Groundwater Research Report
WR03R005

An Assessment of Aquifer Storage Recovery for Selected Representative Hydrogeologic Settings in Wisconsin

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

PROJECT SUMMARY

Title: An Assessment of Aquifer Storage Recovery for Selected Representative Hydrogeologic Settings in Wisconsin

Project I.D.: WR03R005

Principal Investigator(s): Mary P. Anderson, Professor, Department of Geology and Geophysics, University of Wisconsin-Madison

Research Assistant: Christopher S. Lowry, Department of Geology and Geophysics, University of Wisconsin-Madison

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Background/Need: Owing to increased demand on groundwater accompanied by increased drawdown in water levels, emerging technologies, such as aquifer storage recovery (ASR), are being used in the State of Wisconsin to optimize available water resources and reduce adverse effects of pumping. ASR is defined as the injection and storage of water in a suitable aquifer when demand is low and recovery from the aquifer when demand increases. ASR reduces the effects of peak demand on an aquifer by supplementing water in storage in the aquifer when demand is low. An ASR pilot facility in Green Bay, Wis., was recently closed owing to concerns over mobilization of arsenic. An ASR facility in Oak Creek, Wis., near Milwaukee, has gone through several test cycles and is awaiting final approval from the Wisconsin Department of Natural Resources. Another facility is contemplated for the City of Waukesha.

Objectives: The objectives of this research were to: (1) investigate the hydraulic controlling factors on ASR as they relate to the amount of water that can be recovered, i.e., the recovery efficiency, in selected representative hydrogeologic settings in Wisconsin; (2) develop a methodology using numerical flow and transport models whereby the hydraulics of ASR systems can be investigated.

Methods: Three representative settings in Wisconsin were chosen to evaluate the hydraulic controlling factors on recovery efficiency: a confined sandstone aquifer, a glacial drift system and an unconfined dolomite aquifer. Flow models were created using the groundwater flow code MODFLOW (McDonald and Harbaugh, 1988) linked to the particle tracking code MODPATH (Pollock, 1994) and transport code MT3DMS (Zheng and Wang, 1999) in order to simulate movement of injected and ambient water. The effects of regional hydraulic gradient, hydraulic conductivity, effective porosity, dispersion (mixing), volume of injected water, storage period, and rates of injection and recovery were considered.

Results and Discussion: Results from the three settings were qualitatively similar. Dispersion, as quantified by the dispersivity parameter, controls the mixing between injected and ambient water and is the most important control on recovery efficiency. Recovery efficiency varies inversely with dispersivity, effective porosity, regional hydraulic gradient and storage period. High values of dispersivity caused more mixing while high regional gradient and high values of effective porosity caused high flow velocities causing water to move more quickly away from the ASR well. Under high velocities, injected water moved down gradient rapidly and out of the capture zone of the ASR well. Under long storage periods there was more time for the injected water to mix with the ambient water and move down gradient. Recovery efficiency increased asymptotically with volume of injected water. Increasing the hydraulic conductivity in a layer intersected by the ASR well caused an initial increase in recovery efficiency that leveled off and then decreased. Injection and recovery rates had little effect on recovery efficiency. Groundwater mounding and dewatering occurred in the unconfined dolomite aquifer when large volumes of water were injected and removed. Low values of transmissivity, characteristic of the dolomite aquifer, also caused significant groundwater mounding under some injection scenarios.

Conclusions: ASR is most suitable for confined systems such as the Sandstone Aquifer in the southeastern portion of the state and confined glacial drift systems. Groundwater mounding, which could cause flooding at the ground surface, and dewatering will limit the use of ASR systems in unconfined systems such as the Silurian Dolomite Aquifer in the northeastern portion of the state. The methodology developed in this project, in combination with site specific hydrogeologic data, will be useful to water utilities, consultants, and state agencies to determine suitable locations for ASR systems. With a clear understanding of controlling factors that affect recovery efficiency these agencies can determine if ASR potentially might meet a community's water supply needs before the initial test injection of water into the aquifer.

