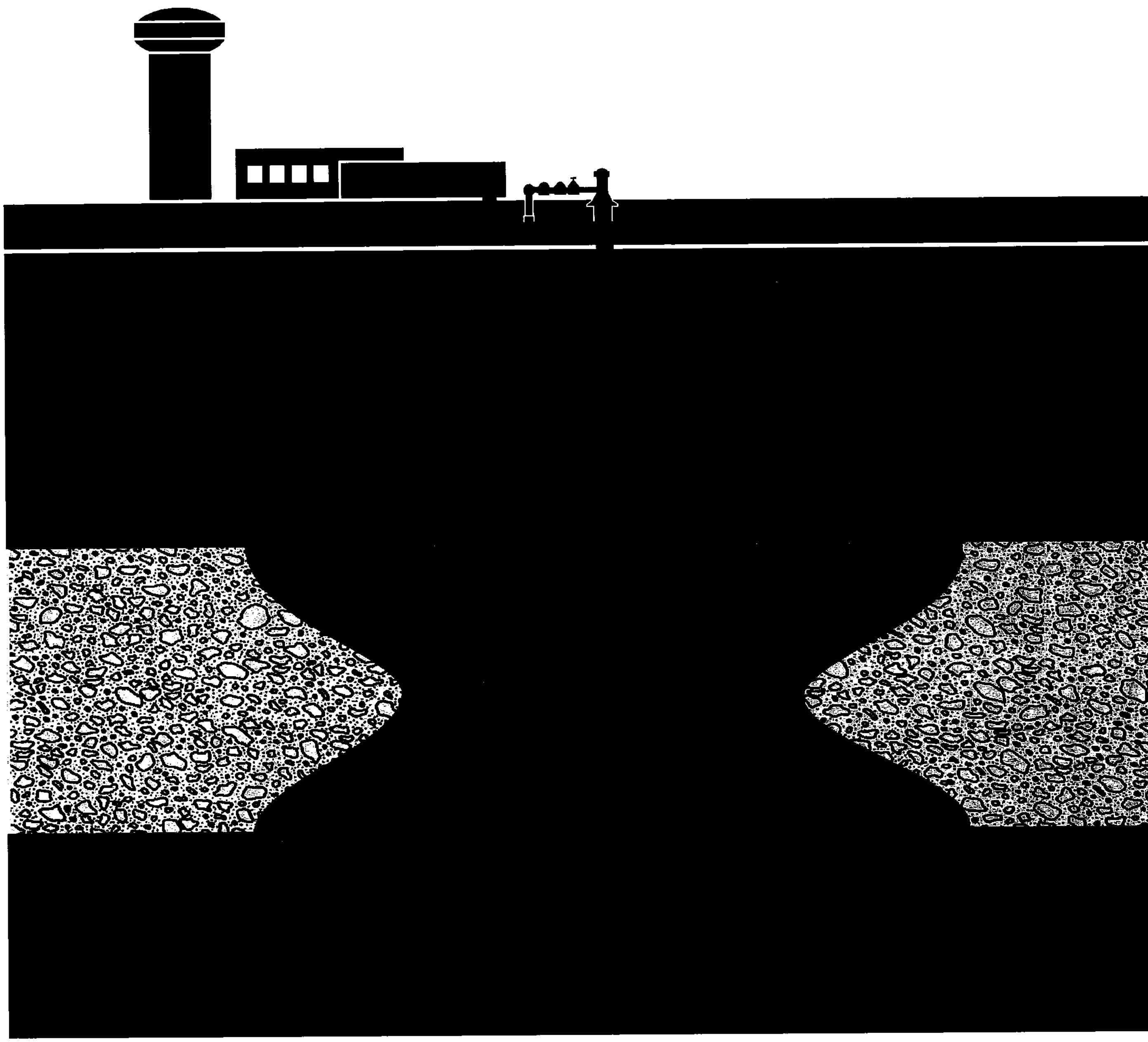
CH2MHILL

Proposal for an

AQUIFER STORAGE AND RECOVERY (ASR) Program

Presented to:

Dare Regional Water Supply System
Dare County, North Carolina



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Engineers
Planners
Economists
Scientists

September 17, 1997

Bob Oreskovich
Water Director
Dare Regional Water Supply System
600 Mustian St.
Kill Devil Hills, NC 27948

Dear Mr. Oreskovich:

It was a pleasure meeting with you and other staff members of the Dare Regional Water Supply System (DRWSS) last month to discuss potential aquifer storage and recovery (ASR) applications for your system . Based on the meeting, our research and subsequent discussions, we have a better understanding of DRWSS water supply and demand issues. You have also indicated that you now have a better understanding of the potential advantages of incorporating ASR water management strategies into the DRWSS system. It is apparent that ASR could be an integral, cost-saving measure of the DRWSS expansion process.

As requested, CH2M HILL is pleased to present this proposal for an ASR Program for the DRWSS. For your convenience, this cover letter provides a Project Background and summaries of the Program Approach, Costs, and the Project Team. The accompanying proposal attachment provides the following elements: an ASR Program Approach with a detailed scope of services; breakdown of the ASR Program Costs; a typical ASR Program Schedule; CH2M HILL ASR Project Experience; proposed Project Team Member Resumes; and selected CH2M HILL ASR Publications. We have enclosed 6 copies of the proposal for your use.

Project Background

DRWSS was originally formed to provide water to the northern Dare County beach towns (from Nags Head to Duck). Bulk wholesale purchasers include Nags Head, Kill Devil Hills, Manteo, and Dare County Water System. To supply customers north of the Oregon Inlet, operating water treatment plants include the Skyco Ion Exchange plant on Roanoke Island, the Reverse Osmosis (R.O.) plant in Kill Devil Hills, and the Fresh Pond surface water facility in Nags Head. South of the Oregon Inlet, the Dare County Rodanthe, Waves, and Salvo R.O. plant (DCRWS) became operational in March 1996 and DRWSS also recently acquired the Cape Hatteras Water Association system in July 1997.

Based on our discussions and review of the 1992 Local Water Supply Plans, the DRWSS north of the Oregon Inlet has a maximum water supply/treatment capacity of 9.5 million gallons per day (MGD). This main region served by DRWSS experiences significant seasonal variation in system demands. Average demands are approximately 2.5 to 3 MGD, whereas short-term summer peak demands are as high as 7 to 7.5 MGD with an increasing trend. This ratio of peak to average day demand (2.3 to 3) faced by DRWSS is more extreme than ratios faced by most water systems in the country.

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South of the Oregon Inlet, the capacity of the DCRWS system is approximately three times its peak day demand. This system is considered separately because the current projections indicate that this system is capable of meeting peak demands in its region, autonomously, at least through the year 2020. Still, DRWSS is considering upgrading the DCRWS system by 1 MGD or more. Also, the Cape Hatteras system is currently in the study/design phase to upgrade and expand that facility via R.O. treatment to better serve its customer base with higher quality water and more reliable capacity.

Based on these statistics, DRWSS is able to meet current and near future water demands. During the next three years, capital investment plans include expenditures of almost $7 million, mostly for treatment, storage and well site acquisitions. However, several regional water supply and demand issues are converging and are forcing difficult questions to be asked. The most basic question is whether the DRWSS system will be able to meet regional demands into the next century. Several of the contributing issues and questions are explained here.

Regional Agreements

The ability of the Outer Banks region to build out is dependent on an adequate and sustainable water supply. Originally, a gentleman's agreement existed among the capital investment entities (now, the wholesale purchasers) of the DRWSS. The agreement was that DRWSS would not expand the production capacity of the system until the present production capacity of the DRWSS could not supply enough water for every wholesale purchaser. When any one of the entities could not receive their required allotment, the expense of expanding the production capacity of the DRWSS was to be borne by that entity. A more recent agreement (the June 1996 "40-Year Agreement") has relegated control of the individual water systems and the burden of capital improvement/expansion investment to DRWSS. A stipulation of the 40-Year Agreement is that service can not be expanded outside of the County without conducting studies to determine that a sustainable, safe yield exists to accommodate that expansion. As a result, Missimer International will be conducting a hydrogeologic study aimed at determining the safe yield for county aquifers.

Internal Demand Projections

Demographic statistics indicate that Dare County is expected to experience a greater than two-fold increase in year-round county population between 1990 and 2020 (i.e. population increase from 12,050 to a projected 30,680). This year-round growth will be supplemented by a similar growth rate in tourism, as buildout continues to accommodate the summer influx. Commercial and minimal industrial growth will also continue. Average water demands are anticipated to grow from approximately 3 to 6 MGD in this time frame, while peak demands are anticipated to exceed 12 MGD. It is projected that, somewhere between the years 2000 and 2010, peak demands will be greater than the current system capacity. This issue raises the questions of how, where, and how much it will cost to expand the existing DRWSS production capacity to meet these projected peak demands. Also, it must be determined whether the safe yield of the aquifers will sustain that growth.

Expansion

Along with the anticipated internal growth of the original DRWSS service area are the issues of external system acquisitions and expansion. DRWSS has already expanded south with the addition of the DCRWS R.O. facility and the acquisition of the Cape Hatteras Water Association service area. In addition, Currituck County (Carolina Water Service) has requested an interconnection to the northern end of the DRWSS system for "emergency" water supply. These issues raise the question of whether there is a safe, sustainable yield within the DRWSS water supply to provide water outside the existing service area. The critical importance of a safe yield is to avoid continued effects of salt water intrusion, due to overpumping, such that the current design criteria and costs to operate the existing R.O. plants do not become obsolete or prohibitive, respectively.

The ASR Solution

The water supply issues faced by DRWSS are not uncommon. Developing, coastal resort areas are often short on water supplies and/or faced with the possibility of using poor water quality sources. In addition, significant seasonal variations in demand are common, with extreme peak demands often being limited to just a few days of the year.

As a major regional purveyor with significant investment in advanced treatment and distribution systems, it is reasonable for DRWSS to provide water to an increasing customer base, so long as the proper planning and water supply management strategies are practiced. With the advent of ASR, the traditional engineering solution of designing production capacity to meet future peak demands no longer needs to apply. This is a potentially significant shift in water supply management strategy since the unit costs for ASR are significantly lower than for provision of reverse osmosis peak production capacity.

ASR is the concept of storing excess off-peak treated water underground via wells, for use during peak and emergency demand periods. The stored water is recovered from the same wells and, other than disinfection, typically requires no further retreatment. By utilizing ASR, DRWSS can provide solutions to many of the issues discussed above.

ASR makes economic sense. ASR actually takes advantage of seasonal demand variations and the resulting excess capacity that is available during times when the system capacity exceeds demand. For DRWSS, this condition where system capacity exceeds average day demand will exist throughout most of the year into the foreseeable future (e.g. beyond 2020). By storing hundreds of millions of gallons of water during average demand periods for peak use, systems need only to be designed to meet future average demands. Incorporating ASR, therefore, will maximize your current investment in the existing infrastructure and water supply sources simply by making more efficient use of them. By developing and then expanding ASR capacity, it is possible that plans for expensive future investment can be deferred for many years or even become altogether unnecessary. Or if necessary, system expansions can be designed and constructed at much smaller scales, often saving millions of dollars in capital investment. The typical unit cost for installed ASR peak capacity is approximately $0.40 per gallon per day ($400,000 per MGD) as compared to approximately $3.00 per gallon per day ($3,000,000 per MGD) for installed R.O. capacity, based upon planning documents that we have reviewed for the Outer Banks area (Hobbs, Upchurch and Associates, June 1996).

ASR makes operational sense. Using ASR wells would reduce, eliminate or reverse the advance of saltwater intrusion, which is at the core of the sustainable safe yield question. Recharging into strategically located ASR wells would allow for incremental increases in baseload production and significant increases in peak production from the same shallow aquifers, that are currently perceived as being overutilized. By recharging treated water via ASR wells from existing water supplies, deeper and lower quality (more saline) aquifers may also be utilized for their better storage and production capacity without the need for additional treatment when that water is recovered to the distribution system. In addition, recharging via ASR well(s) helps to maintain a steady baseload demand on expensive treatment plants, where excess off-peak water produced from these plants is used to recharge the ASR well(s). This aspect facilitates operational stability and associated cost savings. If ASR wells are located at strategic distal portions of the distribution system, this may also keep a steady flow of water passing through otherwise underutilized portions of the distribution system, thus maintaining system pressures and chlorine residuals. Underground storage of large volumes of treated drinking water can also augment system reliability, such as during hurricane emergencies.

In summary, utilizing ASR could be a cost-effective solution for meeting the DRWSS water demands and represents a potential significant future source of revenue by supplying adjacent communities with peak period water supplies. The ASR Program Approach and Costs are summarized below. The accompanying proposal attachment provides further details about potential objectives of ASR and the scope of services.

ASR Program Approach and Costs Summary

In the accompanying proposal attachment, the detailed Scope of Services and Costs sections are separated into two subsections, reflecting two phases of our ASR Program. The first section describes an ASR Preliminary Feasibility Assessment. This is a paper study that will utilize existing information on water supply and demand, hydrogeology, aquifer water quality, surface water quality (if applicable), aquifer mineralogy, and related information from federal and state agencies, drilling companies, nearby water purveyors, and DRWSS. The study will assess the feasibility of successfully implementing a comprehensive Phase Two Test Program.

Our preliminary assessment will focus on the feasibility of implementing an ASR demonstration project at as many as three locations in the DRWSS system we currently believe would benefit from ASR: the northern section of the distribution system near the Dare/Currituck County border; the southern section of the distribution system, south of the Oregon Inlet; and hydraulically seaward of one of the existing central wellfields as a line of defense against salt water intrusion. Additional potential ASR sites could be evaluated at the request of DRWSS personnel. The actual locations of the ASR evaluation sites will be determined during a project kickoff meeting where DRWSS objectives will be discussed. If feasible, CH2M HILL will recommend implementation steps to proceed with a Phase Two ASR demonstration project at one of the locations that shows the highest priority. Funding source and project delivery approach options will be evaluated for Phase Two implementation.

Steps that follow the preliminary feasibility assessment include: detailed data collection and analysis; design and construction of a demonstration ASR well(s); ASR cycle testing; permitting; and development of operational facilities. This sequence makes up the Phase Two ASR Test Program. At the completion of the Phase Two ASR Test Program, DRWSS will have a fully operational and permitted ASR well that is ready for full scale use in its system. Assuming a successful Phase Two demonstration, a third phase of the ASR program would entail expanding ASR capacity as needed with additional ASR wells.

The cost estimated for Phase I ($48,500) is a lump sum estimate, not to be exceeded without prior approval from the DRWSS. The range of costs provided for Phase Two ($550,000 to $680,000) are order of magnitude estimates intended for budgetary purposes only. They are based on previous CH2M HILL project experience and vary, depending on the complexity of each project. An engineering estimate for the Phase Two Test Program will be provided in the Preliminary ASR Feasibility Assessment Report. The estimated costs for a third phase (ASR capacity expansion) would be dependent on the depth, complexity and number of additional ASR wells.

Project Team

The ASR concept has been pioneered by CH2M HILL and we have more ASR experience than all other firms combined (Attachment A of the proposal). Of the 26 operating ASR facilities, CH2M HILL is responsible for 19. We have greater than 40 additional ASR projects in design, construction, or testing phases in 15 states. Many of our ASR projects have been completed or are in the process of being completed in similar Atlantic Coastal Plain hydrogeologic conditions, including several projects in the neighboring states of South Carolina and Virginia.

CH2M HILL recognizes the importance of this project and ASR technology in helping the DRWSS meet future water demands. For this program, we have put together a group of highly competent hydrogeologists and engineers whose experience working on similar ASR projects in the Atlantic Coastal Plain Aquifers will provide the DRWSS with the necessary skills and capabilities to effectively carry out this important project.

David Pyne will be the overall Program Manager, overseeing all phases of the ASR program. David is CH2M HILL's director of ASR and groundwater recharge projects. He pioneered ASR technology in the early 1980's and is the world's leading expert in the field.

Mitchell Bormack will be the Project Manager. Mitchell will be responsible for data collection, review, and evaluation during the Phase One and Phase Two portions of the ASR program. He will serve as principal liaison between DRWSS and CH2M HILL staff and will be responsible for project planning and coordination, review, budget, and technical input as necessary. Mitchell has experience with all phases of ASR projects, including preliminary feasibility assessments, detailed subsurface investigations, ASR cycle testing, facility permitting, and operator training. His ASR project experience includes four Atlantic Coastal Plain projects and a project in Ontario, Canada.

Mark Lucas will be the Lead Hydrogeologist. Mark has extensive experience in ASR studies, hydrogeologic investigations and modeling, and surface and borehole geophysical surveys in the Coastal Plain Aquifers. He has worked on five ASR Phase One and Phase Two projects in the New Jersey Coastal Plain. Mark will guide technical aspects of the ASR program.

As part of the project team, CH2M HILL has assembled a highly talented and experienced Senior Review Team. Each member of the Review Team will be consulted, as necessary, for their various areas of technical and project delivery expertise. Doug Dronfield has extensive experience with hydrogeologic and groundwater resource investigations in northeastern North Carolina and the Tidewater Area of Virginia. Ken McGill has over 19 years experience with hydrogeologic investigations throughout the Coastal Plain Aquifers and has managed six of the seven Phase One and Phase Two ASR projects in New Jersey. Bryan McDonald has extensive ASR project management and hydogeologic investigation experience in the southeastern United States. Among other projects, Bryan was the project manager for the Mt. Pleasant, South Carolina ASR project. This project was recognized as a state engineering excellence, award-winning project and has strong parallels to the DRWSS situation.

We appreciate the opportunity to present this proposal to you and look forward to working with you and your staff on this very important project. If you have any questions during your review of this proposal, please do not hesitate to call us.

Sincerely,

CH2M HILL

Mitchell Bormack for

David Pyne, P.E.
Program Manager

Mitchell Bormack

Mitchell Bormack, C.P.G.
Project Manager

Proposal Attachment

Table of Contents - Proposal Attachment

Project Approach

Introduction

Aquifer Storage and Recovery (ASR) is the seasonal underground storage of treated drinking water in a suitable aquifer during times when the capacity of water supply facilities exceeds system demand, and the subsequent recovery from the same wells to meet peak or emergency demands. Other than disinfection, retreatment of the recovered water has been generally unnecessary. By making more efficient use of existing raw water supply, treatment, transmission, and distribution facilities, water purveyors have found that ASR is a highly cost effective component of expansion programs. ASR can often reduce capital costs of such expansions by at least 50 percent, and delay the time at which capital investment for additional facilities must be made.

In northeastern North Carolina, ASR can provide unique advantages to an area that is growing, but where water resources are relatively limited. Currently, Dare Regional Water Supply System (DRWSS) with the largest service area in northeastern North Carolina, has undertaken an extended program to develop a sufficient source of supply to serve customers throughout Dare County and possibly beyond the county. With a progressive and well-planned program of exploring for groundwater resources in the Surficial, Yorktown, and possibly deeper aquifer systems, DRWSS could achieve this goal in the next five to ten years.

Balanced against this supply expansion are numerous issues, including: 1) population, tourism, and commercial/ industrial growth in the DRWSS service area (within the county); 2) the possibility of expanding the service area both within the county and beyond the county boundaries into areas which, themselves, are growing; 3) the need for sufficient treatment capacity; and 4) the need for sufficient storage and distribution capability. Officials from DRWSS understand that water supply expansion needs to occur in safe, sustainable manner. Because of the exorbitant costs associated with treating poor quality water, overutilizing certain aquifers to the point of progressively degrading already poor water quality (e.g. with high chlorides or TDS because of saltwater intrusion) needs to be avoided. In this scenario, premium costs will be associated with to upgrading or expanding the treatment plants and process. These costs will require charging increasingly higher rates to DRWSS' customers.

DRWSS System Overview

DRWSS relies almost strictly on groundwater supplies from over 50 wells that are screened in the Surficial and Yorktown Aquifer Systems. DRWSS both baseloads their system and peaks from these wells. North of the Oregon Inlet, DRWSS also peaks with approximately 1-MGD from the Fresh Pond surface water source. In order to maintain a safe yield, the daily withdrawal from Fresh Pond is limited, particularly in the dry summer months. The Surficial Aquifer system is a water table source of supply from discontinuous, permeable surficial sediments along the Outer Banks. The Yorktown Aquifer System consists of two aquifer units called the Upper and Lower Yorktown Aquifers. In some areas, the Upper Aquifer is directly overlain by the Surficial Aquifer and is unconfined. However, in most areas, both aquifer units of the Yorktown Aquifer system are confined.

The DRWSS water supply sources require a variety of water treatment methods. Ion exchange is used for the treatment of water with high hardness from the Upper Yorktown wells on

Roanoke Island. Reverse osmosis (RO) is required to treat water with elevated TDS. This treatment process is used at the Kill Devil Hills plant and the Rodanthe, Waves, Salvo plant. RO is being considered for the Cape Hatteras plant, which currently utilizes conventional treatment and iron resin to treat elevated TOCs in its Surficial Aquifer supply. Along with upgrading the Hatteras facility, DRWSS has an aggressive capital improvement plan to increase aquifer production and upgrade or expand storage and treatment facilities throughout its system.

ASR Advantages Overview

ASR offers numerous advantages to DRWSS during the present period of expansion to become the primary regional purveyor. With well-planned water management strategies, including using ASR, DRWSS would be able to meet future county-wide water demands and provide peak/emergency demand water to neighboring county systems with minimal capital investment in treatment and storage facilities. The DRWSS maximum to average day demand ratio ranges from approximately 2.3 to 3.0 and is based on an annual seasonal demand cycle with occasional short-term, extreme summer peaks. This seasonal demand ratio would allow DRWSS to store water in the winter when demand is low and recover water in the summer when demands begin to exceed the capacity of the present system.

Excess treated water can be stored in ASR wells during off-peak periods and then used to meet peak period demands in the summer or for emergency demands as they arise. In this scenario, the DRWSS well stations and treatment plants would be operated more smoothly on a relatively constant annual schedule, rather than on the current, intermittent basis of reacting to peak period demands. With sufficient ASR capacity and strategically located ASR wells, enough treated water could be stored in various aquifers that DRWSS would also be able to supply neighboring county water systems with excess peaking capacity.

ASR is well suited to the DRWSS current program for expanding groundwater supplies. By making more efficient use of available groundwater and surface water supplies, ASR optimizes the use of these water supplies, and at the same time limits the concern regarding sustainable safe yield of individual aquifers. By recharging to an overutilized aquifer in strategic locations, DRWSS can sustain or incrementally increase the baseload supply production from the same aquifer without experiencing excessive drawdown, or landward encroachment of salty water. Utilizing ASR wells during the short-term, extreme summer peak periods also increases the peaking capacity of that aquifer.

ASR will facilitate use of productive aquifers that have less desirable water quality and can prevent further degradation of useful aquifers. The Castle Hayne and Cape Fear Aquifer systems typically exhibit elevated TDS concentrations that can range up to several thousand parts per million (ppm). Even the relatively shallow Yorktown Aquifer systems can exhibit elevated chlorine concentrations when overpumped to the point of inducing saltwater encroachment. With ASR, treated drinking water can be stored in a brackish of aquifer and recovered without elevated TDS or chlorides. Recharged treated drinking water displaces the more dense, high TDS water, driving it away from the well. The stored water only requires disinfection for treatment before being pumped into distribution systems upon recovery. Therefore, the productive capacity of these aquifers are used to meet peak period demands, without the need for expensive membrane filtration (reverse osmosis) treatment plants. At least, the need for expansion of existing plants can be eliminated or the expansion process and capital outlay can be significantly reduced. Furthermore, ASR wells can be used to protect existing wellfields from saltwater encroachment and may help to reverse the process.

With an ASR approach, DRWSS can focus on exploring the Surficial and Yorktown Aquifers for baseload source of supplies, while relegating the deeper, more saline aquifer systems for ASR storage and peaking use. ASR should also be considered for use in the Surficial and Yorktown aquifers if water quality is degraded and costs for treatment become increasingly high. In this manner ASR can be used as a hedge against expensive water treatment plants, while still utilizing the storage and production capacity of the aquifers to meet peak period demands.

ASR wells could be strategically located within the distribution system to maintain peak period distribution pressures along with chlorine residuals. With the growing population, this advantage could become important with expansion into the southern areas of the system, the mainland, and if DRWSS ever expanded its system into the Currituck County Outer Banks to the north.

General ASR Program Approach

CH2M HILL was the first engineering firm in the United States to implement ASR technologies with more experience than all other engineering firms combined. We have performed feasibility assessments, pilot studies, and have designed most of the ASR systems in use today. We are currently developing ASR systems at many sites in the Atlantic Coastal Plain for clients including: Evesham Municipal Utilities Authority, Moorestown Township Department of Public Works, Brick Municipal Utilities Authority, and New Jersey-American Water Company in New Jersey; Chesapeake Water Authority in Virginia; and Mt. Pleasant, Hilton Head and Myrtle Beach in South Carolina. We will apply our experience and state-of-the art technical knowledge to help DRWSS utilize ASR initially at a demonstration project site.

The general ASR program approach is to evaluate existing data and, as necessary, new data from hydrogeologic investigations to determine how to optimize the use of existing water supplies, treatment, transmission, and distribution facilities. By making more efficient use of existing and available raw supplies and infrastructure, water sources can be utilized in a more sustainable manner and infrastructure upgrades can be conducted at a slower pace and at a smaller scale than previously considered. Thus, DRWSS could expand to become the primary regional water supplier with minimal capital outlay and much smaller scale treatment expansion than probably anticipated.

The scope of services for this proposal is separated into two sections. The first section describes an ASR preliminary feasibility assessment that is focused on evaluating the feasibility of implementing an ASR demonstration project. CH2M HILL currently believes that at least three areas of the DRWSS would benefit from utilizing ASR. ASR scenarios might include:

- Utilizing a deeper aquifer (Castle Hayne or Cape Fear Aquifers) for ASR use in the northern section of the distribution system, near the Currituck/Dare Counties border. This would facilitate providing peak or emergency use water to Currituck customers while also backfeeding the Dare County system from the north

- Forming a "line of defense" of ASR wells to prevent further salt water intrusion in one of the central Yorktown Aquifer wellfields (Skyco or Kill Devil Hills wellfield) and for peak period supply during extreme peak demand or emergency use periods.

- Utilizing a deeper aquifer for ASR south of the Oregon Inlet. This application would facilitate meeting future water demands during the buildout of that region and possibly growing the system south of the county line, if DRWSS desired. ASR would be used for peaking purposes. An ASR well(s) could also help limit the scale of treatment plant

Scope of Services

Our Scope of Services for the entire ASR program is organized into the following tasks:

- Task 1 - Preliminary Feasibility Assessment and Report
- Task 2 - Subsurface Investigation and Monitor Well Installation
- Task 3 - Core Laboratory Testing and Geochemical Analysis
- Task 4 - Permitting
- Task 5 - ASR Well and Wellhead Design and Construction
- Task 6 - Services During Construction
- Task 7 - Aquifer Testing
- Task 8 - ASR Test Cycles
- Task 9 - Operations and Maintenance Manual Preparation and Training
- Task 10 - Final Report

A detailed description of each task follows.

The description of the Scope of Services is separated into two sections. The first section describes the preliminary feasibility assessment, which will help focus the scope of work for the Phase Two Test Program. Section 2 of the Scope of Services describes the Phase Two Test Program.

Section 1

Preliminary Feasibility Assessment and Report

The scope of services for the ASR preliminary feasibility has been organized into the following seven subtasks:

Subtask 1 - Project Kickoff Meeting

Subtask 2 - Review ASR Criteria Related to the DRWSS

Subtask 3 - Collect Background Data

Subtask 4 - Review Background Data

Subtask 5 - Develop the ASR Test Program

Subtask 6 - Engineer's Estimate

Subtask 7 - Evaluate Funding Options

Subtask 8 - Prepare Report

Subtask 9 - Regulatory Agency Meeting

A detailed description of each subtask follows:

Subtask 1 - Project Kickoff Meeting

A project kickoff meeting will be conducted with key members of the DRWSS staff and the CH2M HILL project team. The kickoff meeting is intended for two primary purposes: (1) to determine initial project objectives and (2) to collect available system data and determine which data will be necessary to retrieve from archives or be collected new.

Although most ASR systems are utilized for seasonal, long-term, or emergency storage of drinking water, over twenty objectives or applications have been considered or implemented at ASR sites. During the meeting, CH2M HILL and DRWSS staff will discuss potential ASR applications, as system information is compiled and discussed. The goal for the meeting will be to limit the potential ASR scenarios that will initially be evaluated to five or fewer. CH2M HILL project team members will serve as the meeting facilitators.

Many times, ASR systems are utilized to serve multiple objectives. Several potential ASR applications were discussed in the cover letter proposal and in the Program Approach section of this attachment. A summary of those and other applications of potential interest to DRWSS include:

- seasonal storage
- long-term storage or "water banking" for drought year use or other necessary uses
- emergency storage

- restore groundwater levels
- prevent saltwater intrusion
- enhance wellfield production
- defer, eliminate, or downsize expansion of water facilities
- maintain distribution system flow, pressure, and chlorine residual
- reduce environmental effects of streamflow or other surface water (pond) diversions
- improve water quality
- disinfection byproducts reduction
- reclaimed water storage for reuse
- hydraulic control of contaminant plumes

To conduct a proper evaluation and provide a focused ASR feasibility assessment, CH2M HILL will require the most current system information available. Important informational elements include system layout, capital improvement plans, raw and treated water supply and demand, water quality, operating procedures, and well maintenance records.

Subtask 2 - Review ASR Criteria Related to the DRWSS

This task will consist of reviewing the ASR criteria as it relates to the DRWSS. Three principal physical criteria that govern the site-specific feasibility of ASR have been developed, based on long-term, not well documented operation at five sites, shorter-term satisfactory operation at approximately twenty fully documented CH2M HILL sites, and numerous test programs by the USGS, CH2M HILL, and others. These ASR feasibility criteria are the following:

1. A seasonal variation in water supply, water demand, or both. Typically, when the ratio of maximum to average day demand exceeds 1.3, this criterion is met.
2. A reasonable scale of water facilities capacity. Due to economies of scale and the initial cost of developing ASR wells, it may be an inappropriate technology below 0.4 mgd useful recovery capacity.
3. A suitable storage zone, considering mineralogic, hydrologic, productive capacity, water quality, engineering, and several other factors.

A preliminary review of information related to the DRWSS indicates these criteria appear to be met. This task will include a detailed evaluation of the ASR criteria related to several proposed ASR options such as the conversion of existing production wells to an ASR well configuration or installation of a new ASR well.

Subtask 3 - Collect Background Data

This task will consist of the collection and organization of available background information and data. CH2M HILL has already reviewed some background data on the DRWSS system, including 1992 Local Water Supply Plans, USGS reports, and some North Carolina Division of Water Resources (DWR) literature. A literature search will include additional USGS and DWR information on the local hydrology and hydrogeology along with well record information from the State database and recent state investigations or drillers of any wells or test borings in the area that have been completed in the potentially suitable aquifers. DRWSS files will be reviewed and pertinent data or information related to system layout, capital improvement plans, water supply and demand, water quality, operating procedures, and well maintenance records will be assembled.

CH2M HILL assumes that certain important sources of information will be available use. Missimer International's hydrogeologic characterization study should provide the most recent estimates of sustainable yields for the shallow Surficial and Yorktown aquifers at critical areas of the system that may require increased capacity. The study should also provide new boring logs and estimates of aquifer coefficients from new well installations and pumping tests. In addition, the study should synthesize available regional hydrogeologic information. CH2M HILL would like access to the study results/reports as they become available, in order to avoid duplication of effort.

The proposal also assumes that much of the hydrogeologic modeling work to be completed by Missimer will include scenarios involving full buildout of the DRWSS service areas. It would be helpful if Missimer's demographic statistics utilized for estimates of full system buildout and their calculation assumptions were available to CH2M HILL for independent analysis. Should this information be considered unacceptable by CH2M HILL or if it is unavailable, the information may be needed to be collected.

CH2M HILL has also already recommended having the state Division of Water Resources (DWR) conduct a Time-Domain Electromagnetic (TDEM) Survey along the Outer Banks. Interpretation of this data should provide a decent baseline for the current geometry of the fresh water/salt water interface in the underlying aquifer units. CH2M HILL can assist DRWSS in coordinating and overseeing this effort. CH2M HILL would utilize this information in modeling the effects on this boundary for various ASR scenarios.

Subtask 4 - Review Background Data

This task will consist of an in-depth review and evaluation of the background data and information collected during Subtask 2. A critical portion of the review of this data involves evaluating well construction of the DRWSS existing wells and water quality to determine if the wells are suitable for conversion to an ASR well. The task will also entail a hydrogeologic assessment and an evaluation of recharge water availability and water quality. Following these approaches, the objectives of this subtask will be four-fold:

1. To determine if any existing wells at one of the preliminarily selected locations are suitable for conversion to ASR, or if a new well(s) would be required to be constructed for ASR use.
2. To characterize the deeper Castle Hayne and/or Cape Fear Aquifers (if information is available) and develop a recommendation for installation of a new ASR well(s).
3. Prioritize the need for ASR implementation at the preliminarily selected locations in these aquifers.
4. Select a single location in the DRWSS system to implement an ASR demonstration project based on the prioritization.

The hydrogeologic assessment includes reviewing available well records, geophysical logs, drillers logs, aquifer tests, pumpage, and water level information on the suitable aquifers. The assessment will provide an understanding of the geology, recharge, and groundwater movement and aquifer properties that are needed to determine the feasibility of ASR for the proposed locations. In addition, several basic flow models may be run to simulate well interference characteristics between the proposed ASR well and nearby DRWSS wells or wells from other purveyors. These modeling simulations are important for determining whether well interference will impact an ASR well(s) in the commonly utilized Surficial or Yorktown Aquifers. If well interference is significant, a new ASR well in one of the deeper aquifers may be warranted. Assuming the TDEM data is available, these modeling simulations will also evaluate the potential impact of ASR on the geometry of the fresh/salt water interface.

The evaluation of recharge water availability and water quality assists in determining the ASR demonstration project site selection, the selection of recharge processes, and the overall conceptual ASR design. The recharge water availability and quality evaluation entails reviewing water supply data, water demand data, operating pressures, treated water quality data, and the water quality of the storage zone formation. An examination of the water geochemistry will be conducted to determine the feasibility of injecting and successfully recovering treated groundwater in the suitable aquifer storage zone. There is also a potential for chemical interaction of the recharge water with aquifer matrix soils. Changing the existing chemical balance in the storage zone might cause precipitation of salts or swelling of clays; both of those elements pose potential clogging problems. These factors will be evaluated during this phase using geochemical thermodynamic equilibrium models. An appraisal will also be made of the ability of the subject aquifers to accept recharge, the feasibility of recharging treated distribution water, and the optimum recharge and recovery rates.

Subtask 5 - Develop the ASR Test Program

This task will consist of developing recommendations regarding ASR within the DRWSS system. If the recommendations are negative, due to geochemical problems such as iron precipitation or clay swelling or operational constraints that cannot be overcome, an analysis of the situation will be prepared and documented. If the recommendations are positive, the elements for the positive recommendations will be summarized. In addition, a preliminary ASR demonstration program will be prepared. This program will include a conceptual program design, proposed testing, data collection, schedule, and permitting requirements. CH2M HILL will also prepare a budget level estimate for the cost of testing, permitting, construction, and startup of an operating ASR facility.

A critical factor in any feasibility assessment is the state and federal regulatory process. To date, regulatory agency support for ASR has been strong in every state where development programs have been implemented (9 states). In New Jersey, for example, the New Jersey Department of Environmental Protection's Bureau of Water Allocation (BWA) recognizes recovery from an ASR well as zero net withdrawal from the permit applications with supporting data are submitted to BWA at the completion of the testing program. Based on preliminary conversations it appears that the North Carolina Department of Environmental Health and Natural Resources (DEHNR) is open to a similar permit-by-rule approach and will allow a testing program to be conducted. The addition of an ASR well to the DRWSS system might require a temporary injection well permit for the testing program. However, the Division of Water Resources (DWR), which operates as a sort of consulting agency within DEHNR regarding the utilization of water as a has been supportive to date.

As no ASR facilities have been tested or permitted to date in the State of North Carolina, additional meetings with the North Carolina DEHNR will be conducted to further educate DEHNR on ASR technology and permitting experiences/requirements in other states. In several states including New Jersey, South Carolina, Florida, Virginia, and Washington, CH2M HILL has helped educate and develop regulatory programs for the permitting of ASR wells. As long as the volume of recovered water is less than the volume of recharge water, there is zero net withdrawal from the storage aquifer. Because an ASR well represents zero net withdrawal, requests for additional allocation are not required. Typically a permit application with final results from the ASR testing are presented to the state BWA at the completion of testing. Also, each state's safe drinking water group [i.e. North Carolina's Division of Environmental Health (DEH) Public Water Supply Section and the Division of Water Quality (DWQ)] has the same permitting requirements for ASR wells as for standard production wells.

Subtask 6 - Engineer's Estimate

This subtask is comprised of the development of an engineer's estimate for the design, construction, permitting, and testing of the selected ASR facility. Based on the findings of the feasibility assessment, CH2M HILL will develop a budget level (+30 to -15 percent) engineer's estimate of the costs to design, construct, and test the ASR facility. This estimate will include costs for converting the existing wellheads to an ASR configuration or installation of a new ASR well, all appropriate piping and pumping equipment, overseeing construction of the project, and permitting all elements of the facility. The estimate will enable DRWSS to make decisions regarding development of the facility and to plan for funding if they decide to move forward with implementation of the ASR facility.

Subtask 7 - Evaluate Funding and Project Delivery Approach Options

As part of the Phase One feasibility assessment, CH2M HILL will assist DRWSS in evaluating sources of funding and project delivery approaches for implementing the Phase Two portion of the ASR program. One source of funding that should be considered is the State Revolving Fund (SRF). The feasibility of using SRF funding will be linked to the ASR project delivery approach.

Several project delivery approaches will be evaluated, including standard Design-Bid-Construct and alternative project delivery approaches: Construction Management (CM) At Risk; Design-Build; and Professional Services Construction Management. Each project delivery approach provides DRWSS with differing economic advantages and carries varying levels of inherent risk for CH2M HILL. The advantages and risks will be described and a project delivery approach will be recommended.

CH2M HILL will evaluate whether SRF funding is feasible for the Phase Two project implementation. Preliminary discussions with DEHNR funding staff indicate that this type of funding is available and that DEHNR would welcome the opportunity to support an innovative water management strategy like ASR. SRF funding is likely to be more readily available for "ready to go" projects, according to DEHNR personnel. The alternative project delivery approaches have traditionally been less likely to receive state funding. In order to grant SRF funding for the implementation of a design-build type project in North Carolina, typically an emergency situation must be documented or a special statute must be instituted. However, a design-build approach would define the "ready to go" project and the timing might be right to leverage the state's present interest in ASR as a water management strategy.

CH2M HILL will make contacts and conduct meetings, if necessary, with DEHNR and DRWSS personnel to evaluate the potential of utilizing SRF funding for various project delivery options. CH2M HILL will evaluate whether, because of state funding, an unacceptable level of state oversight or DRWSS administration would be required and interfere with project completion. If SRF funding appears feasible and DRWSS chooses, CH2M HILL could then assist DRWSS in procuring SRF funding for the implementation of the Phase Two ASR program.

CH2M HILL will make contacts and conduct a meeting, if necessary, with DEHNR and DRWSS personnel to evaluate the potential of utilizing SRF funding. If DRWSS chooses, CH2M HILL could assist DRWSS in procuring SRF funding during the Phase II portion of our ASR program.

