

Optimizing the cycle testing and chemical monitoring program for new ASR wells by a monitoring expert system in water resources

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ABSTRACT: Cycle testing and its inherent water quality monitoring are essential steps in getting Aquifer Storage and Recovery (ASR) operational on an economic basis. Suggestions are given to improve the usual cycle testing and water quality monitoring, in order to raise their benefits and reduce the costs. The following aspects are addressed: the general set-up of cycles, calculations of the bubble position in a layered target aquifer, the position of a separate monitoring well, the distinction of various analytical packages, and coupling the monitoring interval to the calculated bubble position. All these aspects have been interconnected in a spreadsheet program called MEXIWA-ASR, which is a kind of monitoring expert system directing and facilitating all calculations. It yields a calendar showing for each observation facility when to sample for which analytical package, and gives the total costs of water quality monitoring. Normally, few iterations are required to balance the costs with the available budget.

1 INTRODUCTION

Application of the technique of Aquifer Storage and Recovery (ASR) on a new site requires a solid feasibility study, followed by cycle testing (Pyne, 1995). A cycle testing program with inherent chemical monitoring is crucial for successful operation, because it reduces the following: (a) water losses; (b) the risk of undesired quality changes of the injected water; (c) the chance of well clogging; and (d) the expenses for monitoring on the long term.

The construction of a monitoring program for water quality control is a very cumbersome process, because it involves so many variables. These are: the capricious financier or budget keeper, the set-up of cycle testing, the number of observation wells and screens within them, their distance or rather travel time to the ASR well, the hydrochemical and geochemical stratification or porosity type of the target aquifer, quality fluctuations in the infiltration water, the individual analytical package for each observation facility, and the often neglected costs for sampling in the field (including transport, flushing riser plus screen, filtration).

In this contribution a tool is presented which helps to design a cycle testing scheme with a solid yet flexible monitoring program for water quality control for an ASR system. This spreadsheet tool in EXCEL, is called MEXIWA-ASR, the ASR branch of Kiwa's Monitoring EXpert system In WATER resources.

2 CYCLE TESTING

In its operational stage an ASR scheme is composed of annual cycles, with 3-4 phases each. The first phase consists of injection during the water surplus period, during the second phase this water is stored, during the third the water is recovered to cope with the increased demands, and in some cases the fourth phase is a pause before surplus water is available to inject. The operational stage is in general preceded by a stage of cycle testing.

The general purposes of cycle testing are (partly from Pyne, 1995): (a) to quantify the dispersion of the water recharged in the aquifer, including its mixing with the native groundwater; (b) to pretreat the aquifer such that reactive solid phases like pyrite are coated with a thin layer of reaction products that decrease their reaction rate; (c) to test all facilities; and (d) to diagnose problems at an early stage, in order to optimise the ASR system as soon as possible.

Important boundary conditions in the set-up of cycle testing and the operational ASR scheme are: (1) the period with water surplus to inject and with increased water demands to cope with by pumping; (2) the safe injection and pumping rates (m^3/h), as derived from previous pumping tests; and (3) the details regarding cycle testing, shown in Table 1.

Our suggestions to improve the general set-up and boundary conditions of cycle testing are given in Table 1. They are based on the following:

Table 1 The set-up for cycle testing with specific boundary conditions. Q_{IN} , Q_{OUT} = total volume of resp. injected and pumped water. The number of test cycles (normally 5-20) depends on aquifer reactivity and dispersivity.

The usual cycle testing (Pyne, 1995)	Additional suggestions for cycle testing (this publication)
<p>GENERAL SET-UP: Cycle 1 $Q_{OUT} = 2-3 * Q_{IN}$, no storage time Cycle 2-4 $Q_{IN} > Q_{OUT}$, + storage time Cycles 5-7 as 2-4, higher volumes, + storage time Cycles 8-10 as 5-7, higher volumes, + storage time</p> <p>GENERAL CONDITIONS:</p> <ul style="list-style-type: none"> Allow time to recover to static aquifer pressures in between cycles Diameter of injected cylinder > thickness aquifer 	<p>SET-UP Repeat cycle 1 1-2 times, double Q_{OUT} each time</p> <p>CONDITIONS:</p> <ul style="list-style-type: none"> During initial cycles (1-4) O_2 and NO_3^- should be used up by reactions Check diameter > thickness for individual aquifer beds Saturate influent with O_2 and/or add NaOH (to increase pH) During each cycle (also 1) the influent should reach the observation well, in each aquifer bed

(a) the target aquifer normally is stratified, resulting in different travel times and leaching rates; (b) the observation well yields the best information with separate piezometers in each aquifer layer, at a sufficiently close distance from the ASR-well to notice the various chemical fronts early enough; and (c) reactions which coat the reactive aquifer phases (like pyrite) need to be stimulated and given enough time.