Related Publications:

Lowry, C.S. and Anderson, M.P., 2004, Modeling Aquifer Storage Recovery for a Representative Setting in Wisconsin, (abstract), *in* Wisconsin Ground Water Association Annual Conference Program: Wisconsin Dells, Wis., Wisconsin Ground Water Association, p. 4. Award: Best Graduate Student Paper.

Lowry, C.S. and Anderson, M.P., 2004, Defining Controlling Factors of Aquifer Storage Recovery Using Advection and Dispersion Models, (abstract), *in* Understanding and Managing Water Resources for the Future: Wisconsin Rapids, Wis., Wisconsin Section of the American Water Resources Association, p. 9

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Lowry, C.S., 2004, Assessment of Aquifer Storage Recovery: Defining Hydraulic Controls on Recovery Efficiency at Three Representative Sites in Wisconsin, MS Thesis, Department of Geology and Geophysics: Madison, Wis., University of Wisconsin - Madison, 104 p.

Key Words: aquifer storage recovery, groundwater, modeling, recovery efficiency, water resources management, Wisconsin

Funding: State of Wisconsin Groundwater Research Program through the University of Wisconsin Water Resources Institute, Department of Geology & Geophysics, UW-Madison.

INTRODUCTION

Aquifer storage recovery (ASR) systems have been in operation since the late1960s in the United States (Pyne, 1994) mostly in coastal areas (i.e., Florida and California). An ASR facility in Oak Creek, Wisconsin, near Milwaukee, has gone through several test cycles and is awaiting final approval from the Wisconsin Department of Natural Resources. Another facility is contemplated for the City of Waukesha.

The theory behind ASR is that water can be stored in an aquifer much like it is stored in a surface reservoir or tank for later use. Water is diverted from a source when demand is low and injected into an aquifer. Injected water then displaces ambient groundwater and creates what is termed a "bubble" (Figure 1). The injected water is stored in the aquifer until demand increases when it is pumped out of the aquifer. A successful ASR system requires a suitable aquifer in which to store the water and a source of water such as a river, lake, reclaimed water or even water from another aquifer. In most sites in the United States, water used in ASR systems is treated before injection inasmuch as injection of untreated water poses a risk of contamination from surface water sources.

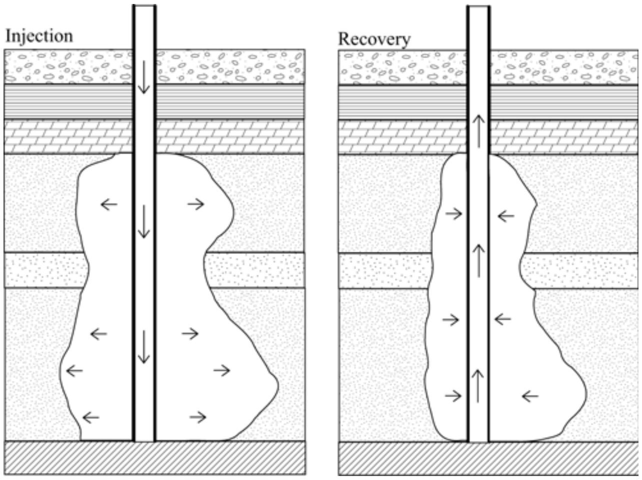

Figure 1. Diagram showing injected water in an ASR well forming a "bubble" within ambient groundwater.

The term recovery efficiency is used to describe the percentage of water that can be recovered after injection and storage. There are two definitions of recovery efficiency and both are used in this research. Consider a glass filled with blue colored water where the blue water represents ambient groundwater in an aquifer. If we add yellow water to the glass, representing the water injected into the aquifer, the yellow water displaces the blue water. If we assume that the injected water does not mix with ambient groundwater, recovery efficiency is defined as the percentage of injected (yellow) water that can be recovered during pumping. When the waters mix, recovery efficiency is defined as the percentage of water recovered having a concentration below a specified concentration for a given chemical constituent. The specified chemical concentration is generally set at the limit for potable water. Using the colored water analogy, this definition of recovery efficiency assigns a target quality criterion represented by some shade of green water, i.e., a mix of blue and yellow water. Thus, recovery efficiency is defined as the ratio of the volume of green water recovered from the aquifer to the volume of water injected. An example of a specified chemical concentration is total dissolved solid (TDS), in which case the ASR well is pumped until the specified level of TDS is reached (usually 500 mg/l, the secondary drinking water standard).