Subtask 8 - Prepare Report

The deliverable subtask for the ASR Feasibility Assessment will be the preparation of a report. The report will contain a summary of the background data, analysis of the background data, an analysis of the ASR criteria and the degree to which the criteria are met, and recommendations. The report will describe the preliminary Phase Two ASR test program and will discuss the environmental, permitting, and economic issues involved in the program.

Subtask 9 - Regulatory Agency Meeting

Prior to initiating the Phase Two portion of the ASR program, CH2M HILL will coordinate a meeting with key members of the four sections of the DEHNR that will be involved in reviewing the ASR testing and construction plans and permit applications. These groups include the Division of Environmental Health (DEH, Public Water Supply Section), Division of Water Quality, Division of Water Resources, and the Washington Regional Office group of engineers and hydrogeologists. The purpose of the meeting will be to receive agency endorsement of the Phase Two program approach. Their technical comments will be incorporated into the data collection and ASR cycle testing program, only as appropriate.

Section 2

Phase Two Test Program

Tasks involved in the Phase Two ASR test program are described below. The scope of work for this section was based on the assumption that an ASR Demonstration Project will be implemented at one of the preliminarily selected system locations described above via the installation of a new ASR well(s). The scope of work described below is presented as a guideline for a tentative Phase Two ASR program approach. The exact scope of work may be modified, depending on which site is selected for the ASR demonstration project and what DRWSS resources and data available at that location. For instance, if the Preliminary Feasibility Assessment indicates that retrofitting an existing production well for ASR use is feasible, this scope of work and associated costs will be significantly reduced.

Task 2 - Subsurface Investigation and Monitor Well Installation

To identify potential ASR zones within the Surficial, Yorktown, and deeper aquifer systems, a brief subsurface investigation will be conducted associated with the installation of a monitor well for the ASR facility. This investigation is intended to achieve the following objectives:

- to identify zones in the aquifer sediments that may contain abundant problem trace minerals (e.g. iron-bearing minerals);
- to identify clay minerals with each aquifer sand;
- to obtain groundwater quality data from each sand unit;
- to determine the productive capacity of each sand unit; and
- to determine the design criteria for a full-scale ASR well.

Once the following objectives have been achieved, CH2M HILL can determine if an existing DRWSS well can be cost-effectively retrofitted for ASR use or if a new well will need to constructed.

The investigation will consist of the following three elements:

- Collection of depth discrete formation samples
- Flowmeter logging of the monitor well
- Collection of depth discrete groundwater samples within the monitor well.

Prior to installing the ASR well, a fully penetrating monitor well should be installed to the bottom of the lowest aquifer unit to be considered at the ASR demonstration site. During the drilling of the well boring, depth discrete cores of the formation should be collected using either a split spoon sampler or, preferably, a wire line coring tool that accommodates continuous sampling of the formation. Samples will be logged onsite by a CH2M HILL geologist for lithology, texture, bedding, morphology, and mineralogy.

Selected cores will be frozen and submitted to a core laboratory for mineralogic analysis. Core handling procedures will be tailored to the planned disposition of cores. Some sections will be frozen, while others will be carefully wrapped, sealed and stored for later analysis.

Upon completion of the core hole/well boring, geophysical logs should be obtained, including natural gamma, electric (single point resistance, spontaneous potential, resistivity, etc.), and if possible neutron or acoustic logs. A monitor well penetrating the entire thickness of the selected ASR aquifer would then be installed in the well boring. Well screens would be placed against each sand unit within the selected aquifer.

After development of the monitor well, depth discrete groundwater samples should be collected and analyzed for a number of chemical parameters that provide a geochemical profile of the intervals of interest. CH2M HILL will evaluate at this time whether it is more practical and cost-effective to collect depth discrete samples via an electronic wireline device or via straddle packer tests.

To identify the most productive sand units in the selected aquifer and correlate this hydraulic capacity with water quality in individual sands, the last subsurface investigation element consists of performing a flowmeter log of the monitor well. This logging should be performed under dynamic conditions with an impeller type flowmeter.

Task 3- Core Laboratory Testing and Geochemical Analysis

Approximately 20 core sections will be shipped to a qualified core laboratory for analysis to determine porosity, intrinsic permeability, mineralogy and clay mineral composition, and several other tests designed to increase understanding of storage zone chemistry and hydraulic characteristics. Although core lab testing is not usually associated with water well projects and may appear exotic, actual analyses are not sophisticated and lab costs are reasonable.

Analytical data from depth discrete samples of water from the selected aquifer will be evaluated along with typical treated water chemistry from the distribution system. This data, combined with results from the core lab analyses and flowmeter logging, will be used in a geochemical simulation model to estimate reactions that may occur in the storage zone due to mixing between stored water and native water in the presence of formation clays and minerals. This data will be used to design the appropriate screen intervals and blank zones for the ASR well.

Task 4 - Permitting

DEHNR should be notified early of the DRWSS intent to conduct ASR testing. Although DEHNR has no ASR permitting requirements, personnel within the DWR, DWQ, DEH (Public Water Supply Section) and the Washington, NC field office have indicated they are relatively amenable to any reasonable data collection program if contacted early in the permitting process. CH2M HILL will coordinate a meeting with key regulatory officials from each group early at prior to initiating the Phase Two Test Program (Phase One, Subtask 8). The objective would be to receive DEHNR endorsement of our investigation process and, most importantly, our ASR test cycle data collection plan.

In many states where ASR wells have been installed, once a reasonable program has been negotiated, a complete permit application package is not required until the facility is for operation. Currently, a formal water allocation permit is not required for Dare County, because it is not located within a Capacity Use Area. However, there has been some discussion in the regulatory circles of classifying new areas of North Carolina (including the Outer Banks region) as Capacity Use Areas. Should this become reality, CH2M HILL has vast experience in working with regulatory agencies to permit ASR facilities.

An aquifer test plan will be prepared and submitted to DWR before installation of the monitor well to ensure they are in concurrence with the number of monitor wells, monitor well locations, and the aquifer test program.

Prior to initiating the Phase Two Investigation, CH2M HILL and DRWSS will evaluate whether to proceed with construction of the ASR system in separate design and bid construction phases or if a design-build approach is warranted. This decision will effect specific permitting requirements and review periods but the general procedures and the DEHNR contacts will remain the same.

Before construction of the ASR well, a permit application and technical report will be submitted to DEHNR to obtain Well Construction and Safe Drinking Water Permits for operation of the well. Wellhead engineering drawings and specifications will be submitted with the report. A statutory limit of 15 days is imposed on DWQ/DWR to complete their review of the plans and issue an authorization to construct. Typical review time is even shorter, approximately 7 days. DEH review time is similar for Safe Drinking Water Permits unless the source water is expected to be surface water.

The DEHNR Washington field office will also be required to review the ASR expansion plans. Their standard review period is 30 days. However, based on preliminary discussions with Washington personnel, it is anticipated that faster processing time will be achieved by working closely with this office.

During the permit processing time, bidding, constructor selection, contract award, and mobilization can proceed. Additional submittals to DEHNR can be made throughout the construction or design-build period. If a design-build approach is utilized, DEHNR staff will need to be more closely involved to get faster approvals.

An Underground Injection Control (UIC) Class V well permit will be submitted to DEHNR and/or USEPA within one year of commencing operations. If a temporary injection permit is required to initiate Phase Two testing, this will be submitted also. Permit requirements include general well inventory information such as location, depth, and usage.

Task 5 - ASR Well and Wellhead Design and Construction

The ASR well will be constructed last to maximize the use of data collected from the monitor well installation and other preceding tasks. However, construction of the ASR well can be implemented relatively rapidly under the same drilling contract as the monitor well installation. Construction can be completed as a phase separated from the design or in design-build fashion. This proposal assumes a standard project delivery; however, significant cost savings can typically be achieved utilizing a design-build project delivery method.

ASR wells typically consist of 12-inch screen and 18-inch well casing as median diameters for wells in the Atlantic Coastal Plain. Screen slot size and the filter pack will be based on grain size analysis of the core samples and cuttings. A production pump capable of delivering the optimum production capacity of the well will be installed, based on pumping test results. Design drawings and general specifications for the ASR well and wellhead facilities will be developed.

Piping, valves, and other fittings will be required to convey water to and from the ASR well. Valves will be required to control borehole pressure during recharge, and to control flow rate during recovery. Flow meters will be required for both recharge and recovery. Piping will be necessary to convey water from the ASR well to the local sewer system or acceptable surface water discharge location during the ASR testing, well development, and during times of well maintenance. CH2M HILL will evaluate whether a permanent well house may need to be constructed complete with freeze protection. Engineering drawings for the wellhead and landscaping will be developed. The wellhouse design will be tailored to the aesthetic standards of the community. An electrical supply will be required at the ASR well. Telemetry may be added later to facilitate routine operations and automation, if desired.

If a wellhouse for the ASR well is required, CH2M HILL will contact the local planning board for site plan requirements. Also, CH2M HILL will prepare and submit a soil erosion control plan to the proper agency. These relatively small permitting tasks are best handled during the design portion of the project.

Assuming that DRWSS wants to procure a drilling contractor through a formal bidding process, CH2M HILL will prepare biddable contract documents that will be used to procure a contractor to construct the ASR facility. These documents will include design drawings and technical specifications for expansion of the station, along with the DRWSS standard contract documents for construction projects. We have assumed that a kick-off meeting will be held with personnel from the DRWSS prior to commencing the design effort to obtain insight regarding preferred equipment and design criteria. Design drawings will be prepared in a format specified by the DRWSS. We assume the DRWSS can provide a camera-ready copy of their contract forms and general conditions for integration into the bidding and contract package. These documents will be processed in one of CH2M HILL's specifications and design centers.

Upon completion of greater than 50 percent of the design of the station, CH2M HILL will develop a definitive-level, engineer's estimate of the construction costs to implement the station upgrades. A definitive level estimate as defined by the American Association of Cost Estimators (AACE) consists of an estimate that ranges from +15 to -5 percent of the actual costs to perform the construction. This estimate is based on detailed unit cost data and quantity surveys, along with equipment and system quotations from suppliers and vendors.

A representative from CH2M HILL will attend the opening of the bids. CH2M HILL will review the bid amounts along with the qualifications of the bidders and references, and will provide a recommendation for the winning bidder based on this technical review. If a potential low bidder is not qualified to perform the work, CH2M HILL will draft a memorandum that justifies disqualification of the low bidder and technically supports the award to the second lowest bidder.

Task 6 - Services During Construction

CH2M HILL will provide oversight services during construction of the ASR facility. These services will include:

- Review of contractor's submittals.
- Oversight of construction.

- Documentation of construction progress including attending periodic progress meetings, preparing periodic progress reports, and photographing construction activities.
- Review of contractor's invoices and recommendations for payment and/or penalties including liquidated damages.
- Oversight of ASR startup and testing of facilities.
- Preparation of a report documenting the completion of construction. This report will include equipment manuals as appendices.

To reduce costs for DRWSS, actual oversight of construction will focus on observing important or complex construction activities, such as installation of the new well screen, installation of mechanical components, or installation of major electrical components. Oversight of more routine construction activities will be covered by periodic visits to the construction site by representatives from CH2M HILL.

Task 7 - Aquifer Testing

Existing test data are unsuitable for estimating aquifer hydraulic characteristics for ASR purposes. A 72-hour, constant rate pump test of the ASR well with careful monitoring of water levels in the pumping well, monitor wells, and nearby wells installed in the selected aquifer during the drawdown and recovery periods, should enable determination of transmissivity, storativity, leakage, specific capacity, and well efficiency. Accurate aquifer coefficient data is required to establish a baseline against which test program results can be compared. The design of the aquifer test will follow guidelines established by DWR, or an agency from another state, if no North Carolina guidelines exist. Prior to the 72-hour, constant rate test, a step drawdown test will be conducted to determine the optimum pumping and well characteristics for the ASR well.

Task 8 - ASR Test Cycles

Final design of the test cycles will depend on results of the geochemical analysis and ASR well construction. Tentatively, it is expected that about three cycles will be conducted during the test period, extending through a single ASR cycle year (September or October through the following August). Table 2 shows a typical schedule, assuming that the recovery rate is 0.6 mgd. The exact schedule will be designed so that DRWSS can recover up to 54 million gallons (mg) during the summer following project initiation.

Table 1

Typical ASR Test Cycle Schedule for DRWSS ASR Well

Cycle	Avg. Rate (mgd)		Duration (days)				Volume (mg)	
	Recharge	Recovery	Recharge	Storage	Recovery	Total	Recharge	Recovery
1	0.6	0.6	15	0	15	30	10	9
2	0.6	0.6	50	0	45	95	30	27
3	0.6	0.6	100	10	90	190	60	54

Note: This is a typical ASR test schedule. However, rates, duration, and volumes will be adjusted during the program as needed to meet Phase Two objectives.

Task 9 - Operations and Maintenance Manual Preparation and Training

An operations and maintenance (O&M) manual will be developed for use by DRWSS personnel in running the ASR facility. The manual will provide a brief overview of ASR technology and provide an explanation for each of the important O&M procedures for each mode of operation (recharge, storage, and recovery). Checklists will be prepared for each O&M task to provide the operators with step-by-step procedures for running the ASR station. The checklists will be supported with color design drawings of the system components. Valves and other components will be designated on the design drawings in their sequence of use. In conjunction with preparation of the O&M manual, CH2M HILL field personnel will train DRWSS operators in running the ASR facility.

Task 10 - Final Report

A final report will be prepared, including test program results and recommendations for possible ASR facilities expansion, if appropriate. This report would be used to support issuance by DEHNR of an operational permit for ASR facilities upon test program completion.

Project Cost

The Preliminary Feasibility Assessment described in this proposal will be completed within 15 weeks after receipt of a signed agreement from the DRWSS.

Section 1 - Preliminary Feasibility Assessment

The estimated CH2M HILL cost of executing the scope of services for the preliminary feasibility assessment is $48,500. The cost breakdown by task is as follows:

Subtask 1:	Project Kickoff Meeting	$3,000
Subtask 2:	Review ASR Criteria Related to the DRWSS	$2,000
Subtask 3:	Collect Background Data	$5,000
Subtask 4:	Review Background Data	$14,500
Subtask 5:	Develop the ASR Test Program	$5,000
Subtask 6:	Engineer's Estimate	$2,500
Subtask 7:	Evaluate Funding Options	$2,500
Subtask 8:	Prepare Report	$11,000
Subtask 9:	Regulatory Agency Meeting	$3,000
	TOTAL:	**$48,500**

We are assuming that the contract for professional services during the preliminary feasibility assessment will be on a cost reimbursable basis with a not to exceed figure of $48,500. The work will be done under the terms and conditions of our Standard Agreement for Professional Services. We have attached a copy of our Standard Agreement for your information.

Section 2 - ASR Program

The following table presents estimated total costs for the Preliminary Feasibility Assessment and the Phase Two ASR Test Program. For cost estimation, it is assumed that a single monitoring well will be installed following collection of core samples in the well boring, and a single ASR well will be constructed in either the Upper Yorktown Aquifer near the Kill Devil Hills wellfield or the Castle Hayne Aquifer near Kitty Hawk or Duck.

Task No.	Task	Labor	Expenses	Contracting (labs, drilling, construction)	Total
1	Preliminary Feasibility Assessment	$38,500	$9,500	$500	$48,500
2	Subsurface Investigation	20,000 - 25,000 [3]	5,000	65,000 - 100,000[3]	90,000 - 130,000
3	Core Lab and Geochemical Analysis	7,000	2,000	7,000	16,000
4	Permitting	10,000	4,000	0	14,000
5	ASR Well and Wellhead Design and Construction[1,2]	36,000	4,000	200,000 - 290,000[3]	240,000 - 330,000
6	Services During Construction	40,000	5,000	0	45,000
7	Aquifer Testing	16,500	3,500	0	20,000
8	ASR Test Cycles	52,000	10,000	4,000	66,000
9	O&M Manual/Training	11,000	4,000	0	15,000
10	Final Report	16,500	3,500	0	20,000
Total Costs		$247,500 - $252,500	$50,500	$276,500 - $401,500	$574,500 - $704,500

1 = We have assumed that a single drilling contract will be issued for the ASR Phase Two Program. Work under this contract will include Task 2: Subsurface Investigation ($65,000) and Task 5: ultimate installation of the ASR well, wellhead piping and

chemical feed systems ($200,000). Because the subject aquifer is not known, drilling depths and coring footage are not conclusive.

2 = Design costs are based on developing plans and specifications for the ASR well, mechanical piping, and chemical feed systems. As the preferred location has not yet been selected, it is unknown whether wellhouse facilities are required.

3 = Cost ranges for Tasks 2 and 5 reflect increased oversite time and subcontractor costs associated with completing wells in either the Upper Yorktown or Castle Hayne Aquifers, due to significant differences in their depths of completion.

Project Team

The key personnel for this project, presented below, have been selected because of their ASR technical background and experience in the Coastal Plain Aquifers of southern New Jersey and Delaware.

R. David G. Pyne, Program Manager

Mr. Pyne is CH2M HILL's director of aquifer storage and recovery and groundwater recharge projects. He has managed many groundwater hydrology, surface water hydrology, water quality, water supply, and aquifer recharge projects. Mr. Pyne pioneered ASR technology in the 1980s and is the world's leading expert in the field. He has been consulted, in one form or another, for every ASR project conducted by CH2M HILL in the United States.

Mitchell Bormack, Project Manager

Mr. Bormack is a project manager and hydrogeologist in CH2M HILL's Philadelphia office. Mr. Bormack will serve as project manager and principal liaison between CH2M HILL and DRWSS staff. Mitchell has experience with all phases of ASR projects including preliminary feasibility assessments, detailed subsurface investigations, ASR cycle testing, facility permitting, and operator training. His ASR project experience includes five Atlantic Coastal Plain projects (NJAWC's Cherry Hill, Aberdeen, and Swimming River facilities, Brick Township MUA, and the Evesham Township MUA, all in New Jersey) and the Mannheim ASR project in Ontario, Canada.

Mark C. Lucas, Lead Hydrogeologist

Mr. Lucas is a hydrogeologist and project manager in CH2M HILL's Philadelphia office who has extensive experience in ASR studies, hydrogeologic investigations, and borehole geophysical surveys. He will be responsible for planning technical aspects of the project and technical input, as necessary. He performed hydrogeological services for the Swimming River Reservoir, NJAWC-Cherry HILL, NJAWC-Devonshire, NJAWC-Aberdeen, Brick Township MUA, Toms River Water Company, and Evesham MUA ASR feasibility assessments.

Richard K. Glanzman, Senior Geochemist

Mr. Glanzman will serve as the senior geochemist for the project and will provide geochemical technical consultation and review to the project team. He has served as the senior geochemist on the aquifer storage and recovery projects at numerous ASR sites in Florida, New Jersey, California, and at Myrtle Beach, South Carolina.

Robert A. Bergman, Water Treatment Engineer

With a professional background encompassing many areas of technical knowledge gained through more than 25 years of engineering in water treatment, Mr. Bergman has been responsible for projects involving equipment design and construction, engineering management, water utility operation, and research. He will serve as water treatment engineer for this assignment.

Kenneth McGill, Senior Reviewer

Mr. McGill is a senior hydrogeologist and project manager in CH2M HILL's Philadelphia office. He has managed 6 of the 7 ASR preliminary feasibility assessment projects and the ASR Phase Two test program projects conducted by CH2M HILL in New Jersey. He has over 19 years of experience conducting numerous other water supply and hydrogeologic investigations in the Coastal Plain Aquifers of New Jersey, Delaware, Virginia, and Long Island, New York.

Douglas G. Dronfield, Senior Reviewer

Mr. Dronfield is a registered professional geologist in North Carolina and a senior hydrogeologist with CH2M HILL. He has extensive experience in coastal plain hydrogeology in eastern North Carolina and southeastern Virginia. He was the senior hydrogeologist for the Chesapeake, Virginia ASR project and many other water supply projects in the Tidewater, Virginia area. He has been the senior hydrogeologist for groundwater investigations for major industrial clients in Greenville, Kinston, Grifton, and Gastonia North Carolina.

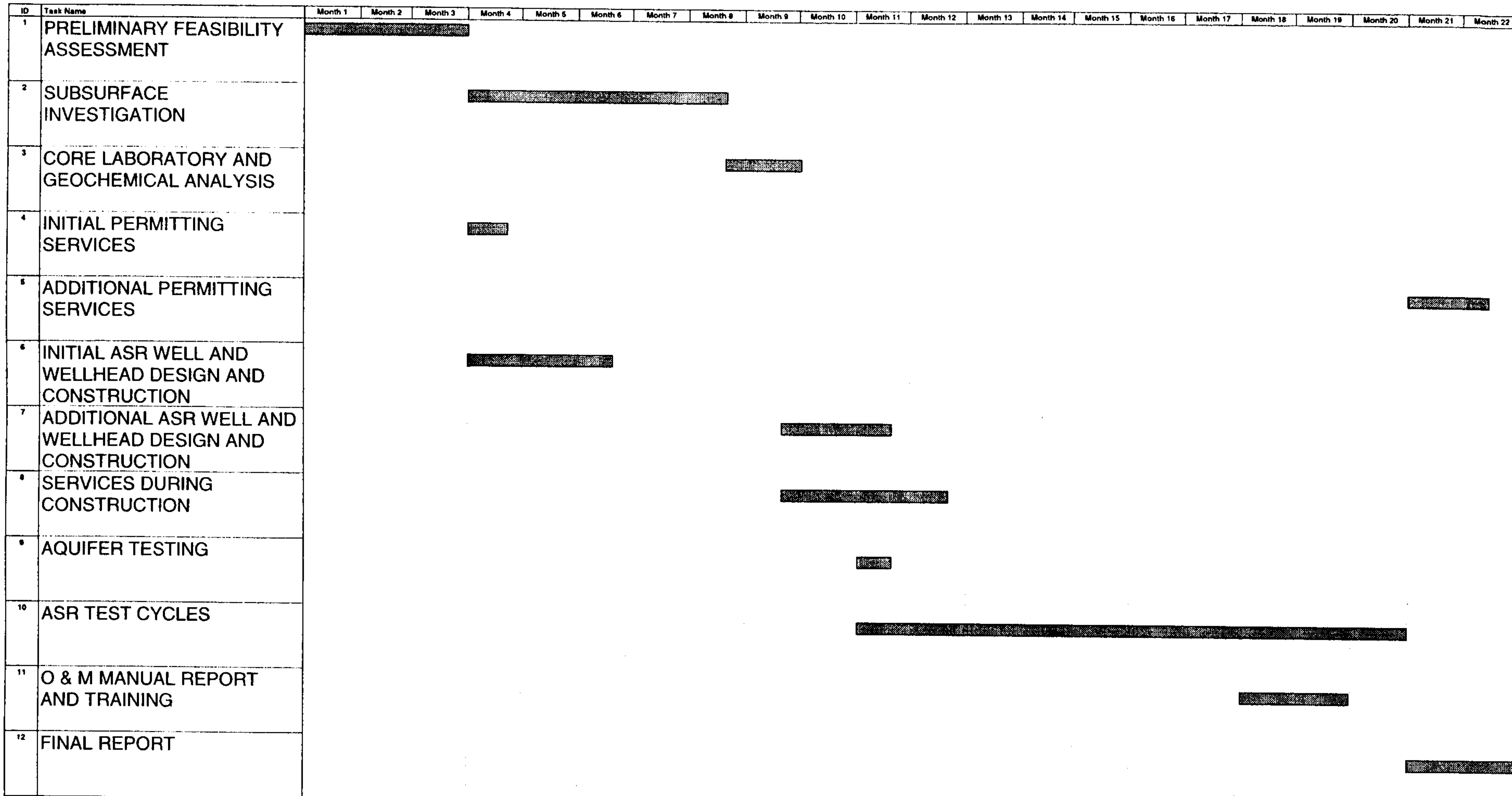
Bryan B. McDonald, Senior Reviewer

As a hydrogeologist in CH2M HILL's Gainesville, Florida office, Mr. McDonald specializes in conducting remedial investigations, groundwater supply development, and groundwater modeling. He will serve as Senior Reviewer for this assignment

Complete resumes for all the project personnel are in Appendix B.

Project Schedule

Figure 1 presents the estimated project schedule to obtain a fully operational ASR. The schedule was based on installation of a new Upper Yorktown Aquifer well near the Kill Devil Hills wellfield. For this schedule CH2M HILL assumes that the ASR well can be installed outside with chemical feed systems housed in existing buildings at the Kill Devil Hills facilities. Time and costs have not been estimated for the design or construction of a new wellhouse.



(1) Assumes that installation of ASR well, monitor well and subsurface investigation performed under same drilling contract.
(2) Assumes no wellhouse has to be constructed.

Task	Summary	Rolled Up Progress	
Progress	Rolled Up Task		
Milestone ◆	Rolled Up Milestone ◇		

FIGURE 1 - ESTIMATED PROJECT SCHEDULE

Appendix A

Project Experience

Project Experience

During the past 10 years, CH2M HILL has pioneered development of Aquifer Storage and Recovery (ASR) technology for recharge to meet seasonal, long-term, emergency and other water supply needs. Recharge occurs through dual-purpose ASR wells that are used for both recharge and recovery. Storage zones include fresh, brackish and seawater aquifers. This technology is very cost-effective, typically reducing capital facility costs by at least half. It also has received consistently strong support from the environmental community.

In addition to developing the technology, CH2M HILL is working with US regulatory agencies to develop an appropriate regulatory framework for ASR, including requirements for pretreatment before recharge that reflect treatment processes occurring under saturated and unsaturated conditions in the aquifer. With 18 operational ASR sites (the largest of which has a recovery capacity of 50 MGD (190,000 CMD) and about 40 ASR systems in development, we are gathering substantial data regarding well plugging and redevelopment; disinfection byproduct (DBP) reduction during ASR storage; reduction of nutrients, coliforms and DBP precursors; iron and manganese control, and other issues. We have learned that careful integration of water treatment process design, ASR well recharge design and operations can yield improved overall system performance and reduced costs.

CH2M HILL provides consultant services for both surface recharge and well recharge projects, the latter including injection wells, ASR wells and vadose zone wells. We have pioneered development of the ASR concept, including completion of most of these projects in the United States to date. Attached are selected ASR project descriptions; United States and New Jersey maps showing the location of ASR projects, and a list of well recharge projects.

Aquifer Storage and Recovery

Swimming River, New Jersey

The Swimming River water treatment plant (SRTP) obtains water from the Swimming River Reservoir (SRR) to meet an average day demand of 33 mgd. The ratio of maximum to average day demand is 1.8., prompted mostly by summer usage for lawn watering. Faced with a need to expand the treatment plant to meet peak demands the client requested that CH2M HILL conduct an ASR Phase One Preliminary Feasibility Assessment in 1989. This preliminary assessment of ASR feasibility addressed the following issues: water supply and demand, hydrogeology, water quality compatibility, environmental issues, permitting, and necessary facilities.

2NJ MAP

A suitable ASR storage zone was identified in the Upper Potomac-Raritan-Magothy Aquifer beneath the water treatment plant. Analysis of safe yield and demand have revealed that SRR has excess flow during the off-peak season of greater than 750 million gallons per year.

Based on the results of the Phase One Assessment, the client elected to proceed with a Phase Two Field Investigation to confirm ASR feasibility in a prototype ASR well modified from one of three existing supply wells at the plant. This investigation was completed and the ASR well was permitted by the NJDEP. The program could be expanded as required to meet increasing water demands. Four ASR wells at the SRTP could increase ASR capacity to at least 6 mgd, thereby delaying treatment plant expansion.

Aquifer Storage and Recovery

Evesham, New Jersey

The Evesham Municipal Utilities Authority (MUA) provides water for a rapidly growing residential and commercial community located 20 miles east of Philadelphia, Pennsylvania, in southern New Jersey. Evesham obtains all its water from eight production wells screened in the Potomac-Raritan-Magothy (PRM) aquifers. There is substantial seasonal variability in demand with summer peaks nearing 6 mgd and winter low flows below 3 mgd. Because of overpumping and declining water levels in the PRM aquifers, the State has designated this part of South Jersey a Critical Area and restricted withdrawals from these aquifers. Faced with cutbacks in pumpage from the PRM aquifers at the same time water demand is increasing at a rate of 8 percent a year, Evesham requested that CH2M HILL conduct an ASR Phase One Preliminary Feasibility Assessment in late 1990. The Phase One Assessment recommended that Evesham obtain water from low producing wells screened in a noncritical area aquifer and store it during the winter in very productive ASR wells screened in the Middle PRM Aquifer. The water would be recovered from the ASR wells and the low producing wells to meet peak summer demands into the next century. Evesham has authorized CH2M HILL to proceed with the permitting, design, and construction of the ASR test well, the noncritical aquifer supply well, and monitor wells, installed in both aquifers. These Phase Two Test Program activities are underway at Evesham.

Aquifer Storage and Recovery

Murray Avenue, Cherry Hill, New Jersey

Since 1991, the ASR Phase One Assessment and Phase Two Test Program has been successfully completed at the New Jersey-American Water Company's (NJAWC) Murray Avenue facility in Cherry Hill, New Jersey, by CH2M HILL. The test program involved installation of an ASR well and a wellhouse facility, which contains two chemical two chemical feed systems, caustic and disinfection. Now operational, the ASR well recharges treated drinking water from the NJAWC distribution system to the Middle Potomac-Raritan-Magothy (PRM) Aquifer during the off-peak winter months. Water is recovered to the NJAWC distribution system during the peak demand summer months.

The Phase Two test program consisted of the 10 tasks listed below:

1. Coring and Monitor Well Installation
2. Core Laboratory Testing

3. Geochemical Analysis
4. ASR Well, Wellhead, and Wellhouse Design
5. ASR Well, Wellhead, and Wellhouse Construction Services
6. Aquifer Tests
7. Pretreatment
8. ASR Test Cycles
9. Final Report
10. Permitting

During the spring of 1994, about 75 million gallons of water from the NJAWC distribution system was recharged through the ASR well. Over 100 percent of the water was recovered at about 1.7 mgd during the summer and fall of 1994 to the NJAWC distribution system at acceptable water quality. The water company has recharged about 120 mgd for recovery this summer in Cherry Hill. We recently provided design and construction services for the automation and SCADA modification of the Murray Avenue ASR pump station. The project allows NJAWC to use the ASR well to meet peak demands, at lower cost than a water treatment plant or supply system expansion. The water company now has plans to convert three of their iron removal plants and six production wells to ASR operations.

Aquifer Storage and Recovery

Brick, New Jersey

The area served by Brick Township Municipal Utilities Authority (BTMUA) lies in northeastern Ocean County, New Jersey. The township covers about 26 square miles near the Jersey Shore and is underlain by the New Jersey Coastal Plain physiographic province. The New Jersey Coastal Plain is part of the Atlantic Plain Province that extends from Georgia to New York. Between March and July of 1992, CH2M HILL conducted a Phase One Preliminary Feasibility Assessment for BTMUA. The primary objective of the Phase One study was to determine if the existing Middle/Lower PRM wells at the BTMUA well field were suitable for ASR conversion. BTMUA supplied water quality, hydrogeologic, and well inventory data from the well field to aid the investigation. In addition, related regional information was collected from local drillers, federal and state agencies, and water purveyors.

Given the results of the Phase One study, BTMUA elected to proceed with a Phase Two Test Program Investigation to confirm ASR feasibility at their production Well No. 10 which was converted to an ASR configuration. The Phase Two test program is ongoing. Assuming ASR feasibility is confirmed, the program could be expanded as required to meet increasing water demands during Phase Three. On the basis of current projections, three ASR wells in the BTMUA System could bring ASR capacity to 7.2 mgd and sufficiently meet peak demands into the next century. BTMUA recently expanded its water treatment plant from 12 mgd to 16 mgd. The unit cost for increasing treated water supply capacity using ASR is about 10 times less than the unit cost of BTMUA's recent water treatment plan expansion program.

Aquifer Storage and Recovery

Toms River, New Jersey

The Toms River Water Company (TRWC) service area is in east-central Ocean County, near Seaside Heights, New Jersey. The demand of the TRWC system during peak use seasons reached the point where the ASR concept is a viable alternative to meet peak demands for treated water. CH2M HILL was authorized by the TRWC to proceed with the Phase One Preliminary Feasibility Assessment Study in March 1992. The primary objective of the Phase One study, completed in June 1992, was to select an ASR location from three preferred sites owned by TRWC in the northern portion of the service area. These sites include the Parkway Well station, the Silverton Road test site, and the Route 70 Pump Station. The study also evaluated the seven New Jersey Coastal Plain Aquifers, exclusive of the Cohansey, for selection of an ASR storage zone and installation of a new ASR well. TRWC indicated that the minimum recovery capacity of the ASR well should be 1.5 mgd.

The preliminary feasibility assessment obtained existing information on the hydrogeology, aquifer water quality, treated water quality, aquifer material composition, and related information from federal and state agencies, drillers, and TRWC to assess the feasibility of a compressive ASR assessment and testing program. The preliminary feasibility assessment provided recommendations to TRWC to proceed with a Phase Two test program investigation to confirm ASR feasibility in a prototype ASR well installed in the Middle PRM Aquifer at the Route 70 Pump Station location. Assuming ASR feasibility is confirmed the program could be expanded as required to meet increasing water demands during Phase Three ASR operations. Given the current projections, two ASR wells in the TRWC system could bring ASR capacity to 6.6 mgd and meet peak demands into the next century.

Aquifer Storage and Recovery

Chesapeake, Virginia

Chesapeake is a rapidly growing community in the Tidewater area of Virginia. Water is obtained from the Northwest River when this source is fresh and through wholesale purchases from adjacent communities during months of the year when the river becomes saline. To meet increasing demands, Chesapeake authorized CH2M HILL to investigate the feasibility of ASR. Raw water would be obtained from the Northwest River and also from the nearby Dismal Swamp Canal during months of the year when these sources are flowing and fresh. It would be treated and stored in unconsolidated sand aquifers for recovery when local surface supplies are unavailable. Storage of treated surface water is expected to provide recovered water quality suitable for potable needs. The ASR project includes permitting, design and construction of an ASR test well, monitor wells and well head facilities, and hydraulic testing.

During the initial pilot program, two suitable storage zones were identified in the Upper Potomac Aquifer and the Middle Potomac Aquifer. An ASR test well and two monitor wells were installed in these two zones. Preliminary injection and recovery cycles confirmed ASR feasibility in the Virginia Coastal Plain. ASR operation has begun, with seasonal recovery to the water distribution system at a rate of 3 mgd. The ASR wellfield is currently being expanded concurrent with predesign investigations for facilities to convey and treat water from the Dismal Swamp Canal for potable use and ASR storage.

Aquifer Storage and Recovery

Myrtle Beach, South Carolina

This rapidly growing coastal community experiences a substantial seasonal variability in demand, with summer peaks exceeding 15 mgd and winter low flows below 8 mgd. Until June 1988 all demand was met through withdrawals from the Black Creek aquifer, a clayey sand formation with steadily declining water levels due to increasing production. At that time the City began operation of a new 20-mgd surface water treatment plant withdrawing water from the Intracoastal Waterway. CH2M HILL was retained by the City during 1987 to investigate the feasibility of ASR to help meet projected future peak demands exceeding plant capacity. During winter months, water would be stored in 28 Black Creek production wells retrofitted for ASR operation and would be recovered to meet summer peak demands. A test well was constructed to bedrock at 1,428 feet, including collection of continuous wireline cores through the Black Creek and also the underlying Middendorf and Cape Fear Formations. Selected cores were analyzed and a geochemical evaluation was conducted. Column tests were performed on selected cores to gain further understanding of geochemical issues. ASR testing at an existing production well is planned to confirm results of earlier tasks.

Aquifer Storage and Recovery

Manatee County, Florida

During the first phase of this project, CH2M HILL evaluated several water supply alternatives that included four instream reservoirs, one offstream reservoir, two new well fields, and ASR. ASR was determined to be the least-cost alternative, assuming confirmation of feasibility. CH2M HILL subsequently was authorized to proceed with construction of ASR test facilities. A series of recharge and recovery cycles demonstrated the recoverability of the stored water. The testing showed that all of the volume stored could be recovered with a quality suitable for potable use, resulting in the issuance of an operational permit for the ASR system. Because of its implications for the water supply industry, this pioneering project received a Grand Award, one of six awarded nationwide in the American Consulting Engineers Council 1984 Engineering Excellence Competition. A second ASR well has been added and the well field is planned for expansion from 3.5 to 11 mgd (11 to 42 Ml/d).

Aquifer Storage and Recovery

Florida Keys Aqueduct Authority (FKAA)

Marathon, Florida

A single pipeline supplies water to the Florida Keys from the well field and water treatment plant in Florida City to the City of Key West, a distance of 120 miles. The pipeline crosses 43 bridges. A break in this pipeline due to a hurricane, for instance, could cause severe water problems for the approximately 80,000 residents of the Keys served by FKAA. Limited land availability and high cost precludes construction of aboveground storage tanks. CH2M HILL conducted an investigation and constructed a test facility at Marathon, Florida, to determine if ASR could be applied to a confined seawater aquifer underlying the Keys. This program was conducted in phases due to the great amount of uncertainty associated with storing potable water in a seawater aquifer. Potable water has been successfully stored in, and recovered from, the saline aquifer with recovery efficiency over 70%. These findings are a major technological breakthrough in the field of ASR. Plans are underway to construct a disinfection facility so that stored water can be recovered to the distribution system. As a result of the success of this test program, the FKAA can expand ASR at Marathon, and possibly other sites, to help meet emergency and peak seasonal needs.

Aquifer Storage and Recovery

Kerrville, Texas

Following several decades of groundwater production, water level in the aquifer beneath Kerrville had fallen about 100 m. In 1980, the Upper Guadalupe River Authority (UGRA) began operation of a 5 MGD (19 Ml/d) surface water treatment facility, withdrawing water from a small, instream reservoir on the Guadalupe River which runs through Kerrville. CH2M HILL was retained by UGRA during 1988 to investigate the potential of ASR to enable UGRA to defer plant expansion and associated construction of an offstream reservoir, thereby achieving major savings. A feasibility study indicated that UGRA could store treated drinking water in the Hosston-Sligo formation, a productive aquifer beneath the Kerrville area. This would restore aquifer water levels and maintain downstream minimum flow, while permitting recovery to meet peak demands. A test well was constructed, including collection and analysis of continuous cores. Construction and testing of ASR well facilities at two sites has been completed successfully and a second well placed in operation, reducing the facilities expansion cost by about 80%. This project received an Honors Award in the nationwide American Consulting Engineers Council Engineering Excellence Competition in 1992.

Aquifer Recharge

Salt Lake County, Utah

Salt Lake County received a grant from the U.S. Bureau of Reclamation under the High-Plains States Groundwater Recharge Program Act of 1983. The purpose of the grant was to construct a system for injecting seasonal excess water from the County's aqueduct into an aquifer underlying the area to recharge this aquifer for supplemental peak water supply purposes. The aquifer includes unconsolidated deposits of boulders, gravel, sand, silt, and clay and has experienced a steady decline in water levels. The aqueduct pipeline obtains water from Deer Creek Reservoir on the Provo River and has excess water during winter months when demand is low. CH2M HILL was retained by Salt Lake County to provide consultant assistance with the planning and design of recharge facilities, including two injection wells, two recovery wells, a monitoring well, and water treatment facilities. Construction and testing of these facilities is under way.

Recharge Feasibility Assessment, Phase A

Tucson, Arizona

CH2M HILL conducted a major recharge feasibility study to assess the potential for recharging water to aquifers in the Tucson area. Sources of recharge water included Central Arizona Project (CAP) water, reclaimed wastewater, and floodwater. Recharge methods included surface methods and injection wells. An initial task on this project was a comprehensive review of state-of-the-art recharge methods. Over 400 abstracts were prepared from the available literature and a number of nationwide site visits to ongoing recharge operations were made. An extensive review of water quality considerations also was completed. Additional tasks included determination of institutional and regulatory requirements at the local, state, and federal levels; characterization of groundwater quality and potential sources of recharge water; and evaluation of the pipeline distribution system and production wells for recharge.