3 CALCULATIONS

In designing the scheme for cycle testing we check the condition that the water recharged should reach the observation well in at least the most permeable layers. This is done using the following equation which gives the front position of the bubble in aquifer layer N ($=R_N$) assuming a 100% penetrating well screen for each layer, radial symmetrical flow within each aquifer layer, and no dispersion:

$$R_N = \sqrt{([t_{INJ} Q_{IN} K_N D_N] / [\epsilon \pi D_N \Sigma KD])} \quad (1)$$

With: t_{INJ} = length of injection period [d]; Q_{IN} = injection rate [m^3/d]; K_N = horizontal permeability of aquifer layer N [m/d]; D_N = thickness of aquifer layer N [m]; ϵ = porosity [-]; ΣKD = transmissivity of target aquifer [m^2/d].

In a similar way the mean travel time from the injection well to the monitoring well in aquifer layer N ($= (T_{50})_N$) is calculated:

$$(T_{50})_N = [\epsilon \pi R_N^2 D_N \Sigma KD] / [Q_{IN} K_N D_N] \quad (2)$$

The results of calculation are shown for our example in Fig.1 and 2: a fine-grained sandstone 19.5 m thick, with 5 aquifer layers (K_N 0.5 to 8 m/d), and $Q_{IN} = 20 m^3/h$. It follows from Fig.1 that, when planning short test cycles of 14-42 days (Table 1), the observation well should be at about 10 m from the ASR well, in order detect changes in each aquifer layer. After cycle 2 the injected bubble starts to

grow, most in layers B and E (Fig.2). These layers deserve most monitoring efforts.

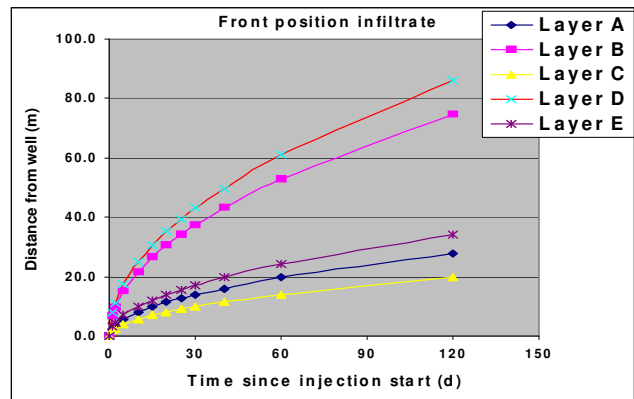


Figure 1. Calculated position of the bubble front in 5 layers within target aquifer during uninterrupted injection at $20 m^3/h$.

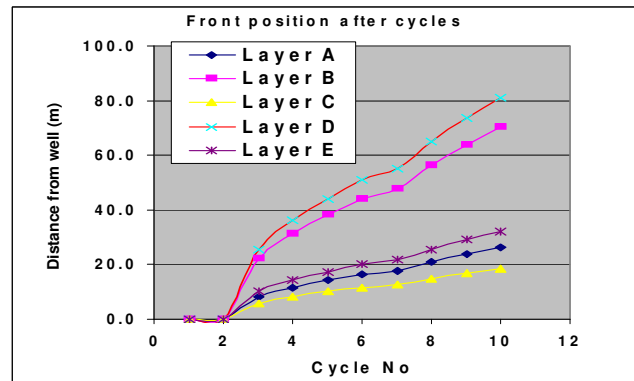


Figure 2. Calculated position of the bubble front in 5 layers within the target aquifer after each of the first 10 ASR-cycles during the scheme shown in Table 2.

4 ANALYTICAL PACKAGES

The analytical program is dictated mainly by the quality of the water recharged, the native groundwater and the chemical reactions of the recharged water with the aquifer.

Table 2 The proposed scheme for cycle testing (cycles 1-7) and the subsequent operational cycles 8-10 for ASR at a fictional site. Cycles >10 as cycle 10. The efficiency is the recovery efficiency for each cycle (=100 * recovery period * pumping rate / (injection period * injection rate)).

