.

Several of the criteria that will be applied in the detailed ranking have already been discussed in the fatal flaw and threshold screening sections. The detailed ranking process will simply extend the application of the criteria based on other existing data, make comparisons relative to other potential AR sites and potential interactions with other criteria. In addition, the detailed analysis will consider four other criteria not applied in the preliminary screening: demand density, geochemical interactions with source water, cost, and qualitative impact. The qualitative impacts could be used to distinguish otherwise quantitatively equal potential sites.

- **Demand Density:** This criterion will be utilized to evaluate the density of demands within a given area. For example, several demands that are located within close proximity to a recharge aquifer would result in a favorable ranking of that aquifer due to its potential to meet multiple demands depending on need. This criterion can also be used to select sites within a larger aquifer area identified in the preliminary screening. It is anticipated the state's well permit database can be used to quantify density of groundwater use.

- **Geochemical Interactions with Source Water:** For the detailed ranking, each potential AR site that passed the preliminary screening will be investigated for potential groundwater/surface water interactions and interactions with the aquifer matrix (e.g. mineral precipitate or leaching). Cases where recharge may result in water quality improvements will receive the highest score, while cases where recharge may result in poorer water quality or dissolution of the aquifer matrix will receive the lowest score. Interactions could lead to dissolution of undesirable metals or compounds into the groundwater, or aquifer clogging due to microbial interactions. On the contrary, recharge of aerobic (surface) water into an anaerobic aquifer could result in immobilization of elements such as arsenic, leading to an improvement in water quality, although this will need to be balanced with the potential clogging effects of precipitating iron.

- **Implementation Cost:** For the detailed ranking, each potential AR site that passed the preliminary screening will be evaluated for the anticipated method of recharge and groundwater extraction, as well as general land value. This criterion will be evaluated under the assumption that gravity-fed systems (such as recharge ponds) would be less expensive than the construction and operation of injection wells. Similarly, it is influenced by the method of extraction, such as supplementing stream baseflow versus using extraction wells. Cost for aquifers requiring well usage will also be influenced by the depth to the aquifer unit. An additional cost that may be incorporated is the cost of land; it can be assumed that the cost of land required to operate an AR project would be higher within the vicinity of metropolitan areas, and would result in a lower score.

  It is likely that alluvial aquifers will receive the highest scores, depending on location (locations near metropolitan areas receive lower scores due to price of land, while rural areas receive the higher scores). Bedrock aquifers will likely receive the lower scores due to the necessity of well usage; differentiation will also depend on the location (municipal versus rural). There is also the possibility that some bedrock aquifers may be able to utilize existing high capacity wells or could be recharged in areas of outcrops or shallow subcrops, which could increase their score to a moderate range.

- **Project Impact:** This qualitative criterion will be utilized to incorporate any additional information on a given aquifer that is available. This may include political or economic reasons a specific aquifer should be given a higher or lower score. This criterion should be used to distinguish otherwise quantitatively equally feasible AR sites.

A scoring matrix was used for the detailed ranking and is presented in Section 4 of this report. All criteria were assigned a raw score from 1 to 5 with 1 being not favorable, and 5 being highly favorable. Criteria were assigned weights to indicate the relative importance the criteria. Final scores for each recharge site were determined by multiplying the raw score by the weight and summing the weighted scores for all criteria. At the January 2010 work group meeting, the relative importance of the criteria was surveyed through a voting exercise whereby each participant was given 14 votes to assign to the 14 criteria in Table 2. It should be noted that for this exercise, source water availability and proximity were considered as one criterion, and cost was divided into capital and operations and maintenance subcategories. The results of the voting are presented in Table 3. There were concerns that the participants present at the meeting may skew the voting results based on their particular professional backgrounds. During the final ranking, a sensitivity test was run on the weights to address these concerns (Section 4).

Table 3. Criteria Weight Voting Results

Category	Criteria	Votes
Source	Quality for Non-Degradation	27
Hydrogeologic Suitability	Available Storage Volume and Ability to Meet Local Demand	25
Groundwater Quality	Native Quality	20
Groundwater Quality	Geochemical Interactions with Source Water	20
Demand	Proximity	19
Source	Proximity and Availability	19
Hydrogeologic Suitability	Transmissivity	16
Hydrogeologic Suitability	Residence Time/Distance to Discharge	14
Demand	Frequency	10
Demand	Density	10
Cost	Operations and Maintenance (O&M)	10
Cost	Capital	8
Source	Regulatory Challenges	7
Project Impact	Qualitative Considerations	5

Weighting factors were utilized in the Colorado SB06-193 study, and the BOR study. Table 4 presents various criteria in each and compares the relative importance placed on each criteria in the studies. The table shows that although each study has a unique scoring system, there are several criteria that are agreed to be more important than others. There are also significant deviations in the work group ranking from other studies. This can be explained in part that the voting occurred after the preliminary screening identified sites that likely have at least adequate levels of available supply and hydrogeologic suitability. These criteria were ranked lower than other studies, but were implicitly ranked higher since they were selected for the preliminary screening. The sensitivity test on weightings allowed analysis with more importance on the criteria used in the preliminary screening.