To date, limited research has been conducted on simulation of the hydraulic effects of ASR systems (Wanless, 2004). These modeling studies primarily relate to the injection of fresh water into a saline aquifer, for example in Florida (Merritt, 1985; Quinones-Aponte and Wexler, 1995;

Yobbi, 1996) although there is a least one previous study of ASR in a potable aquifer (Streetly, 1998). Other previous research on hydraulic effects includes physical simulation using mini-aquifer (physical) models created in the laboratory (Kimbler et al., 1975).

The objectives of the current research were to (1) investigate the hydraulic controlling factors on ASR as they relate to recovery efficiency in selected representative hydrogeologic settings in Wisconsin; (2) develop a methodology using numerical flow and transport models whereby the hydraulics of ASR systems can be simulated.

The scope of this research is limited to an investigation of the hydraulic factors that affect recovery efficiency. Hydraulic factors can be classified into two categories, namely physical and operational. Physical parameters/factors are a function of the aquifer and the groundwater flow system and cannot be changed by the operator. These include hydraulic gradient, effective porosity, dispersivity, and the presence of preferential flow zones in the aquifer. Operational parameters/factors are controlled at the wellhead and can be changed by the operator. These include storage period, volume of injected water, injection/recovery rates.

Although not addressed in this research, geochemical processes are important factors in the success of an ASR system. Geochemical studies of ASR systems have focused mainly on disinfection by-products produced by reactions between the injected chlorinated water and naturally occurring organic compounds (e.g., Thomas et al., 2000; Fram et al., 2003). Elevated levels of mercury (Wendell and Glanzman, 1998) and fluoride (Eastwood and Stanfield, 2001) are also of concern. Most of these studies have investigated short-term chemical effects, with the exception of Herczeg et al. (2004), whose five-year study reported the effects of injection of storm water into a brackish carbonate aquifer.

Three representative hydrogeologic settings were investigated (Figure 2), with focus on a confined sandstone aquifer representative of the hydrogeological conditions in southeastern Wisconsin, specifically in the vicinity of Waukesha, Wis., where an ASR facility is being considered. Other hydrogeological settings evaluated included a glacial drift system and an unconfined dolomite aquifer, both of which represent typical hydrogeological settings in Wisconsin.

Figure 2. Locations of representative hydrogeologic settings.

PROCEDURES AND METHODS

ASR systems at the three representative sites were modeled using the finite difference code MODFLOW (McDonald & Harbaugh, 1988) linked to the particle tracking code MODPATH (Pollock, 1994) and transport code MT3DMS (Zheng and Wang, 1999). All three codes were run using the graphical user interface Groundwater Vistas (Rumbaugh and Rumbaugh, 2004).

MODFLOW simulates the flow field in response to injection and recovery of water. MODPATH tracks the movement of injected water without mixing (advection only) by tracking the movement of imaginary particles that move at the average linear velocity calculated from the heads generated by MODFLOW. In this research, particles were placed in the injected water as it was introduced into the aquifer; each injected particle represents a given volume of water moving into the aquifer. The particles were tracked through the duration of the storage and recovery cycles in order to quantify the volume of injected water recovered from the aquifer.

The transport code MT3DMS calculates concentrations of water in the aquifer considering both advection and dispersion (mixing). Inclusion of dispersion to allow for mixing of injected water with ambient groundwater is a better representation of the field system. MT3DMS assumes that the aquifer is an equivalent porous medium, i.e., it has connected pore space or a well-connected dense network of fractures. The code also assumes miscible flow (i.e., solutes are dissolved in water) and no density effects (i.e., the injected water has the same density as the ambient groundwater). For most simulations, the governing equation was solved using the total-variation-diminishing (TVD) explicit finite difference solution technique (Zheng and Wang, 1999) to minimize the effects of numerical (artificial) dispersion. For simulations of the dolomite aquifer, the implicit finite difference solution with upstream weighting was used.

