

Advanced Well Test Analysis and Traditional Methods For Injection Well Evaluation ¹

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Introduction

Seemingly miniscule concentrations of suspended particles in injected water accumulate in the tight confines of an injection well's interface with an aquifer. In this limited space, microbes also feed on the seemingly miniscule organic carbon content of source water and build interconnected colonies. Without regular action to remove sedimentary and microbial accumulations, clogging from these two processes can cause the injection rate for an acceptable delivery pressure to fall below desired levels.

Knowing when to take action on clogging is based on regular evaluation of injection well performance. Established, traditional methods for evaluating injection wells are in fact limited. There is a bewildering galaxy of traditional measures of injection well performance. Some provide more insight than others, but none provides both reliable insight and is transferable to other wells and other settings for injection. We as a profession can do better by using advanced well test analysis (AWTA) to focus our attention on mechanical wellbore skin. We can then track how mechanical wellbore skin changes in an injection well with time and act to maintain it at low levels. The levels to be maintained are largely project-specific, but if we can establish a transferable measure, we can all foresee project needs from a broader base of shared experience than is possible now.

In this paper I describe four classes of traditional measures for injection well performance, propose a single measure derived systematically from AWTA, and compare the various measures for three realistic example situations

The Measure of an Injection Well

A useful injection well measure should be:

1. Actionable: useful for initiating cost-effective maintenance
2. Reliable: physically based, free of extraneous effects
3. Comparable: at a well, over time, with accumulated injection
4. Comparable: between wells in a well field and between wells in different well fields, aquifers

A key technical challenge in selecting and applying a useful injection well measure is that it should be clearly distinct and isolated from other effects that cause water levels to rise

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in an injection well. Many factors cause water levels to change in a well but unless all but clogging are eliminated, the evaluation of injection well performance will be less than it could be and so will the resulting decisions.

Figure 1 shows the arrangement of a well in an aquifer. The mechanical wellbore skin surrounding a well is the thin (inches at most) radius starting at the original borehole wall and extending out into the aquifer. It is the radius where sediments finer than that in the aquifer and microbial colonies accumulate. The adjective mechanical is needed because the petroleum and natural gas industry well tests analysts have called a wide variety of near-well processes that add to drawdown or build-up “skins”: partial penetration, non-linear flow, etc. Before discussing AWTA further, a review of traditional measures of injection well performance is in order.

Traditional Measures of Injection Well Performance

I have organized the traditional measures of injection well performance into three categories:

1. purely data-based methods,
2. methods comparing data and simple models, and
3. simulation model parameter estimation methods.

Purely Data-based Methods

The purely data-based methods compare only measured quantities or simple arithmetic operations on measured quantities. The catalog accumulated here includes:

1. Water-level rise in injection well at a standard time
2. Water-level rise/injection rate for injection well at a standard time
3. Injection rate/water-level rise for injection well at a standard time
4. Difference in water-level rises at a standard time between injection well and separate observation well
5. Water-level rise at a standard time normalized to standard injection rate and standard viscosity

The purely data-based methods are by far the most attractive because they are very simple to compile and many professionals have compiled some or all of these measures for several decades, which lends confidence in their use.

The disadvantages of these purely data-based methods are that:

1. The base for calculating the rise of water levels can be complex – the pre-injection water level may not be a stable starting point

2. The standard time for comparison has an unreliable foundation - it isn't standard and analysis of injection in each well and aquifer combination would likely benefit from a unique standard time
3. With the exception of comparing rises in an injection well and a nearby observation well, these measures don't isolate mechanical wellbore skin from other effects
4. These measures can't be reliably compared across other wells and well fields and therefore the profession is limited from accumulating transferable experience and judgment as has developed using AWTa in the petroleum and natural gas industry

Comparisons of Data and Simple Models

These measures are variations on the efficiency idea from engineering in which observations are compared to theoretically perfect operations. The catalog accumulated here includes:

1. Ratio of observed water-level rise in the injection well at standard time to water-level rise simulated with the Theis equation at standard time
2. Difference between observed water-level rise in injection well at standard time and water-level rise simulated with Theis equation at standard time

The advantages of these efficiency-based methods are that they are relatively simple to compile and that many professionals have calculated these measures for several decades, which lends confidence to their use.