Table 4. Comparison of Relative Importance of Criteria

Criteria	OWRB Work Group Weighting	Colorado SB06-193	BOR
Source Water Quality for Non-Degradation	1	NA	NA
Suitable Storage Volume	2	1	1
Native Groundwater Quality	3	4	NA
Geochemical Interactions with Source Water	4	4	NA
Proximity to Demand	5	1	NA
Proximity to Source	6	NA	NA
Hydrogeologic - Transmissivity	7	2	1
Hydrogeologic - Residence Time/Distance to Discharge	8	3	1
Demand Frequency	9	NA	NA
Demand Density	10	NA	NA
Cost/Recharge Method	11/12	4	2/3/5
Source Water Regulatory Challenges	13	NA	4/5
Project Impact/ Qualitative Considerations	14	3	NA
Land Ownership/Use	NA	4	NA
Existing Infrastructure	NA	3	NA
Engineering Feasibility	NA	NA	4
Monitoring Plan	NA	NA	4
Rehabilitation Plan	NA	NA	5
Environmental Issues	NA	4	5
Uniqueness	NA	NA	4

Note: 1 indicates highest weighting

2.3 Data Requirements

Data requirements for analysis of the various criteria relied on multiple sources of data, including GIS data files. The following presents a summary of the data sources used for evaluation of each criterion. Data used for each recharge region in the detailed analysis are presented in the appendices. Refer to the references section for proper citations.

- **Demand Frequency:** Tables and figures and original data from the OWRB Gap Analysis project were utilized to determine seasonality of demands.

- **Proximity to Demand:** GIS maps of public water supply (PWS), aquifer footprint and surface water sources were utilized to determine distances and spatial relationships.

- **Proximity and Availability of Source Water:** Data from the OWRB Gap Analysis project were utilized to determine the amount and frequency of available source water. Additional data, including precipitation and streamflow gage data were used to supplement the evaluation in the detailed screening. Distances from surface water sources to recharge areas were determined from GIS maps.

- **Storage Availability:** The availability of storage volume, or freeboard, within an aquifer was analyzed using depth to water, ground surface elevation and groundwater elevation contours Grid surfaces of the groundwater contours were generated and compared against ground surface digital elevation models (DEM) to determine depth to water. Storage coefficients were used to compute available storage.

- **Groundwater Quality:** Groundwater quality data were obtained from OWRB, USGS, and EPA online databases.

- **Source Water Quality for Non-Degradation:** Data were gathered for the OWRB Marginal Quality study, as well as the OCWP, Plentiful data were obtained from the USGS and EPA online databases.

- **Regulatory Challenges:** Data from the OWRB Gap Analysis work in progress, as well as information from the OWRB were utilized to assess the magnitude of regulatory challenges, including legal availability.

- **Transmissivity:** The AWI preliminary screening report provided a summary of transmissivity data for the major aquifers.

- **Residence Time/Distance to Discharge:** The Glover equation was used in conjunction with hydrogeologic parameters and GIS maps to estimate residence time and losses.

- **Demand Density:** Demand density information was available from the OWRB Gap Analysis and from the groundwater permit database.

- **Geochemical Interactions with Source Water:** Groundwater and surface water quality data from the online USGS and EPA databases were utilized to assess geochemical interaction and Langelier indices.

- **Implementation Cost:** Relative costs (both capital and operations and maintenance [O&M]) were estimated based on recharge type (e.g., spreading basins, retrofit of existing wells, new wells), treatment needed due to source water quality, and conveyance method.

- **Project Impact:** Data from the OCWP were utilized to help determine the magnitude of an impact a pilot project would make relative to the local demand.

Section 3
Preliminary Screening

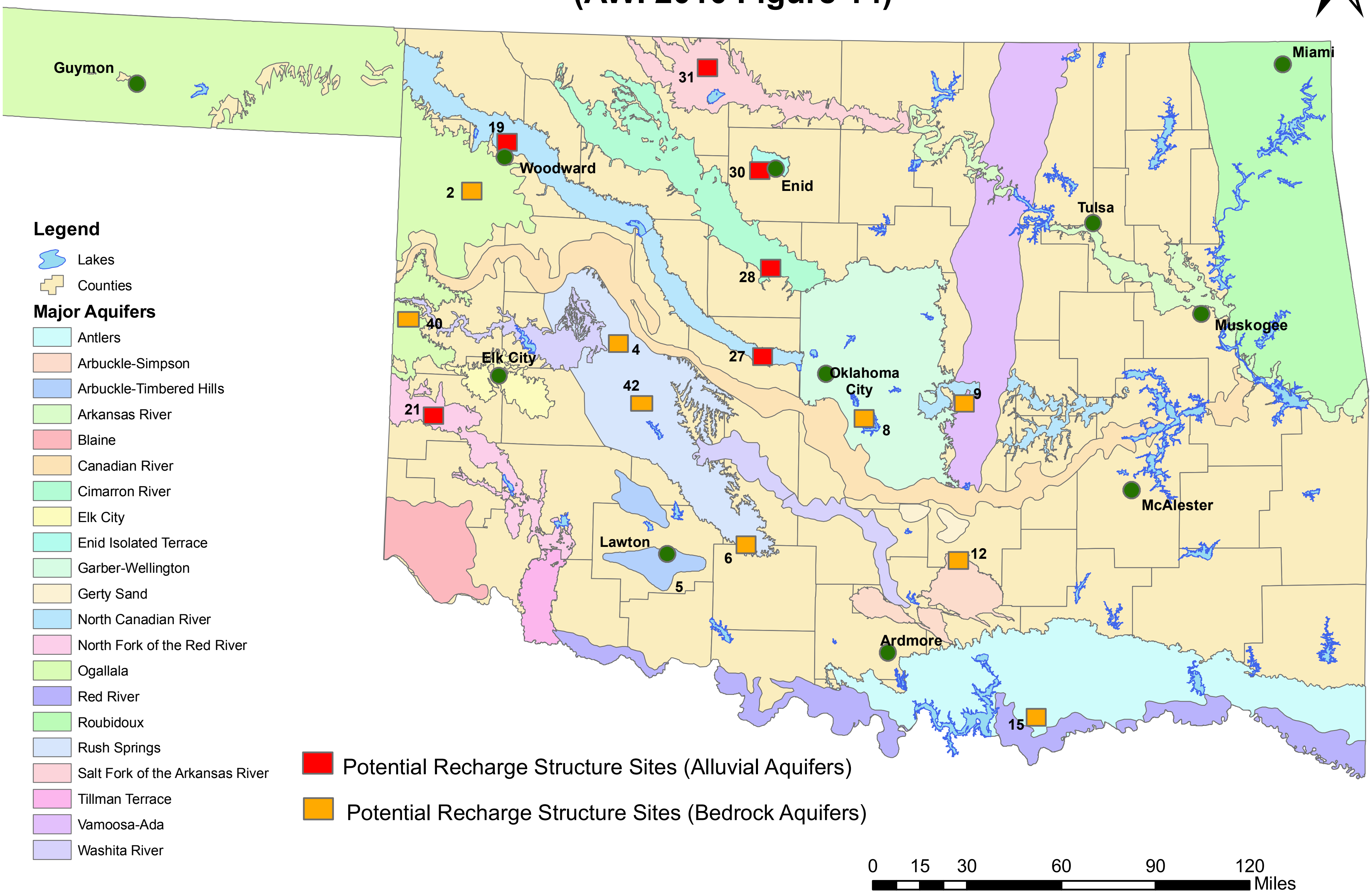
The preliminary screening was performed by Wayne Kellogg with the AWI using the criteria identified in Table 2 for a fatal flaw and threshold screening analysis (AWI 2010). The purpose of the preliminary screening is to eliminate many areas from further consideration based on relatively simple application of a small number of the criteria. All sites that are not eliminated through the preliminary screening would likely be suitable for an AR demonstration project. Sites that passed through the fatal flaw and threshold screening were considered in the detailed ranking. Only basic results of the AWI 2010 report are presented here. The reader should refer to the AWI 2010 report for detailed discussion of methods, analyses, and results.