Recharge Feasibility Assessment, Phase B

Tucson, Arizona

CH2M HILL completed a $5 million pilot recharge program for the City of Tucson. Pilot projects include surface spreading and well injection recharge methods. Tucson, which previously depended entirely on local groundwater, began receiving 130 MGD (500 Ml/d) of Colorado River Water via the Central Arizona Project in 1992. The City plans to maximize direct use of CAP water and store the excess through aquifer recharge.

Aquifer Storage and Recovery

Seattle, Washington

A $2.3-million ASR program is approaching completion for the City of Seattle under the Bureau of Reclamation Recharge Demonstration Program. The Seattle Water Department (SWD) is designing and constructing a well field in the Highline area immediately south of Seattle to augment the Cedar River surface water supply during the peak summer demand months. SWD's ultimate goal is to develop a peaking supply of 12 MGD (45 Ml/d) from the well field. Hydrogeologic studies of the intermediate and deep aquifers indicate that groundwater withdrawal in excess of 6 to 8 MGD (23 to 30 Ml/d) for 4 months will result in a long-term water level decline. Initial studies show that this decline can be stabilized by injecting recharge water during the off-peak winter months. In addition, recharging high-quality Cedar River water should improve groundwater quality and thereby reduce treatment requirements.

The approach to the Highline Well Field ASR project was to initially demonstrate the ASR concept at an unused intermediate aquifer well. This testing was completed with encouraging results, following which two full-scale intermediate aquifer tests were conducted at new production wells equipped for ASR purposes. The ASR concept was then demonstrated for the deep aquifer by first conducting a pilot-scale and then a full-scale test at a deep aquifer production well. All ASR wells are now operational.

Aquifer Recharge Preliminary Feasibility Study

Tacoma, Washington

For the City of Tacoma, CH2M HILL completed a study to determine the feasibility of recharging water from the Green River into the South Tacoma aquifer. This preliminary feasibility study evaluated both recharge basins and injection wells as potential recharge methods. Study tasks included:

- Evaluation of the compatibility of Green River water and groundwater in the South Tacoma aquifer.
- Evaluation of the hydrogeology of the South Tacoma aquifer and its potential response to recharge.
- Evaluation of the costs of constructing, operating, and maintaining recharge facilities and of meeting legal and institutional requirements.
- Development of a pilot program to test the feasibility of either recharge basins or injection wells.

Dual-purpose injection, or ASR, wells were recommended to store water for seasonal peak withdrawals while ensuring that the water table is relatively unaffected in the vicinity of landfills.

Feasibility Investigation for the Crescent Basin Reclamation and Recharge Plant

Orange County Water District

Orange County, California

The Orange County Water District is evaluating the feasibility of increasing artificial recharge with reclaimed wastewater in the Crescent groundwater basin. CH2M HILL was retained to prepare an analysis of the regulatory steps needed to gain approval of an expanded groundwater recharge or injection program using this reclaimed wastewater. CH2M HILL provided a review of applicable federal and state regulations, and highlighted key areas of concern, including requirements for disinfection, filtration and oxidation.

Wastewater Reclamation Study

Goleta Water District

Goleta, California

The Goleta Water District retained CH2M HILL to provide an analysis of options available to it for the purchase and use of reclaimed wastewater from the City of Santa Barbara. As part of this work, CH2M HILL was requested to evaluate the regulatory issues associated with injecting and extracting reclaimed wastewater from an aquifer. Applicable federal and state regulations were reviewed, and federal, state, and local regulatory agencies contacted. Potential issues were analyzed in light of proposed new state policies regarding recharge of aquifers with reclaimed wastewater. The analysis indicated that the recharge of reclaimed wastewater into a drinking water aquifer can be feasible within proposed regulations.

Demonstration of a Rapid Infiltration and Extraction System

San Bernardino and Colton, California

The cities of San Bernardino and Colton are evaluating the use of rapid infiltration and extraction (RIX) as an alternative to tertiary treatment to meet State of California Title 22 reclaimed water requirements. Title 22 requires that chemical coagulation and mechanical filtration followed by disinfection be performed on the secondary wastewater effluent prior to discharge to the Santa Ana River. An RIX facility has been designed and constructed in the alluvial aquifer of the Santa Ana River for demonstration purposes. The facility consists of pipelines from the two wastewater treatment plants, two sets of rapid infiltration basins of about 5 acres (2 hectares) each and capable of infiltrating 2 MGD (8 Ml/d), 10 extraction wells capable of extracting 2.4 MGD (9 Ml/d), chlorination, and dechlorination facilities to disinfect the extracted groundwater, and 38 monitoring wells to monitor the effectiveness of the RIX demonstration facilities and effects on local groundwater. Monitoring was performed to assess specifically the removal of viruses, reduction in nitrogen, and general improvement in effluent quality. Program results were satisfactory, as a result of which the system is being expanded.

Baseline Water Quality Monitoring Program

West Basin Municipal Water District

Los Angeles, California

Injection of reclaimed wastewater from the Hyperion Treatment Plant into the West Basin has been proposed to conserve potable water resources. CH2M HILL has been retained by the West Basin Municipal Water District to develop baseline water quality data as a first step in this program. As part of this work, a baseline water quality monitoring program has been developed to establish groundwater quality prior to injection of the effluent.

Aquifer Storage and Recovery

North Las Posas Basin

Moorpark, California

CH2M HILL was selected by the Metropolitan Water District of Southern California (Metropolitan) to develop and implement a demonstration project to assess the feasibility of using dual purpose injection/extraction wells (ASR wells) in the North Las Posas groundwater basin. The scope of work of this project included the following: characterize the hydrogeology of the basin, identify an existing well to convert to an ASR well, design the modifications to convert a production well to an ASR well, supervise the modifications to the well, supervise the installation of an adjacent monitoring well, sample for detailed mineralogical analysis and geochemical assessment, instrument the well to monitor water levels and suspended sediment, supervise the injection and extraction tests, evaluate the results, and prepare a report. In addition, CH2M HILL assisted in obtaining approvals from the regulatory agencies to implement the test program because the well selected for the test is part of a potable water supply. The testing conducted on the retro-fitted ASR well demonstrated that injection into the aquifer could be accomplished without adverse effects from well plugging or geochemical reactions. The water stored was successfully recovered and well hydraulic capacity was retained.

The testing was completed with excellent results. A second new ASR well was constructed, and the ASR system is now being expanded to include 6 more wells.

First Technical Assessment for the Devil's Gate Multi-Use Project Raymond Groundwater Basin Pasadena, California

The City of Pasadena and Metropolitan Water District of Southern California are considering conjunctive use of the Raymond groundwater basin, whereby water would be imported and stored in the basin for later recovery to meet seasonal and drought water demands. CH2M HILL was selected to evaluate the feasibility of this concept, including evaluation of the storage capacity of the groundwater basin, peaking demands, and potential impacts on groundwater quality. The assessment is being conducted in two phases. In Phase 1, 10 conjunctive use alternatives were identified and evaluated in concert with local water purveyors, and a Geographical Information System (GIS; a computerized spatial data base) was developed to store and process hydrogeologic data. In Phase 2, the alternatives will be developed and evaluated in more detail, and a preferred conjunctive use alternative selected. Benefits and beneficiaries of conjunctive use will be identified for cost-sharing purposes. A specific implementation plan will be prepared for adoption by the Raymond Basin Management Board.

CH2M HILL ASR Experience

List of Operational ASR Projects, August 1997

About twenty-six ASR systems are in operation in the US as of August 1997. This may be compared with three in 1983. Each system has wells that recharge and recover treated drinking water to meet seasonal peak, emergency, long-term or other water needs. Nineteen of these operational ASR systems have been developed with engineering consultant assistance from CH2M HILL, and are marked with an (*) in the list below. About 40 others are in various stages of investigation, design, construction or testing by our firm, in the US and overseas. References for all known operational ASR systems are as follows:

(*) Peace River/Manasota Regional Water Supply Authority, Florida

Began operation in 1985, expanded in 1988, and 1995. Currently 9 ASR wells, being expanded to 25 wells. Water source is from the Peace River.

Pat Lehman, Acting Director
Peace River/Manasota Regional Water Supply Authority
813-741-3049

(*) Cocoa, Florida

Began operation in 1987, expanded in 1991, and 1995-1996. Currently 6 ASR wells, being expanded to 10 wells. Water source is from a distant wellfield, and in the future will be from Taylor Creek reservoir.

Mr. Carl Larrabee
Director of Utilities/Public Works
407-639-7650

(*) Palm Bay (formerly Port Malabar), Florida

Began operation in 1989. One ASR well. Water source is from a local shallow aquifer.

Mr. Tim O'Brien
Plant Superintendent
407-724-0255

(*) Manatee County, Florida

Began operation in 1983. Major expansion underway. Currently 2 ASR wells. Water source is from the Manatee reservoir and a distant wellfield.

Mr. John Zimmerman
Assistant Director of Public Works
813-792-8811

(*) City of Boynton Beach, Florida

Began operation in 1993. One ASR well. Water source is from a local shallow aquifer.

Mr. Pete Mazella
Assistant Director of Utilities
407-375-6400

(*)Mount Pleasant Waterworks & Sewer Commission, South Carolina

Began operation in 1995. Two wells operational, with expansion underway to three ASR wells. Water source is from local deep, brackish aquifer and reverse osmosis treatment.

Mr. Amar Dwarkanath
Director of Utilities
804-547-6390

Wildwood, New Jersey

Began operation in 1968. Four ASR wells. Water source is from a distant wellfield.

Mr. Ron Grookett
Director of Water
609-522-7744

Gordons Corner, New Jersey

Began operation in 1971. Two ASR wells. Water source from local wellfield.

Mr. Paul Burdan
General Manager
908-946-9333

(*) New Jersey American Water Company (NJAWC), Swimming River, New Jersey

Operation began in 1995. One ASR well. Water source is from the Swimming River reservoir.

Mr. Howard J. Woods, Jr.
Vice President - Engineering
609-547-3211

(*) NJAWC Western Division, Haddon, New Jersey

Began operation in 1994. One ASR well. Water source is from the Delaware River.

Mr. Joseph Kish, Engineer
609-573-6831

(*) Upper Guadelupe River Authority, Kerrville, Texas

Began operation in 1996. One ASR well. Water source is from the Guadelupe River.

Mr. Jim Brown
General Manager
210-896-7050

(*) Kerrville, Texas

Began operation in 1996. One well. Water source is from the Guadelupe River.

Mr. John Wendele
Water Resources Administrator
City of Kerrville
210-257-8000

(*) Seattle Water Department, Washington

Began operation in 1992. Three ASR wells. Water source is from the Cedar River.

Mr. Robert Schwartz
Senior Civil Engineer
206-684-5926

(*) Centennial Water & Sanitation District, Highlands Ranch, Colorado

Began operation in 1993. Four ASR wells, with expansion underway. Water source is from the McClellan reservoir.

Mr. Paul Grundemann
Director of Utilities
62 W Plaza Dr.
Highlands Ranch, CO 80126
303-791-7181

Willows Water District, Denver, Colorado

Began operation in 1995. One well. Water source is from the Denver Water Department.

Mr. Khanh T. Le, P.E.
Manager
303-770-8625

(*) City of Pasadena, California

Began operation in 1992. Two or more ASR wells. Water source is from the Metropolitan Water District of South California (MWDSC).

Mr. Brad Bowman
818-770-8625

City of Oxnard, California

Began operation in 1991. Four ASR wells. Water source is from MWDSC.

Mr. Richard Eccles
Water Production Supervisor
805-385-8141

Goleta Water District, California

Began operation in 1978. Nine ASR wells and several injection wells. Water source is from the Cachuma reservoir.

Mr. Kevin Walsh
General Manager
805-969-6761

(*) Calleguas Municipal Water District, California

Began operation in 1992. Expansion in 1994 to two ASR wells. Eighteen additional wells are under design/construction. Water source from MWDSC.

Mr. Don Kendall
General Manager
805-526-9323

(*) Foothills Municipal Water District, California

Began operation in 1994. One ASR well. Water source is State Water Project.

Mr. Ron Palmer
General Manager
818-790-4036

Camarillo, California

Began operation in 1992. Two wells. Water source is State Water Project.

(*) Las Vegas Valley Water District, Nevada

Began operation in 1988 with expansion continuing. Over 35 ASR wells with more than 100 MGD recovery capacity, plus several injection wells. CH2M HILL retrofitted 18 wells for ASR operation. Water source is from Lake Mead.

Mr. Mark Peterson, P.E.
Manager of Recharge Operations
702-870-2011

City of North Las Vegas, Nevada

Began operation in 1990. Expansion to 6 ASR wells during 1995. Water source is from Lake Mead.

Mr. Ken Allbright, P.E.
Administrator
Department of Public Works
702-657-2203

(*) Salt Lake County Water Conservancy District, Utah

Began operation about 1993. One ASR well and one injection well. Expansion underway to 24 ASR wells. CH2M HILL provided technical assistance. Water source is from the Salt Lake aqueduct.

Mr. Richard Bay
Assistant Chief Engineer
801-565-8903

(*) Salem, Oregon

Began operation in 1996. One ASR well, expansion to 6 wells. CH2M HILL provided feasibility investigations. Water source is from the North Santiam River.

Mr. Paul Eckley, P.E., Chief Utilities Engineer
City of Salem Public Works Department, Room 325
555 Liberty Street, S.E.
Salem, OR 97301-3503
503-588-6211

(*) Evesham, New Jersey

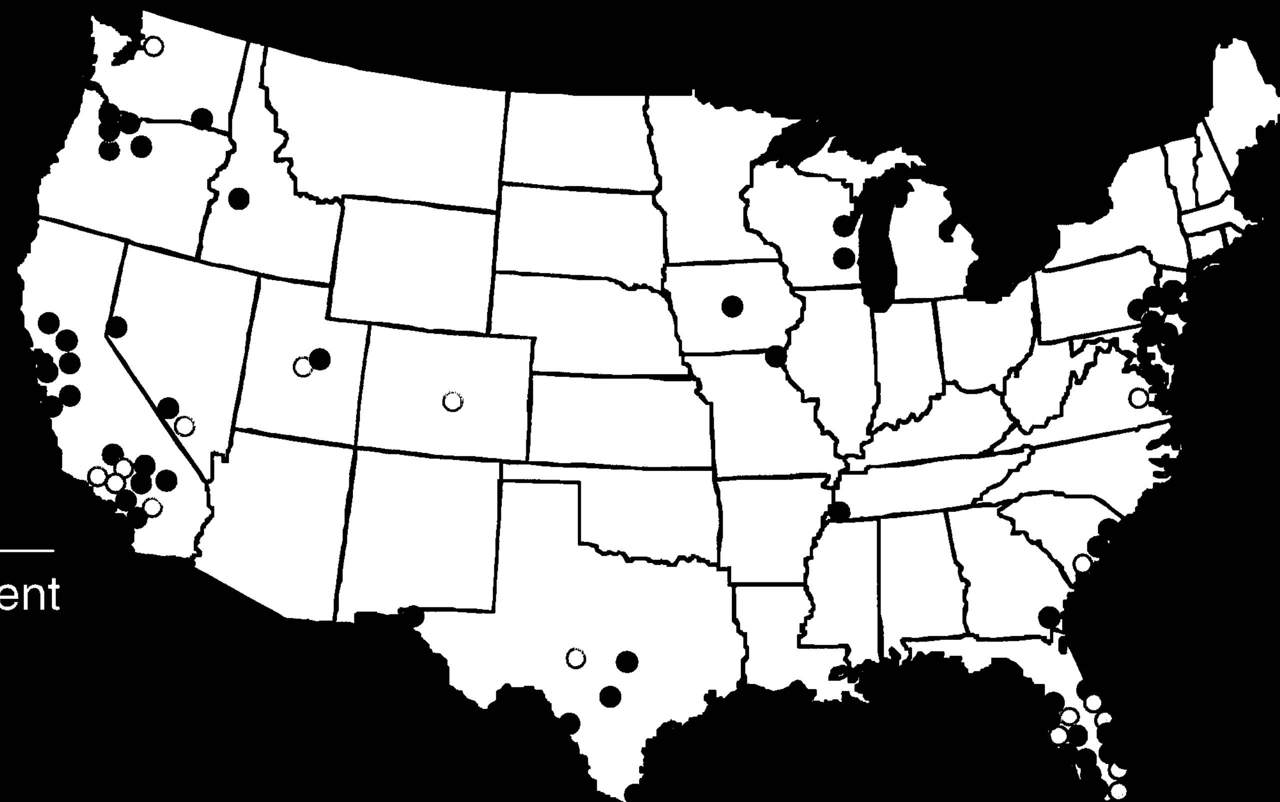
Began operation in 1997. One ASR well. Water source is from a local shallow aquifer.

Mr. Robert Flynn
Executive Director
Evesham Township Municipal Utilities Authority
609-983-1878

For additions, corrections, information regarding other ASR systems that may be in operation, or if we can assist with obtaining further information on these systems, please contact:

David Pyne
CH2M HILL
PO Box 147009
Gainesville, FL 32614-7009
352-335-7991 ext. 386
dpyne@ch2m.com

ASR Projects - August 1997



CH2M HILL

In Development

● In Operation

Others

○ In Development

○ In Operation

Appendix B

Resumes of Project Team

R. David G. Pyne

Education

M.S., Engineering, University of Florida, 1967

B.S., Civil Engineering, Duke University, 1966

Professional Registrations

- Professional Engineer: Florida

Distinguishing Qualifications

- CH2M HILL Firmwide Director of aquifer storage recovery (ASR), surface recharge, and groundwater development projects
- Pioneer in the development of ASR concept for water storage in wells in fresh, brackish, and seawater aquifers
- Management of American Consulting Engineers Council (ACEC) award-winning ASR projects in Manatee County, Florida, and Kerrville, Texas
- International expert in ASR technology
- Author of Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery (published in March 1995)

Relevant Experience

Mr. Pyne is the firmwide director of aquifer storage recovery (ASR), surface recharge, and groundwater development projects at CH2M HILL. Before assuming this position, he served as director of water resources engineering. His project management responsibilities have included the areas of groundwater hydrology, surface water hydrology, water quality, hazardous wastes, water supply and wastewater system planning, stormwater management, environmental studies, and aquifer recharge. He has served as an expert witness in numerous legal and administrative hearings in the areas of hydrology, hydrogeology, and water resources.

Mr. Pyne pioneered the development of the ASR concept for storage of water through wells in fresh, brackish, or seawater aquifers to meet seasonal, long-term, or emergency demands. Mr. Pyne has provided direction or technical support for 20 of the 26 currently operational ASR systems in the United States. ASR projects in Manatee County, Florida, and Kerrville, Texas, received national awards in the American Consulting Engineers Councils 1984 and 1992 Engineering Excellence Competitions. Mr. Pyne's international experience includes ASR projects and other water and wastewater development projects in England, Kuwait, Saudi Arabia, Nigeria, Canada, and the Bahamas. He authored *Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery*, which was published in 1995.

Project Experience

- For Miami-Dade Water and Sewer Department, Mr. Pyne has served as project manager for the development of two aquifer storage recovery wellfields with a combined capacity of 25 mgd. These wells will store untreated groundwater produced from the shallow Biscayne aquifer during offpeak periods and recover it to help meet peak demands. The five ASR wells, now under construction, will store this fresh water in a brackish limestone artesian aquifer at a depth of 850 to 1250 ft. As part of the permitting for this ASR system, Mr. Pyne assisted the Authority to obtain the first Water Quality Criteria Exemptions issued in the state of Florida, for injection of water that has concentrations of certain constituents that exceed secondary drinking water standards for color, odor and iron. He also assisted the Authority to obtain the first Water Use Permit to incorporate the concept of seasonal allocation of water. In prior years, Mr. Pyne provided engineering services during development of a comprehensive South Dade Wastewater Master Plan.

- Mr. Pyne has managed the development of several municipal and industrial water supply systems, including planning studies, conceptual and final design of wellfields, surface supply and storage facilities, and construction services. Typical projects include the 60-million gallon per day (mgd) Pinellas County Water System and the 15-mgd Starkey Well Field and Wilderness Park for the West Coast Regional Water Supply Authority in Florida.

- For Manatee County, Mr. Pyne managed the development of Florida's first ASR wellfield from 1979 to 1983. The effort included feasibility studies, design, permitting, construction services, and successful testing of two ASR wells at Lake Manatee. The project was jointly funded by Manatee County and the Southwest Florida Water Management District and won a national award from the American Consulting Engineers Council in 1984.

- In the fields of surface water hydrology and water quality, Mr. Pyne has applied linear programming, modeling, and simulation techniques to the analysis of stream and reservoir water quality degradation resulting from combined sewer overflows, urban runoff, and wastewater treatment plant effluent for the City of Atlanta, Georgia. He was project manager for hydrologic and hydraulic analysis, preliminary engineering design, and cost estimation for the Cypress Creek flood detention area in Pasco County, Florida.

- Mr. Pynes involvement in ASR and well design projects elsewhere includes direction or technical support for most of the 23 operational ASR systems in the U.S. Among these are the following:

  - Conceptual development of the Northern Monterey County ASR project, the Sonoma County Water Agency ASR demonstration project, the Raymond groundwater basin conjunctive use feasibility study, and the North Las Posas basin ASR demonstration project in California

- Senior review/technical consulting for the Centennial groundwater recharge system at Highlands Ranch in Colorado
- Evaluation of the reduction in disinfection by-products occurring during ASR storage, which led to the Las Vegas basin ASR wellhead modification project

- For the City of Cocoa, Florida, he directed a program to develop an integrated, reliable regional water supply from wellfields, a surface reservoir, and an ASR system. This included wellfield development to increase yield and reduce saline intrusion, with associated environmental impact assessment, hydrogeologic modeling, well testing, and permitting. It also included reservoir hydrologic modeling, environmental impact assessment and permitting, and development of an 8-mgd ASR system at the water treatment plant.
- Mr. Pyne was project manager for a hazardous waste study to develop alternatives for site closure and to evaluate engineering feasibility and costs for Love Canal, Niagara Falls, New York.
- For the Florida Keys, he managed the development of the wastewater facilities master plan, evaluated alternatives for the water supply master plan, and developed the world's first ASR system to store emergency drinking water supplies in a seawater aquifer. Other water supply experience includes Grand Strand Water and Sewer Authority, South Carolina; Peace River/Manasota Regional Water Supply Authority, Florida; Kerrville, Texas; Swimming River, New Jersey; and Seattle, Washington.
- Mr. Pyne has managed the development of several municipal and industrial water supply systems, including planning studies, conceptual and final design of wellfields, surface supplies and storage facilities, and construction services. Typical projects include the 60-mgd Pinellas County Water System; the 15-mgd Starkey Well Field and Wilderness Park for the West Coast Regional Water Supply Authority; and the 12-mgd water supply and ASR system for the Peace River Manasota Regional Water Supply Authority in Florida.

Membership in Professional Organizations

- **American Society of Civil Engineers (ASCE)**
  - Control Member, Ground Water Recharge Committee, Irrigation and Drainage Division, 1990-present
- **American Water Resources Association (AWRA)**
  - President, Florida Section, 1976-1977
- **American Water Works Association (AWWA)**
- **Florida Engineering Society (FES), National Society of Professional Engineers (NSPE)**
  - President, North Central Chapter, 1975-1976
  - Engineer of the Year, 1984
- **Florida Pollution Control Association (FPCA)**

- Chairman, AWWA/FPCA Joint Water Resources Committee, 1973-1976

Publications and Presentations

- *Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery.* Lewis Publishers, Boca Raton, Florida. March 1995.
- Artificial Recharge Developments in the United States. Presented at the International Conference on Groundwater. Brighton, England. February 1994.
- With P.C. Singer, Mallikarjon AVS, C.T. Miller, and C. Mojonnier. *Impact of Aquifer Storage and Recovery (ASR) on Disinfection By-Products.* Journal of the American Water Works Association. November 1993.
- With O.K. Buros. Extending Water Supplies in Water Short Areas. Presented at the International Desalination and Environmental Association Conference. Tokyo, Japan. October 1993.
- With D. Wendell. Well Injection with Reclaimed Water: Regulatory Issues and Current Experience. Presented at the Sixth Biennial Symposium on Artificial Recharge of Groundwater. Phoenix, Arizona. May 19-21, 1993.
- Aquifer Storage Recovery (ASR): Ensuring Water Supply Reliability for the Gulf Region. Presented at the Gulf Water Conference in Dubai. October 1992.
- With Andrea R. Aikin. Aquifer Storage Recovery: Recent Developments. Presented at the American Institute of Hydrology. Orlando, Florida. November 1991.
- Aquifer Storage Recovery: Some Proposed Applications in Southern California. Presented at the American Water Resources Association Symposium. San Diego, California. June 1991.
- With Herman Bouwer and James A. Goodrich. "Recharging Groundwater." Civil Engineering. June 1990.
- With A. Muniz, L. Rainger, and S. Skehan. Application of Aquifer Storage Recovery in a Brackish/Saltwater Environment. Presented at the Fourth Symposium on Artificial Recharge of Groundwater in Arizona. Tempe, Arizona. May 1989.
- Recent Developments in the Design, Testing, and Operation of Aquifer Storage Recovery (ASR) Wells. Presented at the Fourth Symposium on Artificial Recharge of Groundwater in Arizona. Tempe, Arizona. May 1989.
- With J.I. Garcia-Bengochea, G.E. Eichler, and F.A. Eidsness. Aquifer Storage Recovery: Current Status in the United States. Presented at the IWSA 17th International Water Supply Congress. Rio de Janiero, Brazil. September 1988.
- Aquifer Storage Recovery: A New Water Supply and Groundwater Recharge Alternative. Presented at the ASCE International Artificial Recharge Symposium. Anaheim, California. August 1988.

- With S. Franklin Reynolds. Recharge-Recovery: A New Alternative for Municipal Water Supply Expansion. Proceedings of the NWWA Eastern Regional Conference on Groundwater Management. Orlando, Florida. October 1983.

- With C.R. Sproul. "Drilling Through Sinkholes: A Success Story at the Jay B. Starkey Wilderness Park, Florida." Groundwater. June 1983.

- Impact of the New Florida DER Groundwater Rule from the Perspective of Consultants and Contractors. Presented at the Engineers in Government Short Course. Tampa, Florida. January 1983.

- Recharge/Recovery: A New Tool for Water Management in Florida. Presented at the Florida Water Management Seminar. January 1982.

- With C.R. Sproul. Underground Disposal of Treated Effluent and Storm Runoff. Presented at Annual Conference, ASCE. September 1976.

- With Emily W. Black and J.I. Garcia-Bengochea. Florida's Water Resources: AnEvaluation and Management Philosophy. Prepared for Pinellas County Water System, Florida. November 1975.

- With R.L. Wycoff. Urban Water Management and Coastal Wetland Protection in Collier County, Florida. Water Resources Bulletin. June 1975.

- With M.R. Vilaret. Storm and Combined Sewer Pollution Sources and Abatement. Presented at XII AIDIS Congress. Caracas, Venezuela. 1970.

Mitchell Bormack

Education

M.S., Geology, Rutgers University, 1993

B.S., Geology, Lafayette College, 1988

Professional Registrations

Professional Geologist: Pennsylvania, 1995

Distinguishing Qualifications

- Aquifer Storage and Recovery Phase One Feasibility Assessments
- Aquifer Storage and Recovery Phase Two investigations and construction
- Aquifer Storage and Recovery operation and maintenance coordination
- Aquifer Testing, Analysis, and Reporting
- Production Well, Injection Well, and ASR Well Design
- Site Characterization Program Planning and Participation
- Groundwater and soil sampling programs design
- Drilling and sampling supervision
- Test trench excavation and sampling supervision
- Expertise in UST management, removal and closure supervision
- Hazardous waste field investigations (RCRA, CERCLA, state and local)
- RI/FS Investigations and Reports
- Due Diligence Data Search Coordinations
- Groundwater Remediation Design and Operation
- Soil Vapor Remediation Design and Operation

Relevant Experience

Mitchell Bormack is a project manager and hydrogeologist in CH2M HILL's Water Group. He is experienced in managing water resource and environmental assessments for industrial, commercial, state/federal agency, and utility clients. Mr. Bormack ahs been successful in client service roles and maintaining strong client relationships when managing projects. He is experienced with interacting with regulatory agencies and case managers, including federal (USEPA), state, and local agencies.

Mr. Bormack's projects often include site characterization of soil and groundwater to determine physical and/or chemical characteristics of subsurface material. FIELD INVESTIGATION EXPERIENCE includes: test boring/Geoprobe/Hydropunch sampling programs; wireline rock and soft-sediment coring; vibratory soft-sediment coring; well installations using hollow-stem auger, direct and reverse rotary, and air drilling methods; test-trench excavations and sampling; downhole and surface geophysical surveys; air sampling; surface water and groundwater sampling; hydrofracturing; and aquifer testing including slug tests, step injection and drawdown tests, short duration (<24 hrs) and long duration (>72 hrs) pumping and injection tests.

WATER RESOURCE project experience includes: aquifer testing and analysis; production well siting and design; aquifer storage and recovery (ASR) Phase I and II feasibility analyses, injection/recovery test and operational cycles of up to greater than 200 million gallons per year, and well and pump house construction oversite; surface water/tidal fluctuation studies; groundwater and saltwater intrusion modeling; training of operators and design of Operation & Maintenance (O&M) manuals; and the permitting of production and ASR wells for allocation and Safe Drinking Water Criteria.

ENVIRONMENTAL SITE CHARACTERIZATION AND REMEDIATION project experience includes: remdedial investigations (RI) including sampling program design; feasibility studies (FS), including calculation of intrinsic remediation (no action) alternatives; remedial design and action (RD/RA) for contaminated soil and groundwater sites, including groundwater capture zone modeling; and O&M, system performance, and regulatory compliance monitoring of groundwater recovery and treatment systems, as well as home potable water treatment systems.

Project Experience

- Resident Project Inspector for production well installation for Monroe Township, New Jersey. Project elements included: test well and production well lithologic logging; downhole geophysical surveying; aquifer testing programs (step-drawdown tests, 8- and 24-hour stress tests, time-related water quality analysis; and 72-hour constant rate tests); well design and construction oversite.
- Resident Project Inspector for production well installation for Woodstown, New Jersey. Project elements included: lithologic logging; downhole geophysical surveying; aquifer testin program; water quality testing, including chloride tracking; and well design and construction oversite.

- Participated in the design, supervision, and analysis of aquifer testing investigations to predict the regional effects of a 3-mgd diversion by a proposed additional production well at NJAWC's Smithville Station. The methods of investigation included a 72-hour aquifer test and 24-hour stress test. The potential regional effects of concern included saltwater intrusion, effects on environmentally sensitive areas such as forested wetlands, effects on other groundwater users, and contamination from man-made pollution.

- Primary researcher/writer and hydrogeologist in development of "5-year environmental plans" to determine the levels of groundwater protection compliance and/or future liabilities, with respect to present and proposed/predicted local, state, and federal regulations at 11 PSE&G generating stations in New Jersey.

- Managed elements of Aquifer Storage Recovery (ASR) Programs for EveshamTownship MUA, NJAWC-Cherry Hilll, NJAWC-Swimming River, NJAWC-Aberdeen, Brick Township MUA (all in New Jersey), and Mannheim, Ontario, Canada. Program elements included: phase one feasibility assessments; detailed subsurface investigations; aquifer testing; recharge/recovery cycle testing of cycles up to 200 million gallons; ASR well and wellhouse construction oversite; existing well retrofit to ASR application; ASR facility permitting; and operator training and O&M manual preparation.

- Supervised the geologic and hydrogeologic site characterization investigations at a Superfund facility in Upper Black Eddy, Pennsylvania, the site of a former illegal hazardous waste disposalproperty. The investigation included the installation of 21 first-water monitoring wells, aquifer testing via slug tests, monitoring and sampling the wells, and the collection of approximately 500 soil samples. The site investigation involved determining the nature of hydraulic connectivity between weathered in-situ soil, saprolite/weathered bedrock, and competent fractured bedrock.

- Supervised UST closure plans, removals, tank delistings, and closure reports for at least 10 NJAWC distribution facilities in southern and northern New Jersey with tank capacities ranging from 550-gallons to greater than 10,000 gallons, in compliance with NJ UST regulations and technical guidance.

- Supervised the removal of a Cherry Hill, NJ, NJAWC distribution facility 8,000-gallon fuel oil UST, interceptor trenching activities, and ensuing soil/groundwater trench system remediation program, which included pumped groundwater recovery, activated carbon treatment, soil flushing with clean water, and enhanced soil flushing and treatment using dilute hydrogen peroxide.

- Participated in Discharge Investigation Corrective Action Report (DICAR) studies, including UST removals, post-excavation soil sampling, test borings, monitoring well installations, routine ground water monitoring sampling and the completion of routine DICAR status reports for number of NJAWC facilities in New Jersey.

- Installed water table aquifer monitoring wells and developed routine manual monitoring procedures at six NJAWC western division facilities as substitute leak detection systems for NaOH USTs in accordance with N.J.A.C. 7:14B.

- Provided technical and litigation support to Arco Products Company during litigation with PGW to determine liability levels in several-hundred-million-dollar cleanup effort at Philadelphia refinery. As primary hydrogeologist, responsibilities included review of previous consultants' reports, review of all related existing ARCO and PGW files, source(s) identification, hydrogeologic assessment, interpretation of groundwater flow and product migration pathways. Delicate handling of client service and quick responsiveness was required.

- Participated in Discharge Investigation Corrective Action Report (DICAR) studies, including UST removals, post-excavation soil sampling, test borings, monitoring well installations, routine groundwater monitoring, sampling and the completion of routine DICAR status reports for approximately 20 gasoline service stations in New Jersey, Pennsylvania and Delaware for clients including Arco, Star Enterprises, Getty, and Kirschner Brothers Company.

- Managed a PADER-directed UST project in Blakeslee, PA. The site of an operating former Arco service station, the project involved the semiannual monitoring and sampling for volatile organic compounds (VOCs) of 25 bedrock and glacial overburden wells, and the routine sampling of 20 to 30 residential and commercial potable water treatment systems to monitor the systems' effectiveness at removing VOCs and elevated levels of iron and manganese. The elevated metal levels resulted from previous consultants' attempts to enhance groundwater bio-treatment through nutrient overloading. The groundwater problem was a long-term (10 years) public nuisance, andrequired delicate handling of questions and concerns of residents, as well as local and state authority figures.

- Managed a PADER-directed monitoring and remedial design project for HARCROS Pigments in Easton, PA. Supervised the removal of a 3,000-gallon gasoline UST and coordinated the removal schedule of eight other UST's (1,500 to 12,000 gallons) with PADER. The tanks had deteriorated due to highly acidic groundwater conditions resulting from sulfuric acid used in plant operations. Designed and participated in long-term aquifer testing and product removal feasibility studies to determine most effective removal and treatment scheme of gasoline, fuel oil, and acidic aqueous phases. Participated in pump and treat design and interim product removal program.

- Designed and supervised a test boring sampling plan, in direct coordination with NJDEPE case manager, to delineate the extent and quantity of contamination and determine the need for removal of a replacement 20,000-gallon fuel oil tank and/or the remediation of surrounding soil for Carter-Wallace in East Windsor, New Jersey. The task was complicated by the fact that the original tank had leaked and already contaminated the soil to some degree.

- Supervised tank tightness testing, designed and supervised soil gas surveying for preliminary site assessment, reviewed separate phase product "fingerprinting" analyses, and reviewed available geologic boring log data at Kirschner Brothers Company Gasoline Service Stations in Williamstown and Millville, New Jersey to determine which current or historical USTs were the likely sources of gasoline separate-phase product and dissolved phase contamination and/or which current USTs needed to be removed, if any.

- Helped prepare an ECRA cleanup plan, including the design of a UST decontamination and closure plan for several USTs at a Getty facility in Piscataway, NJ.

- Project manager for Operation & Maintenance of pump and treat system at Croydon TCE site. System consists of 6 groundwater extraction wells pumping 100 gpm to air stripper system with gas activated carbon treatment of off-gas. Weekly, monthly, and quarterly monitoring data is used to evaluate groundwater quality, system capture zone effectiveness, system air/water treatment effectiveness, and effluent regulatory limit compliance.

- Project manager for oversite of Ohio River remedial action feasibilty studies and natural attenuation evaluations. Soil and groundwater contamination remedial investigations and fate/transport studies led to a feasibility study and a potential remdial action plan that evaluated groundwater cleanup scenarios ranging from no action to a $40 million cleanup involving soil capping and long-term pump and treat. The demonstrations indicated that natural attenuation, coupled with source capping should prevent migration of hazardous substances resulting from buried coke waste product. Although ground water wihtin 1,000 feet of the site contaminant plume in the same aquifer is drawn by the Coraopolis municipal wellfield, natural attenuation has been selected as the groundwater remedy and will be monitoried for effectiveness.

- Conducted a hydrogeologic assessment and participated in various aspects in the submission of a RCRA Subpart X permit application for Hercules, Inc., an explosives manufacturer in Kenvil, New Jersey, attempting to obtain a permit for open burning on site grounds. Field investigations included oversite and logging of 4 50-100 ft soil borings through glacial outwash material to bedrock and aquifer testing of existing monitoring wells via short duration (several hours) stress tests and slug tests.

- Conducted, 24-hour aquifer pumping tests in Wissahickon Formation bedrock to determine aquifer characteristics and pump and treat remedial feasibility and design for a former Kirschner Bros. gasoline service station in Philadelphia, PA. Participated in the design, construction, and operation/maintenance of the pump and treat system.

- Led all field investigations and was principal report writer for PRP-led Remedial Investigation of a former FMC facility (NPL site) in Marcus Hook, Pennsylvania. Field investigations included site characterization via installation of 15 monitoring wells, excavation of approximately 100 test pits and trenches, surface water sampling groundwater sampling of 25 monitoring points, and collection of more than 200 soil and fill material samples.

- Supervised the installation of over 50 soil borings for PCB-contaminated soil delineation at a former Monsanto facility in Yardville, NJ.

- Acted as field team leader and report writer for on RIFS study of a Superfund facility in Bridgeport, NJ, the site of a former waste lagoon. Field responsibilities included oversite of geophysical logging of several 160-300 ft. borings, installation of 8 75-200 ft. monitoring wells, aquifer testing via slug tests, and lagoon sediment sampling via several collection methods in levels B and C personal protective equipment.

- Conducted aquifer testing via slug tests, at several former Arco facilities in Pennsylvania, New Jersey, and Delaware to determine aquifer characteristics and assess the feasibility of remedial alternatives such as pump and treat, interceptor trenching, soil vapor extraction, and stabilization.

Membership in Professional Organizations

- Association of Groundwater Scientists and Engineers (National
- Groundwater Association)

Publications and Presentations

Mr. Bormack has contributed to presentations and led a field trip on structural geologic studies of the Southeastern Pennsylvania Piedmont Region. His undergraduate thesis topic and continued area of study is the transpressional origin and rheologic modeling of a large dome structure in the Southeastern Pennsylvania Piedmont. A complete list is available upon request.