The disadvantages of these efficiency-based methods are that:

1. The base for calculating the rise of water levels can be complex – the pre-injection water level may not be a stable starting point
2. The standard time for comparison has an unreliable foundation - it isn't standard and analysis of injection in each well and aquifer combination would likely benefit from a unique standard time
3. Situations are rare for which the Theis Equation is theoretically perfect performance. Theis doesn't incorporate many significant and well-understood processes (e.g., finite diameter well, mechanical wellbore skin, partial penetration, etc.)
4. These measures are not comparable across different settings.

Parameters from Fitting to Simple Models

Methods in this class match a selected simple model (short equation) to observations by methodically estimating the model parameters (i.e., coefficients). The coefficients can be compared over time to track injection well performance. The catalog accumulated here includes:

1. $BQ+CQ^n$ – parameters are B, C, and n [although n should be 2]

2. Other polynomials or similar equations
3. Artificial Neural Networks

The advantages of these methods that estimate parameters for simple models are that they are very simple to calculate in EXCEL by statistical regression, they can (though ambiguously) address non-Darcy (i.e., inertial) effects, and there is some depth of experience in applying these methods.

The disadvantages of these methods comparing data and simple models are that:

1. Standard time for making calculations has an unreliable foundation
2. Physical interpretation of the coefficients is unclear
3. Casing versus aquifer inertial flows not separated
4. Mechanical wellbore skin is ambiguously mixed in several coefficients
5. Some coefficients change with time, while some do not change with time
6. These measures are not comparable across different settings

Advanced Well Test Analysis (AWTA)

AWTA is defined here to be the application of a relatively complex “analytical” solution to combined flow in a finite diameter wellbore with wellbore storage and 3-D adjacent aquifer with boundaries. The procedure is to match the simulation to all of the observed water-level displacements by estimating parameters of the selected solution. Advantage can be taken of AWTA’s systematic structure to estimate and fix aquifer, boundary and well geometry parameters. The focus can be placed on isolating mechanical wellbore skin and tracking how it changes with accumulated injection volume.

A few AWTA software packages I am familiar with that could be employed to track mechanical wellbore skin include:

1. LTST2/WTAQ (Barlow and Moench 1999) and in AQTESOLV (HydroSolve, 2007)
2. LTST3/WTAQ (Barlow and Moench, 1999) and in AQTESOLV (HydroSolve, 2007)
3. Multi-Layer Unsteady State (MLU) – (Hemker, 2007)
4. Kappa Engineering (2007) and other petroleum/natural gas industry software

I would also note that the Kansas Geological Survey slug test code (discussed in detail in Butler, 1998 and found in AQTESOLV [HydroSolve, 2007]) could be used to analyze periodic slug tests of injection wells to the same effect as analysis of periodic injection tests.

The advantages of AWTA include:

1. Physically based

2. Match all times and measurements from multiple wells – eliminates selection of a standard time
3. Mechanical wellbore skin is isolated from other extraneous physical processes (wellbore storage, continued water rise due to aquifer resistance, interaction with boundaries, partial penetration, interference from adjacent injection wells, etc.)

The disadvantages of AWTA include:

1. Requires additional training
2. There is a lack of wide-spread application and associated accumulated experience with reasonable values for injection well mechanical wellbore skins for typical water recharge projects
3. Available water resources industry codes do not yet:
 - a. comprehensively address non-Darcy effects (petroleum/natural gas industry research is just now identifying and testing physical process descriptions for non-Darcy skin separate from those of non-Darcy formation flow)
 - b. Allow for increasing mechanical wellbore skin with accumulating injection
 - c. Simulate multiple wellbore storage processes
 - d. Simulate stress-sensitive aquifers