Initially, 57 sites throughout the state were identified for the preliminary screening based on aquifer location, existing use, and demands (AWI 2010, Figure 5 and Table 1). Several sites were screened out through the fatal flaw analysis, resulting in 15 alluvial aquifer sites, and 15 bedrock sites. The threshold analysis screened out an additional 15 sites, resulting in 6 alluvial sites and 9 bedrock sites (AWI 2010, Figure 14, reproduced on the next page). The 15 sites that passed the fatal flaw and threshold screening were considered in the detailed ranking presented in Section 4. Table 5 presents the site number, surface water basin, aquifer and nearby municipality of the 15 sites identified for the detailed screening.

Table 5. Sites Identified through Preliminary Screening.

Site	Surface Water Basin	Aquifer	Nearby Municipality
2	Upper North Canadian River	Ogallala	Woodward
4	Upper Canadian River	Rush Springs	Weatherford
6	Beaver Creek	Rush Springs	Marlow
8	Little River	Garber Wellington	Norman
9	Lower North Canadian River	Ada Vamoosa	Shawnee and Seminole
12	Blue River	Arbuckle Simpson	Ada (Byrd's Mill Spring)
15	Red River	Antlers	Durant and Calera
19	Upper North Canadian River	Alluvial	Woodward
21	Upper North Fork Red River	Alluvial	Elk City
27	Middle North Canadian River	Alluvial	El Reno
28	Middle Cimarron River	Alluvial	Kingfisher and Hennessey
30	Lower Cimarron River	Alluvial	Enid
31	Upper Salt Fork of Arkansas River	Alluvial	Cherokee
40	Washita Headwaters	Ogallala	Reyden
42	Upper Washita	Rush Springs	Eakly

Figure 2. Potential Recharge Sites that Passed Fatal Flaw and Threshold Screening (AWI 2010 Figure 14)



OWRB CDM

Section 4
Detailed Ranking and Scoring

Fifteen recharge sites were identified through the preliminary screening that met certain minimum criteria and are all likely suitable locations for a recharge pilot study (Section 3). The purpose of the detailed ranking is to determine the most suitable of the sites for the pilot project through an objective scoring process. All sites were re-evaluated in more detail using each of the criteria used in the preliminary screening and additional detailed analysis criteria as described in Section 2 (Table 2). A 'site' from the preliminary screening is defined as an approximately township (6 miles by 6 miles) located in a favorable area of an aquifer that is proximal to an appropriate source and demand. The preliminary screening 'site' is referred also referred to as a 'recharge region' in the detailed ranking. In the detailed ranking, the size of a site is narrowed to an approximately 1-square-mile 'recharge area'. The exact design-level location of the project remains undetermined to allow for site specific evaluation, such as coordination with local landowners and other environmental factors.

The first step in the detailed screening was to evaluate each recharge region (preliminary screening 'site') to determine the best recharge area (approximately 1- square-mile area within a recharge region). Recharge areas were identified based on locations of PWS wells, recharge source water, available aquifer freeboard (depth to water), and general groundwater flow direction. This initial step resulted in minor shifts in the locations of some recharge regions identified in the preliminary screening to encompass a more favorable area. Some of the larger recharge regions contained more than one possible location for a recharge project. In such instances, the recharge area with the closest source and demand proximities, with sufficient aquifer freeboard and located upgradient from the demand and groundwater discharge areas was selected for the ranking and scoring process. It was assumed that a pilot project would not exceed 1,000 acre-feet per year (AFY), and criteria were scored based on that assumption.

Detailed results for each recharge area are presented in the appendices. The detailed ranking methods summarized results and recommended pilot project recharge areas are presented below.

4.1 Detailed Ranking Methods

Based on the information gathered for each recharge area, individual criteria were compared among all recharge areas, and an appropriate score (high, moderately high, moderate, moderately low, low) was assigned to each recharge area for each criterion. Table 6 presents the criteria that were evaluated for the detailed screening, and presents the scoring guidelines for each criterion. In some cases, further differentiation was deemed appropriate, and a moderately high or moderately low score was assigned for a given recharge region. Detailed justification for the scoring of recharge area is presented in its appendix. A description of the methods used to assign the scores for each criterion follows Table 6.