Mark C. Lucas

Education

M.S., Geology, Rutgers University

B.S., Geology, Rutgers University

Professional Registrations

- Professional Geologist: Arkansas, Indiana, Delaware, Tennessee, Wyoming, Pennsylvania

Distinguishing Qualifications

- More than 12 years experience as a geologist working on hazardous waste, water resources, and energy (petroleum, uranium, coal, etc.) exploration projects.
- Served as a field task or field team leader on more than 15 Superfund sites involving remedial investigation, remedial action and remedial design activities.
- Served as project geologist on seven Aquifer Storage and Recovery (ASR) projects conducting the initial feasibility study, construction and testing of the ASR facility, and final permitting of an operational facility.
- Aided in the design and implementation of three pump and treatment systems intended to hydraulically control and remediate contaminated groundwater at industrial and Superfund sites.
- Five years experience as a geophysicist specializing in surface and borehole techniques for water resources, petroleum, and mining applications.

Relevant Experience

Mr. Lucas is a hydrogeologist and project manager in CH2M HILL's Philadelphia office. He has responsibility for projects relating to hydrogeologic investigations, groundwater contamination, hazardous site assessments, aquifer storage and recovery studies, analytical and numerical modeling for capture zone analysis, geochemical modeling, and surface and borehole geophysical surveys.

Mr. Lucas has numerous years of experience in conducting investigations at hazardous waste sites. He has participated in and supervised field activities such as boring and well drilling, soil, air, drum, tank and groundwater sampling, and various aquifer tests. Mr. Lucas has conducted a number of geophysical investigations involving electromagnetic, seismic, gravity, and ground penetrating radar techniques to define and delimit groundwater contamination. Mr. Lucas has conducted a number of geotechnical investigations to design the installation of interception trenches, pilings, and retaining walls. In addition, Mr. Lucas has been involved in studies to site supply wells in rock aquifers.

Project Experience

- Conducted constant-rate aquifer and step-drawdown tests on 15 wells that supply the Big Vanilla Ski Resort at Fallsburg, New York.
- Performed hydrogeological services for a feasibility study for ASR in the vicinity of the Swimming River Reservoir (SRR) and a Phase Two Field Investigation to confirm ASR feasibility in a prototype ASR well.
- Performed a capture zone-type analytical modeling study of Brick Township MUA's Potomac-Raritan-Magothy (PRM) aquifer wellfield to determine the effect of proximal intermittent pumping on an ASR recharge water storage bubble.
- Performed hydrogeologic services as part of a preliminary feasibility assessment to analyze existing information on the hydrogeology, aquifer water quality, aquifer lithologic composition, and aquifer parameters to design Phase II ASR test programs for Brick Township Municipal Utilities Authority, Toms River Water Company, and New Jersey-American Water Company's Haddon system at their Murray Avenue and Devonshire facilities.
- Designed the subsurface portion of the ASR recharge/recovery wells at New Jersey-American Water Company's Murray Avenue and Devonshire facilities, and Evesham Township's Kings Grant facility.
- Project hydrogeologist for a preliminary feasibility assessment for the Evesham, New Jersey, MUA to obtain existing information about the hydrogeology, aquifer water quality, treated water quality, aquifermaterial composition, and related information from federal and state agencies, drillers, and Evesham MUA files to assess the feasibility of a comprehensive ASR assessment and testing program.
- Conducted a feasibility study of transforming a 30-acre wetland into an artificial recharge basin with induced recharge through wells for the Monroe Township MUA.
- Project Manager for Aquifer Test Program at United Water Toms River (UWTR) well 44. Well 44 is installed in Cohanse/Aquifer that is subject to contamination from two nearby superfund sites. Aided UWTR in difficult permitting negotiations with the state of New Jersey.
- Project Manager for Investigation of Sudden Increase in iron and manganese in City of Newark, Delaware's production wells. Developed integrated model and explanation for elevated iron and manganese concentrations and wellfield management plan to preclude recurrance.
- Site manager, project hydrogeologist, and field task leader on numerous EPA and NJDEPE-lead Superfund sites, including:
  - BROS Site, Bridgeport, New Jersey

- American Thermistor, Catskill, New York
- Florence Municipal Landfill, Florence, New Jersey
- Boarhead Farms, Black Eddy, Pennsylvania
- Sayreville Municipal Landfill, Sayreville, New Jersey
- Lipari Landfill, Pitman, New Jersey
- Swope Oil Company, Pennsauken, New Jersey
- Ludlow Municipal Landfill, Utica, New York
- Fisher-Calo Chemical Reclamation Site, LaPorte, Indiana
- Higgins Farm, Rocky Hill, New Jersey
- Raymark, Hatboro, Pennsylvania
- North Penn Area 5, Lansdale, Pennsylvania
- Malvern TCE Site, Malvern, Pennsylvania
- Metro-Mirror Site, Frackeville, Pennsylvania

- Project geologist on numerous projects for industrial clients involved with RCRA, ECRA, and NPDES compliance.
- Field team leader for confirmation sampling of remedial excavation at the Bridgeport Rental and Oil Services site lagoon.
- Supervised installation and testing of a groundwater pump-and-treat system at General Chemical's sulphuric acid plant in Claymont, Delaware, to remediate a sulphuric acid spill.
- Helped design a pump-and-treat groundwater recovery for the surficial aquifer at the Ludlow site, which is situated in a complex supraglacial terrain.
- Conducted a 72-hour injection test at Lipari Landfill to determine the volume of leakage through the liner and surrounding slurry walls.
- Conducted a 24-hour multiple well aquifer test at the Raymark site to estimate the effectiveness of a pump-and-treat system.
- Served on two projects to site industrial and municipal wells in bedrock aquifers, which required extensive remote sensing analysis, aquifer testing, and field mapping.
- Served as site hydrogeologist, performing monitor well installation, geophysical surveys (EM-31, EM-34, microgravity, ground penetrative radar, and borehole logging), radioactive tracer testing, aquifer testing, and field mapping (joint study) for the Merck, Sharp, and Dohme pharmaceutical firm in Barceloneta, Puerto Rico.
- Drafted initial and negative declaration submissions for ECRA.
- Designed monitor well networks and written draft permits for NPDES and NJDES compliance.

- Helped conduct a study for the Toms River Water Company to identify potential contaminant sources in the Jakes Branch watershed, assess the possibility of those contaminants being released into the stream by estimating transport routes, and describe the potential for movement of those contaminants along the stream to the South Toms River Wellfield.

- Provided hydrogeologic assistance on a project to identify potential contaminant sources in the Davenport Branch watershed, assess the likelihood of those contaminants being released into the stream byidentifying potential transport routes, and describe the potential for movement of those contaminants along the stream to the Berkeley Wellfield.

- Site Manager for Remedial Investigation and Feasibility Study (RI/FS) at Malvern TeE Superfund site. Part of EPA's ARCS III Program, RI/FS activities include field investigation (soil sampling, monitor well installation, aquifer testing, etc.), feasibility study (alternatives screening, alternatives evaluation and alternative selection) and risk assessment. Over 20 residential and public supply wells proximal to site have been contaminated with TeE.

- Performed site geology and geophysical borehole logging in the petroleum and mining industries, including the generation, analysis, and interpretation of geophysical borehole data for petroleum and minerals (uranium, coal, metals) exploration; and petroleum production logging and pipe recovery operations.

- Supervised drilling and coring operations on a number of uranium and coal exploration projects.

- Consultant to a number of petroleum companies during their field studies of lacustrine rocks and tectonism of the Newark Basin in New Jersey and Pennsylvania.

- Managed an evaluation of the existing environmental documentation for two partially completed nuclear power plants that will examine recent Nuclear Regulatory Commission policies and other federal and state legislation to determine if the existing environmental documents can be completed quickly enough to support a decision to resume construction.

- Evaluate potential for Saltwater Instrusion at wetlands restoration sites in southern New Jersey. Client is trading wetland mitigation acreage and creating saltwater wetlands to compensate for continuing fish kills at power plant intake.

Publications and Presentations

- Mr. Lucas has contributed to articles and presentations on mesozoic rift basin structures and foreland-type folding.

- With W. Manspeizer. "Mesozoic Rift Basin Structures, Reading to Pottstown, Pennsylvania." Sedimentology and Thermal-Mechanical History of Basins in the Central Appalachian Orogen. 28th International Geological Congress, Field Trip Guidebook T152. 1989.

- With W. Manspeizer. "Mesozoic Rift Basin Deposits Along the Delaware River, Stockton to Milford, New Jersey." Sedimentology and Thermal-Mechanical History of Basins in the Central Appalachian Orogen. 28th International Geological Congress Field Trip Guidebook T152. 1989.

- With W. Manspeizer and J. Hull. "Foreland Type Folding In the Newark Basin." Triassic-Jurassic Rifting: Continental Breakup and the Origin of the Atlantic Ocean and Passive Margins. Elsevier, 1988.
- With W. Manspeizer and J. Hull. "En Echelon Folds: A Case History of Foreland Type Folding from the Jacksonwald Syncline in the Newark Rift Basins of Eastern North America." Presented at the AAPG Eastern Section Meeting, Williamsburg, Virginia, November 6, 1985.
- With K. McGill and R. Glanzman, "Controlling Iron Concentrations in the Recovered Water from Aquifer Storage and Recovery (ASR) Wells". Proceedings of Second International Symposium on Artificial Recharge of Groundwater, ASCE, 1994.
- With J.P. Dugandzic and K. McGill, "Using pH Adjustment to Control Iron Concentrations in the Recovered Water from Aquifer Storage and Recovery (ASR) Wells. Proceedings of International Groundwater Management Symposium, ASCE, 1995.
- With J.P. Dugandzic and K. McGill, "Adjustment of pH to Control Iron and Manganese Concentrations from Aquifer Storage and Recovery (ASR) Wells. Proceedings of American Water Resources Association Conference, AWRA, 1995.

Membership in Professional Organizations

- American Institute of Professional Geologists
- American Association of Petroleum Geologists
- Geological Society of America
- Geological Association of New Jersey
- National Water Well Association

Honors and Awards

- W.W. Wiles Award for Distinguished Field Studies as a Graduate Student in Geology, Rutgers University, 1984.
- CH2M HILL Office of Innovation Award for Pretreatment of PRM Aquifer as part of Swimming River Aquifer Storage and Recovery (ASR) Test Program, 1992.

geochemical and mineralogical problems associated with heap leach recovery of gold from these deposits.

He was the project manager of a clay minerals program with the U.S. Geological Survey that involved the geochemistry of lithium. The physicochemical paths for the formation, preservation, and alteration of clay minerals in all environments (intense differences in chemical, pressure, temperature, and salinity) were defined along with their stability, fluid-retaining and permeability-reducing characteristics that make them suitable for use as hydrologic barriers.

Mr. Glanzman has a key role in the evaluation of geochemical reactions involved in hazardous wastes, water supply systems, and aquifer recharge. Mr. Glanzman uses both field and computer-based (thermodynamic) models such as PHREEQE, MINTEQ, WATEQ, and the EQ3NR/EQ6 to evaluate potential inorganic geochemical reactions within the hydrologic system. He has applied these and reviewed other geochemical methods to evaluate hazardous waste fate and transport at sites related to metals (California Gulch, Colorado; Cherokee County, Kansas; Silver Bow Creek and East Helena sites, Montana), solvents (South Valley site, New Mexico; Des Moines, Iowa), radioactivity (Paducah, Kentucky; Rocky Flats, Colorado), and landfills (OII, California; IWC, Arkansas; Lowry, Colorado). In addition to the Superfund sites, he has worked with many private industry clients involving hazardous wastes in air, water, and many forms of solids.

Mr. Glanzman developed geochemical programs to evaluate the distribution and future concentration of major ions and dissolved metals (specifically arsenic) in a master plan for the groundwater drinking water supply of a major western city. This involved the application of several innovative field methods for both geohydrological and geochemical techniques. Appropriate groundwater sampling and monitoring methodology is critical to an understanding of the groundwater system, particularly to predict the water chemistry of drinking water 10 to 20 years in the future.

Mr. Glanzman has developed and applied several analytical techniques at the field site, generally considered laboratory techniques, to expedite the nature and extent determination of both natural and synthetic chemical elements, compounds, and minerals. X-ray fluorescence (XRF), infrared (IR), and soil gas techniques have been developed for application at field sites. Field portable XRF can be used to both screen and analyze the total metals concentration at the field site. IR can determine the presence and amount of organics as well as the types and relative proportion of clay minerals. Soil gas can determine the presence and amount of organic and inorganic gases at a site that can be used to distinguish between natural and anthropogenic sources.

Mr. Glanzman has a key role in evaluating the geochemical reactions involved in recharge and aquifer storage retrieval. He developed an initial screening analysis that forms a basis for judging geochemical reaction potential between the recharge water and the in situ groundwater at many recharge sites across the United States (Tucson, Arizona; Myrtle Beach, South Carolina; Kerrville, Texas; Chesapeake, West Virginia; Swimming River, New Jersey; Seattle, Washington; and Los Posas, California). This initial evaluation is a fatal flaw analysis of existing physical, chemical, and biological data for the site or area. From this analysis, specific tests are designed to address the potential problems. His experience in geochemical processes (organic, inorganic, and biological) and clay mineralogy is particularly applicable to the development of a successful recharge project.

In addition to equilibrium geochemical conditions involving concentration, pH, oxidation-reduction potential, complexing, ion-exchange, and adsorption, Mr. Glanzman includes volatilization, kinetics, and the role of microbiota in evaluating the nature/extent and fate/transport of geochemical phases involving most media. Both aqueous and vapor phase isotope evaluations have been applied to separate natural and anthropogenic sources. Quality assurance and control involves the application of both parametric/nonparametric statistical techniques and geostatistical techniques. Basic statistical functions are typically applied. However, other tests that are appropriate for specific applications include discriminate function analysis, several types of cluster analysis, principle components analysis, and factor analysis. Geostatistics provides an effective technique to objectively and quantitatively determine the most effective and efficient sample density of physical and chemical parameters in three-dimensional multimedia.

Several levels of remote sensing have been applied by Mr. Glanzman to the physical and geochemical characterization of areas and sites. Relatively inexpensive, rapid, and highly sophisticated computer processing techniques have been developed that can be used to define not only the present surficial conditions but also surficial conditions since the early 1970s through Landsat imagery. Recent improvements in spectroscopy allow fixed-wing imagery that allows the identification, relative quantification, and mapping of such surficial properties as expandable clay and nonexpandable clay, oxidizing sulfide minerals, and geological structures that control groundwater movement on a 10- to 20-foot scale.

Project Experience

- Mr. Glanzman oversaw Superfund work on the Cal Gulch, Asarco, IWC, and UNC sites. Cal Gulch is a mine tailings water resource Superfund site at Leadville, Colorado. Leadville is a historic silver-rich base metal sulfide mining community built adjacent to mine tailings being oxidized and leached. The Asarco site is a smelter site near Helena, Montana. IWC is a closed industrial waste landfill established in a coal strip mine area near Fort Smith, Arkansas. UNC is a mine tailing site adjacent to a uranium milling facility near Church Rock, New Mexico.

- Mr. Glanzman, working with the U.S. Bureau of Mines, evaluated techniques for the measurement and removal of radon gas from the mine and industrial environment. His work involved the definition of gas transport, physicochemical interaction between groundwater under unsaturated and saturated conditions, and in both porous media and fracture flow. A position paper on health physics of radon gas was produced and test environments were established for the assessment of removal methods.

- Mr. Glanzman worked with the manager of a project involving the fate, transport, and remedial alternative development for an elemental mercury contamination of groundwater in Eastern Europe. Geochemical speciation of mercury evolved from the elemental mercury and increased the mercury mobility. These forms included both inorganic complexing with other dissolved ions and organic biotransformed mercury complexes. The mobility of mercury was increased by its ability to form both liquid and vapor forms.

- Mr. Glanzman is responsible for a series of reports on the geochemistry of arsenic in groundwater for a major city in the southwestern United States. Arsenic hydrogeochemistry describes how arsenic moves in the groundwater system, parameters that both increase and decrease its mobility, and case histories of arsenic problems in groundwater. Reports on the analytical methods for the reliable determination of dissolved and total arsenic concentration and speciation in groundwater, water reservoirs, spatial and temporal trends in the groundwater system, identification of problem areas, long-term monitoring program, and the development of methods to treat the water to control and remove arsenic were prepared. He developed an aquifer treatment alternative in which the groundwater is conditioned in the aquifer to immobilize the arsenic.

- Areal groundwater studies were conducted by Mr. Glanzman working with the Water Resources Division of the U.S. Geological Survey. Areal studies in Colorado included the evaluation of groundwater/surface water relationships in the San Luis Valley, sandstone aquifers in Baca and Prowers Counties, groundwater in fractured oil shale of the Piceance Basin, and an evaluation of an extensive soil and stream sediment erosion abatement system near Kiowa. A groundwater sampling grid was established to monitor groundwater chemistry in eastern Colorado. Multiphase fluid flow and the impact of gases on both the chemistry and hydraulic characteristics of groundwater were evaluated in essentially all projects. Work in Utah involved the collection, analysis, and interpretation of the water chemistry of surface and groundwater. Work included stream sediment measurements and calculations.

- Mr. Glanzman worked with the Water Resources Division of the U.S. Geological Survey on areal studies in Colorado and Utah. Areal studies in Colorado included the interaction of multiple aquifers with surface water in the San Luis Valley, sandstone aquifers of Baca and Powers Counties, groundwater in the fractured oil shale of the Piceance Basin, and an evaluation of an intensive soil erosion abatement system near Kiowa. Work in Utah involved the collection, analysis, and interpretation of the water chemistry of brines and groundwater in the Eastern Basin and Range Province.

- Mr. Glanzman developed a soil gas technique to evaluate and discriminate massive sulfide geophysical anomalies. The field technique involves driving a probe into the soil, extracting the soil gas, and analyzing the organic and inorganic gases by field-portable gas chromatography. The technique is capable of processing 100 samples through interpretation in a 24-hour period. The technique successfully discriminates organic from organosulfide and massive sulfide geophysical conductors. Tested environments ranged from poorly developed soils in the arid southwest (Utah, Arizona, New Mexico, and Colorado) to the well developed, commonly marshy, soils in the midwest and eastern seaboard of both the United States and Canada.

- In addition to the application of statistical techniques to quality assurance and control, Mr. Glanzman utilized statistics to more accurately define and discriminate geochemical anomalies. Basic statistical functions and tests included discriminate function analysis, several types of cluster analysis, factor analysis, and kriging. The geostatistical technique, kriging, was successfully applied to analyze and interpret three-dimensional multimedia (soil, vegetation, stream sediment, rock, drill cuttings, and remote sensing) sample data. Kriging is an effective technique to quantitatively determine the most efficient and effective sample density to define physical and chemical parameters.

- Mr. Glanzman was a radiation safety officer for three years preceding his employment with CH2M HILL. He worked with the geochemistry of natural decay products of both uranium and thorium. The mobility, fate, and transport of radionuclides was investigated in environments that ranged from ambient to 500 degrees celsius and included solid, liquid, and gaseous phases of both organic and inorganic types. Mr. Glanzman has 5 years of experience focused on the radioactive gases in subsurface environments. Transport experience includes multiphase fluid flow, interaction with other stable gases and organics, and controls on the release of radioactive gases and their products to the environment.

- Before joining CH2M HILL, Mr. Glanzman was Division Geochemist for a major oil company. His responsibilities included counseling and advising management and professionals in the use and interpretation of geochemical techniques applied to both domestic and foreign operations. He identified, developed, and applied new technologies for field site geochemistry and mineralogy. He developed and maintained quality assurance and control programs and procedures for analytical data from commercial laboratories.
- Mr. Glanzman's experience before joining CH2M HILL includes his work as project manager of a clay minerals program with the U.S. Geological Survey. The project involved the smectite-type clays, including bentonite, and their particular fluid-retaining and permeability-reducing characteristics that make them suitable for use in hydrologic barriers. The work defined chemical and physical paths for the development of clay minerals in sedimentary, igneous, and hydrothermal environments. He has extensive experience with clay mineral response to intense environmental, particularly chemical, conditions of high pressure, temperatures, and salinity.

Membership in Professional Organizations

- **American Association for the Advancement of Science**
- **Association of Exploration Geochemists**
    - Councilor
- **Clay Mineral Society**
- **Colorado Groundwater Association**
- **Denver Region Exploration Geologists Society**
    - President
- **Geochemical Society**
- **Geological Society of America**
- **National Water Well Association**

Publications

- Mr. Glanzman is the author of 29 publications dealing with geochemistry, hydrology, and geology. The following are several pertinent publications.

- With Dumeyer, R.K. and J.M. Klein. *Chemical Quality of Water in the San Luis Valley, Colorado.* Colorado Water Conservation Board. 1970. 43 p.
- With Coffin, D.L. and F.A. Welder. *Geohydrology of the Piceance Creek Basin between the White and Colorado Rivers, Colorado. U.S. Geological Survey Hydrologic Investigations Atlas HA370.* 1969.
- With Coffin, D.L., F.A. Welder, and X.W. Dutton. *Geohydrologic Data from the Piceance Creek Basin between White and Colorado River, Northwestern Colorado.* Colorado State Circular No. 12. 1968. 38 p.
- With Mason, M. Analytical Data Reliability. Presented at the American Institute of Mining Engineers Meeting, Atlanta, Georgia. 1983.
- With Lindsey, D.A., C.W. Naeser, and D.J. Nichols. Upper Oligocene Evaporites in Basin Fill of Sevier Desert Region, Western Utah. *Bulletin of the American Association of Petroleum Geologists.* Vol. 65, No. 2. 1981. Pp. 251-283.
- With Leach, D.H., and K.P. Puchlik. Geochemical Exploration for Uranium in Playas. *Journal of Geochemical Exploration.* Vol. 13. 1980. Pp. 251-283.
- With Asher, Bolinder, S. and J.R. Davis. *Chemistry of Groundwater from Test Holes Drilled in Esmeralda and Nye Counties, Nevada. U.S. Geological Survey Open-File Report 80-672.* 1980. p. 31.
- With Rytuba, J.J. *Zeolite-Clay Mineral Zonation of Volcani-clastic Sediments within the McDermitt Caldera Complex of Nevada and Oregon. U.S. Geological Survey Open-File Report 79-1668.* 1979. p. 25.
- With Taylor, M.E. *Implications of Evaporites in the Upper Cambrian-Lower Ordovician Notch Peak Formation, Southern House Range, Western Utah. U.S. Geological Survey Open-File Report 79-1428.* 1979.
- With Rytuba, J.J. Relation of Mercury, Uranium, and Lithium Deposits to the McDermitt Caldera Complex, Nevada, Oregon. *Mineral Deposits of Western North America.* J.D. Ridge, ed. Nevada Bureau of Mines of Geology Report 33. 1979.
- With Rytuba, J.J. and W.K. Conrad. Uranium, Thorium, and Mercury Distribution through the Evolution of the McDermitt Caldera Complex. *Basin and Range Symposium of the Rocky Mountain Association of Geologists and Utah Geological Association.* 1979. Pp. 405-412.
- With Otton, J.K. Geochemical Association of Lithium and Uranium. Abstract in *Exploration Geochemistry in the Basin and Range Province, Tuscon, Arizona, Program and Abstracts.* 1979. p. 17.
- With Rytuba, J.J., and W.K. Conrad. Uranium, Thorium, Mer-cury, and Lithium Distribution through the Evolution of the McDermitt Caldera Complex. *U.S. Geological Survey Open-File Report 79-542.* 1979. p. 27.
- With Meier, A.L. Preliminary Report on Samples Collected During Lithium Reconnaissance Studies in Utah and Idaho. *U.S. Geological Survey Open-File Report 79-279.* 1979. p. 52.

- With Brenner-Tourtelot, E.F. Lithium-bearing Rocks of the Horse Spring Formation, Clark County, Nevada. *Energy*. Vol. 3, No. 3. 1978. Pp. 255-262.

- With Rytuba, J.J. Relation of Mercury, Uranium, and Lithium Deposits to the McDermitt Caldera Complex, Nevada-Oregon. *U.S. Geological Survey Open-File Report 78-926*. 1978. p. 19.

- With Rytuba, J.J., and J.H. McCarthy, Jr. Lithium in the McDermitt Caldera, Nevada and Oregon. *Energy*. Vol. 3, No. 3. 1978. 347-353.

- With Rytuba, J.J., and J.H. McCarthy, Jr. Diagenetic and Hydrothermal Alteration and Trace Element Distribution in Tuffaceous Sediments within the McDermitt Caldera, Nevada-Oregon. *Geological Society of America, Abstracts with Pro-grams*. Vol. 9, No. 7. 1977. p. 1151.

- Geochemical and mineralogical Comparison of Surficial Materials in the Great Salt Lake Desert, Pilot Valley and Sevier Lake, Utah. *Proceedings from the International Conference on Desertic Terminal Lakes; Weber State College, May 2-5, 1977, Utah Water Research Laboratory, Utah State University Logan*. Greer, Deon C., ed. Pp. 183-196.

- With Meier, A.L. Lithium Brines associated with Nonmarine Evaporites. *Lithium Resources and Requirements by the Year 2000: U.S. Geological Survey Professional Paper 1005*. 1976. Pp. 88-92.

- With Davis, J.R. et al. Lithium and Future Energy. *Geological Society of America, Abstracts with Programs*. Vol. 7, No. 2. 1975. Pp. 157-158.

- With Vine, J.D. et al. Are Lithium-Rich Sedimentary Rocks and Brines Related to Tectonic Activity? *9th International Sedimentological Contress, Nice, France, Theme 9, La Sedi-mentologie et al geologic economiques; les gisements sedimen-taires*. 1975. Pp. 105-110.

- With Vine, J.D. et al. Geochemical Prospecting for Lithium. *Geological Society of America, Abstracts with Programs*. Vol. 7, No. 5. 1979. Pp. 608-609.

- Configuration of the Precambrian Surface of Colorado, Part 10 of Figure 1. *The Mountain Geologist: Rocky Mountain Association of Geologists, Denver, Colorado*. Vol. 6, No. 4. 1968. p. 194.

- With Richards, D.B. and L.A. Hershey. *Hydrogeologic Data from Baca and Southern Prowers Counties, Colorado. Colorado State Basic Data Release 19.* 1968. 123 p.

- With Brennan, R. Groundwater observations and sedimentation sections. *Watershed Program Evaluation, Kiowa Creek Water-shed, Colorado.* Soil Conservation Service, Economic Research Service, and U.S. Department of Agriculture for the U.S. Geological Survey. 1967. Pp. 1930.

Robert A. Bergman

Education

M.S., Civil Engineering, University of Illinois

B.S., Civil Engineering, University of Illinois

Professional Registrations

- Professional Engineer: New Jersey, Florida, California, Arizona, Illinois

Distinguishing Qualifications

- More than 25 years of water treatment experience
- Internationally recognized specialist in membrane technologies
- CH2M HILL's membrane treatment technical director
- Chairman of American Water Works Association Water Resources Division

Relevant Experience

With a professional background encompassing many areas of technical knowledge gained through more than 25 years of engineering in water treatment, Mr. Bergman has been responsible for projects involving equipment design and construction, engineering management, water utility operation, and research. He is CH2M HILL's technical director for membrane treatment and has specialized in membrane technologies for 20 years.

Project Experience

- Mr. Bergman was the project manager and process engineering designer and currently is the project manager for engineering services during construction for two seawater reverse osmosis (RO) membrane plants for the Florida Keys Aqueduct Authority (FKAA). The two plants total 3 mgd capacity and will be used as an emergency water supply source for FKAA. Major renovations and improvements to an existing RO plant on Stock Island include a new three-story building to house the process equipment and creation of an emergency operations center for FKAA. On Marathon an abandoned "old Navy Pump Station" is being renovated and expanded to house RO equipment which is being relocated from the existing RO plant on Stock Island. The existing 600 horsepower RO feed pumps are being modified to be driven by new diesel-engine and right-angle drives. The plants are scheduled to be operational in the Fall of 1998.

- Mr. Bergman was the senior process engineer for design of a 8-mgd reverse osmosis system treating NW River water and a 4-mgd brackish groundwater RO facility for the City of Chesapeake, Virginia. He also was the technical advisor for a pilot testing program prior to the plant design. The raw surface water has widely varying characteristics, with TDS ranging from less than 50 mg/L to approximately 3,000 mg/L and temperatures ranging seasonally from 1 to 32 degrees centigrade and the groundwater has a TDS of up to 8,000 mg/L. The plant is under construction and is scheduled to be operational in mid-1998.

- Mr. Bergman also has completed a preliminary process design for a 10-mgd nanofiltration (NF) membrane water treatment facility at another site for the City of Chesapeake, which will treat highly-colored, organics-laden, acidic drainage water from a swamp sometime in the future.

- For Cooper City, Florida, he was the membrane process engineer for the design of a 3-mgd (expandable to 6-mgd) membrane softening water treatment plant (WTP). The plant is designed to treat a relatively hard, colored ground water having high iron concentration. The plant is currently under construction.

- For the North Slope Borough in Alaska, Mr. Bergman was the membrane process designer for microfiltration (MF)/nanofiltration (NF) dual-membrane plants for water supply for six remotely-located villages. The plants are designed to produce a year's supply of potable water during a six-week operating period when the raw water supply source is thawed and available. Three plants are designed with a finished water capacity of about 250,000 gpd and three are smaller, with 95,000 gpd capacity each. Construction of the first of six plants is scheduled for completion by the Fall of 1997.

- Mr. Bergman was project manager for the design of a new 4-mgd nanofiltration (NF) membrane water treatment plant for water softening, color, and organics (DBP formation potential) removal for the City of Boynton Beach, Florida. Furthermore, Mr. Bergman designed a 4-mgd expansion to the plant, which will, when construction is complete in 1998, bring the total plant capacity to 8 mgd. Previously, Mr. Bergman prepared a water and wastewater master plan and managed the design of modifications and improvements for the city's existing 20-mgd lime softening plant.

- As part of he program management team, Mr. Bergman is currently the membrane process technical advisor for the North Advanced Water Reclamation Facility for Gwinnett County, Georgia. The project includes pilot testing of microfiltration and ultrafiltration as pretreatment for nanofiltration treating secondary wastewater effluent to meet stringent water quality discharge goals.
- For the Englewood Water District in Englewood, Florida, Mr. Bergman developed and managed a RO membrane characterization pilot test program involving seven different RO membrane types for the expansion of an existing 0.5 mgd brackish water RO plant. He also managed the design of the first 1.0-mgd expansion incorporating site-specific design criteria for each membrane type that was allowed to be bid based on the piloting test results. Furthermore, he was responsible for the process design of the second 1.0-mgd expansion to the plant and emergency generator system and building.
- Mr. Bergman was project manager for an operation and maintenance review study for the U.S. Bureau of Reclamation's Yuma Desalting Plant (YDP) in Yuma, Arizona. The study, which was completed in 1993, developed recommendations to improve operating efficiencies and reduce costs for the water desalting plant. With a 72-million-gallon-per-day (mgd) design capacity, the YDP is the world's largest reverse osmosis plant and includes a 100-mgd lime softening pretreatment facility. Prior to joining CH2M HILL, he was the senior pretreatment engineer for a consulting firm operating the test facility and was responsible for conducting and analyzing test programs developing design criteria for the YDP.
- Mr. Bergman designed and was responsible for an RO and electrodialysis reversal (EDR) membrane pilot test program at Lake Texoma, Texas. He then was senior process engineer for the design of the 7.5-mgd full-scale facility.
- Mr. Bergman provided process design for a 5-mgd RO system for treating municipal wastewater for use as injection water to a seawater intrusion barrier for the West Basin Municipal Water District in southern California.
- For the Barrow Utilities and Electric Cooperative, Inc. (BUECI) in Barrow, Alaska, Mr. Bergman provided an operations review for an existing surface water RO treatment plant. He also was the senior process engineer for bench testing candidate nanofiltration membranes and for the design of a microfiltration and nanofiltration system which will operate in parallel with existing RO system.
- For the University of Alabama at Birmingham (UAB), he designed direct-feed high purity water systems and acid concentrate supply facilities for dialysis water supply at two remote hemodialysis treatment centers. Treatment processes included granular activated carbon (GAC) filters, ion exchange softeners, cartridge filters, reverse osmosis systems, mixed-bed deionizers, and submicron filters.
- Mr. Bergman was responsible for the reverse osmosis and nanofiltration membrane testing for water reuse at the Hookers Point Advanced Wastewater Treatment Plant (WWTP) in Tampa, Florida. The test program included parallel testing of GAC and membrane treatment following aeration, two-stage high-pH lime treatment with recarbonation, and filtration and included extensive health effects laboratory investigations.

- He was a senior technical advisor for a bench and pilot test program evaluating microfiltration (MF) and ultrafiltration (UF) as a pretreatment to reverse osmosis (RO) membranes for treating secondary wastewater effluent to meet stringent phosphorus and nitrogen discharge requirements for the Reedy Creek Improvement District in central Florida. Mr. Bergman was the lead process design engineer for a turnkey 200,000 gpd reverse osmosis water treatment plant for TDS and pesticide removal for Turkmenistan in Central Asia. All treatment process equipment and buildings were designed on a fast-track basis and shipped to the site for construction.

- Mr. Bergman was senior consultant for pilot testing and the subsequent design of two RO plants with a total combined capacity of 4.5 mgd for Mount Pleasant Waterworks and Sewer Commission.

- He has prepared a conceptual design report for the State of Hawaii for a 1.0-mgd demonstration desalting plant using electrodialysis (ED) and reverse osmosis (RO) technologies treating two high-silica groundwater supplies.

- He has also provided troubleshooting services to a major synthetic fuels manufacturer in North Dakota for their 1.7-mgd RO system.

- He has designed several membrane pilot test systems, including the CH2M HILL membrane pilot plant for ultrafiltration (UF), NF, and RO technology testing.

- Mr. Bergman managed an RO pilot test program for Fort Pierce Utilities Authority, Fort Pierce, Florida, for a new 3-mgd initial construction phase WTP (15-mgd ultimate capacity).

- He has conducted several desalting feasibility studies. For South Carolina utilities, studies were conducted for the Grand Strand Water and Sewage Authority near Myrtle Beach, Mount Pleasant Waterworks and Sewer Commission (MPWSC) near Charleston, and the City of Summerville. He also conducted an RO feasibility study for the City of Cocoa, Florida.

- Mr. Bergman was project manager for the design of improvements (conversion to lime softening) for the City of Delray Beach, Florida, 23-mgd water treatment plant. The facility improvements included new lime, chlorine, and carbon dioxide facilities; sludge thickeners; vacuum filters; and a computer control system.

- He also managed the preliminary design of hydrogen sulfide strippers, chlorinators, ground storage reservoirs, and other facilities fro a 48-mgd groundwater treatment plant for the city of Cocoa, Florida.

- Mr. Bergman has prepared master plans for a number of utilities in Florida: water supply master plans for Port Charlotte, Port Malabar, and Englewood, and water and wastewater master plans for Boynton Beach and for Ocala.

- For the City of Morriston, New Jersey, Mr. Bergman provided project management services for the design of a 6.3 mgd upgrade/expansion for an advanced secondary wastewater treatment plant.

- For Hillsborough County, Florida, Mr. Bergman managed the design of an odor control project for an advanced wastewater treatment facility. The project included covers for the primary clarifiers, sulfide scrubbing system, grit handling system, electrical building, and other plant modifications and improvements.

- As the engineering manager for a manufacturer of desalination equipment prior to joining CH2M HILL, Mr. Bergman was responsible for over $40 million (in 1980 dollars) of custom-engineered projects and standard systems for seawater and brackish water RO desalination and ultra-pure water facilities. Among his projects was the Yanbu Seawater RO plant in the Kingdom of Saudi Arabia. This facility, built on a turnkey basis, had a capacity of 1.3 mgd and a 2-year operation and maintenance agreement. He also provided process designs for a 5.3-mgd seawater RO plant (the largest of its kind at the time) and a 1.2-mgd facility treating highly brackish water, both of which are on Malta. He managed the design and startup of a project involving a 0.3-mgd (200 gallon per minute) ultra-pure water system for the Fairchild Camera and Instrument Corporation in Puyallup, Washington. The system included filtration, carbon adsorption, RO treatment, degasification, mixed-bed ion exchange demineralization, ultraviolet (UV) sterilization, and microfiltration.

- Some of the other larger desalination design and construction projects with which Mr. Bergman was involved while working with an RO systems manufacturer include seawater RO facilities at Cape Verde Islands (U.S.A.I.D.) and Jeddah, Saudi Arabia (Intercontinental Hotel); brackish water RO facilities in Dammam, Saudi Arabia (OGEM); and industrial process water RO facilities at San Diego, California (Sony); San Jose, California (IBM); Syracuse, New York (GE); and the United Arab Emirates (Gulf Pharmaceuticals).

- Mr. Bergman also has experience at an investor-owned water utility in Illinois. He managed an engineering office and was involved in the planning, design, and construction of water supply wells and distribution facilities, as well as in the performance monitoring of the utility's 32-mgd lime softening plant. For more than three years, he designed the utility's water main expansions projects, procured components, and managed contracted construction crews for the installation work. He also prepared a cost-of-service study for the utility as part of a rate case request to the state's commerce commission.

- Mr. Bergman has been involved with several research projects. For example, in 1977-1979 he was the senior pretreatment engineer for an operating contractor at the USBR's Yuma Desalting Test Facility in Yuma, Arizona. He was responsible for conducting and analyzing all test programs, including lime softening pretreatment for RO and ED desalting equipment. The test facility was used to develop design criteria for the 72-mgd Yuma Desalting Plant.

- He currently is a member of the AWWA Research Foundation's (AWWARF) Project Advisory Committee (PAC) for "biofouling in membrane processes" and was a PAC member for AWWARF's evaluation of "low-pressure membrane filtration for particle removal" published in 1992. Furthermore, Mr. Bergman is a member of the Technical Advisory Group for the AWWARF project "A Comparative Study of Non-Thermal Technologies for Salinity Removal" as part of the team comprised of the Metropolitan Water District of Southern California, Orange County Water District (Fountain Valley, CA), and Lawrence Livermore National Laboratory.

- Mr. Bergman was a member of the Peer Review Committee for the EPA's development of best available technologies (BAT) for inorganic and radionuclide contaminant removal.

- Mr. Bergman currently is the Chairman of the American Water Works Association (AWWA) Water Resources Division. He was a past Chairman of AWWA Resources Division's Water Desalting and Reuse Committee and has served on the AWWA Water Quality Division's Membrane Processes Committee and the AWWA Water Research Division's Membrane Research Committee. He was chairman of the 1994 Joint AWWA-WEF (Water Environment Federation) Water Reuse Symposium Program Committee and also was a member of the 1991, 1993, and 1995 AWWA Membrane Technology Conference Program Committees. On the state level, he served for several years as a member of the Florida Section AWWA Research Committee and the Florida Water Resources Conference Program Committee.

- Mr. Bergman is currently a lead author for portions of two books now being prepared. For AWWA and ASCE Water Treatment Plant Design Third Edition, he is writing a new chapter entitled "Membrane Processes." For AWWA's new book (tentatively titled "The Water Almanac"), he is responsible for the sections defining water desalting, membrane processes, and water reuse. Mr. Bergman also is one of the authors of the "Water Desalting Handbook", currently being written by the AWWA Water Desalting Committee. He also has been a contributing author for seawater desalting for the World Book Encyclopedia.

Membership in Professional Organizations

- American Water Works Association
- International Desalination Association
- American Desalting Association
- Southeast Desalting Association

Publications

- With James C. Reynolds. Seawater Reverse Osmosis as an Alternative Water Supply. Proceedings of the 72nd Annual Florida Water Resources Conference. Orlando, Florida. April 20-23, 1997.

- Design Challenges of a Combination Surface Water and Ground Water Desalting Plant at Chesapeake, Virginia. Proceedings of the American Water Works Association 1997 Membrane Technology Conference. New Orleans, Louisiana. February 23-26, 1997.