Demonstration of Methods for Synthetic Cases

So how do the traditional measures compare to AWTA-derived mechanical wellbore skin? I used the Moench (1997) three-dimensional water table aquifer simulation model in AQTESOLV (version 4.5) to simulate injection under three examples spanning a broad range of hydrogeologic situations:

1. High Capacity ASR: 1,250 gallon per minute (gpm) injection into a 200 foot-thick aquifer with a hydraulic conductivity of 200 feet per day (ft/d)
2. Moderate Capacity ASR or Remedial Extraction and Injection: 600 gpm injection into a 500 foot-thick aquifer with a hydraulic conductivity of 20 ft/d
3. Low Capacity Recharge under non-optimal conditions: 40 gpm injection into a 200 foot-thick aquifer with a hydraulic conductivity of 2 ft/d

One day injection tests (1 and 2) are run before and after the selected period of injection operations. To show how outside influences or other wells in the system could affect traditional measures, a second, identical injection well starts up after 9 hours during each test. The results are briefly reviewed below.

High Capacity ASR

This situation is of a large capacity aquifer into which large volumes of water can be injected.

- $T = 40,000\text{ft}^2/\text{d}$, $b = 200\text{ ft}$, $K_h = 200\text{ ft/d}$
- $K_z/K_h = 0.2$
- $S_y = 0.25$, $S_c = 2\text{e-}4$
- $Q = 1,250\text{ gpm}$, $Q/s = 125\text{ gpm/ft}$
- The mechanical wellbore skin increased during some period of injection operations from 0 to 3.

Figure 2 shows the simulated build-up of water levels in the injection and nearby observation wells. Table 1 shows the traditional injection measures compiled for this situation.

Moderate Capacity ASR or Remedial Extraction and Injection

This situation is of a moderate capacity aquifer into which moderate volumes of water can be injected. It is also a situation encountered when injection of treated water is used as part of a pump and treat remedial action.

- $T = 10,000\text{ft}^2/\text{d}$, $b = 500\text{ ft}$, $K_h = 20\text{ ft/d}$
- $K_z/K_h = 0.1$
- $S_y = 0.18$, $S_c = 5\text{e-}4$
- $Q = 600\text{ gpm}$, $Q/s = 50\text{ gpm/ft}$
- The mechanical wellbore skin increased during some period of injection operations from 0 to 6.

Figure 3 shows the simulated build-up of water levels in the injection and nearby observation wells. Table 2 shows the traditional injection measures associated with this situation.

Low Capacity Recharge under non-optimal conditions

This situation is of a low capacity aquifer into which water must be injected. These are most non-optimal conditions for recharge.

- $T = 400\text{ ft}^2/\text{d}$, $b = 200\text{ ft}$, $K_h = 2\text{ ft/d}$
- $K_z/K_h = 0.01$
- $S_y = 0.08$, $S_c = 2\text{e-}4$
- $Q = 40\text{ gpm}$, $Q/s = 2\text{ gpm/ft}$

- The mechanical wellbore skin increased during some period of injection operations from 0 to 9.

Figure 4 shows the simulated build-up of water levels in the injection and nearby observation wells. Table 3 shows the traditional injection measures associated with this situation.

Similar results were obtained for the three situations. Of particular interest is the application of the $BQ+CQ^n$ equation when n is allowed to take on values other than 2. Starting from values near 1, 2, and 3, different optimal values of B and C can be found that allow the overall equation to match exactly. This is the topic for an entire paper, but physical considerations (i.e, the range of power dependence of pressure gradient on flow rate between fully laminar and fully turbulent flow) should restrain n to 2. Allowing n to vary creates excessive obfuscation of the remaining processes.

A complete analysis of the findings of these simulations is beyond the scope of this paper, but the reader is encouraged to inspect the findings and come to his or her own conclusions about the various traditional injection well measures. Based on my experience and the inspection of these results, I conclude that, of the traditional measures evaluated for these situations, the comparison of water level rises in the injection and observation wells is the clearest measure of clogging. Unfortunately, this comparison requires ad hoc selection of a standard time. The results of this comparison measure are also very specific to the injection well/observation well pair and can not be readily compared between wells or well fields. In contrast, the application of AWTA results in the mechanical wellbore skin values that are clearly defined, clearly related to clogging, and can be compared between wells and well fields in differing settings.