Table 6. Scoring Guidelines for Detalied Ranking

Criteria	Factors for High Score	Factors for Moderate Score	Factors for Low Score
Demand Proximity (distance from recharge area)	Within 1 mile	Approximately 1.5 miles	Greater than 2 miles
Source Proximity (distance from recharge area)	Within 1 mile	Approximately 1.5 miles	Greater than 2 miles
Available Freeboard and Ability to Meet Demand	Plentiful volume for meeting the associated demand; no areas will raise water level to less than 15 feet bgs	Likely sufficient volume for associated demand, but uncertainty exists	Not enough volume to meet the associated demand; may raise the water level to less than 15 feet
Demand Density (number of wells)	Greater than 10 PWS wells within 1 mile	5 to 10 PWS wells within 1 mile	Less than 5 PSW wells within 1 mile
Source Quality for Non-degradation	Similar concentrations as groundwater or lower concentrations that will improve groundwater; no MCL exceedences; low TDS	Borderline TDS; few exceedences of MCLs	Quality will degrade groundwater; high TDS; many MCL exceedences
Native Groundwater Quality	Low TDS (<500 mg/L); no exceedences of MCLs	Borderline TDS; few exceedences of MCLs	High TDS (>500 mg/L); many exceedences of MCLs
Geochemical Interactions of Source and Groundwater	Similar Langelier Indices (source and groundwater within 0.5 units); similar pH values	Langelier index unable to be computed, but similar pH and hardness values	Langelier indices that are greater than 0.5 units different; largely different pH or hardness values
Transmissivity	T>1,000 ft2/d	T>500 ft2/d, but less than 1,000 ft2/d	T<500 ft2/d
Residence Time	Less than 10% loss in 180 days, >480 days to 25% loss	10 to 25% loss in 180 days, 180 to 480 days to 25% loss	>25% loss in 180 days
Cost (O&M)	No pretreatment required; gravity flow delivery; spreading basin use	Combination of some more expensive and less expensive components	Pretreatment required; ASR wells utilized; force mains required
Cost (capital)	Gravity flow delivery; ASR well retrofit	Spreading basin in rural area	Spreading basin near municipality; ASR well construction; pipeline construction
Qualitative Considerations	Project size meets 100% of demand	Project size meets 25% of demand	Project size meets <10% of demand

Source Availability

The source availability included an analysis of the available water from a given source for each recharge area. Availability of source water was evaluated in the preliminary screening using basin-wide availability data. For the detailed ranking, a finer level of source availability was investigated using both the basin water availability from the Draft OCWP (CDM 2009), and gaged flow data from the listed source when available. The period of record of gaged streamflow data in the different recharge areas varies significantly. To evaluate all recharge areas on a common basis and to ensure the pilot project would have sufficient water in most years, long-term precipitation records for different OCS's precipitation regions were used to identify years with precipitation well below average (approximately the 25^{th} percentile or less). Only sites with gage data with a period of record overlapping a low precipitation year were considered as representative of a low-year flow, representing a conservative estimate of source water availability for a recharge project.

Gage data on the source stream for the most recent low-precipitation year was chosen to represent a reasonable lower-end estimate of flow availability for the recharge area. The daily gage flows for that year were then utilized to determine the seasonal total flows. Each source was also evaluated to determine whether source availability could be adversely affected by upstream or downstream influences, such as legal availability constraints or reservoir releases. Additionally, an analysis of whether high-yield irrigation wells had been installed in the vicinity of the source since the selected year was completed to determine whether less water may be available. It was assumed that if a large number of wells had been installed after the representative year, the source availability would likely be less than predicated by the gaged data prior to the well installations. Stormwater runoff was not considered in the evaluation of source availability due to limited data on storm runoff flows; also, a continuous source is desirable for a pilot project. In addition, streamflow is an indicator of runoff potential at some sites and further investigation into the availability of stormwater runoff could be used to augment the project.

For scoring of this criterion, sources that have plentiful water available during the spring season received the highest scores, as it is anticipated that the water utilized for the recharge pilot project would be diverted during the spring. However, sources that have additional water available throughout the year received higher scores than those where only spring flows were available. Also, sources with gage data older than approximately 1990 received lower scores due to uncertainty in current availability due to potential land water use changes. Additionally, gages that were present downstream of the probable diversion resulted in a lower score due to uncertainty associated with downstream gains and tributary inflows.

Aquifer recharge regions 27 and 40 (El Reno and Reyden) were identified as having legal availability constraints based on existing permits and reservoirs in the basin and likely regulatory challenges in obtaining a permit to divert surface water. Information on the legal availability was obtained after the preliminary screening was complete.

The maximum volume of water needed for a pilot recharge project is estimated at 1,000 AF. Thus, the available water required for each recharge area was at most 1,000 AF. Some demands were less than 1,000 AF; in these cases the desired volume of water was equivalent to the demand. Scoring of source water availability resulted in the following recharge areas receiving high scores: 9, 28.

Available Storage Capacity

The available storage and ability to meet the demand criterion was assessed using depth to water maps generated for each recharge region. These maps were created using digitized groundwater elevation contours from the USGS (2009), and were gridded. The gridded groundwater elevation data were subtracted from the gridded surface elevation data (DEM). Three recharge regions (Site numbers 12, 21 and 31) did not have groundwater contours, so wells with water level data were plotted on the appropriate maps. The wells utilized were all available in the groundwater permit database, and had a measured water level value. The value plotted on the figures was the shallowest water level measurement over the period of record to generate a conservative depth to water estimate.