- With Steven R. Lavinder, David Ailstock, and Stuart A. McClellan. The Boynton Beach Start-up Experience - Optimization Techniques to Meet Product Water Quality Requirements and reduce Costs. Proceedings of the American Water Works Association 1997 Membrane Technology Conference. New Orleans, Louisiana. February 23-26, 1997.

- Cost of Membrane Softening in Florida. Journal American Water Works Association (AWWA), Vol.88, No.5 (May 1996).

- Membrane Softening vs Lime Softening: Florida, USA, A Cost Comparison Update. The International Desalination & Reuse Quarterly. Vol. 5 No. 3 (November/December 1995).

- The Cost of Membane Softening Water Treatment Plants in Florida. Proceedings of the American Water Works Association 1995 Membrane Technology Conference. Reno, Nevada. August 13-16, 1995.
- Comparative Economics of Membrane Softening and Lime Softening for Florida's Colored Groundwaters. Florida Water Resources Journal. December 1995. Also, Proceedings of the 70th Annual Florida Water Resources Conference. Jacksonville, Florida. April 2-5, 1995.
- Membrane Softening versus Lime Softening in Florida - A Cost Comparison Update. Desalination 102(1995) 11-24. Also presented at the American Desalting Association 1994 Biennial Conference and Exposition. Palm Beach, Florida. September 12, 1994.
- With James C. Lozier, Brent Fulgham, and H. Robert Kohl. The Innovative Use of Membrane Processes for High-Level Nutrient Removal from Wastewater Effluent. Florida Water Resources Journal. May 1994.
- Membrane Technologies for Large and Small Public Drinking Water Systems. Proceedings of the New England Environmental Expo. Boston, Massachusetts. April 26-28, 1994.
- The Water Reuse Paradigm. Proceedings of the AWWA/WEF 1994 Water Reuse Symposium. Dallas, Texas. February 27-March 2, 1994.
- With James C. Lozier. The Use of Membrane Processes in Water Reuse. Proceedings of the AWWA/WEF 1994 Water Reuse Symposium. Dallas, Texas. February 27-March 2, 1994.
- With James C. Lozier. Membrane Process Selection and the Use of Bench and Pilot Tests. Proceedings of the AWWA 1993 Membrane Technology Conference. Baltimore, Maryland. August 1-4, 1993.
- Anatomy of Pressure-Driven Membrane Desalination Systems. Proceedings of the AWWA 1993 Annual Conference (Engineering and Operations Section). San Antonio, Texas. June 6-10, 1993.
- Nanofiltration System Components and Process Design Considerations. Proceedings of the AWWA 1992 Annual Conference (Engineering and Operations Section). Vancouver, British Columbia, Canada. June 18-22, 1992.
- With Dean E. Bedford, Ed Minchew, and Robert L. Kenyon. Design of the Boynton Beach, Florida Membrane Softening Water Treatment Plant. Proceedings of the AWWA 1992 Annual Conference (Engineering and Operations Section). Vancouver, British Columbia, Canada. June 18-22, 1992.
- With H. Robert Kohl, Dean E. Bedford, and James C. Lozier. Innovative Reverse Osmosis Pretreatment Processes For Wastewater Reclamation. Proceedings of the AWWA 1992 Annual Conference (Water Resources Section). Vancouver, British Columbia, Canada. June 18-22, 1992.
- With O.K. Buros. Custom Membrane Warranties: Are They Necessary? Proceedings of the AWWA Seminar, Membrane Technologies In The Water Industry. Orlando, Florida. March 10-13, 1991.

- With James C. Lozier. Expanding Applications for Membrane Processes in Water Treatment. Proceedings of the National Water Supply Improvement Association, 1990 Biennial Conference. Lake Buena Vista, Florida. August 1990.

- As Chairman of AWWA Water Desalting and Reuse Committee. Committee Report: Membrane Desalting Technologies. Journal of American Water Works Association. November 1989.

- With Gregory N. Jones and David Pickard. Recovery of Municipal Wastewater Using Advanced Treatment Technologies at Tampa, Florida. Proceedings of the AWWA Annual Conference. Los Angeles, California. June 1989.

- With H.W. Harlow and P.E. Laverty. Characterizing and Controlling Microbial Activity at the Englewood RO Plant. Technical Proceedings of the National Water Supply Improvement Association 1988 Biennial Conference. San Diego, California. July 31-August 4, 1988.

- With H.W. Harlow. Reverse Osmosis Process Experience at Englewood, Florida. Proceedings of the AWWA Annual Preconference Seminar Membrane Processes: Principles and Practices. Orlando, Florida. June 19, 1988.

- With H.W. Harlow. Is Pilot Testing Necessary for Desalting Groundwater by Reverse Osmosis? Presented at the American Water Works Association Annual Conference. Denver, Colorado. June 24, 1986.

- With H.W. Harlow and P.E. Laverty. Resolution of Reverse Osmosis Flux Decline Problems at Englewood, Florida. Proceedings of the Second World Congress on Desalination and Water Reuse, International Desalination Association. Bermuda. November 17-22, 1985.

- With William T. Andrews. The Malta Seawater RO Facility. Proceedings of the First World Congress of Desalination and Water Reuse, International Desalination and Environmental Association. Florence, Italy. May 23-29, 1983.

- Madinat Yanbu Al-Sinaiyah Seawater RO Facility, Kingdom of Saudi Arabia. Technical Proceedings WSIA 10th Annual Conference of the Water Supply Improvement Association. Honolulu, Hawaii. July 25-29, 1982.

Kenneth McGill

Education

B.S., Geology, Upsala College, New Jersey, 1974

Graduate Studies, Hydrogeology, Wright State University, Ohio

Groundwater Modeling, Drexel University, Pennsylvania

Professional Registrations

- Certified Professional Geologist: American Institute of Professional Geologists (1984) No. 6538
- Certified Professional Geologist: Virginia (1984) No. 269; Pennsylvania (1995) No. 2999

Distinguishing Qualifications

- Senior project manager for several hazardous waste site investigations and aquifer recharge programs
- Senior hydrogeologist specializing in studies within the Atlantic Coastal Plain Physiographic Province
- Expert in aquifer storage and recovery (ASR)
- Manager for numerous large and small projects
- Expert in Resource Conservation and Recovery Act (RCRA) Subpart F and Corrective Action
- Project manager for Superfund remedial investigation/feasibility study (RI/FS) and remediation projects
- Certified Professional Geologist registered with the American Institute of Professional Geologists, Pennsylvania, and Virginia

Relevant Experience

Mr. McGill is a senior hydrogeologist and project manager for CH2M HILL. He has more than 20 years of professional experience in managing and conducting hydrogeologic investigations, ASR assessments, groundwater contamination studies, hazardous waste site investigations, removal and remediation projects, and subsurface drilling programs. Mr. McGill has managed projects and groundwater contamination assessments at former manufactured gas plant (MGP) sites, active Environmental Cleanup Responsibility Act (ECRA) and RCRA facilities, and inactive solid and hazardous waste Superfund sites. He has managed and been the senior hydrogeologist on numerous RI/FS and remediation projects for CH2M HILL.

Mr. McGill was a member and leader of the Technical Assistance Team, under contract to the United States Environmental Protection Agency (EPA) Superfund program. He managed an office and supervised a 10 person technical staff. He monitored cleanup contractors and drilling and removal activities for EPA. He supervised more than 25 environmental emergency responses to oil and hazardous material spills. He also was involved in preliminary hydrogeologic evaluations; soil, surface water, and groundwater sampling; site characterizations; extent of contamination studies; removal alternatives evaluation; and remediation at coal-tar- contaminated MGP sites.

Mr. McGill served for several years as a regional expert hydrogeologist for the Hazardous Waste Management Division of the EPA in Region III. He has extensive experience in conducting contamination assessments, evaluating groundwater monitoring systems and plans, determining the technical requirements of RCRA and Superfund, and conducting experience in site remediation. He also has also conducted enforcement case development, provided technical oversight, participated in negotiations, and given expert witness testimony. Mr. McGill has extensive expertise in dealing with technical RCRA enforcement issues in relation to federal and state regulations. He served with many EPA work groups and task forces in developing national guidance.

Project Experience

- Managed a Phase One feasibility study for ASR near the Swimming River Reservoir (SRR) in New Jersey after which the client elected to proceed with a Phase Two field investigation to confirm ASR feasibility in a prototype ASR well modified from one of three existing supply wells at SRR.

- Managed a preliminary feasibility assessment at the New Jersey-American Water Company's Murray Avenue ASR site. The purpose of the assessment was to evaluate information on the hydrogeology, aquifer water quality, treated water quality, aquifer material composition, and related information from federal and state agencies, drillers, and New Jersey-American Water Company. The assessment led to conducting a comprehensive ASR investigation and testing program that is now under way. These activities include coring, well installation, geochemical analysis, aquifer testing, ASR wellhead/wellhouse design, pretreatment construction oversight, ASR cycles, and permitting. The ASR facility was constructed, automated, and has been operating successfully for several years.

- Project manager for a preliminary field investigation of groundwater contamination at the Toms River Water Company's Parkway Wellfield. The project entailed determining whether trichloroethylene (TCE) contamination was present in the capture zones of the wellfield production wells as predicted by the groundwater flow and transport modeling study conducted by CH2M HILL.

- Managed a study for the Toms River Water Company to identify potential contaminant sources in the Jakes Branch Watershed, assess the possibility of those contaminants being released into the stream by estimating transport routes, describe the potential for movement of those contaminants along the stream to the South Toms River Wellfield, and assess the stream bed infiltration on the wellfield water quality.

- Managed a project for United Water - Toms River, to identify potential contaminant sources in the Davenport Branch Watershed, assess the likelihood of those contaminants being released into the stream by identifying potential transport routes, and describe the potential for movement of those contaminants along the stream to the Berkeley Wellfield.

- Managed a Phase One ASR feasibility assessment for United Water - Toms River.

- Managed a preliminary ASR feasibility assessment for the Evesham, New Jersey, MUA to evaluate existing information about the hydrogeology, aquifer water quality, treated water quality, aquifer material composition, and related information from federal and state agencies, drillers, and Evesham MUA files and to assess the feasibility of a comprehensive ASR assessment and testing program. The preliminary assessment led to an ASR Phase Two testing program currently under way. The program includes NJDEP, Delaware River Basin Commission, and New Jersey Pinelands Commission permitting, coring and monitor well installation, core laboratory testing, geochemical analysis, production well, ASR well and wellhouse design and construction, aquifer testing, ASR test cycles, and report preparation.

- Managed an ASR preliminary feasibility assessment for the Brick MUA. The Brick preliminary assessment led to a Phase Two testing program, including design for the retrofit of an existing PRM production well to ASR operations.

- Oversaw a preliminary feasibility assessment of water treatment and supply alternatives for the Township of Moorestown, New Jersey, Kings Highway and North Church Street water treatment plants. The work included an engineering evaluation of the Kings Highway and the North Church Street water treatment facilities to determine options for expanding water treatment, evaluate ASR as a water supply alternative for the Kings Highway Plant, prepare a report, comparing costs and permit implications of the various expansion alternatives, and provide recommendations on future expansion options that included a combination of upgrades.

- Managed a follow-up to the preliminary assessment for the Township of Moorestown, New Jersey. CH2M HILL was contracted by Moorestown to provide engineering support services during the expansion of the North Church Street water treatment plant from 900 to 1,500 gallons per minute (gpm). The project included the developing of bidding and contract documents, preparing an engineer's estimate, providing support in selecting a contractor, providing construction oversight services, and conducting an evaluation of increased manganese concentrations from the production well

- Managed the engineering and drilling subcontractor services associated with the evaluation and rehabilitation of the Borough of Woodstown, New Jersey, Upper PRM production well 2. CH2M HILL also provided technical and permitting support to Woodstown for recovering lost water allocation from the PRM Aquifer system for production wells 2 and 3. The technical elements included time-related analysis of sodium and chloride concentration and static water levels from wells 2 and 3, along with a hydrogeologic study, groundwater modeling, and preparation of a technical memorandum supporting the water allocation saturation by the New Jersey Department of Environmental Protection (NJDEP). The last

PRM water allocation was restored by the NJDEP. CH2M HILL is now providing engineering support services for installation of a new upper PRM production well. Managed all these activities.

- Managed a multimillion-dollar program for the EPA to perform a detailed remedial investigation (RI) and feasibility study (FS) of the soil and aquifer underlying the Bridgeport Rental and Oil Services (BROS) Superfund site. The purpose of the project is to determine the extent of soil and groundwater contamination and to define, evaluate, and design remedial alternatives to reduce remaining hazards associated with the site. Also managed sampling of remedial action lagoon sediments to confirm soil remediation activities at the site. The contaminants at the BROS site include polychlorinated biphenyls (PCBs), volatile organic compounds, polycyclic aromatic hydrocarbons (PAHs), phenols, and metals.

- Site leader on a Superfund Emergency Removal Project in King of Prussia, Pennsylvania. Monitored remediation contractors and supervised installation of a groundwater interception trench and aeration stripping/carbon filtration treatment system. The system effectively eliminated the threat of direct human contact and treated up to 50,000 gallons per day of leachate contaminated with volatile chlorinated organic chemicals and dense nonaqueous phase liquid (DNAPL).

- Technical Assistance Team hydrogeologist for the EPA groundwater investigation project at the Butler Water Tunnel Hazardous and Toxic Materials Discharge in Pittston, Pennsylvania, and the Broadhead Creek site in Stroudsberg, Pennsylvania. A slurry wall and a DNAPL collection system were installed along with a monitoring system.

- Supervised the field team at the Mill Creek Landfill site in Erie, Pennsylvania, during the surface and subsurface soil sampling operation to determine the extent of contamination at the site.

- At a former MGP coal tar site in Stroudsburg, Pennsylvania, directed the extent of contamination study as a technical assistance team representative on a federal/state geologic task force. The investigation included installing test pits, soil borings, piezometers, and monitoring wells. The study determined the area affected, estimated the volume of coal tar present in a shallow groundwater aquifer, and determined the aquifer characteristics. Prepared the conceptual design and cost estimates for the remedial alternatives. The remediation included installing a 700-foot-long cement bentonite slurry cutoff wall. A DNAPL collection system also was installed. Helped design the monitoring well system for the site closure.

- Project manager on two Superfund RI/FSs for the state of New Jersey at both the JIS Landfill and Sayreville Landfill sites. The RI/FSs, included geophysical, hydrogeologic, surface water and subsurface soil investigations.

- Managed the RI and design for mitigation of a sulfuric acid spill at the General Chemical Corporation's (GCC's) Delaware Valley Works in Claymont, Delaware. A successful groundwater collection and treatment system was installed for remediation.

- Project manager who oversaw preparation of numerous submittals to NJDEP as required under ECRA for a manufacturing facility in Perth Amboy, New Jersey.

- Project manager for the hydrogeologic investigations at a steel fabricating facility in Newark, New Jersey, pursuant to the Subpart F requirements of RCRA and the state NJPDES permit application.
- Directed a detailed evaluation of an ECRA site. The work included soil borings, surface and subsurface soil sampling, and a hydrogeologic investigation, including monitoring well installation, groundwater sampling, aquifer testing, and a plan for soil venting and bioreclamation remediation of solvent-contaminated soil and groundwater.
- Project manager of an environmental assessment at a former gasoline station in Maple Shade, New Jersey. The project included a drilling and sample program and a feasibility study evaluation. The drilling and sampling program was designed to characterize the hydrogeologic conditions beneath the site and determine the source and area of soil and groundwater contamination. The feasibility study evaluation of the range of possible groundwater and soil remedies provided more precise cost estimates for remedial action.

Membership in Professional Organizations

- American Institute of Professional Geologists
- American Water Works Association
- Association of Ground Water Scientists and Engineers of NWWA
- Philadelphia Geological Society
- Virginia Board of Geology
- Water Resources Association of the Delaware River Basin

Publications and Presentations

- Contributed to "Resource Conservation and Recovery Act (RCRA) Technical Enforcement Guidance Document (TEGD)" for the United States Environmental Protection Agency (USEPA). 1986.
- With S. Brown. "Beating Peak Water Demand with Aquifer Storage and Recovery." *The Authority*. December 1990.
- With S. Brown. "Beating Peak Water Demand with Aquifer Storage and Recovery." *The Authority View*. April 1991.
- With M. Lucas and R. Glanzman. "Controlling Iron Concentrations in the Recovered Water from Aquifer Storage and Recovery (ASR) Wells." Proceedings of Second International Symposium on Artificial Recharge of Groundwater, American Society of Civil Engineers (ASCE). 1994.
- With J. P. Dugandzic and M. Lucas. "Using pH Adjustment to Control Iron Concentrations in the Recovered Water from Aquifer Storage and Recovery (ASR) Wells." Proceedings of International Groundwater Management Symposium, ASCE. 1995.

- With J. P. Dugandzic and M. Lucas. "Controlling Iron Concentrations in the Recovered Water from Aquifer Storage and Recovery Wells." Proceedings of American Water Resources Association Conference, AWRA. 1995.
- With R. D. Pyne. "Groundwater Recharge and Wells: A Guide to Aquifer Storage and Recovery." CRC Press. 1995.
- "Monitoring Well Installation Methods". Presented to USEPA. Philadelphia, Pennsylvania. 1983.
- "Basics of Hydrogeology." Presented to USEPA. Philadelphia, Pennsylvania; 1985.
- "RCRA Technical Enforcement Guidance Document." Presented to the National Water Well Association. Columbus, Ohio. 1986.
- "Case Study on RCRA Monitoring Well Systems." Presented to the USEPA Region 3 State Enforcement Regulators. Charleston, West Virginia. 1986.
- "Overview of Aquifer Storage and Recovery (ASR)", Presented to the Massachusetts Water Purveyors Association. Boston, Massachusetts. 1992.
- "Case Studies of ASR for New Jersey-American Water Co." Presented to the New Jersey section of the American Water Works Association. Atlantic City, New Jersey. 1993.
- "ASR Overview and Case Study." Presented to the Water Resources Association of the Delaware River Basin. Haddon Heights, New Jersey. 1994.
- "Practical and Technical Considerations of ASR." Presented to the Artesian Water Co. and the Delaware DNREC. Newark, Delaware. 1996.
- "Aquifer Storage and Recovery." Presented to the New Jersey Section of the American Water Works Association Water System Reliability Seminar. Princeton, New Jersey. 1996.
- Mr. McGill has contributed to other publications on aquifer storage and recovery (ASR). He has made other presentations on aquifer recharge, hydrogeology, Superfund investigations, and RCRA corrective actions. A complete list is available on request.

Douglas G. Dronfield

Education

M.S., Groundwater Hydrology, University of Arizona

B.A., Environmental Science, University of Virginia

Professional Registrations

- Professional Geologist: North Carolina, South Carolina

Distinguishing Qualifications

- Senior technical advisor on groundwater supply and groundwater contamination projects
- Specialist in evaluating alternatives for groundwater remediation
- Specialist in groundwater chemistry and its relation to groundwater supply and groundwater contamination

Relevant Experience

Mr. Dronfield specializes in evaluating groundwater resources, assessing groundwater contamination from hazardous waste and solid waste sites, and developing alternatives for groundwater remediation. He provides senior technical support throughout the East Coast to CH2M HILL staff in the groundwater discipline.

Project Experience

- Hydrogeologist for an Aquifer Storage and Recovery(ASR) project for the City of Chesapeake, Virginia that involved evaluating the effectiveness of injecting treated drinking water into an aquifer and then pumping the water out of the aquifer during peak demand. Major factors influencing the effectiveness of the system were the physical plugging of the aquifer and well and the geochemical reactions from mixing different water types. This was the first ASR project for CH2M Hill in Coastal Plain sediments.
- As senior hydrogeologist and project manager, he has continued to provide technical support the City of Chesapeake during the five years of operational use of the ASR system at Chesapeake. The City continues to inject, store and recover drinking water to meet peak demands.

- Project manager and senior hydrogeologist for a soil and groundwater investigation and remediation project near Charlotte, North Carolina. Responsible for all phases of the work. At this industrial facility, solvent and petroleum compounds were detected and have caused noncompliance with the North Carolina 2L and 2N regulations. Negotiations with the state during the comprehensive site assessments and development of corrective-action plans have been continuing. Field investigations have included installation of groundwater-monitoring wells; sampling of groundwater, surface water, and soil; and aquifer testing. A groundwater remediation system has been installed. Provided the client with expert witness support for their opposition to an administrative order from the state agency. The order was later received by the state based on the technical presentation by the client.

- Project manager and hydrogeologist for groundwater investigation and remediation work for a *Fortune* 10 company near Richmond, Virginia. The project has included containment of groundwater contamination by the installation of a 49-well groundwater extraction and treatment system. The effect of contaminant migration on the James River also has been evaluated.

- Planned and supervised all aspects of subsurface and surface investigations for Comprehensive Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act corrective action at 22 hazardous waste sites for 5 naval bases in Virginia, and at 11 hazardous waste sites at a naval base in Maryland. Responsibilities included managing the project; installing more than 100 monitoring wells; sampling groundwater, surface water, sediment, biota, and soil; and preparing site reports.

- Senior hydrogeologist for a feasibility study, design, and remediation of a 30-acre site contaminated with fuel in southern Maryland. The free-phase fuel was discharging into wetlands. Interceptor trenches and recovery wells were used to collect groundwater.

- For Patuxent River Naval Air Station in Maryland, project manager and senior hydrogeologist for hydrogeological and groundwater-contamination studies at 12 sites on the station. One of the sites, Fishing Point Landfill, is in a wetland area at the confluence of the Patuxent River and Chesapeake Bay. At this site, multiple-aquifer monitoring wells were installed and evaluated for the effect of tidal fluctuations on groundwater flow. Other work included investigation and remediation of a 30-acre groundwater area affected by petroleum, two additional landfill areas, and various disposal areas for solvents and metal-plating wastes. Had extensive interaction with the Maryland Department of the Environment, Solid Waste and Hazardous Waste sections.

- Program manager for a Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI), a corrective measures study (CMS), and a corrective measures implementation (CMI) at Oceana Naval Air Station in Virginia Beach, Virginia. The work involves environmental evaluation and assessment of contamination at 17 solid waste management units (SWMUs). The sites include disposal pits for liquid hazardous waste, landfills, waste-solvent disposal areas, pesticide-storage areas, hazardous-waste spill areas, and fire-fighting training facilities. Responsible for all aspects of the work, including writing work plans, sampling plans, and health and safety plans; conducting fieldwork; and writing interpretive reports containing recommendations. The fieldwork has included installing more than 45 groundwater-monitoring wells; sampling soil gas; collecting groundwater, surface water, soil, and sediment samples for chemical analysis; and conducting *in situ* hydraulic-conductivity (slug) tests. Three of the SWMUs are in the CMS phase, four are in the RFI phase, five are in a fast-track CMS and CMI phase, and five have been completed.

- Project manager and lead hydrogeologist for a remedial investigation (RI) at the Camp Allen landfills at Norfolk Naval Base. The project involved evaluating the transport of chlorinated solvents in multiple aquifers. Responsibilities included drilling and installation of 20 monitoring wells; sampling of groundwater, surface water, and sediment; sampling of 55 offsite residential wells; interpretation of hydrogeologic data; and making presentations to a technical review committee and community groups. Also senior hydrogeologist on the remediation design and oversight at a PCB-removal action at Norfolk Naval Base.

- Project hydrogeologist for a remedial investigation and feasibility study evaluating migration of metal contamination from a CERCLA fly-ash landfill in Virginia. Studied the effect of the landfill on the tidal estuary of Chesapeake Bay.

Memberships in Professional Organizations

- National Groundwater Association
- American Geophysical Union
- International Association of Hydrologists

Publications and Presentations

- With S. E. Silliman. ``Velocity Dependence of Dispersion for Transport Through a Single Fracture of Variable Roughness." *Water Resources Research*. Vol. 29, No. 10. October 1993.

- With J. Vandeven. ``Interceptor Trench and Chemical Oxidation to Collect and Treat Contaminated Groundwater." Water Environment Federation Conference. March 1994.

- With M. A. Ibison, F. A. Sanders, and R. K. Glanzman. ``Manganese in Recovered Water from an Aquifer Storage and Recovery Well." International Symposium on Artificial Recharge of Groundwater. July 1994.

- With S. J. Druschel and J. Vandeven. ``NAPL Collection System for Difficult Terrain." HMCRI 92 Conference. November 30 - December 4, 1992.

- With M. A. Ibison and T. J. Buchanan. ``Aquifer Storage and Recovery in Virginia: An Innovative Water Supply Alternative." American Water Resources Association, Future Availability of Groundwater Resources. April 1992.

- Defining Remedial Objectives. Presented at Executive Enterprise Course: Controlling the Environmental Remediation Process and Cost. Washington, D.C. March 1991.

Appendix C

Aquifer Storage and Recovery Publications

AQUIFER STORAGE RECOVERY: RECENT DEVELOPMENTS

Andrea R. Aikin[1]
R. David G. Pyne[2]

ABSTRACT: Aquifer Storage Recovery (ASR) is a water supply concept in which treated drinking water is stored underground by injection into a suitable storage zone during those months of the year when available supply and capacity of treatment facilities exceeds system demand. The stored water is recovered from the same wells to meet peak demands exceeding supply or treatment plant capacity, usually without the necessity for retreatment other than disinfection. With ASR systems, water facility expansion capital costs are typically reduced by at least 50 percent.

A number of operational ASR facilities currently exist in the United States and abroad. The concept of ASR is especially relevant in areas where reservoirs are becoming less feasible due to environmental and political concerns. The surface requirements of the technology are minimal, with the stored water not susceptible to evaporative loss, and less susceptible to contamination. Other benefits of ASR are also addressed.

ASR is having a major impact upon water resources management and water supply development within the United States.

INTRODUCTION

In today's water marketplace, efficient management of available resources is vital to maintaining viability. Long-term planning to optimize resources is critical. Existing massive water conveyance and storage projects are proving inadequate to meet increasing and competing needs for water by agriculture, people, and industry. The marginal cost of water is increasing, precipitating serious consideration of water supply alternatives, their feasibility, and cost. Among the alternatives that deserve consideration is Aquifer Storage Recovery (ASR). It is not a total solution to current needs; however, it can be an important and cost-effective part of the overall solution.

Aquifer recharge has received growing attention in recent years throughout the United States. Many water utility systems are faced with declining groundwater levels, limited water sources, increasing water demands, and more stringent water quality constraints.

Some water utility systems, in areas with suitable geology and adequate land availability, can recharge aquifers through economical surface methods. However, the majority of utility systems can recharge only through wells. While single-purpose injection wells have been used to recharge aquifers in several areas of the United States and have received the most attention, use of the dual-purpose wells associated with ASR is expected to become a preferred aquifer-recharge technique.

Even in areas where the need for aquifer recharge is not acute, it is still expensive to expand facilities associated with raw water supply, transmission, treatment, and distribution in order to meet increasing peak demands. Water supply and treatment facilities usually are designed to meet annual maximum-day demand for the present and for several years into the future. Maximum-day demand typically exceeds average-day demand by a factor of 1.3 to 2.0, and factors as high as 5.0 have been reported.

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As an alternative to investing in facilities able to meet peak demand, an ASR system can be used to store water during months when demand is down and recover it to meet peak demands that exceed existing capacity. Typical ASR storage is the order of hundreds of millions of gallons; in comparison, distribution systems at elevated or ground storage tanks typically hold only a few million gallons.

CONCEPT AND HISTORY

ASR is a water supply strategy by which treated drinking water is stored underground in a suitable aquifer through wells during "wet" months, and then recovered later in "dry" months from the same wells to meet peak demands that exceed the capacity of existing water facilities. Usually no further treatment of the recovered water is needed other than disinfection. The concept allows a utility to use ASR wells to meet increasing peak demands in lieu of an immediate expansion of water supply, treatment, or transmission capacity, whichever is critical. This is achieved typically at less than half the cost. In addition, the concept can be used to build up a bank account of stored water for future demand or for emergencies by leaving more water in the ground than is recovered each year.

ASR is a management tool that can be used to balance out seasonal and other variation in water demand. By smoothing out the peaks and valleys of the demand cycle, ASR optimizes use of existing facilities and minimizes capital expenditures by postponing the need for expansion of treatment plants or other facilities.

ASR has evolved during the past twenty years and is now operational at eleven sites across the United States, as shown on Table 1. Its increasing acceptance by water utilities is indicated by the accelerating rate of new systems becoming operational or expanding within the past five years and by the fact that new systems are now being designed or constructed at approximately thirty sites in the United States and overseas.

FEASIBILITY CRITERIA

Three principal criteria that govern the site-specific feasibility of ASR have been developed by CH2M HILL. The criteria are as follows:

- Is there a seasonal variation in water supply, water demand, or both? Typically, when the ratio of maximum-day demand to average-day demand is equal to or greater than 1.3, this criterion is met.
- Is there a reasonable scale of water facilities capacity? Balancing economies of scale against the initial cost of developing ASR wells, ASR is usually an appropriate technology if useful recovery capacity is above 1 million gallons per day (mgd).
- Is there a suitable storage zone, considering geologic, hydrologic, quantity, quality, engineering, and logistical factors?

Each site must be evaluated individually to assess the feasibility of ASR. Typically, the investigation is conducted in phases, the first of which is a feasibility assessment or conceptual plan requiring a few months and addressing significant technical and regulatory issues. Facilities construction and testing occur in the second and subsequent phases.

BENEFITS

ASR has a number of benefits that can be accrued by a utility using the technology. These benefits fall into two principal categories: economic and environmental.

Economic Benefits

During the past ten years, CH2M HILL has completed several economic evaluations of water supply alternatives involving ASR facilities. Generally, costs are developed comparing solutions to local needs with conventional technology and with ASR technology. The ASR approach is cost-effective, typically reducing capital costs by at least fifty percent. The reason for this is that ASR systems make more efficient use of existing investment in capital facilities. Increases in demand are met with water stored during times when demand is below the capacity of existing water supply, treatment, or transmission facilities. With ASR, water facilities can be designed closer to average demands than peak demands, with associated cost savings. Nature provides the treated water storage reservoir at very low cost. Following is a summary of selected economic analyses:

Wyoming, Michigan

Completed in 1985, this detailed feasibility assessment indicated that the conventional solution of extending a parallel pipeline to Lake Michigan would cost about $31 million. The ASR solution was estimated at $9 million. CH2M HILL proceeded with design of the parallel pipeline and associated facilities since the City was unwilling to take the risk that ASR would not work. At that time there were only three known ASR systems in operation in the United States, each of which operated at a small scale.

Peace River, Florida

Water system expansion to meet expected ultimate demand of the Port Charlotte service area would include a 40 mgd ASR wellfield and other facilities, estimated to cost $46 million. Without ASR, it would be necessary to provide a large offstream reservoir expansion and treatment facilities sized to meet the 60 mgd maximum day demand. This was estimated to cost about $108 million. This ASR system is operational with a recovery capacity of 4.9 mgd and is being expanded to meet increasing peak demands.

Manatee County, Florida

This system is operational with a capacity of 3.5 mgd. Investigations completed in 1984 indicated that it could be expanded easily to provide a capacity of 17 mgd at a cost of under $2 million by adding wells around the existing surface water treatment plant. The County elected to proceed with development of another water supply alternative that increased capacity by about 19 mgd at a cost of $38 million, since to do otherwise would have caused them to lose that option forever. The alternative involved extensive land acquisition for a distant wellfield, plus transmission and treatment facilities. They plan to expand the ASR system in a subsequent phase.

Florida Keys Aqueduct Authority

With water conveyed 120 miles over 42 bridges, this water system is highly vulnerable to catastrophic failure during hurricanes. Planned provision of additional ground storage reservoirs was expected to cost about $70 million. ASR can probably achieve the same objective at a cost under $5 million, storing water in a confined sand aquifer containing salt water. The test program is still underway, but results to date suggest that it will be successful. This is the first project worldwide to successfully store potable water in a salt water aquifer.

Kerrville, Texas

Expansion of the existing 5 mgd surface water treatment plant to 10 mgd is expected to cost about $3.9 million. Expansion to 7.5 mgd along with three ASR wells would meet the same system demands at an estimated cost of $3 million. The major advantage of ASR at this site, however, is the anticipated opportunity to defer or eliminate the need for construction of an off-channel reservoir in conjunction with the plant expansion, substituting aquifer storage. This cost savings is estimated at about $30 million. The ASR facilities are constructed and operational.

Other Sites

ASR systems are now in operation or under development in ten states and four foreign countries. In each case, the system is perceived as very cost effective, although detailed economic studies are not always available. In some cases, the utility systems have performed the economic analyses. One example is Chesapeake, Virginia, which now has 3 mgd ASR capacity and is adding 6 mgd additional capacity. Their internal studies showed that ASR would be the most cost-effective water supply alternative for this fast growing area, which otherwise would be faced with desalination or imported water piped from a distant source.

In many cases, ASR is selected for other than economic reasons. For instance, ground-water recharge through wells is the only way to get the water into storage for those areas where hydrogeology or land availability prohibit surface recharge. ASR technology facilitates well recharge by minimizing the potential for well plugging. The cost savings are then a secondary benefit.

Where surface recharge is feasible, it is usually less expensive than well recharge unless land cost or availability constrain recharge operations. However, if the water is then recovered and requires treatment for potable or other purposes, ASR can be less expensive than surface recharge.

A detailed assessment of ASR operating costs has not been performed to date. Experience with ASR operations at five sites designed by CH2M HILL, and in operation for one to seven years, suggests that such costs are slightly higher than for a conventional wellfield. Other than disinfection, the water generally does not require retreatment. Marginal costs incurred are primarily power consumption resulting from head loss during recharge and pumping during recovery; disinfection; instrumentation and control of ASR wells; monitoring of water quality and cumulative storage volumes in each well; and, the labor associated with changing periodically from recharge to recovery mode, or vice versa. Such operational changes typically occur perhaps two to four times per year.

Capital costs for ASR systems are highest for the initial well, which carries the full burden of feasibility assessment, engineering, modelling, permitting, water quality monitoring, and hydraulic testing. Typically, this may cost in the range of $200,000 to $500,000 per mgd recovery capacity. Subsequent wells at the same site generally cost substantially less, reflecting only well and wellhead construction costs and associated piping.

Environmental Benefits

ASR has some important environmental advantages now that public opinion frequently dictates against the development of large reservoirs and dams. The Two Forks project in Denver, Colorado is an example of public opinion eventually resulting in the indefinite postponement of the surface water supply project. In terms of surface facilities, an ASR project needs only the amount of land a wellhead requires, with some additional piping to the site. The entire facility can be contained in a wellhead structure. Additionally, there is the advantage that the users are not depleting the aquifer if they only remove what they added to the aquifer during the injection periods. With a typical ASR project, positive publicity is generated in the form of newspaper articles and reports.

In addition to economic and environmental benefits, there are several potential applications of ASR technology. Usually at each site there exists a primary objective and one or more secondary objectives. Table 2 lists 21 objectives associated with existing ASR operational projects and others in planning or development. Consideration of various potential objectives during the first phase feasibility assessment can help to ensure that test facilities are located and designed to achieve maximum benefit, and that testing encompasses a sufficient range of issues and parameters required to achieve these objectives.

REPRESENTATIVE SITES

A number of sites were mentioned briefly from an economic perspective in the previous section on ASR benefits. In this section, five applications are presented to convey the broad range of situations and circumstances where ASR is possible and beneficial.

Wildwood, New Jersey

With operation commencing in 1968, Wildwood is believed to be the oldest operational ASR facility in the U.S. Located on the Cape May peninsula, this area experiences a dramatic increase in population during the warm summer months and, in particular, holiday weekends that bring tourists to the beaches. Because of the proximity of salt water in the local aquifers, water supply is obtained from a distant wellfield. During the off-peak months, approximately 100 million gallons are stored in each of four local wells located within the distribution system. This water is recovered to help meet peak summer demands, leaving 20 million gallons in each well as a saltwater intrusion prevention measure. To maintain recharge rates, wells are backflushed every day or two for a few minutes.

Manatee County, Florida

Manatee County began ASR investigations in 1978 in a cooperative venture with the Southwest Florida Water Management District and CH2M HILL, consulting engineers. Manatee County Utilities Department operates a 54 mgd surface water treatment facility adjacent to the County's principal water source, Lake Manatee, an impoundment on the Manatee River. Beneath the area is an artesian limestone aquifer.

Table 3 shows the water quality in the aquifer and in the recharge source during the test program. The investigations included construction of an ASR well and several monitor wells. Testing of the wells indicated the following aquifer hydraulic properties: Transmissivity—40,000 ft2/day; Storativity—1.5×10^{-4}, and Leakance—2.8×10^{-4}/day. A series of cycles was conducted to investigate the effect of changing storage time as well as repetitive cycles on recovery water quality. Extensive data on flows, water level, and water quality were collected during this program. It was concluded that, within a range of 1 to 326 days, recovery water quality is independent of storage time. Some improvement in recovery quality occurred with successive cycles at the same storage volume. Based upon the results of the test program, Manatee County could meet peak water demands as high as 70 mgd without water treatment plant expansion.

Because of its implications for the water supply industry, this project received a Grand Award in the American Consulting Engineers Council 1984 Engineering Excellence Competition, one of six awarded nationwide.

Peace River, Florida

The Peace River/Manasota Regional Water Supply Authority operates a 12-mgd surface water treatment plant in southwest Florida, supplying water to Port Charlotte. Raw water is obtained from the Peace River. Due to the considerable variability in both flow and quality of the source, including occasional upstream movement of salt water above the intake, the authority also operates a 1,920 acre-feet off-stream reservoir for raw water storage. Faced with the need to expand this reservoir, CH2M HILL was retained in 1983 to investigate the feasibility of ASR as a potentially less expensive storage alternative.

Water in the limestone artesian aquifer underlying the site is brackish, as shown in Table 3. Also shown in this table is typical recharge water quality for selected constituents, representative of product water being supplied to Port Charlotte. Numerous additional water quality constituents were monitored during the test program. Two ASR zones were tested, each of which was provided with an ASR well and a monitor well. Two additional monitor wells were constructed in overlying aquifers. Aquifer testing on the principal Suwannee zone has indicated the following hydraulic characteristics: Transmissivity—6,000 ft2/day; Storativity—1×10^{-4};

Leakance—6 x 10^{-3}/day. A series of five ASR cycles demonstrated improvement in quality with successive cycles. Recovered water met potable standards throughout recovery.

A monthly simulation model for both flow and quality was developed to test the optimum sizing of components and staging of expansion phases, as well as sensitivity to changes in various parameters. Based upon successful results of the test program, an initial phase of ASR expansion to 4.9 mgd was completed at a cost of about $1.5 million. Over a period of several decades, ASR is expected to reduce capital investment over fifty percent for water supply and treatment facilities at Peace River. This reduction is calculated based on the reservoir expansion alternative.

Seattle, Washington

The Seattle Water Department (SWD) retained CH2M HILL in 1986 to investigate construction of ASR well field in the Highline area of Seattle for the purpose of augmenting the municipal Cedar River surface water supply during the peak demand summer months. The potential for increasing the peak supply from the Cedar River is limited by the reduced river flow during the peak demand months and by the economics of constructing twelve miles of new water transmission pipeline. The goal of ASR for the SWD is to develop a ground-water peaking supply of 12-million gallons per day for up to four months per year.

The Highline well field is located in an area of glacial outwash deposits with three distinct aquifers: shallow, intermediate, and deep. The focus of the ASR study has been on the intermediate zone, which is composed of sandy, cobbly gravel with extremely high transmissivities in the range of 47,000 ft2/day.