Conclusions

Traditional methods do not measure injection well clogging in a way that can be reliably compared both with time at an injection well and between injection wells in different settings.

The best traditional measure is comparing the water level rise in the injection well and an adjacent observation well. However, the experience gained from applying this measure is not easily transferred to other wells or to wells in other settings.

For many traditional measures, the problem in their application is that one can't evaluate what has been assumed away or lumped together with other factors at the outset.

AWTA incorporates mechanical wellbore skin as a widely accepted physical process and allows isolation of it from other physical processes. Mechanical wellbore skin holds significant promise for reasoned comparison of clogging in injection wells between wells in a well field and between wells in different settings. Our profession can then accumulate transferable expertise in injection well performance commensurate with that developed in the petroleum and natural gas industry for extraction and injection wells.

Recommendations

Try using AWTA to track the increase in mechanical wellbore skin with accumulated injection volume. Experience gained in the first few AWTA analyses for a well will make succeeding periodic analysis routine rather than challenging.

AWTA would be much improved for water injection analyses by addressing the continuous increase in mechanical wellbore skin with accumulated injection volume.

AWTA would be also be improved for high-flow rate water injection analyses by addressing non-Darcy skin and non-Darcy aquifer flow separately from mechanical wellbore skin.

References

Barlow, P.M. and A. F. Moench, 1999. WTAQ – A Computer Program for Calculating Drawdowns and Estimating Hydraulic Properties for Confined and Water Table Aquifers, U.S Geological Survey WRIR-99-4225.

Butler, J.J., Jr., 1998. The Design, Performance and Analysis of Slug Tests, Lewis Publishers, Boca Raton, 252 pages.