The concentration of the injected water was arbitrarily set equal to zero and the concentration of the ambient groundwater was 1000 units. The definition of recovery efficiency (i.e., percentage of potable water recovered based on the volume of injected water) for the advection-dispersion model is based on a specified concentration of potable water. Two limits were set for potable water represented by a 50% and 25% mixing limit. The 25% mixing limit describes the point where three quarters of the water recovered has a concentration of zero (representing the injected water). The 50% mixing limit is reached when half of the recovered water is the injected water and half is the ambient groundwater.

The ASR model of the sandstone aquifer, representative of hydrogeologic conditions around Waukesha, Wisconsin (Figure 2) contains 13 layers (Appendix B, Figure B.1) that represent the unconfined system (layers 1-3), the regional confining unit (layers 4 and 5) and the confined bedrock system (layers 6-13). Layer thickness and variations in elevation of each model layer were taken from the Southeastern Wisconsin regional groundwater model (Feinstein et al., 2003). The ASR well was open to layers 7-13. The discretization around the ASR well was 10 ft by 10 ft and an expansion factor of 1.5 was used between the 10-ft cells around the well and 400-ft cells at the boundary. Lateral boundary conditions in layers 6–13 were set as constant head boundaries on the eastern and western sides of the model based on the potentiometric surface map of the deep bedrock aquifer (SEWRPC/WGNHS, 2002). Elsewhere the boundary conditions were based on the heads computed by the regional model. Hydraulic conductivity and effective porosity were taken from the regional model of Feinstein et al. (2003) (Appendix B, Table B.1). The base ASR cycle consisted of 39 days of injection at 1 million gallons per day followed by 90 days of storage and 39 days of recovery at 1 million gallons per day. The sensitivity of the model to the full range of physical and operational parameters/factors was tested (Lowry, 2004).

The hydrogeologic setting for the glacial drift aquifer (Figure 2) was based on conditions in Troy Valley in southeastern Wisconsin (Conlon, 1991). The model consisted of three horizontal layers, including an upper unconfined sand and a clay confining unit underlain by a sandy confined aquifer (Appendix B, Figure B.2, Table B.2). Constant head values were set to simulate horizontal flow under nonpumping/injection conditions. The ASR well was placed in the center of the model and was open to layer 3, the confined aquifer. The base hydraulic gradient across the system was 0.001 ft/ft with a pumping rate of 1 million gallons per day and a storage period of 90 days. Uniform dispersivity values of 10 ft, 1 ft, and 0.1 ft in the longitudinal, transverse horizontal, and transverse vertical directions were assumed. The sensitivity of the model to regional hydraulic gradient and volume of injected water was tested.

The dolomite aquifer is representative of the area around Sturgeon Bay in northeastern Wisconsin (Figure 2) where the Silurian Dolomite is an important aquifer. Hydrogeological parameters were taken from Rayne et al. (2001) (Appendix B, Table B.3). Following Rayne et al. (2001), the three-layer model (Appendix B, Figure B.3) accounts for the presence of vertical fractures by assuming an enhanced vertical hydraulic conductivity in the model. At the scale of the ASR system, it was assumed that the aquifer could be represented as an equivalent porous medium consisting of a network of connected fractures. Rapid transport of injected water through fractures was simulated by using a low effective porosity inasmuch as groundwater velocity is inversely related to effective porosity. The ASR well was open to all three layers of the unconfined system. The base hydraulic gradient across the system was 0.001 ft/ft. The base period of injection was 20 days at a rate of 0.25 million gallons a day for a total volume of five million gallons; storage period was 90 days and recovery period was based on the limit of potable water recovered. The smaller rates of injection and recovery, as compared to the other two settings, were necessary due to mounding of water around the ASR well during injection and the potential for dewatering in the first layer during recovery. Porosity was assumed to be 0.001 and dispersivity values were 10 ft, 1 ft, and 0.1 ft in the longitudinal, transverse horizontal, and transverse vertical directions. The sensitivity of the model to regional hydraulic gradient and volume of injected water was tested.

The low effective porosity and high groundwater velocities caused the TVD solution in MT3DMS to require a transport time step on the order of 10^{-5} days, which caused the solution to take too long to run. Hence, the implicit finite difference solution with upstream weighting was used for these simulations, as it did not require such small time steps. Results were checked for the effects of numerical dispersion by running the model with an effective porosity of 0.01 for both TVD and implicit finite difference solutions. Both solutions produced similar concentrations at the ASR well (Lowry, 2004).