Pilot testing has been completed successfully. Three ASR wells have been installed with full-scale testing to begin in the fall of 1991. The project will be completed in 1993. Recharging the Highline aquifer with surface water from the Cedar River during off-peak periods of the year will allow ground-water withdrawals in excess of natural recharge during the peak demand season without significant ground-water level declines.

Kerrville, Texas

The Upper Guadalupe River Authority (UGRA) needs to expand its water supply capacity to meet the demands of the City of Kerrville, Texas, which are expected to grow significantly in the next 40 to 50 years. UGRA is also required to provide sufficient storage capacity to meet water demands and low streamflow requirements during a historic drought. Demand is currently met through a combination of surface and ground-water supplies: the Guadalupe River that flows through town and the Hosston-Sligo formation of the Trinity Group aquifer, a dolomitic sandstone formation approximately 500-feet below ground surface. However, because of limited ground water, fluctuating surface water supplies, and the expense of above-ground reservoir construction, alternative means to meet the City's future water needs are required.

Water demand for the City is projected to increase from the current average of 3.2 mgd to about 5.0 mgd by the year 2015. Since existing ground-water supplies are sufficient to meet daily peaking needs, but cannot supply extended peaks, the maximum month demand becomes the controlling criterion. Seasonal demands range from a December low of 72 percent of annual average to an August high of 153 percent.

One prototype ASR well has been constructed and the results of testing indicate that ASR will work at Kerrville. Plans are underway to retrofit an existing city well into an ASR well. Using the two ASR wells will permit UGRA to meet the normal demand and historic drought conditions through the year 2015 without expansion of the existing water treatment plant.

TECHNICAL DEVELOPMENTS

The design of ASR wells and wellhead facilities has evolved during the past few years, to accommodate different needs and opportunities at each new site. The various reasons why recharge wells have historically plugged have been addressed with the result that ASR facilities are now operating satisfactorily at several sites. These wells have a unique design approach that is different than for production wells or injection wells. Storage zones include a wide variety of geologic settings and storage zone water quality ranges from fresh to brackish to seawater. Recharge water quality to date has been potable water, however the technology is also applicable for the storage and recovery of reclaimed water or non-potable water where consistent with applicable technical and regulatory constraints.

Work is progressing on several ASR technical frontiers. Among these is the storage of potable water in an aquifer containing very high iron concentrations in the native water. Pretreatment of the recharge water and the storage one is being evaluated to control iron concentrations in the recovered water and to minimize formation plugging due to precipitation of ferric oxyhydroxide.

Another significant area of ASR research and development is the reduction in trihalomethane concentrations observed at many ASR sites during aquifer storage. Work is underway to determine the mechanisms causing these reductions so that ASR systems can be designed and operated to maximize reduction of these disinfection byproducts during aquifer storage. To date, THM reductions up to about 80% have been recorded.

Potable water storage in aquifers containing poor water quality has been proven feasible at several sites. Constituents of concern to date have included high concentrations of chloride, total dissolved solids, nitrate, iron, hydrogen sulfide and arsenic. Many aquifers exist that are unsuitable for potable water supply but are ideally suited for ASR purposes.

Progress is being made on these and many other areas of ASR activity, both technical and regulatory. As new issues are identified and resolved, ASR systems are expected to become an increasingly important part of the solution to many of the challenges facing water utility systems.

CONCLUSIONS

ASR is a cost-effective water supply concept that is being adopted by a rapidly growing number of utilities in the United States and overseas. It is a unique technology that is different from either injection wells or production wells. It is generally applicable and environmentally acceptable. Through the development of ASR technology, the plugging and other problems that have frequently been associated with well recharge projects in the past have been addressed and, in most cases, resolved. All of the water stored is usually recovered, generally without the need for retreatment other than disinfection. In addition to water storage, site operations are showing other benefits, principal among which is improvement in water quality during aquifer storage at many sites. With the growing attention in the water utility industry to the newly promulgated Surface Water Treatment Rule, and also to control of Disinfection By-Products, ASR provides a new tool to utility managers to help meet growing water demands and water quality requirements at reduced cost and with no adverse environmental effects.

TABLE 1. OPERATIONAL ASR FACILITIES IN THE UNITED STATES

LOCATION	YEAR OPERATION BEGAN	STORAGE ZONE	ASR WELL CAPACITY (mgd)	MAXIMUM DAY DEMAND (mgd)
Wildwood, NJ	1968	sand	3.5	12
Gordons Corner, NJ	1971	clayey sand	2.4	10.5
Goleta, CA	1978	silty, clayey sand	6	21
*Manatee County, FL	1983	limestone	3.5	40
*Peace River, FL	1985	limestone	4.9	10
*Cocoa, FL	1987	limestone	8	37
Las Vegas, NV	1988	sand	20/50	196
*Port Malabar, FL	1989	limestone	1	6
Oxnard, CA	1989	sand	8.6	--
*Chesapeake, VA	1990	--	3.0/10	15
*Kerrville, TX	1991	dolomitic sandstone	1	7
*CH2M HILL PROJECTS				

TABLE 2. TYPICAL ASR OBJECTIVES

- °Seasonal storage
- °Long-term storage or water banking
- °Emergency storage or strategic water reserve
- °Diurnal storage
- °Restore ground-water levels
- °Reduce subsidence
- °Maintain distribution system pressure
- °Maintain distribution system flow
- °Improve water quality
- °Prevent salt water intrusion into aquifers
- °Agricultural water supply
- ° Nutrient reduction in agricultural runoff
- °Enhance wellfield production
- °Defer expansion of water facilities
- °Reclaimed water storage for reuse
- °Soil aquifer treatment
- °Stabilize aggressive water
- °Hydraulic control of conaminant plumes
- °Maintain water temperature for fish hatcheries
- °Reduce environmental effects of streamflow diversions
- °Compensate for surface salinity barrier leakage losses

TABLE 3
TYPICAL WATER QUALITY AT ASR FACILITIES FOR SELECTED CONSTITUENTS

WATER QUALITY (mg/1)

Location	TDS	Chloride	Sulfate	H2S	Total Hardness	Iron
Manatee--Recharge Water	110	9	50	0	60	0
Manatee--Native Water in Storage Zone	355	18	160	2.6	314	0.04
Peace River--Recharge Water	247	55	83	0	133	0
Peace River--Native Water in Storage Zone	800	180	224	4	482	0
Cocoa--Recharge Water	400	110	95	0	110	0
Cocoa--Native Water in Storage Zone	914	400	60	2.8	344	0.54
Port Malabar--Recharge Water	490	180	31	0	170	0
Port Malabar--Native Water in Storage Zone	1,360	600	125	3.5	600	0.08

BEATING PEAK WATER DEMAND
With Aquifer Storage Recovery

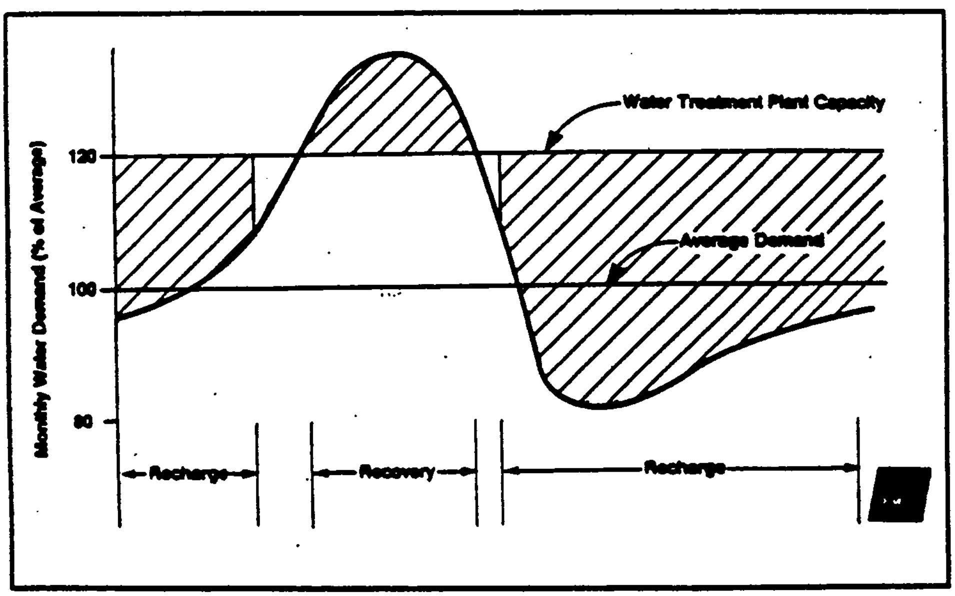
by KENNETH McGILL, C.P.G.
and STEPHANIE BROWN
CH2M HILL

The Pennsylvania Safe Drinking Water Act, Pennvest, and federal initiatives for improved water quality are prompting water system upgrades all across the state. Hundreds of millions of dollars will be spent over the next few years in order to meet growing water quality constraints as well as increasingly high demand in the dog days of summer. Unfortunately, the facility capacity provided by these costly expansions may be uselessly idle during the winter months.

But a new technology is evolving that can dramatically reduce upgrade costs and curtail the challenges presented by limited water resources, declining groundwater levels, and a host of other conditions. No tanks or reservoirs need to be built: storage capacity is provided by Nature herself. It's called Aquifer Storage Recovery, or ASR.

ASR is the practice of storing treated drinking water underground in a suitable aquifer during times when the capacity of water supply facilities exceeds system demand. Water is "recovered" (pumped back into the distribution system) from the same wells to meet seasonal peak, emergency, or long-term demands. Disinfection is generally the only necessary retreatment of the recovered water.

With ASR, seasonal storage may reach several hundred million gallons in a single well, compared with the few million gallons normally available elevated or ground storage tanks. By making more efficient use of existing raw water supply, treatment, transmission, and distribution facilities, water utility managers are finding that, where feasible, ASR systems typically reduce capital costs of facility expansions by at least 50 percent.



Some people will recognize ASR as a variation on older recharge methods. Single-purpose injection wells, for example, are used in some states for injecting highly treated wastewater effluent in order to recharge aquifers or form barriers against saltwater intrusion. In most of these cases, recovery occurs at distant wells after substantial movement and mixing with native groundwater.

Another common recharge practice is to pond stormwater in permeable spreading basins or dry river beds through which water percolates to the aquifer. Although surface methods are economical in areas with suitable geology and adequate land availability, aquifer recharge can only be achieved through wells for the majority of utility systems.

ASR is distinguished from these more familiar techniques by the use of dual-purpose wells, which put the treated water into the aquifer as well as pump it out again. Since there is an extremely low risk of pathogens being present in the treated drinking water used for recharge, environmental permitting for ASR can be simpler than with other methods. In addition, the clogging of wells is less of an issue with ASR, since such high quality water is used for recharge.

Nine ASR systems are currently operational in the United States, including two in New Jersey and one in Virginia, and investigation or testing is underway at numerous additional sites. Communities in a total of eleven states are developing ASR systems in both consolidated and nonconsolidated aquifers.

A well field in nearby Wildwood, New Jersey is believed to be the oldest operational system in the U.S., beginning operations in 1968. During the winter, Wildwood stores about 100 million gallons of treated water in each of four wells located within the distribution system. The water is recovered to meet the sharply escalated demand created by summer vacationers in the Cape May Peninsula area. Wildwood leaves about 20 million gallons of treated water in each well to act as a barrier against saltwater intrusion from the Atlantic Ocean.

Reduced facility expansion costs and preventing saltwater intrusion are not the only advantages of ASR. By reducing the need for dry-season diversions from surface water sources, ASR decreases the environmental impact of withdrawals on rivers, reservoirs, and estuaries. Where applicable, ASR can also prevent land subsidence and restore declining groundwater levels. Other benefits include improved utility system reliability in the event of droughts or emergency loss of water sources, long transmission mains, or other key facilities. Water quality may even be improved due to subsurface treatment or mixing, or due to hydraulic control of contaminated areas of an aquifer.

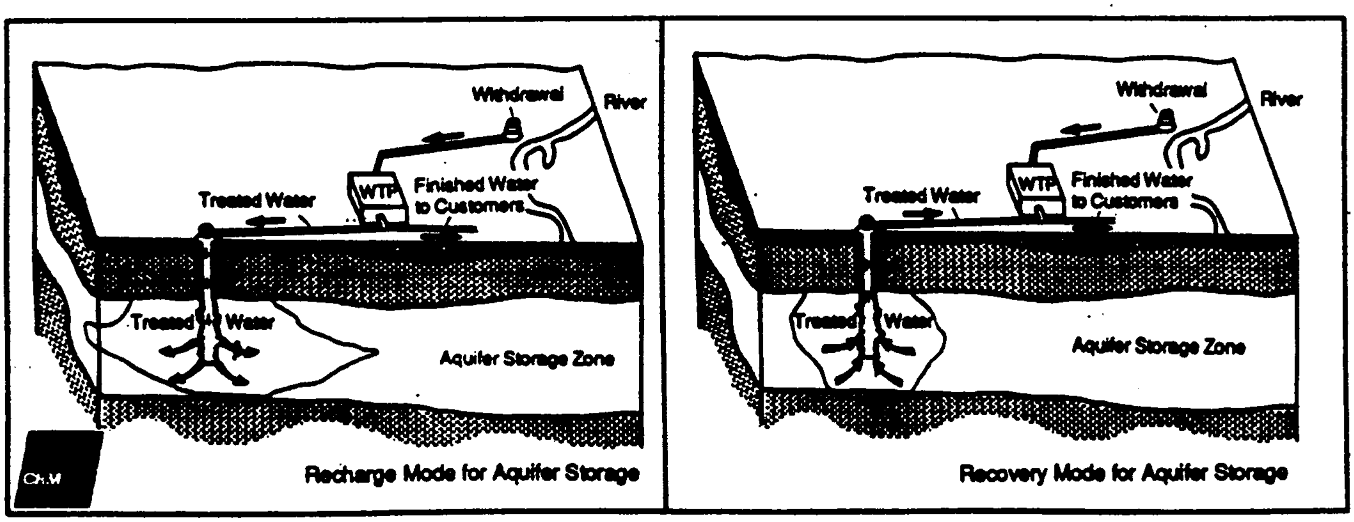
Three principal criteria govern the site-specific feasibility of ASR. First, a seasonal variation in water supply, water demand, or both is essential. Typically, the ratio of maximum to average day demand exceeds 1.3. Second, due to economies of scale and the initial cost of developing ASR wells, ASR may be an inappropriate technology if less than one mgd useful recovery capacity exists. Typically, this capacity corresponds to an average demand of about three mgd or greater. Third, a suitable aquifer storage zone must be available, based on geologic, hydrologic, quantity, quality, engineering, and other factors.

Misapplication of ASR can cause a well to plug and can jeopardize public acceptance. Therefore, preliminary testing and ongoing monitoring of water quality are key to ASR program success. Each potential ASR site must be evaluated on its own merit, since negative indications of feasibility according to certain factors can often be compensated by positive indications according to other factors. A thorough understanding of engineering, hydrogeology, water chemistry, water treatment process design, surface water hydrology, economics, and other disciplines is extremely important. The active involvement of utility operations personnel during program planning and implementation is also essential.

Typically, a Phase One feasibility study and a Phase Two test program, culminating in an operational ASR well, are conducted over two to three years. But critical state and federal regulatory processes can impact the length of time required for the feasibility assessment. To date, regulatory agency support for the concept has been strong in every instance. However, since ASR does not yet fit established practice and is easily misunderstood, seemingly minor issues on the wording of permits can have a profound effect upon whether full use of an ASR facility can be achieved.

During the past 10 years, much progress has been made with the ASR concept as many technical, operational and regulatory issues have been resolved. Experience gained at one site is rapidly applied to improve performance at other sites. With continued technical development combined with wise and enlightened regulatory practices, ASR will have a major impact upon water supply development within the United States during the next decade.

For additional information, please contact Stephanie Brown at (215) 563-4220.



Recharge Mode for Aquifer Storage

Recovery Mode for Aquifer Storage

APPLICATION OF GROUND-WATER ARTIFICIAL RECHARGE IN A BRACKISH/SALTWATER ENVIRONMENT

Albert Muñiz, Sean Skehan, Peter J. Kwiatkowski[1]

ABSTRACT: Aquifer Storage Recovery, the storage of water through wells into confined aquifers for subsequent recovery, offers a cost-effective potential solution for providing potable water for emergency use in the Florida Keys. The purpose of the project is to study the feasibility of using Aquifer Storage Recovery to store potable water in a confined saline aquifer and to subsequently recover the water to meet emergency or seasonal demands. The scope of the project is to evaluate the recharge and storage capacity of the aquifer, the potential rate and volume of recovery, the quality of the recovered water, and the economic feasibility. A test Aquifer Storage Recovery well and adjacent observation wells were constructed and tested to provide data for the study. The Aquifer Storage Recovery well was recently completed to a depth of 440 feet, with a screened interval from 410 to 435 feet. The observation wells were located approximately 100 feet and 250 feet away from the Aquifer Storage Recovery well and are similar in design to the Aquifer Storage Recovery well. An aquifer test was conducted to determine hydraulic characteristics of the storage zone. Numerical modeling was conducted to evaluate the feasibility of Aquifer Storage Recovery in a saline aquifer, determine the critical parameters affecting calibration, and optimize cycle testing. Several cycles of injection and withdrawal will be performed to further develop and evaluate the storage zone.
KEY TERMS: Aquifer Storage Recovery, Florida Keys, Saline Aquifer, HST3D

INTRODUCTION

The Florida Keys, home to approximately 80,000 permanent residents and 65,000 seasonal residents, is supplied with potable water through a 120-mile long transmission line. The line crosses 42 bridges in its route from Florida City to Key West (Figure 1) and is especially susceptible to damage by hurricanes. Along the transmission line are two pump stations and 30 million gallons (MG) of aboveground storage. All water facilities are owned and operated by the Florida Keys Aqueduct Authority (FKAA). Aboveground storage capacity is limited by the availability of land and the high cost associated with providing suitable sites in the Keys.

The projected average annual daily flow for 1990 to the FKAA service area is 13.5 million gallons per day (mgd). In the Florida Keys,

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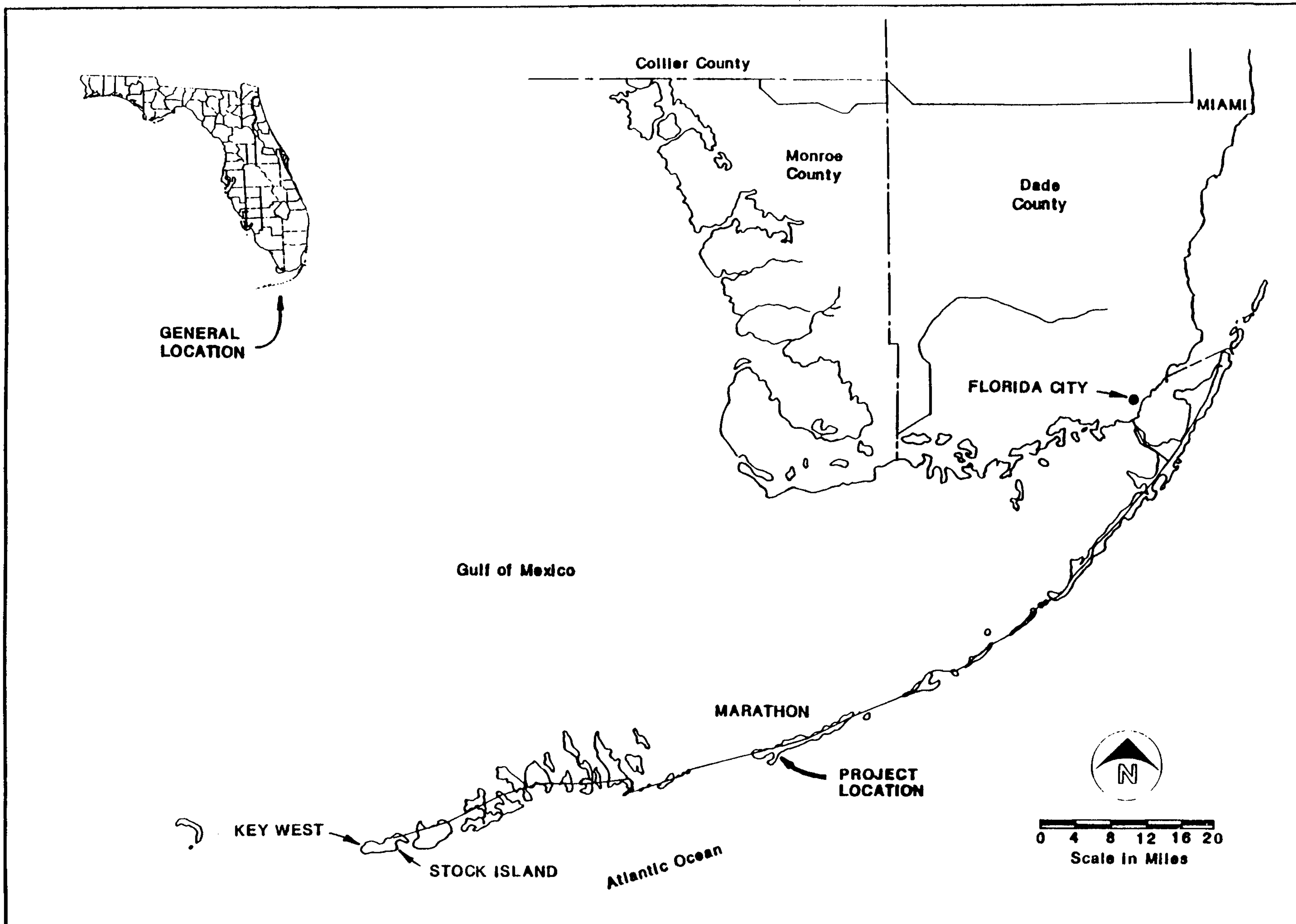

FIGURE 1. Location Map

treated drinking water must be stored to meet seasonal and normal variations in water demand, as well as to meet emergency demands. At present, the volume of storage is inadequate to provide a reliable supply in the event of emergency loss of a transmission line, which may occur during a hurricane. Since the pipeline from mainland Florida was constructed over 40 years ago, breakage from a variety of causes has impaired its ability to convey water for periods of many days. To address the storage need, the use of Aquifer Storage Recovery (ASR) was evaluated as a potential technique.

ASR Development

ASR is the underground storage of treated drinking water within a suitable aquifer to be recovered at a future time. The recovered water should require no re-treatment other than disinfection. Typically, all of the water volume stored is recovered, although this may require several cycles of injection and recovery to fully develop the storage zone. In areas such as the Keys, ASR provides a very cost-effective solution to system storage needs, but storage zone conditions may limit full recovery. Careful testing and investigation are necessary at each proposed ASR well field site to properly design the wells and wellhead facilities. Principal criteria that dictate the general feasibility of ASR are: 1) a seasonal variation in water supply and/or demand (minimum ratio of maximum day to average day demand is about 1:3), 2) a useful recovery capacity exceeding 1 mgd, and 3) a suitable storage zone.

Using ASR in the Keys will require a thin, well-confined, moderately permeable storage zone to prevent extensive mixing between native and injected water and to acquire a higher recovery percentage. Recovery percentages (cycle efficiencies) play an important role in the feasibility of using ASR in the Keys because of the high unit costs for water.

A preliminary 10-inch-diameter test well was constructed in early 1989 to an approximate depth of 550 feet to identify potential ASR zones, to confirm water quality, and to obtain qualitative indications of the zones' potential productivity. A 16-inch-diameter operational ASR well was recently (early 1990) constructed for the purposes of conducting a series of ASR cycles and developing and calibrating a mathematical model for use in assessing the feasibility of full implementation of ASR in the Keys.

Geology and Hydrology

The ASR well and monitor wells were designed based on documented hydrogeological data, formation samples collected during drilling activities, and geophysical log interpretations as presented in Figure 2. A general profile of the lithology encountered during pilot hole drilling included a hard, coralline limestone from land surface to 180 feet; a loosely-consolidated sandstone from 180 to 300 feet; a sandy clay from 300 to 410 feet; a quartz sand and gravel from 410 to 440 feet; and a sandy clay from 440 to the total depth of 450 feet. The thin interval of poorly consolidated gravel and sands from 410 feet to approximately 440 feet was identified as the potential storage zone.

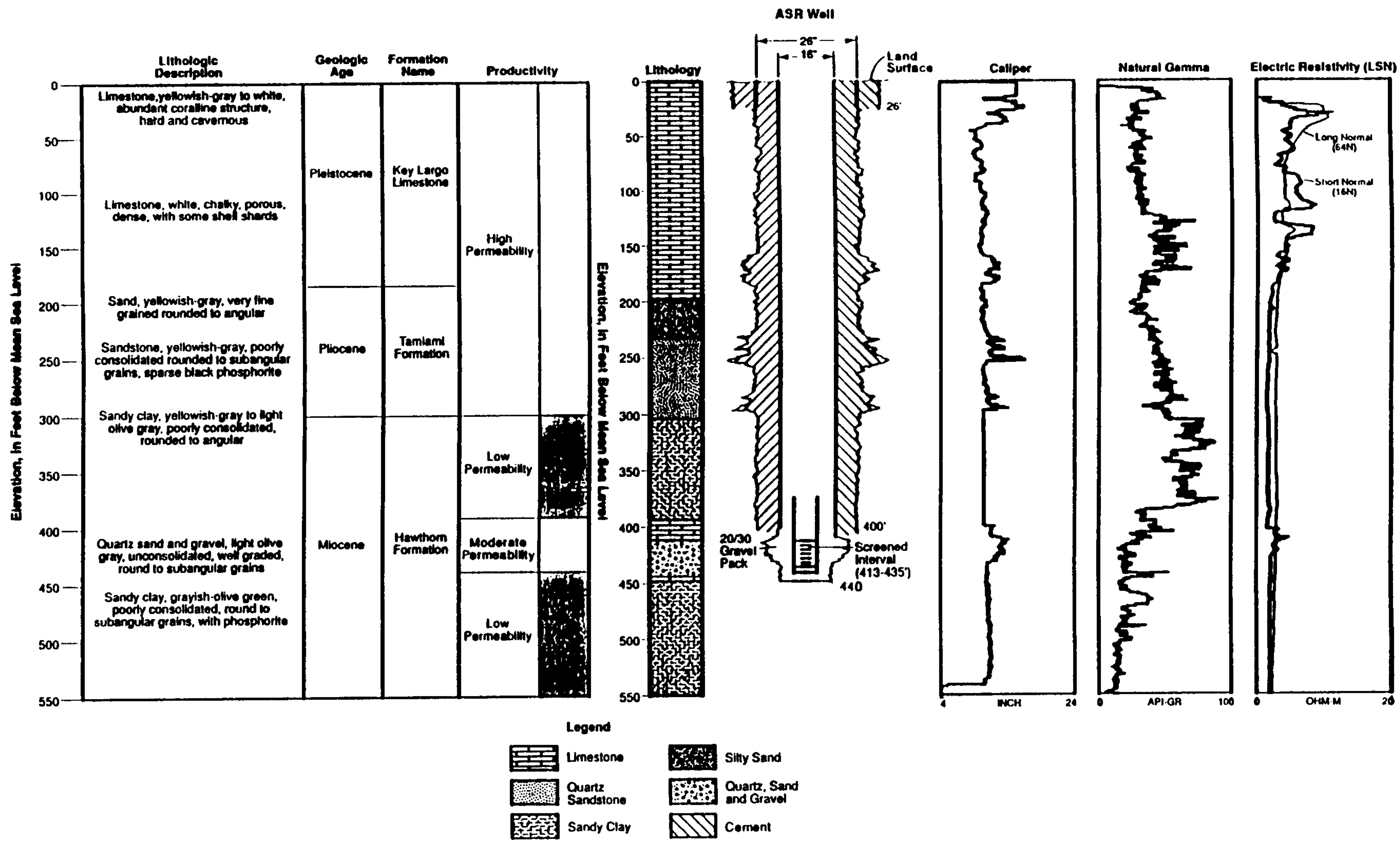

FIGURE 2. Generalized Construction Details and Lithologic Features for the ASR Well in Marathon, Florida

Construction of the ASR well consisted of setting a 26-inch-diameter steel surface casing to 22 feet and a 16-inch-diameter PVC casing to 400 feet. The 16-inch-diameter casing was set immediately above the thin interval of poorly consolidated gravel and sands, and through the overlying coralline limestone, sandstone, and clay. The ASR Well was completed by setting 40 feet of 10-inch-diameter stainless steel blank casing, 22 feet of 10-inch-diameter stainless steel screen (0.025 slot), and 5 feet of blank casing (to act as a sump) from 372 to 440 feet. Type 316 stainless steel was used because of the corrosive nature of the formation water. The screened interval from 413-435 feet was gravel packed with a graded (20/30) silica sand.

A 24-hour pumping test was conducted to determine aquifer characteristics, to evaluate the storage zone's ability to store and transmit water, and to determine the optimum flow rate during injection and withdrawal for each cycle. Preliminary analyses of the field data indicate a specific capacity of 4 gallons per minute per foot (gpm/ft) and a transmissivity value of 12,000 gallons per day per foot (gpd/ft). Additionally, geophysical logs such as fluid velocity, temperature, and fluid resistivity were conducted during pumping conditions to determine if there were any preferential flow zones within the storage interval. Water samples collected during the test indicated a maximum chloride level of 23,350 milligrams per liter (mg/l) and total dissolved solids content of approximately 36,000 mg/l.

Numerical Modeling

Numerical modeling of the ASR system at Marathon, Florida, was performed to evaluate the feasibility of using ASR in a saline environment, to determine the critical parameters affecting operation, and to develop an optimal cycle testing program.

The computer code used in this modeling was HST3D. HST3D is a three-dimensional, finite difference code developed by the U.S. Geological Survey (Kipp, 1987) that simulates fluid flow coupled with heat and solute transport in variable density environments. The code was modified slightly so that during the recovery portion of each cycle, recovery ceased when the chloride concentration reach 250 mg/l, corresponding to Florida primary drinking water standards. The initial model of the Marathon site included a two-dimensional, radially axisymmetric grid that represents a 30-foot-thick confined aquifer with the ASR well coinciding with the left-hand boundary and with a hydrostatic-pressure boundary set at the right-hand boundary--800 feet from the well (Figure 3). Water-quality data from the test well confirmed that the native fluid in the aquifer is similar in composition to seawater.

A summary of initial parameters specified in the original model set up is shown in Table 1. The model and its initial parameters are referred to as the base model.

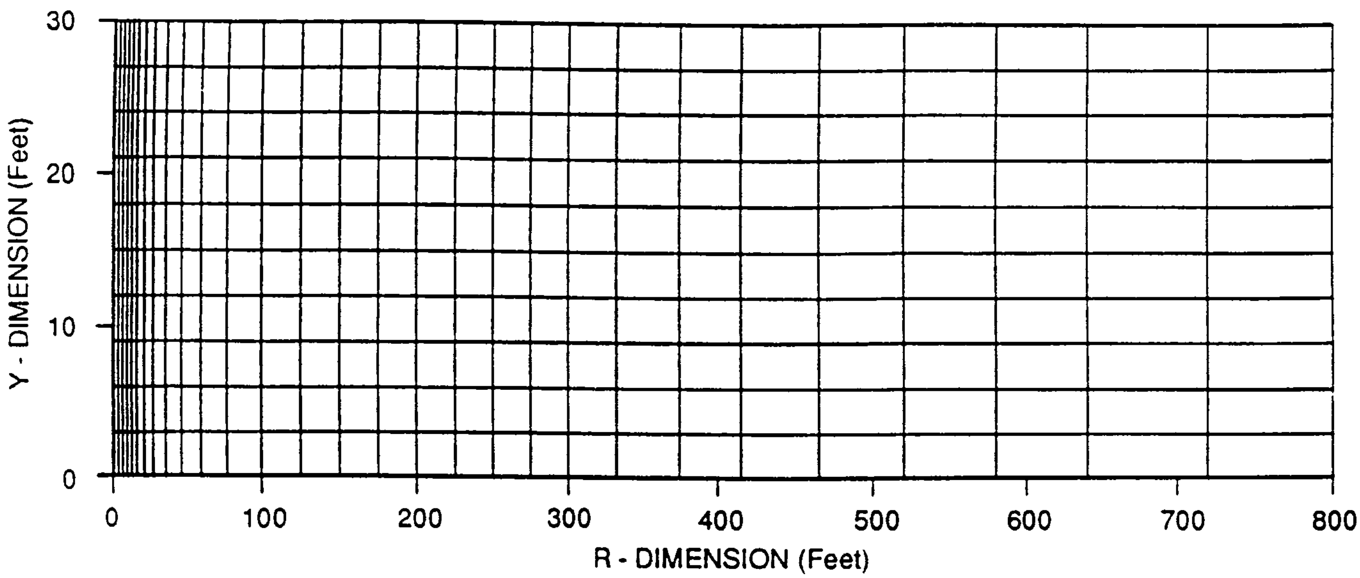

FIGURE 3. Finite Difference Grid

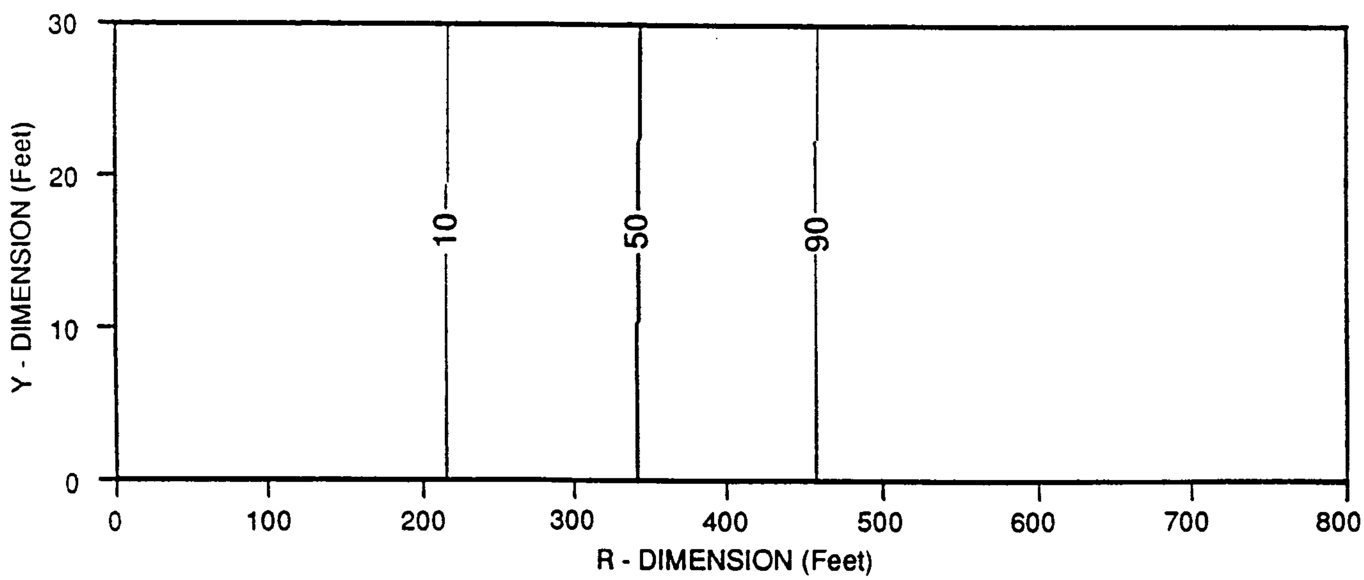

FIGURE 4. Percent Seawater Contours in the Model Domain

TABLE 1. Summary of Aquifer and Model Parameters Specified in the Base Model.

Parameter	Value
Aquifer Type	Confined
Aquifer Thickness	30 feet
Hydraulic Conductivity	53.5 ft/day
Intrinsic Permeability	2.024×10^{-10} ft^2 (isotropic)
Porosity	0.20
Aquifer Compressibility	1.0×10^{-7} psi^{-1}
Longitudinal Dispersivity	10 feet
Transverse Dispersivity	5 feet
Molecular Diffusivity	0.001 ft^2/day
Freshwater Density	62.31 lbs/ft^3
Seawater Density	63.87 lbs/ft^3
Fluid Compressibility	3.3×10^{-6} psi^{-1}
Temperature	68°F (isothermal)
Freshwater Viscosity	1.002 cP
Seawater Viscosity	1.068 cP
Native Fluid Cl^- Conc.	20,000 mg/l
Injected Fluid Cl^-	0 mg/l
Shutoff Criteria (CWKT)	1.3% (250 mg/l Cl^-)
Storage Duration	0 Days
Number of Cycles	5
Pumping Rate	350 gpm
Storage Volume	6.35 million gallons

The base run consisted of five cycles of injection and withdrawal, with each injection volume equal to 6.35 MG). Figure 4 shows the transition zone (defined in this paper as the width bounded by the 10 percent and 90 percent seawater contours) for this simulation. Because these contours are vertical, it can be assumed that buoyancy effects due to density differences are minimal. After conducting a sensitivity analysis, it was determined that the following parameters had the greatest effect on the ASR system: intrinsic permeability, effective porosity, longitudinal dispersivity, and leakance. The field investigation was geared to obtaining the most accurate data for these parameters.

In addition to the sensitivity analysis, several simulations were conducted to help determine optimum storage volumes and cycle frequency. The first task was to develop a curve relating cycle efficiency for the initial cycle to storage volumes of 6.35 MG, 15 MG, 25 MG, and 50 MG. These efficiencies were 22.9 percent, 32.2 percent, 38.5 percent, and 47 percent, respectively. A curve relating these values is shown in Figure 5. Unfortunately, this curve does not level off at any obvious point to determine the optimum storage volume. However, the steepest part of the curve occurs up to 15 MG.