HydroSolve, Inc., 2007. AQTESOLV Version 4.5, URL: www.aqtesolv.com

Hemker, C.J., 2007. MLU Well Test Analysis Package, URL: www.microfem.com

Kappa Engineering, Inc., Saphir Well Test Analysis Package, URL: KappaEng.com

Table 1 - Traditional Measures Applied to High Capacity ASR Situation

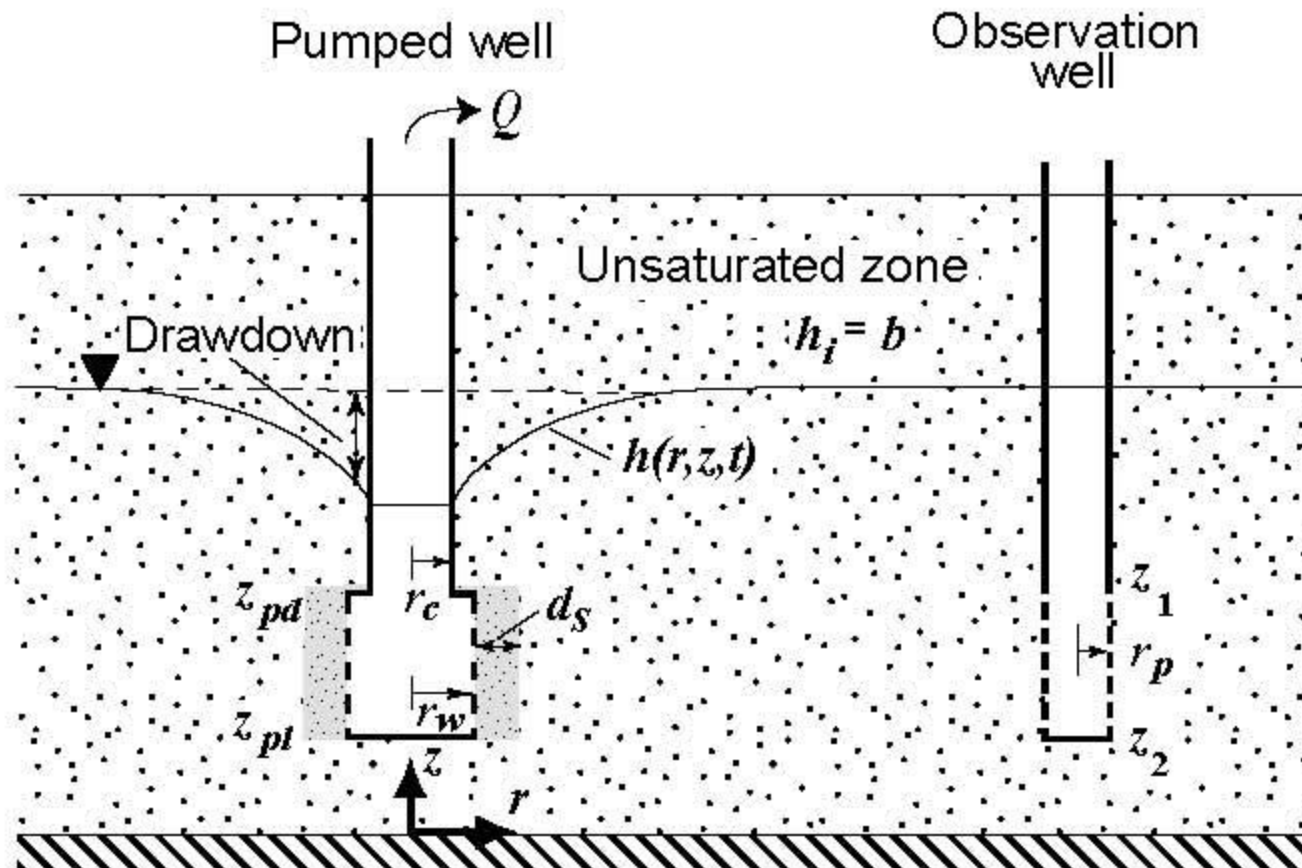
	Test 1->	Sw=0	Test 2->	Sw=3	Change	Sw=0->3
Q = 1250 gpm	1 hour	8 hour	1 hour	8 hour	1 hour	8 hour
Rise -S_inj (feet)	8.4	9.4	11.3	12.2	34.5%	29.8%
Rise - S_obj (feet)	5.1	6.1	5.1	6.1	0.0%	0.0%
S_inj (feet)/Q (gpm)	0.00672	0.00752	0.00904	0.00976	34.5%	29.8%
Q (gpm)/S_inj (feet)	148.8	133.0	110.6	102.5	-25.7%	-23.0%
S_Inj - S_obj	3.3	3.3	6.2	6.1	87.9%	84.8%
S_Inj_Theis_Sc	8.4	9.4	8.3	9.4		
S_Inj_Theis_Sy	5.1	6.1	5	6		
S_inj/S_Inj_Theis_Sc	1	1	1.36	1.30	36.1%	29.8%
S_inj/S_Inj_Theis_Sy	1.65	1.54	2.26	2.03	37.2%	32.0%
S_inj - S_Inj_Theis_Sc	0	0	3	2.8		
S_inj - S_Inj_Theis_Sy	3.3	3.3	6.3	6.2	90.9%	87.9%
S_Inj_est	8.4	9.4	11.3	12.2		
B (n fixed at 2)	1.00	1.00	1.00	1.00	0.0%	0.0%
C (n fixed at 2)	-7.9E-04	-7.9E-04	-7.9E-04	-7.9E-04	-0.2%	-0.2%
S_Inj_est	8.4	9.4	11.3	12.2		
B (n optimized)	0.83	0.84	0.84	0.84	0.6%	0.1%
C (n optimized)	-1.1E-01	-1.1E-01	-1.1E-01	-1.1E-01	1.2%	0.0%
n	1.28	1.28	1.28	1.28	-0.1%	0.0%
S_Inj_est	8.4	9.4	11.3	12.2		
B (n optimized)	0.60	1.00	1.00	1.00	67.3%	0.0%
C (n optimized)	-4.7E-04	-7.9E-04	-7.9E-04	-7.9E-04	67.7%	-0.2%
n	2.00	2.00	2.00	2.00	0.0%	0.0%
S_Inj_est	8.4	9.4	11.3	12.2		
B (n optimized)	0.50	1.00	1.00	1.00	98.4%	0.0%
C (n optimized)	-3.2E-07	-6.3E-07	-6.3E-07	-6.3E-07	99.2%	-0.2%
n	3.00	3.00	3.00	3.00	0.0%	0.0%