For scoring, it was assumed that the pilot AR project size was the smaller of the local demand or the assumed upper pilot project size of 1,000 AF. Specific yield (or storativity for confined bedrock aquifers) was used to calculate the area required to store the specified volume of water with an increase in water level of either 25 or 10 feet. The required area was then compared to the depth to water in the vicinity of the recharge area to determine whether a decrease in depth to water to less than 15 feet bgs would occur. A depth to water of less than 15 feet bgs is undesirable due to potential flooding of underground structures or non-beneficial losses due to evapotranspiration. Recharge regions that had depths to water of less than 25 or 10 feet in the vicinity received lower scores due to the likelihood of these issues. Generally, recharge areas located in areas with greater than 50 feet of available freeboard were given the highest scores. Confined aquifers were generally rated lower due to the small storage available per unit area. It should be noted that multiple successful Aquifer Storage and Recovery (ASR) projects have been implemented in highly confined aquifers. Recharge regions that received a high score include: 2, 4, 6, 12, 15, 19, 30, 42.

Proximity to Demand

The proximity to demand analysis included an assessment of the approximate distance from a recharge area to the demand points. For this analysis, the demand points were assumed to be at or near the location of PWS wells for the selected demand (town or city) that was identified during preliminary screening. The majority of demand points were located very close (within 1 mile) of the recharge area. Recharge areas were located within a recharge region based on locations of demands, as discussed previously. This ensures that a recharge project would have an observable impact to a known demand. The highest ranking recharge regions had demand points located within a 1 mile radius of the recharge area. Two towns that did not have PWS wells (recharge regions 9 and 15) were scored based on the distance from the recharge region to the outer proximity of the town. Since there are no existing wells that could be retrofitted for recharge, there would be additional costs at these locations. The recharge regions that received a high score included: 2, 4, 6, 8, 12, 19, 21, 28, 30, 31, 42.

Demand Density

Areas with existing groundwater development are better candidates for a recharge project than areas without groundwater development due to the existing infrastructure and proven use of the groundwater source. Higher density of wells indicates heavier development of the aquifer and results in a more favorable ranking. The demand density criterion was assessed by counting the number of PWS wells for the given demand at a recharge region within a 1- and 2-mile radius of the recharge area. Recharge regions that had a density of greater than 10 wells within 1 mile received high scores, while recharge regions with fewer than five PWS wells within 1 mile received moderately low or low scores. The recharge regions that received high scores included: 4, 6.

Source Water Proximity

The source water proximity analysis included an assessment of the approximate distance from the identified source to the chosen recharge area for each recharge region. Generally, the recharge areas were located closer to the demands to utilize existing infrastructure (PWS wells and pipelines) for the demand. The proposed recharge area for recharge regions with towns without PWS wells was located approximately halfway between the town limits and the source water location to minimize the length of pipelines that would be required for a pilot project. Recharge areas without existing PWS would incur higher costs for construction of new recharge project wells. Highest scoring recharge regions had sources located within 1 mile of the recharge area. The recharge regions that had a high score included: 28, 12.

Effects on Groundwater Chemistry and Clogging

This criterion was assessed by analyzing differences in the geochemistry parameters that were included in surface and groundwater sampling by the USGS and EPA; data were compiled from USGS and EPA online databases (USGS 2010; EPA 2010). For this criterion, the wells located in close proximity to the recharge areas were selected for data presentation. Source water data included for the analysis was generally available from the gage location used for source availability; additional data points were also utilized as available. Analysis included evaluation of geochemistry parameters such as hardness and pH. An additional analysis that was completed was a comparison of Langelier indices, or Langelier Saturation Indices (LSI), which indicate the potential for geochemical interactions. The Langelier index is calculated using hardness values to determine the potential for water to precipitate or dissolve calcium carbonate, a common component of groundwater aquifers. Overall, the highest scoring recharge regions had similar concentrations for parameters such as hardness and pH, and similar values for the Langelier index. The highest scoring recharge regions include: 12, 28.

Groundwater Quality

The groundwater quality criterion was assessed using the data available from USGS and EPA. The water quality within the aquifer is important to consider; both for how it could impact the quality of the source recharged water and how it might be affected by it. For this criterion, data were utilized from the same wells that were utilized for the groundwater chemistry and clogging analysis. Water quality parameters evaluated included nutrients, bacterial contamination, high salinity or TDS, and any other common water quality parameter that could have a negative effect on the implementation of an AR project. Potential contaminants (compounds with a regulated drinking water maximum contaminant level or MCL) were also evaluated when data were available. As a conservative assumption, if a compound was not detected in the sample, the detection limit value was used in the analysis. The highest scoring recharge regions had similar groundwater and surface water parameter concentrations, and did not exceed MCLs. Recharge regions that received a high score included: 12, 19.

Source Water Quality

Source water quality analysis included an assessment of water quality data that was available for the recharge water source. Data were compiled from USGS and EPA online databases. Sample locations utilized in the analysis were the same as used for the groundwater chemistry and clogging analysis. The surface water quality analysis utilized the same suite of parameters that was utilized for groundwater quality. The highest scoring recharge regions had concentrations of parameters that closely matched that of the groundwater, and did not contain large concentrations of effluent or MCLs. The highest scoring recharge regions included: 9, 12, 15.

Hydrogeologic Suitability - Transmissivity

The transmissivity and hydraulic characteristics of an aquifer are important to a recharge project, as they provide an estimate of an aquifer's ability to receive or yield water. Characteristics such as hydraulic conductivity (K) and transmissivity (T), and storage coefficients (S, Sy) are important aspects to consider. Well yields are also important to consider for this criterion. Different criteria are necessary for alluvial and bedrock aquifers since hydraulic properties vary widely between alluvium and bedrock. However, unconfined bedrock aquifers behave similarly to alluvial aquifers, and thus are scored in the same manner. Transmissivity values between unconfined aquifers and alluvial aquifers were comparable. Only two recharge regions were present within confined bedrock aquifers. Scoring was completed by comparing the hydraulic characteristics among all of the recharge areas. Highest scoring recharge regions included: 2, 4, 6, 12, 15, 19, 21, 28, 30, 31, 42.