RESULTS AND DISCUSSION

Simulations of ASR in all three hydrogeologic settings produced similar results with respect to the relative effect of each hydraulic factor on recovery efficiency as summarized below and discussed in detail by Lowry (2004).

Mixing is an important factor governing recovery efficiency. The results of the advection-only model of the sandstone aquifer show much higher recovery than the advection-dispersion model, which includes mixing (Figure 3). In all simulations recovery efficiency decreases as regional hydraulic gradient increases (Figure 3). A high regional gradient creates high groundwater velocities allowing water to move away quickly from the ASR well. Hydraulic gradient becomes an even more sensitive parameter when smaller volumes of water are injected and in combination with high values of hydraulic conductivity and low effective porosity (Lowry, 2004).

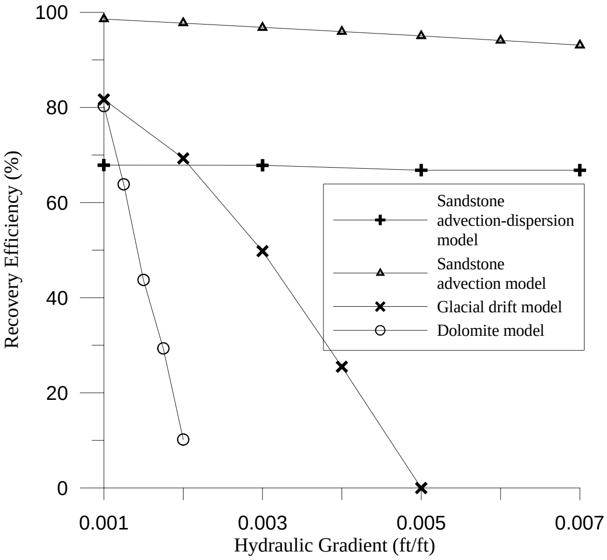

Figure 3. Effect of hydraulic gradient on recovery efficiency.

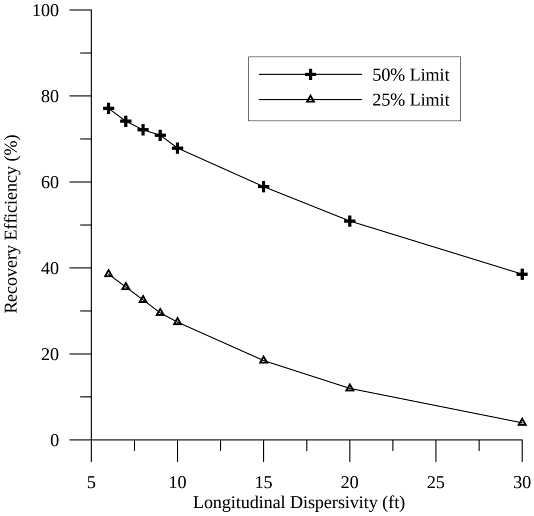

Figure 4. Effect of dispersivity on recovery efficiency for the sandstone aquifer model.

Dispersivity and advective velocity directly affect the dispersion or mixing between ambient and injected water. Increased mixing causes a decrease in recovery efficiency. Recovery efficiency in the sandstone aquifer model was calculated for mixing limits of 50% and 25% while varying dispersivity values from 6 ft to 30 ft. The rate of change in recovery efficiency decreases as dispersivity increases (Figure 4). In these simulations horizontal transverse dispersivity is one-tenth of longitudinal dispersivity and vertical transverse dispersivity is one-tenth of horizontal transverse dispersivity.