According to the sensitivity analysis, density differences do not appear to be affected by the recovery efficiency, which leads to the question of what effect storage time has on recovery efficiency. To help answer this question, storage intervals of 0, 30, 60, 90, and

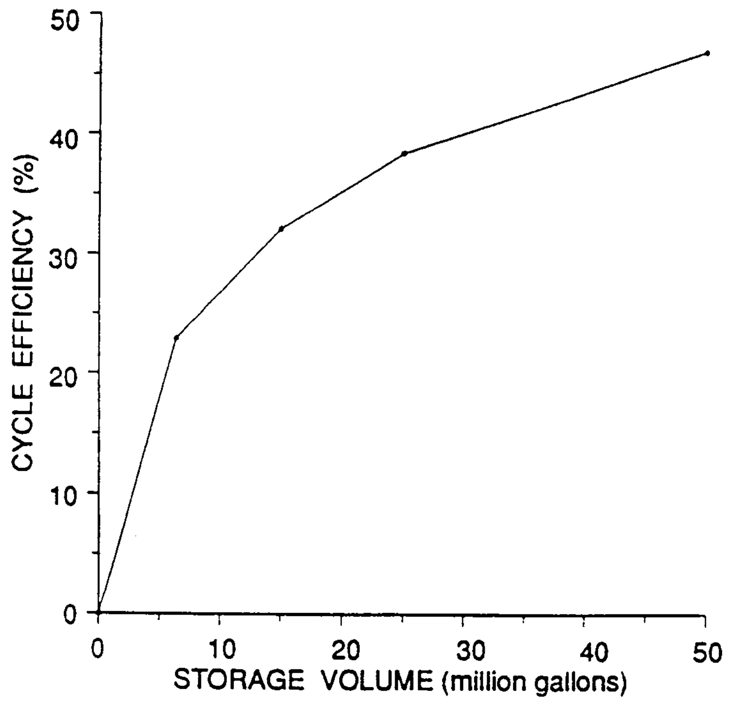

FIGURE 5. Relationship Between Cycle Efficiency and Intial Storage Volume

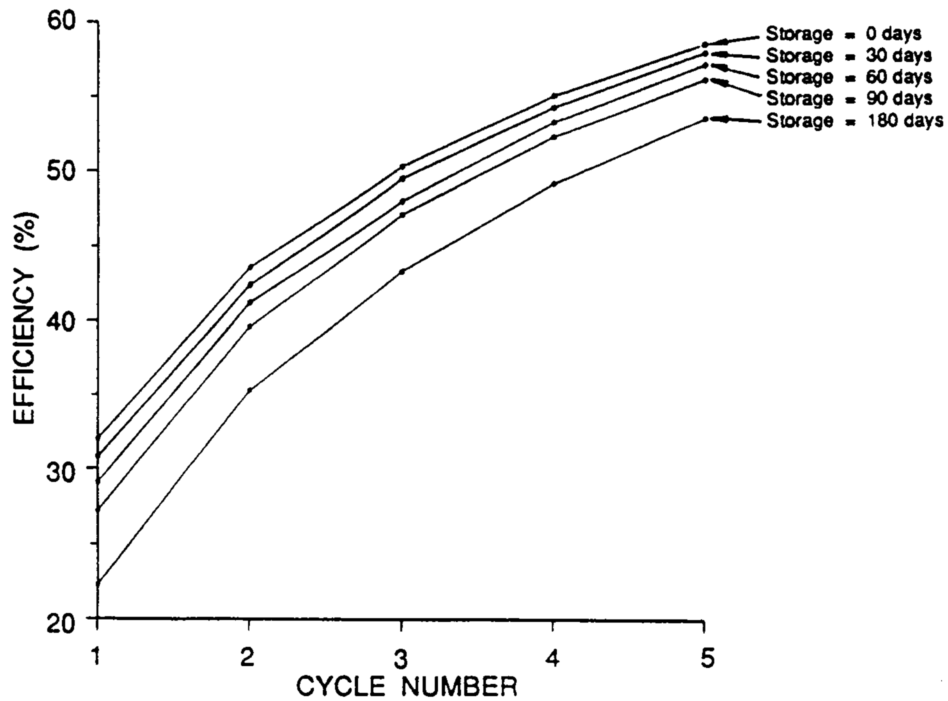

FIGURE 6. Efficiency Vs. the Number of Cycles for Given Storage Duration

180 days were simulated with a storage volume of 15 MG. To be consistent with the previous simulations, five cycles of each storage duration were simulated.

Figure 6 relates efficiency of the ASR system to the number of cycles simulated for each storage interval between injection and recovery. In general, the largest difference in cycle efficiency occurs in the early cycles, but becomes less noticeable with increasing number of cycles. This figure also indicates that as the number of cycles is increased, the efficiency increases, as expected.

ASR Cycles

A tentative schedule of test cycles has been proposed. This schedule may need to be adjusted to accommodate system constraints and improved understanding gained during the test program. Water-quality data will be collected and analyzed for selected cations, anions, and physical properties. Cycle No. 1 will be used to determine the mixing properties of the storage aquifer. Treated water will be injected at a rate, determined by the initial aquifer test, until approximately 15 MG has been injected. There is no planned storage duration for Cycle No. 1. Recovery will begin upon completion of the injection cycle and will proceed until the background quality of the storage aquifer is reached.

The next four cycles are designed to evaluate the improvement in water quality with successive equal-volume cycles and to assess plugging potential. There is no planned storage duration for Cycles No. 2 and 3, and a volume of water equal to that injected will be recovered. Cycles No. 4 and 5 will continue testing for improvement in water quality with successive equal-volume cycles and will also test the effect of storage time on recovery. The same volume will be used for injection and recovery as for Cycles No. 2 and 3, but the water will be stored in the aquifer for one week and four weeks, respectively, before recovery.

CONCLUSIONS

The ASR concept was investigated as a potential means of storing fresh water to meet the emergency needs of the Florida Keys Aqueduct Authority. Preliminary evaluation of ASR at Marathon, Florida, identified a potential storage zone between depths of 410 and 435 feet. Numerical modeling was conducted and confirmed the feasibility of using ASR in a saline aquifer. A 16-inch-diameter ASR well was constructed and screened within the storage zone. Two observation wells were completed in this same zone so that aquifer characteristics could be determined from a 24-hour pumping test. Results of this test indicate the storage zone is moderately permeable, a desirable criterion for ASR. Cycle testing should provide the final data necessary to evaluate full-scale implementation of ASR in the Florida Keys.

ACKNOWLEDGEMENTS

This project is being funded by the Florida Keys Aqueduct Authority (FKAA) as part of a program to provide emergency freshwater resources to residents of the Florida Keys. The authors wish to express their appreciation to Thomas E. Hartye, Director of Engineering of the FKAA, for the support of this project.

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TESTING OF A SALINE AQUIFER FOR AQUIFER STORAGE RECOVERY POTENTIAL

Sean T. Skehan, Albert Muniz, Peter J. Kwiatkowski and Kevin M. Bral

ABSTRACT

An investigation was conducted in the Florida Keys to test the feasibility of Aquifer Storage Recovery (ASR), the underground storage of fresh water, in a saline aquifer. The test site is located in Marathon, the approximate midpoint of the Florida Keys. Potable water supply throughout the Florida Keys is provided by a mainland well field near Miami and is conveyed through a 130-mile pipeline from the well field to Key West. The ongoing investigation focuses on the feasibility of obtaining potable water from the Keys distribution system and storing it in a confined aquifer which contains essentially seawater. Using ASR in the Keys could provide a reserve of fresh water to meet emergency or seasonal demands. During construction of a test well, continuous core samples identified an unconsolidated sand aquifer, bounded above and below by confining units. Using core analytical data, an ASR well was designed and constructed. Results of subsequent hydrologic testing and the performance of four cycles of injection, storage and recovery indicate that high recovery efficiencies of potable water are possible.

INTRODUCTION

Background

Noted for its resort areas and sport fishing, the Florida Keys are home to approximately 80,000 permanent residents and 65,000 seasonal residents. With the exception of small fresh water lenses on Big Pine Key and Key West, potable water is supplied through a 120-mile long transmission line from the Florida Keys Aqueduct Authority (FKAA) well field, located in Florida City, to Key West (see Figure 1).

Along the transmission line, there are several pump stations and 30 million gallons (mg) of aboveground storage owned and operated by the FKAA. Aboveground storage capacity is limited by the availability and high cost of land in the Keys. To meet seasonal and daily peaks in water demand, as well as emergency demands, treated drinking water must be stored. The current storage volume is too limited to provide a source of potable water should an emergency occur. To address this storage need, Aquifer Storage/Recovery (ASR) is being evaluated as a cost-effective solution to system storage needs.

In 1991, the projected average annual daily flow to the FKAA service area is 13.5 million gallons per day (mgd). Since the pipeline from mainland Florida was constructed over 40 years ago, occasional line breaks have impaired its ability to convey water for many days. Because the pipeline crosses 42 bridges in its route, it is especially susceptible to damage by hurricanes.

Principal criteria dictating ASR feasibility and use for the FKAA are: (1) seasonal variations in water supply and/or demand (minimum ratio of maximum day:average day demand is about 1.3:1), (2) useful recovery capacity exceeding 1 mgd, and (3) suitable hydrogeologic conditions for storage and recovery.

To use ASR in the Keys, a thin, well-confined, moderately permeable storage zone was deemed necessary. This would prevent extensive mixing between native water (seawater) and injected water, thereby yielding high recovery percentages. Recovery percentages play an important role in the feasibility of using ASR in the Keys because of the high unit costs for water. Higher recovery percentages will help maintain unit costs.

Based on the findings of a literature search conducted during Phase I of this project (CH2M HILL, 1987), favorable hydrogeologic conditions for ASR were thought to exist at Marathon, Florida. The Marathon pump station was selected by the FKAA as the site for the ASR investigation. Located on Vaca Key the island is the approximate mid-point of a chain of small coralline limestone islands extending south from Miami to Key West.

The second phase of work consisted of constructing a 10-inch-diameter test well (OW-2) to 550 feet below land surface (bls) to identify a suitable ASR zone. Native water quality and hydrologic data were also obtained. Results of this investigation identified a thin, semiconfined, unconsolidated sand aquifer from approximately 390 to 435 feet bls. Water quality of this aquifer indicated chloride and conductivity concentrations as high as 20,800 milligrams per liter (mg/l) and 49,000 micro mhos per centimeter (μmhos/cm), respectively. Hydrologic data indicated an average specific capacity of 3.9 gallons per minute per foot (gpm/ft). Based on the findings of Phase II, design and construction of an ASR system was implemented in Phase III of this project.

Scope

In the third and current phase of the ASR investigation at Marathon, a 4-inch-diameter observation well (OW-1) and a 16-inch-diameter ASR well (ASR-1) were constructed in early 1990 to conduct a series of injection/recovery cycles to determine ASR feasibility. This paper presents hydrogeologic data collected during drilling, discusses aquifer characteristics and water quality, and presents the results of four cycles of injection, storage, and recovery.

Construction Details and Hydrogeologic Conditions

Construction

Phase III construction commenced with the drilling of OW-1. Based on information from Phase II drilling, continuous coring was conducted from 350 to 450 feet bls. Information gathered during the coring was used to more accurately define characteristics of the storage interval and confirm confinement above and below the target ASR zone. Further details regarding coring are presented in the Coring section of this paper. Following coring completion, geophysical logging was conducted from land surface to a depth of 450 feet bls. Logs included natural gamma ray, electric, and caliper. Using core data and geophysical logs, OW-1 was constructed with a casing interval of 0 to 388 feet bls and a screen interval of 388 to 428 feet bls. The well was constructed with 4-inch-diameter, Schedule 80 polyvinyl chloride (PVC) casing and 40 feet of 0.025-inch slot PVC well screen. A 20/30 gravel pack was installed around the screen from 430 to 356 feet bls, with the remainder of the annular space cemented to land surface. Based on the results of core analyses (see Coring section), the screened interval of OW-1 was divided into three intervals (top, middle, and bottom) with a tubing and packer apparatus. This apparatus was installed so that discrete water samples could be collected to determine the amount of mixing taking place in the storage interval. The intervals are 387 to 405 feet bls (top), 405 to 418 feet bls (middle), and 418 to 428 feet bls (bottom).

Following the completion of OW-1, a pilot hole for ASR-1 was drilled to a depth of 435 feet bls. Geophysical logs were again performed on ASR-1 and correlated to logs performed at OW-1 and OW-2 (Phase II). It was determined from this correlation that the depths of lithologic contacts did not vary appreciably across the site. ASR-1 was constructed with casing and screen intervals similar to OW-1 using a 16-inch-diameter, schedule 80 PVC casing and a 70-foot, 10-inch-diameter, stainless steel well screen assembly. The screen assembly consists of 25 feet of riser pipe connected to 40 feet of 0.025-inch slot screen, followed by 5 feet of tailpipe. ASR-1 is located 126 feet from OW-1 and 258 feet from OW-2.

After construction of ASR-1, a mechanical piping system was installed to convey water from the distribution system to ASR-1 during recharge cycles and from ASR-1 to a shallow drainage well during recovery cycles. When the results of testing indicate that water can be recovered back to the distribution system, drainage well use will be discontinued.

Lithostratigraphic Description

The lithostratigraphic description is based on evaluation of previously reported data (CH2M HILL, 1987; CH2M HILL, 1989), examination of drilling cuttings and core samples from the installation of ASR-1 and OW-1, and the results of geophysical logs that were run during well construction. Strata encountered at this site range in age from Miocene to more recent Pleistocene deposits. Figure 2 presents the major stratigraphic units encountered while drilling ASR-1 and OW-1, as well as brief lithologic descriptions and a natural gamma ray log.

Coring

Coring at OW-1 was conducted from 350 to 450 feet bls through a 4-inch-diameter temporary casing. The cores indicated an interval of moderately-well consolidated sandstone with a calcareous clayey matrix with some fossilization from 350 through 387 feet bls. Below 387 feet bls, an unconsolidated medium-to-very-coarse sand extended to a depth of 428 feet bls. This sand was identified as being favorable for ASR because of the lack of clay throughout this interval. At 428 feet bls, a thin layer (approximately 1 foot thick) of highly plastic clay was encountered. This layer defined the lower limit of the ASR interval. The interval from 428 to 450 feet bls was characterized by thin lenses of interbedded clay and layers of unconsolidated quartz sands.

The deposition of the ASR interval appears to have occurred in three zones of sorted material: a very fine- to medium-grained, poorly-sorted quartz sand from 387 to 411 feet bls, a fine-grained to gravelly, well-sorted quartz sand from 411 to 420 feet bls, and a predominately medium-grained, poorly-sorted sand from 420 to 428 feet bls.

Three samples (400 to 405.5 feet bls, 413.5 to 416.5 feet bls, and 417.4 to 420.4 feet bls) were selected from the cored interval for select laboratory parameters. These samples were analyzed to more precisely determine plugging potential in the storage interval. These analyses included X-ray mineralogy, acid insoluble residue analysis, sieve analysis, porosity, permeability, grain density, specific gravity, cation exchange capacity (CEC), scanning electron microscope (SEM) analysis, thin section analysis, energy dispursive chemical analysis, and core photographs with descriptions.

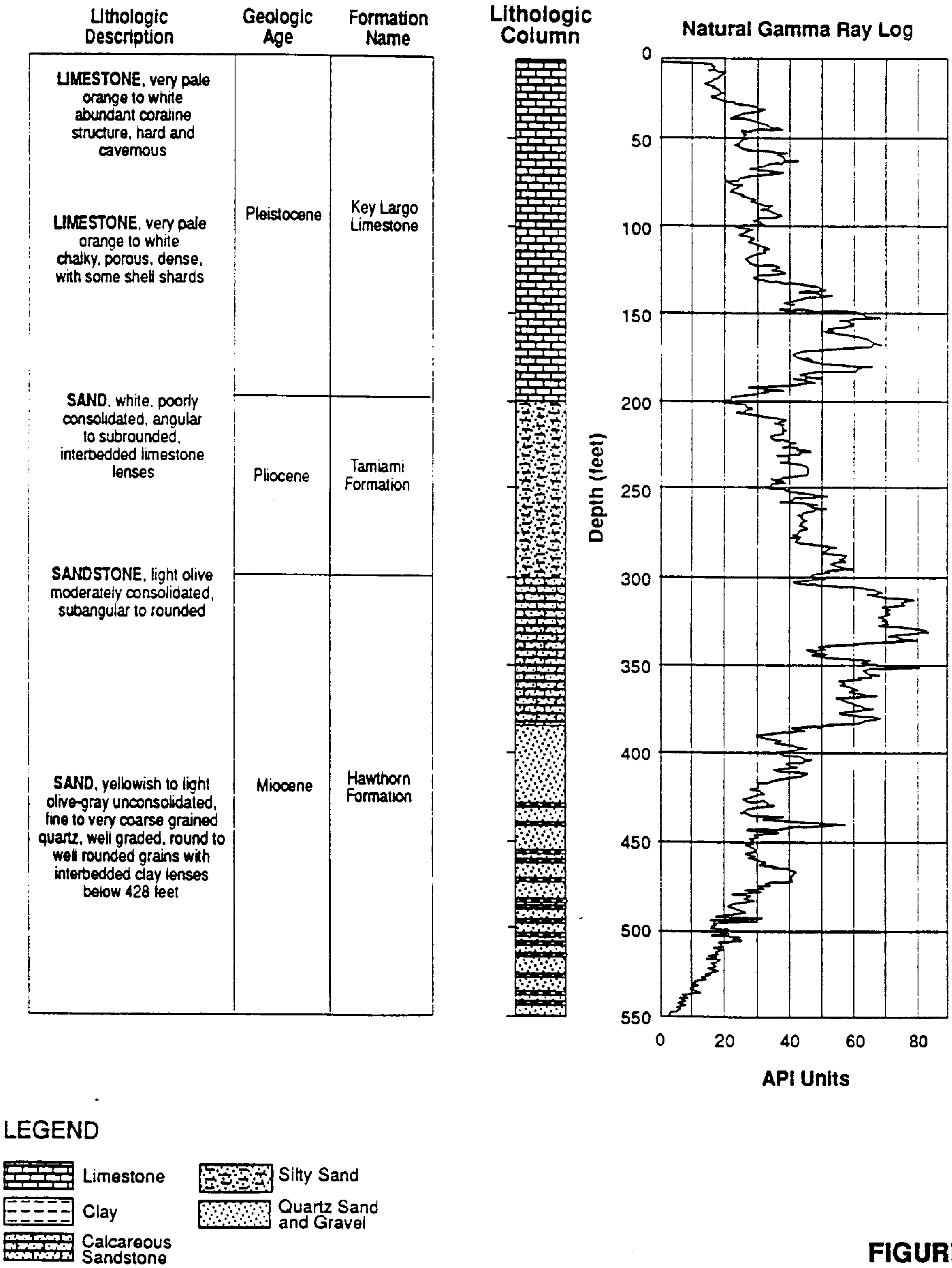

FIGURE 2

Typical Lithostratigraphic Description

The results of these analyses indicated a predominately quartz mineralogy with only minor-to-trace amounts of clay minerals. Fine-grained quartz and carbonate grains were present in significant amounts in two samples, 29.1 percent in the sample from 405-405.5 feet bls and 24.4 percent in the sample from 420-420.4 feet bls. The sample from 416-416.5 feet bls had 5.4 percent very fine sand and silt. The carbonate in each of the samples was concentrated in the fine, particle-sized fraction and appears to be recrystallized shell fragments. Average porosity of the three samples was approximately 31 percent, while average horizontal permeability was 21 ft/day. These data were considered to be favorable for ASR.

Aquifer Characteristics

An aquifer test was conducted at ASR-1 to determine aquifer characteristics at the site. Water level measurements were obtained at OW-1 and OW-2 and the data were analyzed for aquifer parameters using the Walton (1961) Method for unsteady state leaky aquifers. Drawdown data in the pumping well (ASR-1) were also collected to estimate a well loss coefficient and determine the well's specific capacity. Tidal effects were taken into consideration and found to have minimal impact.

Similar aquifer parameters were obtained for the two observation well data sets. The aquifer parameters were then used to calculate the drawdown that would be observed in the pumping well, neglecting well losses. Based on these results, the well losses were estimated and a well loss coefficient calculated. The calculated aquifer parameters reasonably reproduce the observed behavior in the observation wells and the pumping well. Results of the aquifer test are presented below. The storage coefficient obtained is consistent with that of a leaky confined aquifer (Freeze and Cherry, 1979).

Parameter	Well OW-1	Well OW-2
Transmissivity (gpd/ft)	10,050	13,020
Storage Coefficient (dimensionless)	1.7×10^{-4}	2.1×10^{-4}
Leakance (day^{-1})	3.4×10^{-3}	4.2×10^{-3}
Specific Capacity (gpm/ft)	3.8	3.9
Well Loss Coefficient (ft/gpm^2)	9.6×10^{-4}	

Water Chemistry

Water samples of both native and injected waters were analyzed for organics, inorganics, and metals to determine if potential plugging problems might occur. It was determined that the recharge water is alkaline with a pH of approximately 9.5 and low in total dissolved solids (TDS) with a value of 397 mg/l. The pH is important because it controls much of the water chemistry, particularly the precipitation of the carbonate minerals. Based on the concentration of the major ions, the water is classified as a calcium, sodium, sulfate, chloride type.

Native groundwater chemistry is considered to be seawater, with an oxidation reduction potential (Eh) of +100 mv (a slightly oxidizing condition). The dominant water chemistry is sodium chloride at a near neutral pH of 7.1. Trace amounts of silica and aluminum as well as major ions like calcium and bicarbonate are also present. A summary of the major ions and general parameters is presented in Table 1.

Considering the water chemistry of the recharge and native waters, mixture of the two should not create a problem within the storage zone. If the pH remained elevated above 9.5, the concentration of the silica or aluminum in the groundwater could result in the precipitation of clays within the aquifer. However, with porosity values of 0.31, plugging in the storage interval is not considered a problem.

Cycle Testing

Recovery efficiency is a measure of the success of a cycle of injection, storage, and recovery. For this project, the measure of efficiency is expressed as the percentage of recovery in relationship to the chloride concentration of the recovered waters. The drinking water standard of 250 mg/l chloride was used to define usable (potable) water. Water samples were collected on a regular basis throughout each cycle of injection, storage, and recovery. For the purposes of this study, a cycle test is defined as the data collected during a single sequence of injection, storage, and recovery.

Recharge water (potable) was conveyed from the distribution line to ASR-1 by means of a 6-inch-diameter pipeline during four cycles of injection, storage, and recovery. System pressure, typically 50 pounds per square inch (psi), was used as the driving force of injection. Specific capacity during recovery has improved from approximately 2.5 gpm per foot (Cycle 1) to approximately 3.8 gpm per foot (Cycle 4). Improved capacity may be due to the break down of residual drilling mud over successive cycles of injection and recovery. Typical injection and recovery flow rates were from 150 to 200 gallons per minute (gpm).

Table 1
Physical Properties and Chemical Characteristics of Injection and Native Waters

Constituent	Water (mg/l)	Native Water (mg/l)
pH	10.3	7.10
Carbonate Alkalinity	19.0	< 1
Bicarbonate Alkalinity	23.1	120
Conductivity (μmhos/cm)	397	49,000
Carbonate Hardness	110	1,390
Non-carbonate Hardness	95.0	6,480
Turbidity (NTU)	<0.2	0.5
Total Dissolved Solids	212	38,900
Total Suspended Solids	< 1.0	4.2
Calcium	33.8	398
Magnesium	3.75	1,350
Sodium	20	10,500
Potassium	11.4	385
Silica	4.7	6.4
Aluminum	<0.5	<0.5
Iron	0.05	<0.02
Chloride	41.8	20,800
Fluoride	0.80	0.84
Sulfate	91.1	2,910
Nitrate and Nitrite	<0.02	<0.02

ASR Well

To better understand the mixing properties of the recharge water with the native water in the storage interval, recovery efficiency curves from each cycle are plotted in Figure 3. These curves compare the percent volume recovered along the x-axis (volume recovered/total volume injected) with chloride concentrations along the y-axis. For Cycle 1, it was determined that at least 100 percent of the volume of injected water would be recovered. This was equivalent to a total of 5,132,960 gallons of water, representing 113 percent of the volume injected. As shown in Figure 3, approximately 33 percent of the volume stored was recovered before chlorides reached 250 mg/l. At the conclusion of recovery, the chloride concentration (16,200 mg/l) had returned to near background levels (21,000 mg/l). Subsequently, three additional cycles of testing were performed. Table 2 provides a summary of cycle test data showing that cycle efficiency increased from 33 percent in Cycle 1 to 70 percent in Cycle 4. Cycle 2 recovery efficiency was somewhat lower than that observed in Cycle 1 due to a 34-day storage period taking place after Cycle 2 injection.

Observation Well

During injection and recovery, Well OW-1 was constantly pumped at about 2 gpm and samples were periodically taken from each of the three different monitor zones for analysis. The purpose of this sampling was to observe changes in water quality within the aquifer away from the ASR well. Data from these analyses compare chloride concentrations along the Y-axis to the period of injection and recovery, expressed in days along the X-axis (see Figures 4 through 7). Data from Cycle 1 suggests that the salt/fresh water interface was almost vertical as it reached OW-1. Figure 4 shows that a mixing period of about 10 days occurred between recharge and native waters. This was followed by a gradual decrease in chloride concentration. During Cycle 1 complete freshening of the storage interval at OW-1 was not observed. In addition, density stratification was not apparent.

Figure 5 shows the chloride concentrations versus time during Cycle 2. This figure shows that during injection, a mixing period of about 10 days occurred, followed by gradual improvement of water quality with an increase in volume injected. After 22 days of injection, it appears that the bottom zone showed a general trend of having the lowest chloride concentrations (a minimum of 680 mg/l) while upper zone chloride concentrations are consistently elevated above the middle zone. Recovery for Cycle 2 took place over 12 days. Consistent chloride concentrations were observed during the first four days across the storage interval. Thereafter, it appears that some density stratification may have taken place. For example, the bottom zone exhibits chloride concentrations elevated above the top and middle zones while the top and middle zones have similar chloride concentrations.

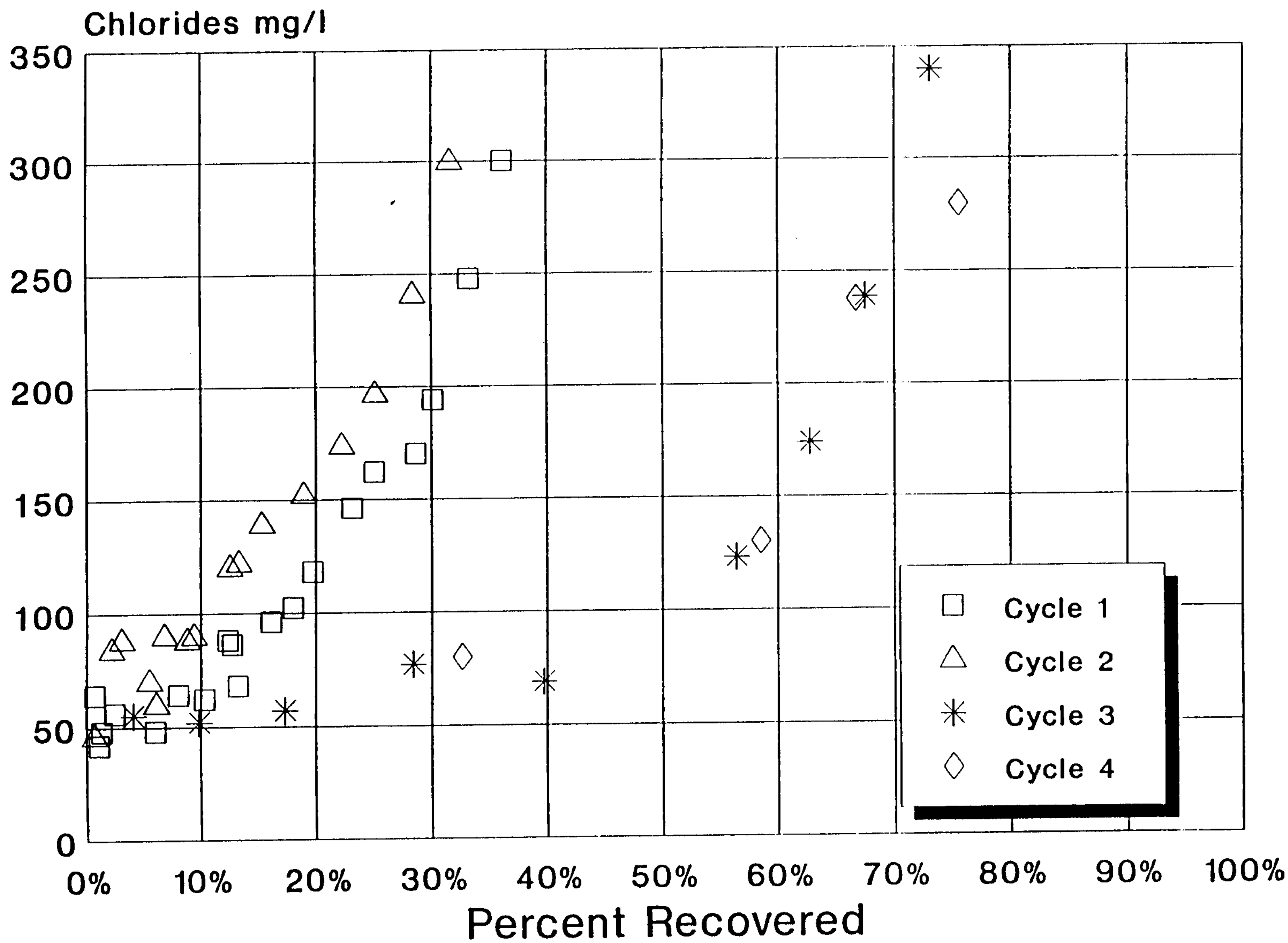

FIGURE 3
Chloride Concentration vs Percent Recovered for Cycles 1-4

Table 2
Summary of Results From Cycle Tests

Cycle	Number of Days Inj./Rec (Days)	Volume Water Injected (Vi) (gallons)	Volume Water Recovered (Vr) (gallons)	Storage Time (Days)	Average Injection/ Recovery Rate (gallons per minute)	Recovery Efficiency (Vr\Vi) (%) Chorides = 250 mg/l
1	18/20	4,514,430	5,132,960	0	200/200	33%
2	44/12	9,698,620	3,457,820	24	153/200	28%
3	28/17	5,322,330	4,181,600	0	132/171	67%
4	15/10	3,623,000	2,751,580	0	167/191	76%

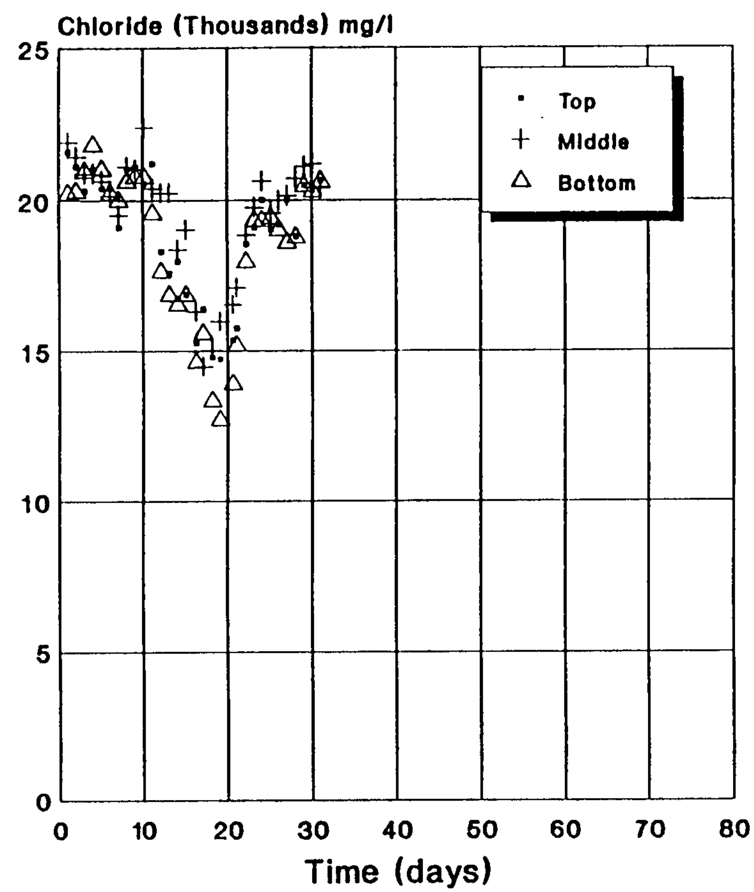

FIGURE 4
Cycle 1 Chloride Concentration vs Time
at OW - 1 During Injection and Recovery

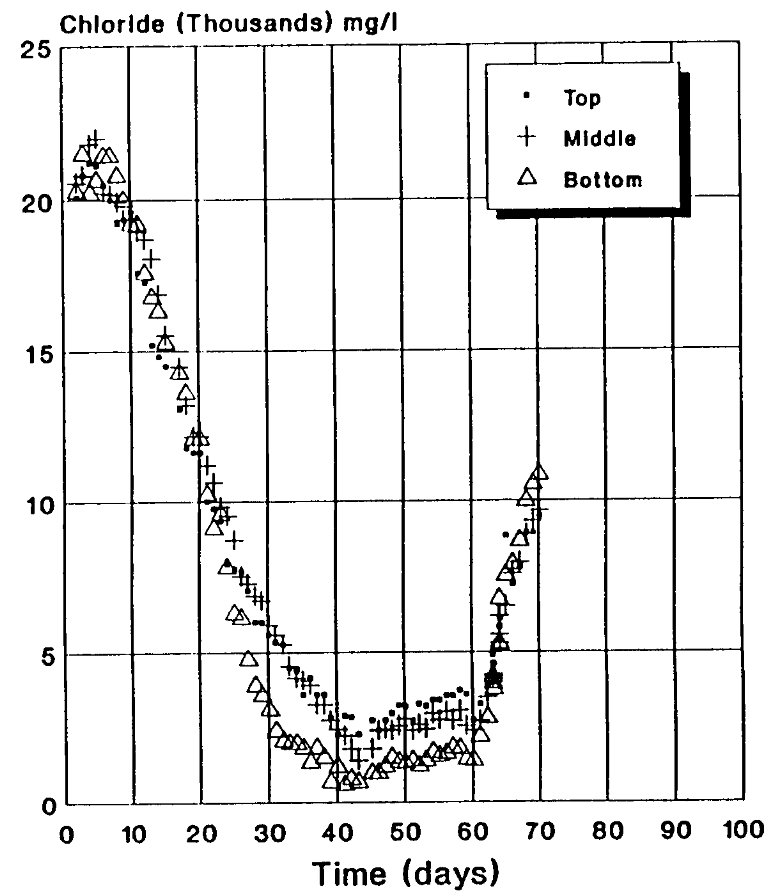

FIGURE 5
Cycle 2 Chloride Concentration vs Time
at OW - 1 During Injection and Recovery

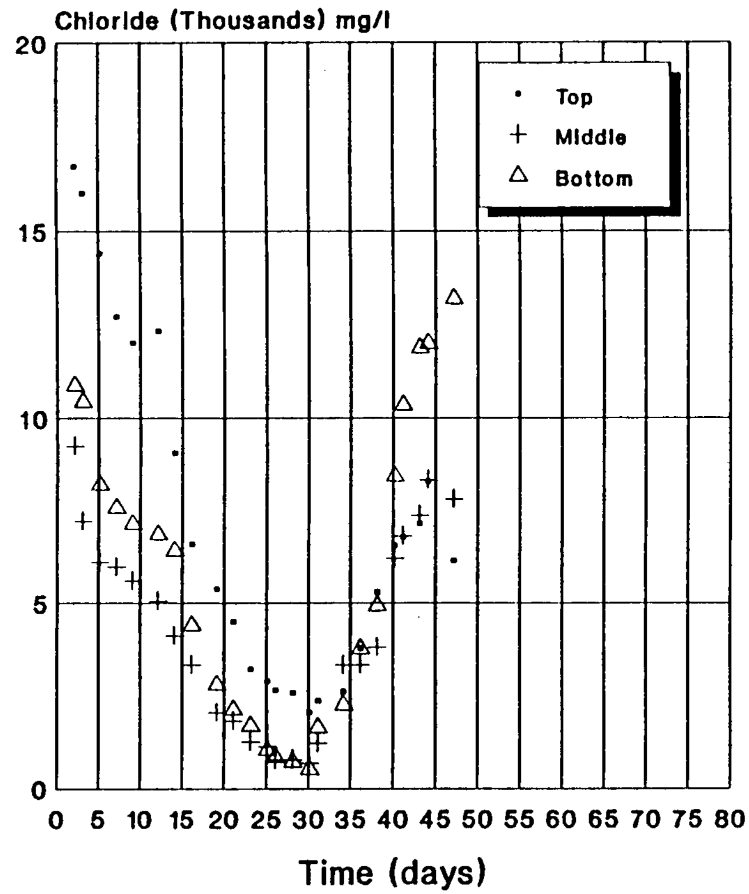

FIGURE 6
Cycle 3 Chloride Concentration vs Time
at OW - 1 During Injection and Recovery

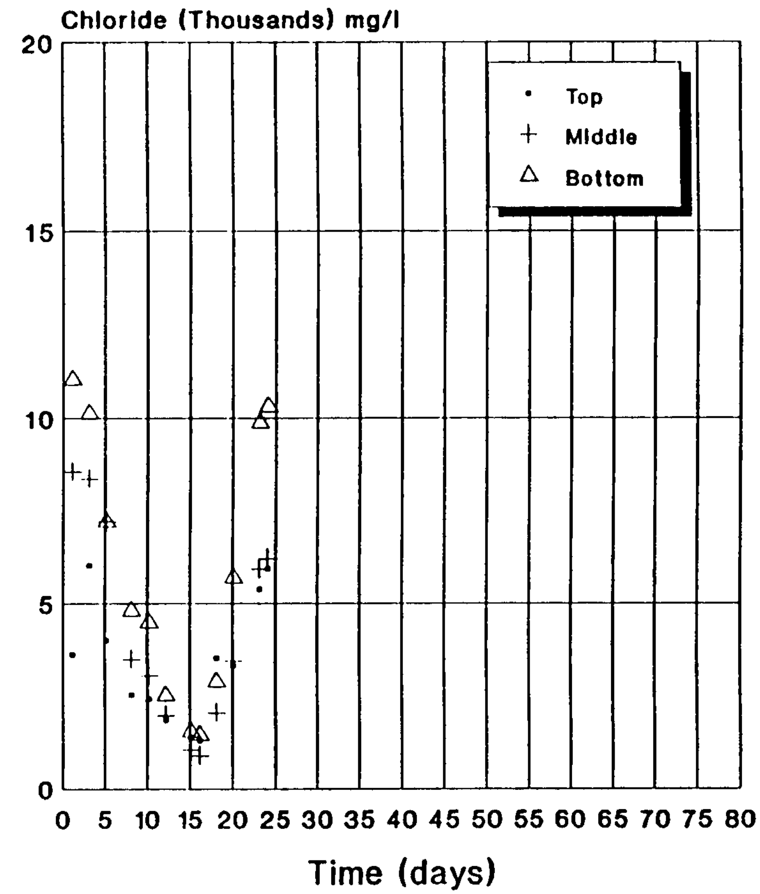

FIGURE 7
Cycle 4 Chloride Concentration vs Time
at OW - 1 During Injection and Recovery

Cycle 3 injection data clearly indicates the top zone having the highest chloride levels throughout the 28-day injection period. During this same period, the middle zone generally exhibited chloride concentrations lower than the bottom. Cycle 3 recovery data at OW-1 see (see Figure 6) exhibited a mixing period of approximately 8 days where chloride levels were similar for each zone. Thereafter, chloride levels in the lower zone again became more elevated than those observed for the upper and middle zones, indicating some density stratification.

Injection and recovery for Cycle 4 (see Figure 7) occurred over a 24-day period. Consistent with results from Cycle 3, bottom zone chloride concentrations are consistently elevated above the middle and top zones during injection and recovery. Based on this data, it appears that some density stratification has taken place.

Summary and Conclusion

ASR investigations conducted at Marathon, Florida, have shown that a thin, well confined aquifer of unconsolidated sand with a saline water composition is present at the site. Aquifer characteristics are conducive to storage of potable water with minimal mixing of seawater, thereby yielding high recovery percentages. Based on geochemical analysis, chemical characteristics of the injected water and native seawater should not create a plugging problem within the aquifer. Four cycles of testing have been conducted using chloride concentrations of 250 mg/l to measure efficiency of recovery. With the exception of Cycle 2, recovery efficiencies have progressively improved from 33 to 70 percent. The results of chloride analyses conducted on water samples from the multi-zone observation well have shown progressive improvement in water quality over time. This chloride data has also shown that the effects of density stratification have been minimized because of the designed construction. Future cycle testing with greater storage periods will be conducted to determine the long-term effects of density stratification within the aquifer.

Results of the investigations have successfully demonstrated ASR as a cost-effective means of storing water in the Florida Keys. Additional testing at the Marathon site and in Key West will determine the extent to which ASR can be implemented.