Residence Time

The residence time criterion is important to this analysis for determining the length of time recharged water can be stored prior to natural discharge or loss. If an aquifer is not capable of containing the recharged water for a long enough time period, losses to streams may negatively impact the project's success. Similar to transmissivity, residence time differs between alluvial and bedrock aquifers. For alluvial aquifers, the residence time is a function of aquifer properties and distance to discharge areas, such as a large stream or lake. For bedrock aquifers, the residence time differs between confined and unconfined areas. For the unconfined portions of bedrock aquifers, the proximity of contact with alluvial aquifers or other discharge areas was analyzed. However, for confined portions, the residence time relies on distance to discharge areas or unconfined areas of the aquifer. The residence time for alluvial aquifers and unconfined bedrock aquifers was calculated using the Glover equation. Recharge regions that received a high score for residence time include: 2, 4, 12, 15, 19, 30, 42.

Cost – Capital

This criterion included an assessment of the ability to convey source water to a recharge region, as well as the likely method of recharge. Conveyance differences include use of pipelines to pump water to a recharge region versus ability to use gravity-fed ditches. This is determined by differences in elevation of the recharge region versus the location of the potential diversion; locations where the recharge area is higher in elevation than the source would require force main pipelines to transfer the water, leading to a higher cost. Another cost associated with construction is use of spreading basins versus existing wells. For this project it was assumed that existing wells could be retrofitted for use in the recharge pilot project. Spreading basins would likely be cheaper to install than new wells, although land acquisition may be a major factor in development of spreading basins and could drive the cost higher. It is anticipated that land costs away from municipalities would likely be lower. Based on these factors, spreading basins located far from municipalities received the highest scores, followed by retrofitted wells, spreading basins closer to municipalities, and finally installation of new wells. The recharge regions that received a high score include: 2, 8, 12, 30, 31.

Cost – O&M

This criterion included an assessment of the likely O&M costs associated with implementing a project at each recharge region. Key O&M costs would be associated with maintenance of wells or spreading basins, and pretreatment of water to be recharged. It is assumed that operation of spreading basins would likely be less costly than operation of wells, thus, higher scores were assigned to projects that would likely be able to utilize spreading basins. Recharge areas with high total suspended solids (TSS) concentrations in the source water would require filtration prior to injection and would negatively impacted project costs. The recharge regions that received a high score included: 30, 31.

Qualitative Factors

The qualitative considerations were most heavily influenced by the impact of the project on the total demand. This was evaluated by determining what portion of the local water provider's demand a pilot project could meet. Other factors include the desire of individual towns or cities to support recharge project, and any other information gathered that indicate a specific location may be better supported by the public. Work group feedback indicated local support and interest could be one of the most important factors in selecting a site, but would be difficult to assess without first evaluating potential sites on the other criteria. Scoring for this criterion was primarily based on the percent of demand that is met by the project, and highest scoring recharge regions included: 31, 42.

Demand Frequency

This criterion was intended to be used for determining whether an area's demand is primarily during the summer season versus over an entire year, and whether the hydrology of the recharge region matched the demand frequency. The preliminary screening identified seasonal demands, and all sites that were passed onto the detailed analysis have a seasonal component. Further analysis of demand frequencies for various towns in the 15 recharge regions indicated that there was very little variance between towns. This suggests that all recharge regions would have received the same score; thus, no analysis was completed for this criterion.

Regulatory Concerns

Regulatory concerns such as legal availability of water and constraints due to water quality were already considered through the availability of source water and water quality criteria. Thus, regulatory concerns did not receive a separate score. At the April 2010 work group meeting, it was brought up that regulatory concerns could impede the pilot project and the ODEQ was asked to provide their input into requirements they might have for permitting a pilot project. In addition, Wayne Kellogg noted that while the Ada water board was interested in such a project, there was concern that current permitting would not allow credit of recharged water, such that water withdrawn from the aquifer under the recharge program would count against existing groundwater permits. While not considered as a discriminator between recharge sites evaluated in this study because of the applicability to all sites, regulatory concerns remain an important aspect to consider before proceeding with a pilot project.

4.2 Scoring and Ranking

A raw score of 1 to 5, with 1 being not favorable and 5 being favorable were assigned to each recharge area for each of the criteria described above. Each score was then multiplied by the criteria weighting factor and summed to arrive at a final score. The scoring matrix is presented in Table 7. Details of the raw scoring are provided in a detailed appendix for each region. The weightings presented in Table 7 are proportional to the number of votes received at the January work group meeting (see Section 2.2) and scaled such that a maximum score is 100.

Table 7. Scoring Matrix (Sorted by Rank)

Recharge Region Number	Nearby Municipality	Source Availability	Demand Proximity	Source Proximity	Available Storage Volume	Demand Density	Source Water Quality	Native GW Quality	Geochemical Interactions	Transmissivity	Residence Time	Cost - O&M	Cost - Capital	Qualitative Considerations	Weighted Score
	weighting factor	*1.8*	*1.8*	*1.8*	*2.4*	*0.9*	*2.5*	*1.9*	*1.9*	*1.5*	*1.3*	*0.9*	*0.8*	*0.5*	
12	**Ada**	3	5	4	5	3	4	5	5	5	5	3	3	1	**85**
42	**Eakly**	3	5	3	5	2	3	4	3	5	5	3	2	5	**75**
19*	**Woodward**	3	5	2	5	4	1	5	3	5	5	3	1	2	**70**
2	**Woodward**	3	5	1	5	3	3	3	3	5	5	3	3	1	**69**
15	**Durant and Calera**	3	2	2	5	1	5	3	2	5	5	3	1	2	**66**
30*	**Enid**	3	5	1	5	4	1	3	2	5	5	5	3	1	**65**
4	**Weatherford**	2	5	3	5	5	1	2	3	5	5	2	1	3	**65**
28*	**Kingfisher and Hennessey**	4	5	5	1	2	1	3	4	5	1	3	1	4	**59**
6	**Marlow**	1	5	1	5	5	1	2	2	5	3	2	1	3	**55**
8	**Norman**	1	5	3	1	4	3	4	2	3	1	3	3	1	**53**
31*	**Cherokee**	3	5	1	1	2	2	1	2	5	3	4	3	5	**51**
21*	**Elk City**	2	5	1	1	1	1	2	3	5	1	3	1	2	**43**
9	**Shawnee and Seminole**	4	1	1	1	1	4	4	2	1	1	3	1	2	**43**