CYCLE No.	Injection period (d)	Storage period-1 (d)	Recovery period (d)	Storage period-2 (d)	Total for cycle days	Time since start days	Injection rate m ³ /h	Pumping rate m ³ /h	Efficiency %	Bubble size at end (m ³)
Testing										
1	21	0	21	0.0	42.0	42.0	20.0	30.0	150.0	0
2	14	0	14	0.0	28.0	70.0	20.0	30.0	150.0	0
3	21	0	7	0.0	28.0	98.0	20.0	30.0	50.0	5040
4	21	7	7	0.0	35.0	133.0	20.0	30.0	50.0	10080
5	21	14	7	0.0	42.0	175.0	20.0	30.0	50.0	15120
6	42	56	21	28.0	147.0	322.0	20.0	30.0	75.0	20160
7	42	28	28	81.0	100.0	422.0	20.0	23.0	83.3	23520
Operation										
8	126	63	91	85.0	365.0	787.0	20.0	23.5	84.9	32676
9	126	63	91	85.0	365.0	1152.0	20.0	23.5	84.9	41832
10	126	63	91	85.0	365.0	1517.0	20.0	23.5	84.9	50988

With chemical transport models like EASY-LEACHER® (Stuyfzand, 1998) these water quality changes can be predicted, so that the analytical program can be tailor made.

The yield/price ratio increases considerably by applying specific analytical packages to water quality monitoring, when each package is intended for specific monitoring points or time intervals. We discern, for the normal clastic aquifers in NW-Europe and high quality influents, the 7 packages defined in Table 4. From left to right the number of parameters to analyse decreases, and so are the costs involved. The price indication in Table 3 derives from VEWIN (2002), includes sampling and administration costs (ca. 20%) and excludes quantum discount (up to 50%). Quite another picture arises in case of noncommercial labs or simultaneous multi-element analysis, e.g. with ICP-MS. In special cases fluoride and radon deserve attention.

The best tracers of the injected water, often electrical conductivity, Cl⁻, CH₄, HCO₃⁻ and tem-

perature, deserve special attention because they are crucial in deciding when to stop the recovery and how to interpret the chemical data collected.

A further fine-tuning of the analytical program may be useful, for instance by column tests with aquifer cores and the influent water, and by watching trends in the evolving quality data.

5 SAMPLING FREQUENCY

The most important principles determining the sampling frequency are listed in Table 3. For monitoring wells the calculated travel time of water (t₅₀) from the injection well is crucial, because the costly analyses should start when the influent has arrived, not earlier (waste of money) and not too late (waste of test cycle). The breakthrough front of the water injected, is efficiently monitored using the rule of thumb that this takes place in between 0.5*t₅₀ and 1.5*t₅₀ (sandy aquifers).

Table 3 The most important principles applied in the design of the monitoring program for ASR schemes. Codes A, M, R, T, F, D refer to the analytical packages defined in Table 4.

1	Before start of ASR all facilities should be sampled for exploring the native situation at that time
2	The recharge water should be sampled only during injection, the recovered water only during pumping, and the water during aquifer passage during all episodes of ASR
3	Intensive sampling during the weekend and holidays should be avoided
4	Sampling frequency increases with diminishing size of analytical package
5	Sampling interval for water in observation wells equals twice the travel time from injection well rounded off to whole weeks; this pertains only to analytical package A (=All). The thus obtained interval is divided by 2 for package M, by 4 for R and by 6 for T. Packages F and D do not apply to observation wells.
6	For tracing purposes: daily log temperature at various depths in deepest screen of monitoring wells, using electrodes.
7	First sampling of water in observation wells for package A starts if clock time t > t ₅₀ (t = time since start of injection; t ₅₀ = mean travel time to observation well). Ditto for M if t > 0.8 t ₅₀ , for R if t > 0.6 t ₅₀ , and for T if t > 0.4 t ₅₀ .
8	Analytical package W only pertains to the water injected, and if necessary, also to the water recovered.
9	Sampling frequency for recovered water is about double that for recharge water
10	If quality of recharge water appears to be quite stable, its sampling frequency can be reduced
11	If monitoring budget is exceeded, frequencies need reduction, parameters must be skipped or monitoring points are taken off
12	The analytes should be related to the objectives of cycle testing and modified during trials to reflect risk management

Table 4 The 7 analytical packages proposed for water quality monitoring during an ASR project using high quality injection water and a 'normal' sandy aquifer.