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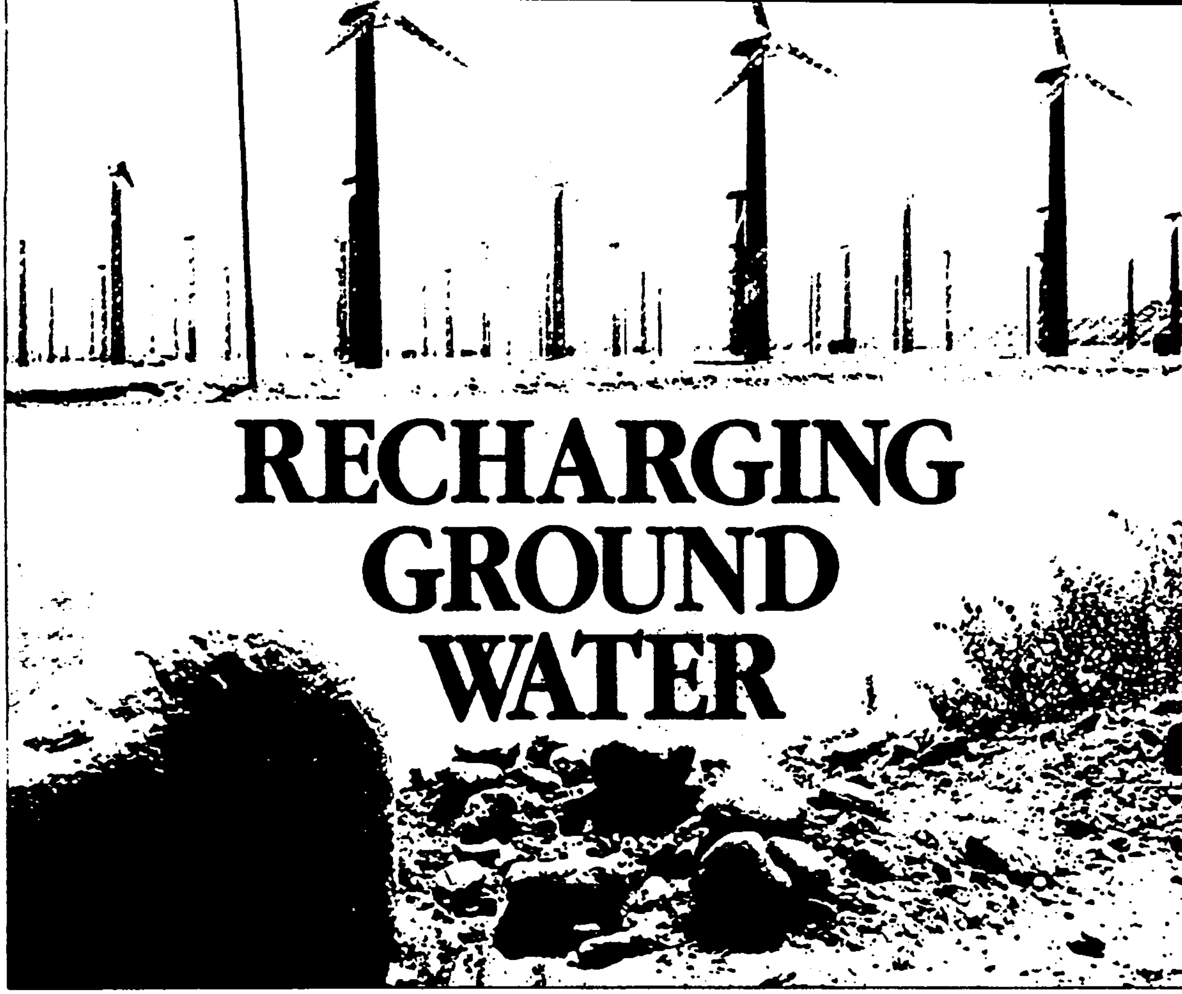


RECHARGING GROUND WATER

Two-way wells are the latest weapons in the fight against depletion of our aquifers.

HERMAN BOUWER
R. DAVID G. PYNE
JAMES A. GOODRICH

The notion that man can assist nature in making ground water a renewable resource is taking hold in many parts of the country. The alternative, especially in arid regions, is to overpump an aquifer until water shortages become disastrous.

Occasional water surpluses, however, do occur in even near-desert areas because of storm runoff, wastewater discharge or excess flow in streams, aqueducts, or other water-delivery systems. Excess precipitation and runoff from weather-modification projects have been known to happen. These surpluses can be stored in surface reservoirs if available or underground through artificial recharge of suitable aquifers.

Advantages of underground storage include high storage capacity, low cost, simplicity and no loss from evaporation. Ground water has been recharged with surface infiltration systems for many years in places where aquifers are unconfined, surface soils are permeable, sufficient land is available and vadose zones have no layers that restrict downward flow. If these conditions do not exist, ground water must be recharged with wells drilled into an aquifer.

Recharge wells are found throughout the U.S. In 1988, 558 of the 719 injection wells surveyed in 14 states were recharging aquifers. The others were being used for saltwater intrusion barriers, drainage and subsidence control.

In 1990, the fastest growing type of recharge is the aquifer storage recovery (ASR) well. Unlike other wells, these are dual purpose: They both store and recover water from the same wells according to supply and demand. Recovered water can be used to help meet seasonal peak, emergency or long-term de-

An off-channel infiltration basin in Southern California recharges ground water with Colorado River water.

Reprinted from Civil Engineering, June 1990

mands. With more efficient use of existing water facilities, the cost of water yielded by ASR wells is low, typically less than half the capital cost of conventional alternatives.

ASR wells can be designed to control movement of stored water within a small radius. Coupling their low cost with this ability to operate with little mixing of recharge and native water shows the ability to store highly treated effluent instead of treated drinking water. The effluent would be recovered from the same wells for beneficial reuse without affecting ground-water quality outside the storage radius.

During storage, the quality of the effluent may be improved by subsurface geochemical reactions that reduce coliforms, nitrogen and phosphorus. Such applications, however, require rethinking the regulations, and they are most likely to be approved where water quality varies with the seasons and where there is a demand for reuse of effluent. In California, Orange County regulations have been rewritten because of the need to reuse effluent (see box).

All of the eight ASR systems currently being operated in the U.S. store treated drinking water. Two are long-term water banks that bridge drought/flood cycles and are expected to meet future demands; the other six are designed to meet seasonal peak demands. The existing storage zones include limestone, sand, gravel, clayey sand, sandstone and glacial drift aquifers. A fractured granite site is being assessed for one of the proposed projects.

Several other systems are in various stages of investigation, design, construction or testing in 10 states. The quality of aquifers targeted as storage zones ranges from fresh to brackish. The total dissolved solids (TDS) concentration of native water at the operational sites ranges from 440 to 1,360 mg/l, while two of the future sites in Florida have concentrations of 7,000 and 35,000 mg/l.

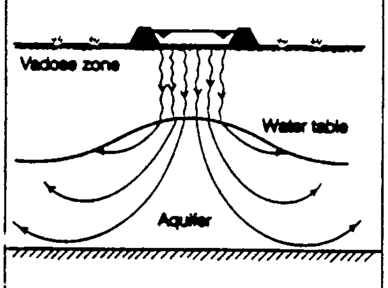
Sources of water for ASR systems include both well fields and surface supplies. General Development Utilities, Inc., a private utility, operates the 12 mgd Peace River Water Treatment Facility serving Port Charlotte in southwest Florida. Because the river varies in both flow and quality, an offstream reservoir of 1,920 acre-ft is used to ensure a reliable water source.

The utility began an expansion program in 1985 that, instead of adding reservoir capacity, drove ASR wells at the water-treatment plant site in two brackish, limestone artesian aquifers. Potable water is stored underground during months of low demand and is recovered at rates of up to 5 mgd to help meet peak demand.

The city of Cocoa, Fla. supplies treated water at peak daily rates up to the 40 mgd capacity of its well field and water-treatment plant. The ASR system at the plant site is being expanded to a recovery capacity of 8 mgd, with a storage zone in a brackish limestone artesian aquifer. The project permits the city to defer expansion of other facilities in its water-supply system while still meeting peak demands.

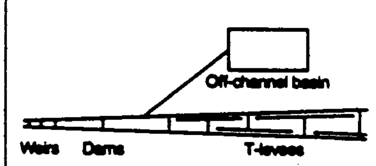
In any ASR system, it is important to recover all the water that has been stored or as close to that as possible. To lessen the chance of plugging the wells, the quality of the recharge water should approach or meet drinking-water standards. At this level of quality, the water is too valuable to waste with less than full recovery.

FIGURE 1.
RECHARGE SYSTEM



Infiltration basin, wetted zone, ground-water mound and flow lines in aquifer.

FIGURE 2.
IN AND OFF CHANNEL



In-channel infiltration facilities (weirs in steep channel, dams in mild channel and T-levees in flat channel) and off-channel basin.

Although ASR wells are usually designed for high recovery with minimum blending of stored and native water, engineers at several installations have found that water quality improves with successive operating cycles. This reflects the flushing of the storage zone within a given radius around the well.

An ASR system must be specific to the site, designed according to the aquifer hydraulics, thickness, density differences and degree of storage-zone confinement. Even where the native ground water is unsuitable, appropriate well design and operation can produce adequate supplies of high-quality drinking water.

A pump in each well is essential in an ASR system. In addition to recovering the stored water, the pump is used to back-flush the well periodically during recharge periods to maintain recharge capacity without the need for a major well redevelopment operation. Recharge occurs through the pump column, the well annulus, one or more injection tubes or a combination of these. The best design is one that gives the greatest degree of flexibility, with a wide range of recharge flow rates, but without causing free-falling wate · ınd air entrainment.

Such a design is more complex than either a recharge well or a normal production well. Typically, recharge-specific capacity is less than recovery-specific capacity. One reason lies in the differential elasticity of the aquifer under recharge and recovery conditions. Reported specific-capacity ratios range from 0.2 to 1.0. To control bacteria, operators normally maintain a disinfectant residual within the well at all times during recharge and storage. This would be, for example, at least 0.5 mg/l chloramine or chlorine.

In some locations, the principal advantage of new ASR wells will be improved system reliability. The Florida Keys Aqueduct Authority is testing the feasibility of ASR as part of its distribution system. Currently, the authority supplies water from its Florida City well field and water-treatment plant to Key West, 120 mi away. The pipelines cross 42 bridges in an area frequented by hurricanes.

Treated water would be stored during off-peak months at Key West and nearby Marathon, then recovered to meet seasonal peak or emergency demands. In addition to improving system reliability, the ASR wells would reduce storage capital costs by more than 90%.

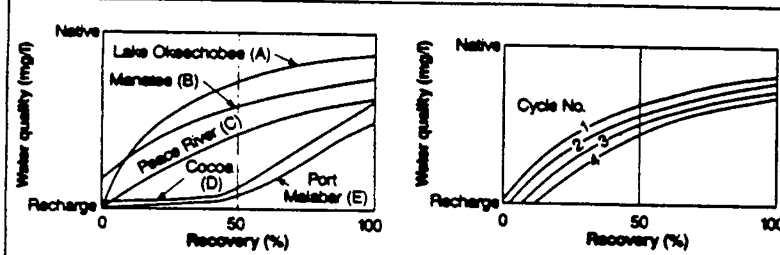
CONVENTIONAL RECHARGE

Throughout the world, aquifers provide the opportunity for storing large volumes of water at far lower cost than reservoirs or tanks. Where geologic conditions are suitable and land is available, surface recharge is the least-cost approach. Conventional infiltration methods can be grouped into in-channel and off-channel systems.

In-channel systems are weirs, dams or levees that spread the water over a streambed or flood plain, usually designed to be replaced or repaired after spring runoff or other flooding. Dams may be built with washout sections, while the smaller weirs and levees are considered expendable and easy to reconstruct completely.

FIGURE 3.

WATER QUALITY



Water quality during initial cycle recovery. Typical water-quality improvement in successive cycles.

Off-channel systems may consist of old gravel pits or of specially built basins or channels. These are most common in California, where there are hundreds of successful projects. Infiltration rates during inundation range from 1 to 10 ft/day. Year-round recharge systems with periodic drying and cleaning of the basins are typically rated at 100–1,000 ft/year.

Periodic drying and cleaning are vital because soil clogging lowers infiltration rates. Silt, clay and other fines can accumulate in clogging layers from 0.1 in. to 2 ft thick. Even with very clear water, biofilms can develop on the wetted perimeter, and algae can clog the bottom soil.

Clogging tends to be more severe when the water is stagnant than when it is moving in recharge channels or T-levee systems. When infiltration rates drop too low, drying the system shrinks and partially decomposes algae, biofilms and other organic deposits. Clogging material such as silt or clay deposits must be physically removed from the bottom by "shaving" with a front-end loader, scraping or other means. Plowing or disking the clogging layer into the soil will improve the bottom temporarily, but the fines will then accumulate deeper in the soil so that eventually the entire top layer must be removed.

Optimum lengths of flooding and drying periods depend on the soil, the suspended-solids content and nutrient levels of the water, and the climate. Some recharge systems in arid regions operate only during rain or flooding. Other cycles are controlled by environmental factors (insect breeding, odors, unsightly floating algae) or recreational demands, so that they vary from four days flooding and 10 days drying to 11 months flooding and one month drying.

The water depth in infiltration basins should be carefully selected. The hydraulic heads of large water depths produce high infiltration rates, but they also tend to compress clogging layers, raising the hydraulic resistance of the bottom. Thus, contrary to intuitive expectations, deep basins can produce lower infiltration rates than shallow basins. Also, the rate of turnover of the water in a deep basin is less than in a shallow basin, allowing more suspended algae to grow in longer exposure to sunlight.

METRICS

1 mi = 1.6 km; 1 ft = 0.305 m; 1 gal. = 3.8 L; 1 oz = 28,000 mg; 1 acre-ft = 233m^3.

The second design criterion is that the ground-water table must be deep enough below the infiltration system so that it does not interfere with the infiltration process. This applies to the permanent water table and the mounding caused by recharging, as well as to perched ground-water mounds that may form on restricting layers in the vadose zone.

Where infiltration rates are controlled by the clogging layer (which is the rule rather than the exception for basins and ponds), the water table must be 3 ft or more below the bottom of the basin. Where there is no clogging layer, the depth of the ground-water table at some distance from the water surface of the infiltration system should be at least 1.5 times its bottom width.

Thus, where ground-water levels are high, maximum infiltration rates can only be obtained with long narrow streams or basins spaced well apart. Equations have been developed to calculate the rise of ground-water mounds below infiltration systems, which must be tailored to local hydrogeology, water quality and climate.

In general, basins should be less than 2 ft deep and hydraulically independent so that each can be flooded, dried and cleaned according to its best schedule. Inlet structures must not allow erosion that could clog the bottom. Drying periods should be started before infiltration rates have reached low values. Drying is then accomplished by infiltration, and pumping or draining the basins is not necessary. Finally, there should be a number of basins for flexible operation, with some in reserve to handle maximum water flows.

WATER QUALITY

For relatively pure water, the quality for ground-water recharge is measured by suspended solids (SS), total dissolved solids (TDS) and major cations such as calcium, magnesium and sodium. Periodic

WASTEWATER REDUX

In the next 25 years, California's Orange County Water District will have to look to new water supplies. Over the 55 years the district has overseen the area's extensive ground-water basin, it has recharged more than 7 million acre-ft of water. But in the next decades, ground-water production will increase from 250,000 to about 450,000 acre-ft per year. Additional imported supplies from the Colorado River and Northern California may not be available in the future, so the district must expand its reclaimed wastewater capabilities.

Wastewater reclamation is the district's legacy and its future. One example is its Water Factory 21, constructed in 1974, which can treat up to 15 mgd of municipal wastewater that the district gets from neighboring Orange County sanitation districts. The treatment train includes coagulation, filtration, carbon adsorption and reverse osmosis. The resulting water is injected into aquifers along the coast to protect the main part of the ground-water basin from sea-water intrusion. Water Factory 21 is scheduled for a doubling of its capacity by mid-1995.

The district is also involved in a subtler form of wastewater reclamation. During the last 20 years, most of its recharged water has been reclaimed wastewater spread in its facilities along the Santa Ana River. Base flow diverted into these basins currently averages about 120,000 acre-ft per year discharged into the river from treatment plants upstream from Orange County. Because of the rapid growth in the upper Santa Ana watershed, this flow will increase to over 200,000 acre-ft per year by 2015.

Currently, the district is either constructing or planning several new reclaimed wastewater projects in a joint effort with Orange County sanitation districts. The 7.5 mgd Green Acres Project, an advanced wastewater-treatment plant, is under construction and will deliver reclaimed water for direct irrigation of parks and greenbelts. Several other projects are also in the planning stages. Orange County Water District is planning to convert a second sea-water intrusion barrier from fresh water injection to reclaimed-water injection in a joint project with the Los Angeles County Sanitation District. Another joint project will treat wastewater at three 25 mgd satellite plants located around the county. The satellites are scheduled to go on line by the end of the century.—JAG

TABLE 1.
OPERATIONAL ASR FACILITIES

		Capacity (mgd)	
	Start	ASR wells	Maximum day demand
Wildwood, N.J.	1968	3.5	12
Gordons Corner, N.J.	1971	2.4	10.5
Goleta, Calif.	1978	6.0	21
Manatee, Fla.	1983	3.5	40
Peace River, Fla.	1984	4.9/11.0*	10
Cocoa, Fla.	1987	1.0/8.0*	36
Las Vegas	1988	20	296
Port Malabar, Fla.	1989	1.0	6.0

*ASR expansion.
Ten other states have ASR systems in various stages of investigations, design, construction or testing.

cleaning is necessary when SS causes clogging of the wetted perimeter of infiltration systems. Where the SS content is too high, the water is first passed through desilting or presedimentation basins to reduce cleaning costs. Coagulants may be added for this process, and on-site experiments will determine the combination of pretreatment and cleaning schedules for optimum economy and hydraulic capacity.

TDS and concentrations of calcium, magnesium and sodium determine whether a clay is dispersed or flocculated and therefore whether it has a low or high hydraulic conductivity. This affects clay in the clogging layer of sand and gravel recharge systems. Thus, TDS, calcium and magnesium should be high enough and sodium low enough to keep the clay in the clogging layer in a flocculated, relatively permeable state.

In conventional systems, recharging sewage effluent, storm runoff or other polluted water can improve its quality. Suspended solids are removed, biodegradable organic matter is decomposed, microorganisms are taken out, nitrate concentrations and some synthetic organic compounds are reduced, and phosphate and heavy metals are immobilized. Because of this, ground-water recharge can be used as a step in the treatment train for reuse of wastewater. It is then called soil-aquifer treatment or SAT.

To protect high-quality native ground water and nearby drinking-water wells, SAT systems are designed as recharge-recovery systems where recharge water is pumped out of the aquifer again with strategically located interceptors. The water typically can be used as such for irrigation and recreation and, with further treatment, for drinking. These systems are inexpensive and simple to operate, and enhance the aesthetics of using recycled sewage for public water supplies by breaking the toilet-kitchen faucet connection.

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Using pH Adjustment to Control Iron Concentrations in the Recovered Water from Aquifer Storage and Recovery (ASR) Wells

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Abstract

Native groundwater from the Potomac-Raritan-Magothy (PRM) Aquifer System of the Atlantic Coastal Plain often exhibits iron concentrations in excess of the Federal Secondary Drinking Water Standard of 0.3 mg/l. The origin of these elevated concentrations appears to be iron bearing minerals in a reduced state within the aquifer matrix. These minerals include iron sulfides such as pyrite (FeS_2), and marcasite (FeS_2), and the iron and manganese carbonate, siderite ($FeCO_3$). The presence of these minerals presents unique geochemical problems for recovering drinking quality water from Aquifer Storage and Recovery (ASR) wells. During the recharge mode of operation, these minerals are exposed to oxygenated drinking water resulting in reactions which produce dissolved Fe II, Fe III and Mn II, decreasing pH and alkalinity, and increasing sulfate (SO_4) concentrations in the stored water.

At an ASR site in Cherry Hill, New Jersey, operated by New Jersey-American Water Company, iron concentrations in the native groundwater of the Middle PRM Aquifer are 2.5 mg/l with a pH of 6.5. The geochemical signature of the native groundwater, and mineralogic analysis of core samples indicates the iron sulfide mineral, pyrite, is present within the aquifer matrix and surrounding confining beds.

To prevent dissolution of pyrite during recharge operations, the pH of the injectant water was adjusted from 7.3 to 8.3 with sodium hydroxide (NaOH). Hydroxyl ions (OH-) released by adding NaOH to the recharge water react with iron sulfides to form an iron oxyhydroxide coating on the mineral grain

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surface which prevents further reaction with the oxygen-containing recharge water. This coating also adsorbs dissolved iron and manganese ions mobile in the aquifer environment. Over the course of three recharge/recovery cycles (of about 38, 77, and 286 thousand cubic meters), iron concentrations in the recovered water were below the method detection limits after 100 percent of the stored water was recovered in the third cycle. Other water quality parameters (major cations and anions, pH, Eh, and manganese) indicate that recovered water quality improves with each recharge/recovery cycle suggesting that the aquifer mineralogy is progressively conditioned by the OH^- ions with successive cycles. Other reactions associated with recharge of oxygenated water, such as cation exchange, manganese dissolution, and oxidation of minerals within the aquifer matrix also decreased with successive cycles.

Introduction

Native groundwater from the Potomac-Raritan-Magothy (PRM) Aquifer System of the Atlantic Coastal Plain often exhibits iron concentrations in excess of the Federal Secondary Drinking Water Standard of 0.3 mg/l. The origin of these elevated concentrations appears to be iron bearing minerals in a reduced state within the aquifer matrix. These minerals include iron sulfides such as pyrite (FeS_2) and marcasite (FeS_2), and the iron and manganese carbonate mineral, siderite ($FeCO_3$).

The presence of iron bearing minerals in a reduced state presents unique geochemical problems for recovering drinking quality water from Aquifer Storage and Recovery (ASR) wells. During the recharge mode of operation, these minerals are exposed to oxygenated drinking water which results in reactions which alter the geochemical signature of the stored water. Reactions between the oxygenated recharge water and pyrite or siderite produce dissolved Fe II, Fe III, and Mn II, a decreased pH and alkalinity, and increased sulfate (SO_4) concentrations.

Method Used to Control Iron

Several insitu and pretreatment solutions have been attempted at standard production wellfields and ASR facilities to control elevated iron concentrations in produced water. These methods include Vyeredox (Rundell and Randtke, 1987), aquifer acidification (Glanzman, et.al, 1994), and pH adjustment/pretreatment of the recharge water. The third method, and the subject of this paper, involves perpetual pH adjustment of recharge water with sodium hydroxide (NaOH) to a pH between 8.3 and 8.6. The method is intended to prevent dissolution of pyrite and siderite by stabilizing the minerals insitu. Hydroxyl ions (OH^-) released by NaOH reacts with iron sulfides to form an iron oxyhydroxide (along with other oxygenated iron species) coating on the pyrite mineral grain surface which prevents further reaction with the oxygenated recharge water. This coating also adsorbs dissolved iron ions mobile in the aquifer environment. A similar reaction occurs with siderite.

During reactions with the hydroxyl ion, a hydroxide coating is precipitated on the mineral grain surface which isolates the grain within the aquifer environment. This coating also absorbs dissolved iron and manganese ions released from the oxidation reaction with siderite (Postma, 1983).

Case Study

New Jersey-American Water Company's (NJAWC) Murray Avenue ASR facility is located in Cherry Hill, New Jersey (Figure 1). The ASR well was installed in the Middle PRM Aquifer. Beneath Murray Avenue, the Middle PRM Aquifer is 36.6 meters thick and consists of coarse to medium quartz sand interbedded with variegated and lignitic clay beds. Core samples collected within the aquifer indicate that pyrite is located within in the aquifer matrix as grains and pore lining cement at amounts ranging from 0 to 1 percent of the bulk mineralogy. Siderite appears restricted to the finer grained confining units (Figure 2).

The chemistry of the native groundwater from the Middle PRM Aquifer is characteristic of groundwater in the presence of pyrite. Groundwater is slightly acidic (pH=6.7) with elevated iron (2.5 mg/l) and manganese (0.2 mg/l) concentrations. Total dissolved solids concentrations are relatively low at 120 mg/l while sulfate is high for groundwater in the PRM Aquifer System, at 25 mg/l. The groundwater is a calcium-bicarbonate type with a slightly reducing redox potential (Eh = 45mv).

Three ASR test cycles were performed at water volumes ranging from 38 to 286 thousand cubic meters (m^3) (Table 1). A single test cycle consists of a period of recharge, storage, and recovery. Two or three water quality samples were collected during the recharge period to characterize the chemistry of the injectant water. Five to seven samples were collected at regular time intervals during the recovery period to evaluate the changes in water chemistry which occurred after storage in the aquifer. Physical parameters including pH, Eh (redox potential), temperature, dissolved oxygen (DO), and specific conductivity were collected at the wellhead in a flow-through cell during each recharge and recovery water quality sampling episode.

Table 1
Summary of ASR Test Cycles at Murray Avenue

Cycle	Volume Recharged (m^3)	Volume Recovered (m^3)	Percent Recovered (%)
1	38,124	34,522	91
2	77,234	67,976	88
3	286,056	285,959	100

During the recharge portion of all three cycles, the pH of the recharge water was adjusted from 7.3 to 8.35 with 50 percent strength NaOH. About ninety percent of the stored water was recovered during the first two cycles and 100 percent was recovered during the third cycle (Table 1). Because of excellent water quality results, the New Jersey Department of Environmental Protection (NJDEP) permitted recovered water to be introduced into NJAWC's distribution system during the third cycle.

Water Chemistry Changes Related to Aquifer Storage

Changes in the chemistry of water that is recharged and stored in an aquifer is dependent upon reactions between the recharge water, the native groundwater and/or the minerals within the aquifer matrix and surrounding confining beds. Physical mixing between the native groundwater and recharge water can also effect the chemistry of water recovered from the storage aquifer.

Chloride concentrations were used as a conservative, nonreactive tracer element during the three test cycles to evaluate the degree of mixing between the two waters. Chloride concentrations of the recharge water (4 to 5 mg/l) are roughly four times the concentrations within the native groundwater (1 mg/l). A graph of chloride concentrations versus recharge water recovered (Figure 3) suggests that there was minimal mixing between the native groundwater and the recharge water during Cycles 1 and 2. Chloride concentration data from Cycle 3 fluctuates between 1 and 4 mg/l after 90 percent of the water was recovered. These fluctuations at the end of the ASR Test Cycle suggest that some mixing between the two waters may have occurred due to migration of the recharge water bubble under the regional hydraulic gradient.

Iron

Total and dissolved iron concentrations from Test Cycles 1 through 3 were below the method detection limits for every cycle (Figure 4). The absence of iron in the recovered water indicates that adjusting the pH of the recharge water with NaOH is effective for stabilizing iron bearing minerals such as pyrite and siderite insitu. The small amount of mixing revealed by the fluctuating chloride concentrations at the end of Cycle 3 suggests that the adsorptive coating developed on iron bearing mineral grains and iron bearing pore lining cements were effective in removing dissolved iron ions migrating with the native groundwater and recharge water mixture.

The geochemical signatures of the recovered water for all three cycles were similar and defined by decreasing pH, alkalinity, and dissolved oxygen. In each cycle, the pH decreased from 8.35 (recharge water) to as low as 6.49 (80 percent recovered Cycle 3; Figure 5). Alkalinity decreased from a concentration close to the recharge water (81 mg/l) to a concentration equivalent to the native groundwater (72 mg/l). These reactions are attributable to the natural background acidity of the Middle PRM Aquifer and the tendency of water to equilibrate to its original chemistry. Because distribution water in NJAWC's system originates predominantly from the PRM aquifer system, the stored water exhibits a tendency to revert to its original chemistry, as OH^- ions are removed during storage in the aquifer environment.

Stable sulfate concentrations are a strong indicator that pyrite has been stabilized. If the amount of hydroxyl addition was insufficient to pervasively condition pyrite grains and cements with an iron oxyhydrode coating, pyrite oxidation would be a continuing reaction with the recharge water during storage in the aquifer. Pyrite oxidation results in the release of a bisulfide ion for each iron ion oxidized. Bisulfide ions then are further oxidized to two sulfate ions, doubling sulfate concentrations and consequently reducing pH (Rundell and Randtke, 1987). In aquifers where pyrite is pervasive, oxidation of the mineral can reduce the pH to less than 6.0 and double the sulfate concentrations (Postma, 1983).

<u>pH</u>

The decrease in pH was uniform over the three Test Cycles (Figure 5). Similarity in pH tracking between cycles indicates that aquifer geochemical characteristics such as pyrite distribution, native acidity, clay mineral distribution and redox potential is fairly uniform in the aquifer storage zone occupied by the recharge water from the three test cycles. The uniformity in pH tracking between the cycles also suggests that the reduction in pH should moderate with successive cycles.

An example of this moderation is shown by comparing pH values at equivalent volumes recovered from Cycles 2 and 3. With 56,840 m^3 of the stored water recovered during Test Cycle 2 (75 percent;Figure 5), the pH of the recovered water was 6.9. In contrast, with 56,840 m^3 of water recovered during Cycle 3, the pH of the recovered water was 7.7.

<u>Eh</u>

Redox potential (Eh) of the native groundwater in the Middle PRM Aquifer is slightly reducing at 45 millivolts (mv). Eh of recovered water samples from Test Cycles 1 and 2 tracked in a similar manner (Figure 6) and ranged from 250 to 120 mv. These values appear to represent a gradient between oxidizing and slightly reducing conditions within the ASR storage zone. These values are consistent with the expected oxidizing conditioning of the aquifer. As OH^- ions in the recharge water dissipate away from the wellbore, the intensity of oxidation reactions decrease.

Eh values during Cycle 3 exhibited a significantly different trend than the first two test cycles. Eh ranged from 177 mv at the beginning of the cycle and increased to 424 mv at the end (Figure 6). Only the initial value at 20 percent recovered, was similar to values collected during the first two cycles (Figure 6). The increase in Eh values during Cycle 3 may provide insight into changes of the redox potential of the aquifer storage zone imposed by conditioning with NaOH. At 20 percent recovered (56,840 m^3) during Cycle 3, water was still being withdrawn from the aquifer zone conditioned during Cycle 2. The remainder of the water quality samples from Cycle 3 represents water that traversed the aquifer zone around the ASR well previously conditioned by recharge water from Test Cycles 1, 2 and 3. This zone was sufficiently oxidized from three cycles of conditioning with NaOH, that water passing through the zone exhibited oxidizing Eh values. Furthermore, recovered water traveling a greater distance through the oxidized, conditioned zone exhibited higher Eh values than water migrating closer to the ASR well.

Conclusions

Results from the ASR Test Cycle Program at NJAWC's Murray Avenue Station indicates that using NaOH to increase the pH of recharge water is an effective method for preventing iron concentrations in the recovered water from ASR wells. The geochemical signature of the recovered water suggests that pyrite and siderite are stabilized insitu. The OH^- ions released from NaOH condition the aquifer matrix by creating an iron oxyhydroxide coating on pyrite and siderite grains and cements. Despite the insitu coating of aquifer minerals, the well specific capacity and aquifer parameters (transmissivity, storativity) remained constant during the three test cycles. With successive cycles, oxidizing conditioning of the aquifer storage zone imparts an oxidizing Eh on the recovered water. The trend of other water quality parameters (pH, Eh, manganese) over the three test cycles indicates that water quality improves with each successive cycle.

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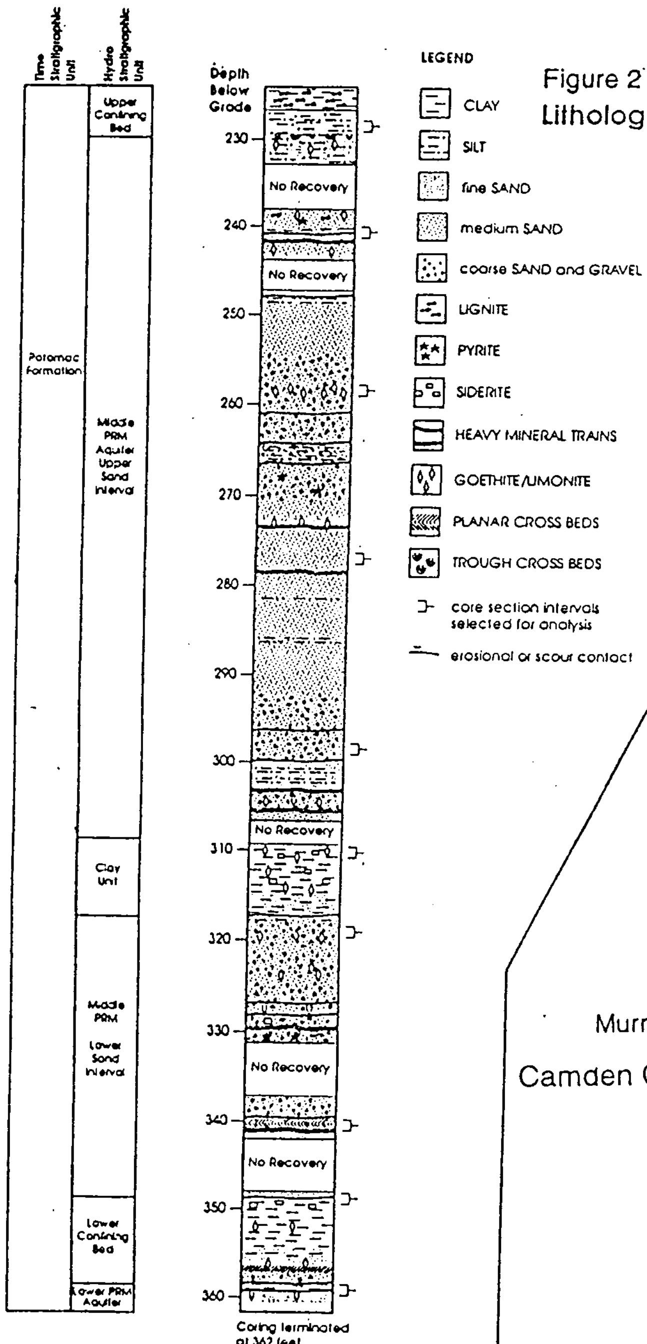

Figure 2
Lithologic Log of Corehole at MW-1

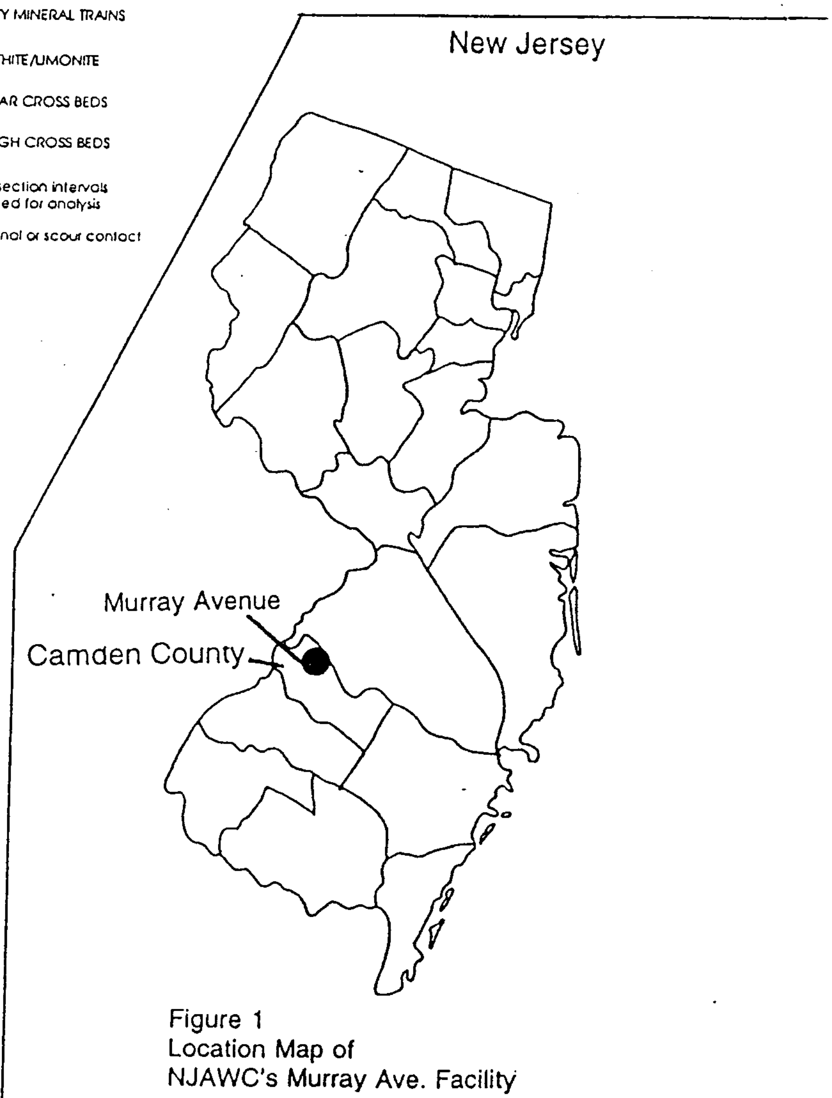

Figure 1
Location Map of
NJAWC's Murray Ave. Facility

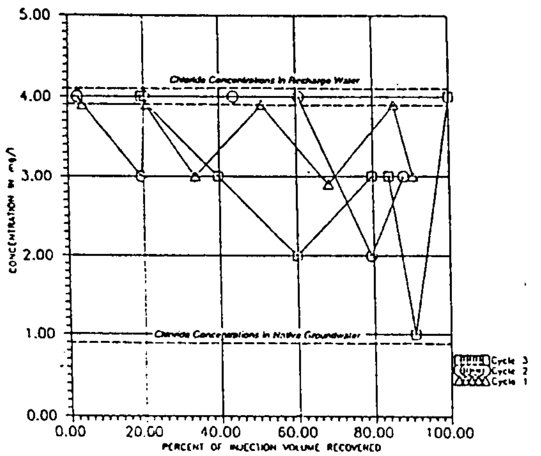

Figure 3 Chloride Concentrations in Recovered Water Cycles 1 Through 3

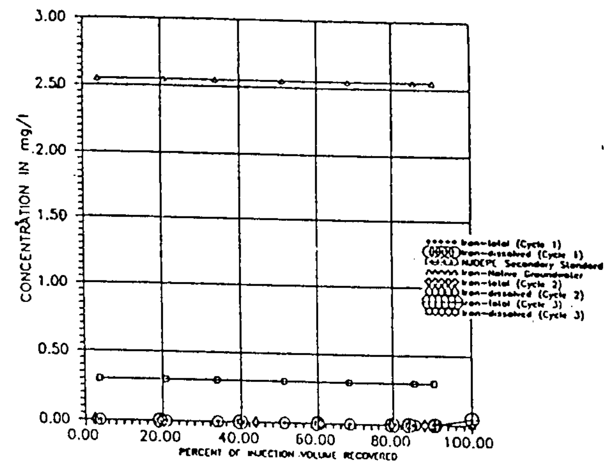

Figure 4 Iron Concentrations in Recovered Water Cycles 1 Through 3

Figure 5 pH Over Recovery Cycles 1 Through 3

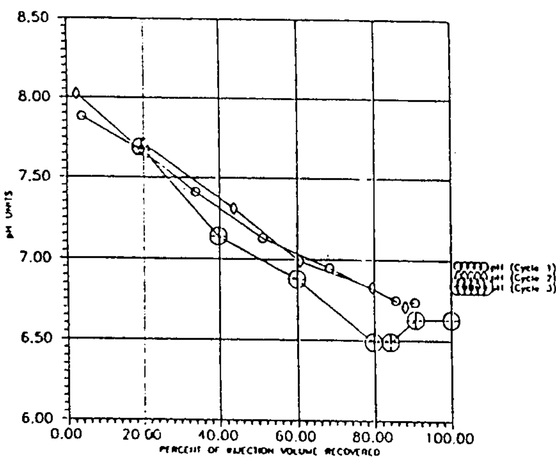

Figure 6 Eh in Recovered Water From Cycles 1 Through 3