Note: sites 27 and 40 were not evaluated due to legal water availability constraints

Asterisk (*) denotes alluvial aquifer

As described in Section 2.2, the relative weights of the criteria were determined through the voting process at the January work group meeting. The weights are potentially biased by the participants at the work group meeting and by the fact that the voting was done after the preliminary screening identified recharge sites that had available water and preliminary level of hydrogeologic suitability. As a check on the sensitivity to the weightings determined through the voting process, the weightings were modified in several different ways, including weightings similar to those used in the Colorado Study and BOR study as presented in Table 4. Modifying the weights had little influence on the top ranked sites. Sites 12, 42 were the top two rated sites in all of the tested permutations of the weightings. Site 19 was the third ranked site in all but one of the tested permutations, in which it ranked fourth.

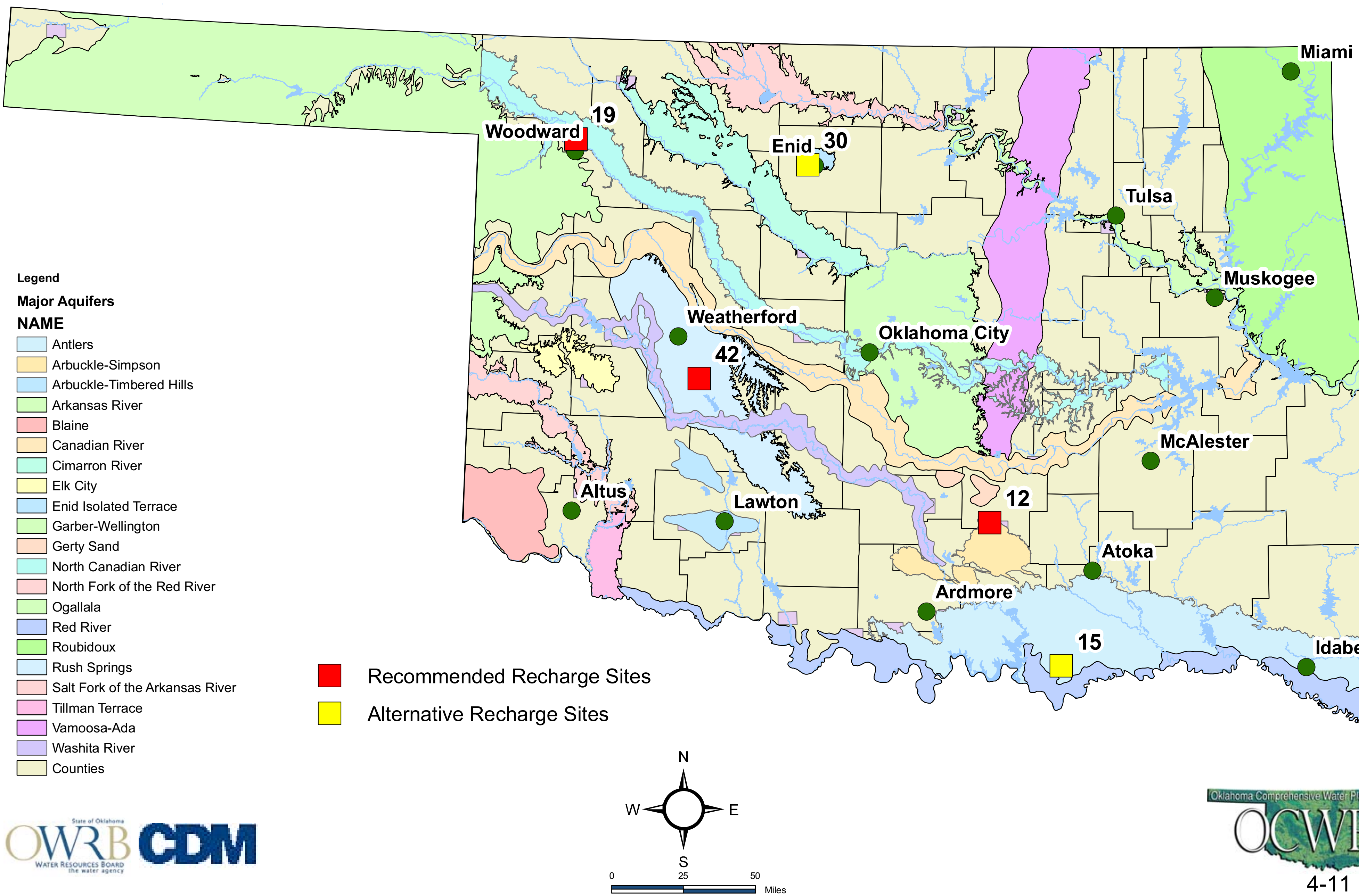
At the April 2010 work group meeting, CDM presented three short-listed sites (site 12, Ada; site 42, Eakly; site 19, Woodward). The meeting participants recommended expanding the recommended number of sites to include two alternates in case local interest is low or new information from follow-up investigations at the recommended sites reveals a limiting factor. The work group selected site numbers 15 (Durant) and 30 (Enid). These sites were added as alternatives because they were consistently in the top group of sites in the rankings under various criteria weightings tested at the work group meeting, and one is a bedrock aquifer (Site 15, Durant, Antlers aquifer) and the other is an alluvial aquifer that can utilize a lower-cost spreading basin (Site 30, Enid, Isolated Terrace Aquifer). The selected sites are shown in Figure 3.