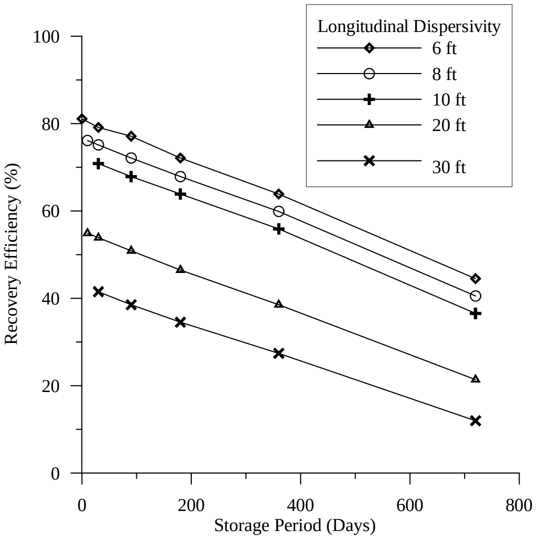

Figure 5. Effect of storage period on recovery efficiency for the sandstone aquifer model.

Effective porosity is inversely related to groundwater velocity and directly related to recovery efficiency. When coupled with a high hydraulic gradient or long storage period, low values of effective porosity cause extremely low recovery efficiencies (<40%). While effective porosity is a difficult parameter to quantify, it varies over a much smaller range than hydraulic gradient or dispersivity.

Recovery efficiency decreases in a nearly linear fashion as storage period increases (Figure 5). As also shown in Figure 4, an increase in dispersivity causes a decrease in recovery efficiency.

Recovery efficiency consistently increased in each of the systems as volume of injected water was increased, except for the unconfined dolomite aquifer (Figure 6), where recovery efficiency decreased after the initial increase. The increase in recovery efficiency is asymptotic in the two confined systems (sandstone aquifer and glacial drift aquifer) and appears to begin to level off in each system, to a value dependent on the combination of parameters specific to each setting. These results suggest that pilot tests using small volumes of injected water may not be helpful in estimating recovery efficiency for the larger volumes of water used in final operation of an ASR system. In the dolomite aquifer, recovery efficiency initially increased with volume of injected water and then decreased as the large volume of water created high hydraulic gradients near the ASR well causing water to move rapidly away from the well. Future work is needed to determine if this effect is also observed with larger volumes of injected water in the sandstone aquifer and glacial drift aquifer.

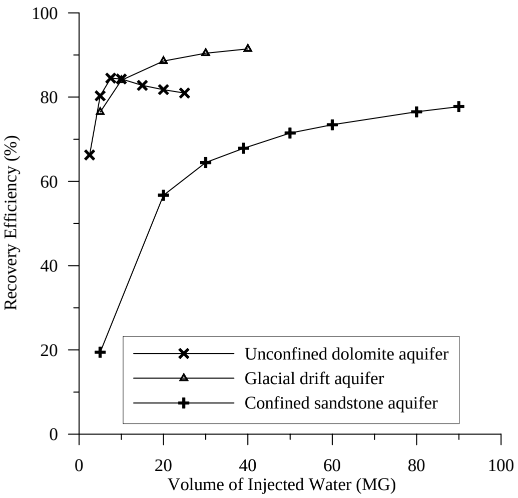

Figure 6. Effect of volume of injected water on recovery efficiency for the three systems with longitudinal dispersivity of 10 ft, gradient of 0.001 ft/ft, storage period of 90 days, and a mixing limit of 50%.

An increase in the hydraulic conductivity of layer 10 in the sandstone aquifer model initially caused an increase in recovery efficiency but was followed by a decrease as hydraulic conductivity continued to increase (Figure 7). The injected water moves preferentially from the ASR well through the layer of high hydraulic conductivity and is drawn back rapidly to the ASR well through the same layer during recovery. As hydraulic conductivity of the layer is increased there is a point at which some portion of injected water moves beyond the capture zone of the ASR well. This same effect would occur in aquifers with connected bedding plane fractures.

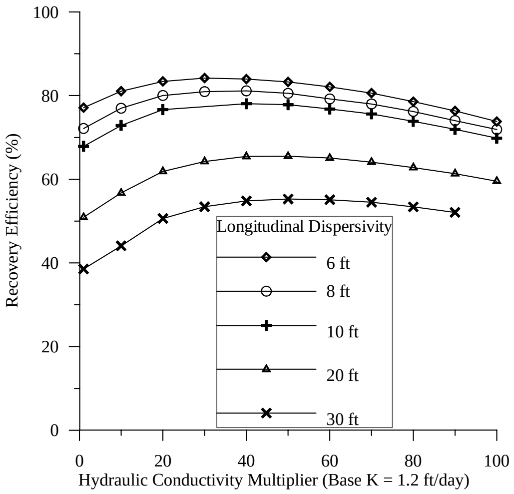

Figure 7. Effect on recovery efficiency of an increase in hydraulic conductivity of layer 10 of the sandstone aquifer model for a mixing limit of 50%.