Table 2 - Traditional Measures Applied to Moderate Capacity ASR Situation

	Test 1->	Sw=0	Test 2->	Sw=6	Change	Sw=1->6
Q = 600 gpm	1 hour	8 hour	1 hour	8 hour	1 hour	8 hour
Rise -S_inj (feet)	14.1	16	25.2	27.1	78.7%	69.4%
Rise - S_obj (feet)	7.8	9.7	7.8	9.7	0.0%	0.0%
S_inj (feet)/Q (gpm)	0.0235	0.0267	0.0420	0.0452	78.7%	69.4%
Q (gpm)/S_inj (feet)	42.6	37.5	23.8	22.1	-44.0%	-41.0%
S_Inj - S_obj	6.3	6.3	17.4	17.4	176.2%	176.2%
S_Inj_Theis_Sc	14.1	16	14.1	16		
S_Inj_Theis_Sy	7.8	9.7	7.8	9.7		
S_inj/S_Inj_Theis_Sc	1.0	1.0	1.8	1.7	78.7%	69.4%
S_inj/S_Inj_Theis_Sy	1.8	1.6	3.2	2.8	78.7%	69.4%
S_inj - S_Inj_Theis_Sc	0	0	11.1	11.1		
S_inj - S_Inj_Theis_Sy	6.3	6.3	17.4	17.4	176.2%	176.2%
S_Inj_est	14.1	16.0	25.2	27.1		
B (n fixed at 2)	1.0	1.0	1.0	1.0	0.0%	0.0%
C (n fixed at 2)	-1.6E-03	-1.6E-03	-1.6E-03	-1.6E-03	-1.9%	-1.9%
S_Inj_est	14.1	16.0	25.2	27.1		
B (n optimized)	0.8	0.8	0.8	0.8	0.7%	0.2%
C (n optimized)	-1.2E-01	-1.2E-01	-1.2E-01	-1.2E-01	-0.2%	-1.3%
n	1.29	1.29	1.29	1.29	-0.2%	-0.1%
S_Inj_est	14.1	16.0	25.2	27.1		
B (n optimized)	0.6	1.0	1.0	1.0	67.3%	0.0%
C (n optimized)	-9.6E-04	-1.6E-03	-1.6E-03	-1.6E-03	66.8%	-1.9%
n	2.00	2.00	2.00	2.00	0.0%	0.0%
S_Inj_est	14.1	16.0	25.2	27.1		
B (n optimized)	0.5	1.0	1.0	1.0	98.4%	0.0%
C (n optimized)	-1.3E-06	-2.7E-06	-2.7E-06	-2.6E-06	99.3%	-1.9%
n	3.00	3.00	3.00	3.00	0.0%	0.0%