Parameter	Price € per para.	Whole = W	±All = A	Main = M	Redox =R	Few =F	Tracers =T	Daily =D
GENERAL								
EC	12.3	◆	◆	◆	◆	◆	◆	◆
Temp.	3.1	◆	◆	◆	◆	◆	◆	◆
pH	12.3	◆	◆	◆	◆	◆	◆	◆
O ₂	18.5	◆	◆	◆	◆	◆	◆	◆
CH ₄	46.2	◆						
Cl ₂	12.3	◆	◆					
Colour	18.5	◆	◆					
MAIN ANIONS								
Cl ⁻	12.3	◆	◆	◆	◆			
SO ₄ ²⁻	21.6	◆	◆	◆	◆			
HCO ₃ ⁻	12.3	◆	◆	◆	◆		◆	
NO ₃ ⁻	21.6	◆	◆	◆	◆			
NO ₂ ⁻	15.4	◆	◆	◆	◆			
PO ₄ -total	46.2	◆						
F ⁻	21.6	◆	◆					
MAIN CATIONS								
Na ⁺	18.5	◆	◆	◆				
K ⁺	18.5	◆	◆	◆				
Ca ²⁺	18.5	◆	◆	◆				
Mg ²⁺	18.5	◆	◆	◆				
NH ₄ ⁺	21.6	◆	◆	◆	◆			
Fe-total	18.5	◆	◆	◆	◆	◆	◆	
Mn-total	18.5	◆	◆	◆	◆			
MAIN, OTHERS								
SiO ₂	21.6	◆	◆	◆				
TOC	46.2	◆	◆	◆				
CLOGGING								
TSS @	24.6	◆	◆			◆		
Turbidity	15.4	◆	◆	◆		◆		◆
MFI #	200	◆						
AOC \$	400	◆						
TRACE ELEMENTS								
Al	18.5	◆	◆			◆		
As	30.8	◆	◆					
B	18.5	◆	◆					
Ba	18.5	◆	◆					
Cd	18.5	◆						
Co	18.5	◆						
Cu	18.5	◆	◆					
Ni	18.5	◆	◆					
Pb	18.5	◆						
Se	18.5	◆						
Zn	18.5	◆	◆					
ORGANIC MICROPOLLUTANTS								
VOHs †	154	◆	◆					
Sum costs €		1484	718	345	188	123	77	62

@: Total Suspended Solids; #: Modified Fouling Index (Schippers & Verdouw, 1980; Desalination 32, 137-148); \$: Assimilable Organic Carbon (Van der Kooij *et al.*, 1982; J.Am.Water Works Ass. 74, 540-545); †: Volatile Organic Halogens incl. trihalomethanes.

6 SAMPLING CALENDAR, TOTAL COSTS

MEXIWA-ASR generates, on the basis of all given information and additional expert rules, a calendar with the whole sampling strategy for test and operational cycles, showing when to sample for which analytical package. Some characteristic lines (days) from this calendar are shown in Table 6.

The total costs involved for the test and operational cycles are calculated as well (Table 6). These need to balance the available budget. This requires several iterations by changing frequencies, parameters or sampling points. This part could be automated as well.

Table 5 Sampling interval (in days) for the analytical packages defined in Table 4. MW-B = Monitoring Well in layer B. In this example MW-A and MW-C were skipped.

Monit. point	Whole =W	±All =A	Main =M	Redox =R	Tracers =T	Few =F	Daily =D
Influent	56	28	14	9999	7	2.3	1
MW-B.	9999	21	14	7	3.5	9999	9999
MW-D	9999	14	7	3.5	2.3	9999	9999
MW-E	9999	84	42	21	7	9999	9999
Output	9999	14	7	3.5	2.3	9999	1

Table 6. Some lines (days) from the sampling calendar generated by MEXIWA-ASR for our demonstration case, including a total cost calculation. Letter codes as defined in Table 4.

Days since start	Cycle No.	Inject, Store, Recover?	ANALYTICAL PACKAGE for:				Date	Day of week
			Input	Monitoring well				
			B	D	E			
0	-	no	-	A	A	A	A	
1	1	inj	W	-	-	-	-	17-10 tue
4	1	inj	F	-	T	-	-	20-10 fri
24	1	rec	-	T	R	-	R	9-11 thu
44	2	inj	F	-	T	-	-	29-11 wed
98	3	rec	-	M	A	T	A	22-01 mon
122	4	sto.1	-	T	R	-	-	15-02 thu
147	5	inj	T	A	M	R	-	12-03 mon
308	6	sto.2	-	M	A	T	-	20-08 mon
696	8	rec	-	T	R	-	T	12-09 thu
Sum costs in k€								
0-422	1-7		15.0	17.1	29.3	6.2	9.5	Σ = 77.0
423-787	8		2.4	3.6	6.3	1.2	2.0	Σ = 15.5

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