CONCLUSIONS

Recovery efficiency can be expected to be relatively high at sites with low regional hydraulic gradient, high effective porosity, low dispersivity and where large volumes of water are injected with short periods of storage. These characteristics describe a site that is very similar to a storage tank, which is exactly what an ASR system is meant to replace. The effect of key hydraulic factors, both physical and operational, on the operation of an ASR system can be evaluated through groundwater modeling. Results from this research are intended to help determine viable locations to implement ASR before the initial injection of water into the aquifer and to illustrate the methodology for investigating site-specific conditions for proposed ASR sites using numerical groundwater models. It is hoped that through a better understanding of the controlling factors water utilities can determine if ASR is potentially viable given the local hydrogeology. The results presented here can be used in a general first assessment of the potential feasibility of sites, but should not be used to assess the operation of a site. The methodology presented in this research can be used with site-specific hydrogeological data along with values of anticipated volumes and storage periods of injected water to predict the hydraulics and help design proposed ASR systems prior to operation. Results from this study show that hydraulic controlling factors are interrelated, causing the prediction of recovery efficiency to be a complex problem best solved using a coupled numerical groundwater flow and transport model that includes the effects of mixing between injected water and ambient groundwater.

ACKNOWLEDGEMENTS

Dr. John Jansen, Aquifer Science & Technology, provided site information and advice on the sandstone aquifer representative setting and ASR system. Dr. David Hart, Wisconsin Geological and Natural History Survey, provided help with the southeastern Wisconsin regional model and Paul Juckem, U.S. Geological Survey, assisted in setting up batch files.

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APPENDIX A. Awards and Publications

Award: Best Graduate Paper, 2004, Wisconsin Groundwater Association Annual Conference, Wisconsin Dells, Wis.

Abstracts:

Lowry, C.S. and Anderson, M.P., 2004, Modeling Aquifer Storage Recovery for a Representative Setting in Wisconsin, (abstract), *in* Wisconsin Ground Water Association Annual Conference Program: Wisconsin Dells, Wis., Wisconsin Ground Water Association, p. 4

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APPENDIX B. Supplementary Material on the Representative Settings

B. 1. Schematic Diagrams of the Representative Hydrogeologic Settings

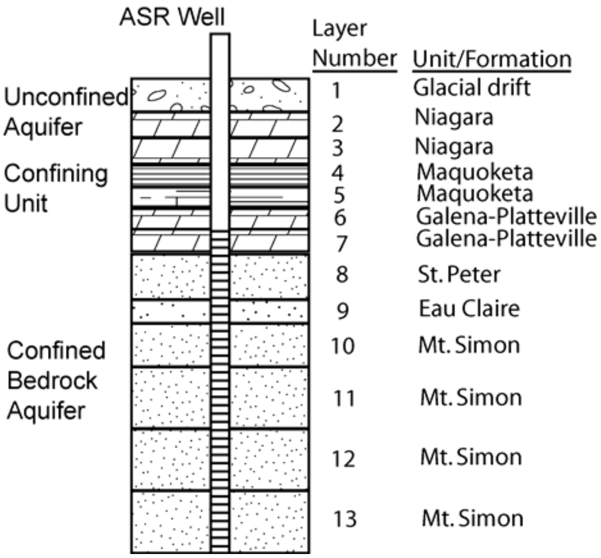

Figure B.1. Hydrogeological units and layers for the sandstone aquifer model. The ASR well was open to layers 7-13.