Table 3 - Traditional Measures Applied to Low Capacity Recharge Situation

	Test 1->	Sw=0		Test 2->	Sw=9	Change	Sw=1->9
Q = 40 gpm	1 hour	8 hour		1 hour	8 hour	1 hour	8 hour
Rise -S_inj (feet)	10.2	11.9		24.4	26.3	139.22%	121.01%
Rise - S_obj (feet)	4.8	6.5		4.8	6.5	0.00%	0.00%
S_inj (feet)/Q (gpm)	0.255	0.2975		0.61	0.6575	139.22%	121.01%
Q (gpm)/S_inj (feet)	3.9	3.4		1.6	1.5	-58.20%	-54.75%
S_Inj - S_obj	5.4	5.4		19.6	19.8	262.96%	266.67%
S_Inj_Theis_Sc	10.3	12		10.3	12		
S_Inj_Theis_Sy	5.5	7.2		5.5	7.2		
S_inj/S_Inj_Theis_Sc	1.0	1.0		2.4	2.2	139.22%	121.01%
S_inj/S_Inj_Theis_Sy	1.9	1.7		4.4	3.7	139.22%	121.01%
S_inj - S_Inj_Theis_Sc	-0.1	-0.1		14.1	14.3		
S_inj - S_Inj_Theis_Sy	4.7	4.7		18.9	19.1	302.13%	306.38%
S_Inj_est	10.2	11.9		24.4	26.3		
B (n fixed at 2)	0.3	0.3		1.0	1.0	235.55%	286.90%
C (n fixed at 2)	-1.1E-03	9.9E-04		-9.7E-03	-8.5E-03	813.93%	-962.54%
S_Inj_est	10.2	11.9		24.4	26.3		
B (n optimized)	0.8	0.8		0.8	0.9	4.64%	4.27%
C (n optimized)	-1.8E-01	-1.7E-01		-8.6E-02	-7.2E-02	-51.09%	-56.94%
n	1.31	1.31		1.27	1.27	-2.90%	-3.00%
S_Inj_est	10.2	11.9		24.4	26.3		
B (n optimized)	0.6	1.0		1.0	1.0	67.32%	0.02%
C (n optimized)	-8.5E-03	-1.8E-02		-9.7E-03	-8.5E-03	13.64%	-51.36%
n	2.00	2.00		2.00	2.00	0.00%	0.00%
S_Inj_est	10.2	11.9		24.4	26.3		
B (n optimized)	0.5	1.0		1.0	1.0	98.39%	0.00%
C (n optimized)	-1.6E-04	-4.4E-04		-2.4E-04	-2.1E-04	56.45%	-51.36%
n	3.00	3.00		3.00	3.00	0.00%	0.00%



EXPLANATION

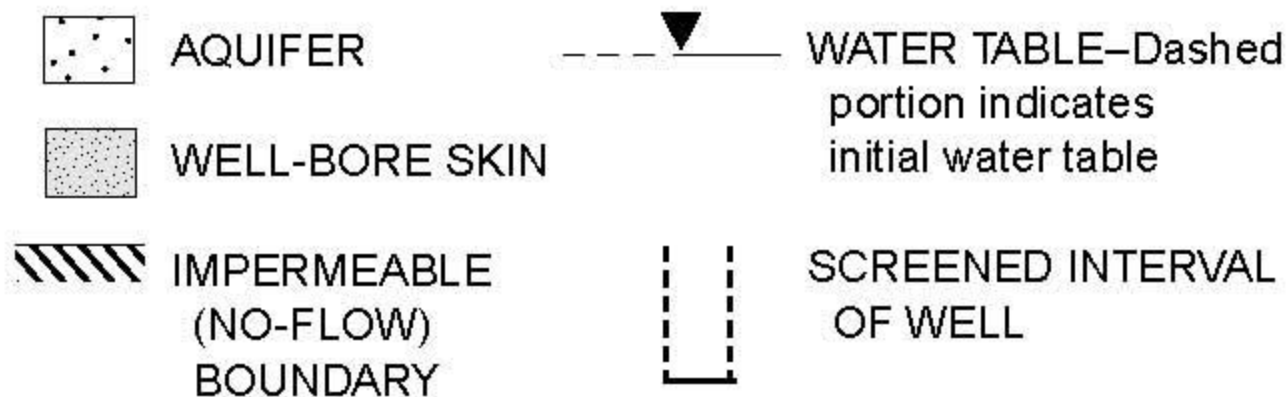


Figure 1 - Representation of a Well and Three-Dimensional Aquifer showing [Mechanical] Wellbore Skin (from Barlow and Moench, 1999)