4.3 Recommended Sites for Recharge Pilot Project

Recharge Region 12 (near Ada)

Recharge region 12 is located near the Town of Ada, with the Blue River providing a water source and the Arbuckle Simpson aquifer providing storage. The Blue River appears to provide adequate source, although the nearest gage is located approximately 17 miles downstream of the probable diversion location for a project. There are no upstream gages to help better quantify source availability, but based on basin size, the source location appears to have an adequate supply. The Town of Ada has existing PWS wells in the vicinity of the recharge region, making it a good candidate for a recharge project. Additionally, there is plentiful storage, and the residence time is appropriate for a pilot project. Given the channelized nature of the karst aquifer, specific site investigations would be required to ensure the recharged water could be recovered. The Blue River had minimal MCL exceedences, and low TDS concentrations, suggesting that pretreatment would not be required. Also, the Langelier indices for the Blue River and Arbuckle Simpson aquifer provided one of the closest pairings of all recharge regions. Perhaps the most negative aspect of Recharge Region 12 is the requirement of a pipeline to convey water from the source to the project site. However, the majority of recharge regions included this requirement, and most would require a longer pipeline than Recharge Site 12.

Figure 3. Recommended and Alternate Recharge Sites



Recharge Region 42 (near Eakly)

Recharge region 42 is located near the Town of Eakly, with Lake Creek providing a water source and the Rush Springs aquifer providing storage. Demand for the entire town is approximately 250 AFY, so a pilot project could potentially meet the entire demand for the town. Flows in Lake Creek are subject to regulation due to nearby Fort Cobb Reservoir, which may limit the supply availability; however the relatively small amount of water required for the project may be negligible compared to the reservoir yield requirements. Overall, Lake Creek appears to provide adequate source, even during drought years. The Town of Eakly has two existing PWS wells in the vicinity of the recharge region, making it a good candidate for a recharge project. Additionally, there is plentiful storage, and the residence time is appropriate for a pilot project. There was limited water quality data available from Lake Creek, but nearby Cobb Creek exceeded MCLs infrequently. Only one sample was collected from Cobb Creek for TDS, and it slightly exceeded the MCL. Thus, it is strongly recommended that further water quality characterization be completed prior to implementing a pilot project at this recharge region to help determine the need for pre-treatment. Pat Billingsley, representing the OCC, provided oil and gas well locations in the area. The nearest wells were over a mile from the recharge region and so were not considered to be detrimental to the site. Recharge Region 42 would also require a pipeline to convey water from the source to the project, and the pipeline is longer than that of Recharge Region 12.

Recharge Region 19 (near Woodward)

Recharge region 19 is located near the Town of Woodward, with the North Canadian River providing a water source, and the North Canadian alluvial terrace aquifer providing storage. The hydrogeologic characteristics of this site are very favorable for a recharge project, and this region is the only alluvial site of the three recommended sites, allowing for use of spreading basins instead of injection wells. Woodward provides an appropriate level of demand for a pilot project. In a representative low-precipitation year, there was approximately 90,000 AF a downstream gage. Supply for a pilot project scale (maximum of 1,000 AF) is most likely available, but could be tempered by Canton Reservoir's yield requirement. Native groundwater quality is good, but source water quality has exceeded MCL for several parameters in the past.

At the April work group meeting, it was suggested that the high TDS levels in the source water were isolated events from nearby oil and gas operations and water source quality may be better than the annual analysis indicated, especially during the high flow times of year when a recharge project would be operating. TDS measurements were examined on a monthly basis, and showed that TDS decreases in the higher flow months, but still exceeds the MCL in those months. Almost none of the TDS measurements for the site were below the MCL. The source water quality data thus indicate pre-treatment would be required before recharging the aquifer. A pipeline approximately 2 miles long would be required to bring water from the North Canadian River to the recharge location.

Alternate Recharge Region 15 (near Durant)

Recharge region 15 is located near the Town of Durant, with the Blue River providing a water source and the Antlers aquifer providing storage. The Blue River appears to provide adequate source, although the nearest gage is located approximately 8 miles downstream of the probable diversion location for a project. There are several tributary streams that enter the Blue River between the probable point of diversion and the downstream gage, but the majority of the basin lies upstream of that point, suggesting that flows associated with those tributaries likely do not have a large impact on the river. The representative low-precipitation year had flows greater than 120,000 AF, suggesting there is plentiful water for a project. Water quality data for both source and groundwater are generally good, although the geochemistry was unable to be effectively compared due to a lack of hardness data. One of the largest hindrances to a project is the proposed location and lack of infrastructure. There are no existing high-capacity wells in the vicinity of the proposed location, and the area is approximately 2 miles from both the Blue River and Durant. Thus, this location will require installation of ASR wells and construction of transfer pipelines.

Alternate Recharge Region 30 (near Enid)

Recharge region 30 is located near the Town of Enid, with Skeleton Creek providing a water source, and the Enid isolated terrace aquifer providing storage. The hydrogeologic characteristics of this site are very favorable for a recharge project, with injection wells nearby or the potential to use spreading basins instead of injection wells. The nearest gage is 7 miles downstream, and annual flow during the representative low-flow year was only approximately 16,000 AF. There may be issues with supplying the project during low-flow seasons. No surface water data was available for Skeleton Creek, suggesting that a monitoring program should be implemented prior to selection of the area for a project. Groundwater quality was relatively good, with few MCL exceedences. Skeleton Creek is located greater than 2 miles from the potential project location, but gravity flow ditches may be usable for water delivery, and the presence of nearby wells and potential for spreading basin use may lower project costs.

Section 5
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