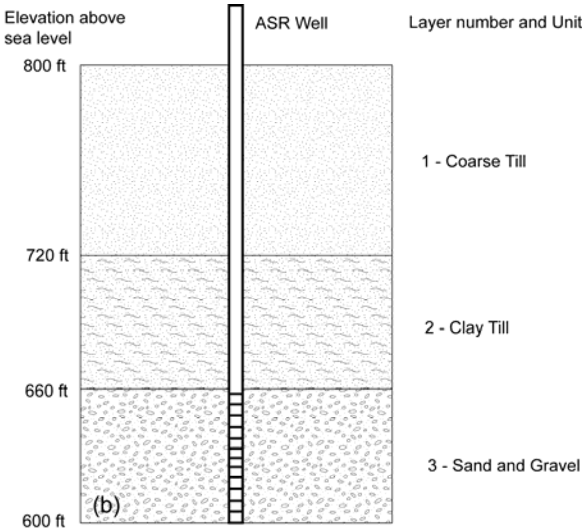

Figure B.2. Hydrogeological units and model layers for the glacial drift system model. The ASR well was open to layer 3.

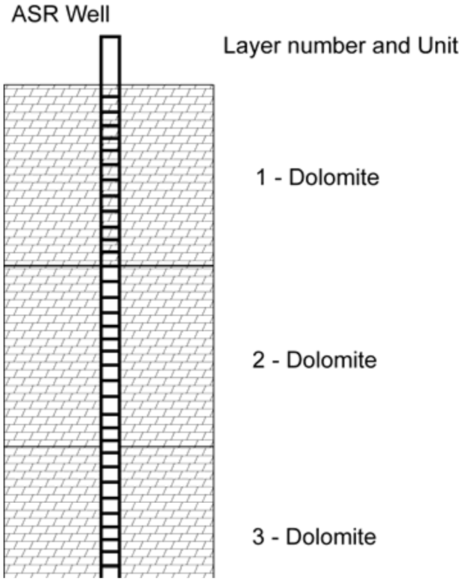

Figure B.3. Layers for the dolomite aquifer model. The ASR well was open to layers 1- 3.

B.2. Parameter Values Used in the Models of the Representative Settings

Table B.1. Hydrogeologic parameters of the sandstone aquifer system. Lowry (2004) tested the effect of three different sets of porosity values. In the simulations discussed in this report effective porosity was equal to the local porosity, as given below.

Layer Number	Unit	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)	Thickness (ft)	Specific Storage (1/ft)	Specific Yield	Local Porosity
1	Glacial Drift	5	0.03	66	2.07E-07	0.25	0.3
2	Niagara	4	0.01	1	2.07E-07	0.05	0.1
3	Niagara	1	0.001	58	2.07E-07	0.05	0.1
4	Maquoketa	0.3	0.001	136	2.07E-07	0.03	0.06
5	Maquoketa	0.0003	5.00E-06	50	2.07E-07	0.03	0.06
6	Sinnipee	0.04	0.0005	100	2.07E-07	0.05	0.1
7	Sinnipee	0.04	0.0005	268	2.07E-07	0.05	0.1
8	St. Peter	2.4	0.0004	149	2.07E-07	0.2	0.25
9	Eau Claire	1.2	0.0004	173	2.07E-07	0.2	0.25
10	Mt. Simon	1.2	0.0004	200	2.07E-07	0.2	0.25
11	Mt. Simon	1.2	0.0004	300	2.07E-07	0.2	0.25
12	Mt. Simon	1.2	0.00012	300	2.07E-07	0.2	0.25
13	Mt. Simon	2.4	0.0012	440	2.07E-07	0.2	0.25

Table B.2. Hydrogeologic parameters for the glacial drift system.

Layer	Unit	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)	Thickness (ft)	Specific Yield	Specific Storage (1/ft)	Effective Porosity
1	Coarse Till	10	0.01	80	0.15	0.0001	0.15
2	Clay Till	0.01	0.003	60	0.01	0.0001	0.15
3	Sand and Gravel	100	1	60	0.3	0.0001	0.3

Table B.3. Hydrogeologic parameters for the dolomite aquifer.

Layer	Unit	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)	Thickness (ft)	Specific Yield	Storativity (ft/ft)	Effective Porosity
1	Dolomite	3.28	0.328	150	0.01	0.0006	0.001
2	Dolomite	3.28	0.328	150	0.01	0.0006	0.001
3	Dolomite	3.28	0.328	150	0.01	0.0006	0.001