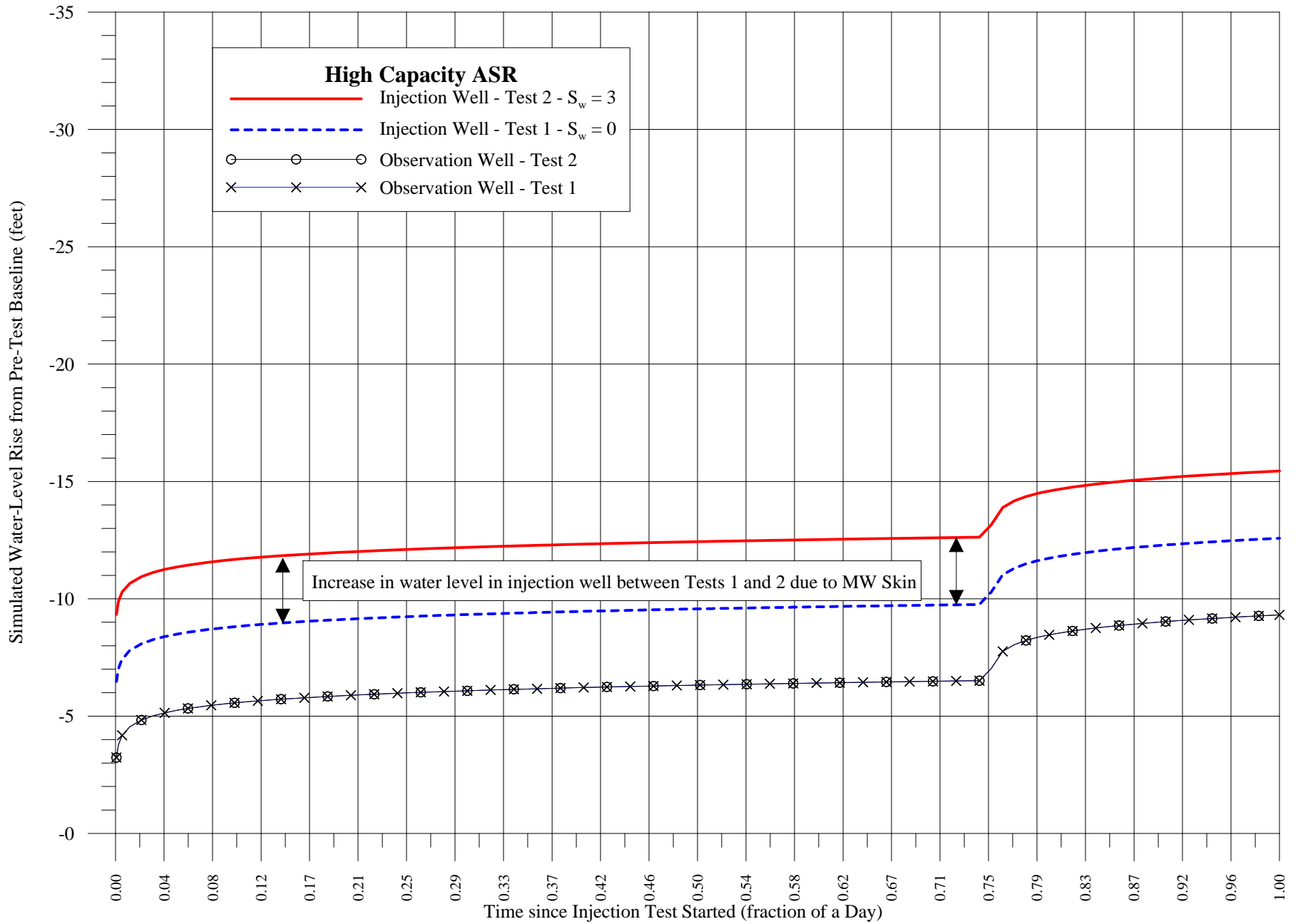


Figure 2 - Simulation for High Capacity ASR Situation

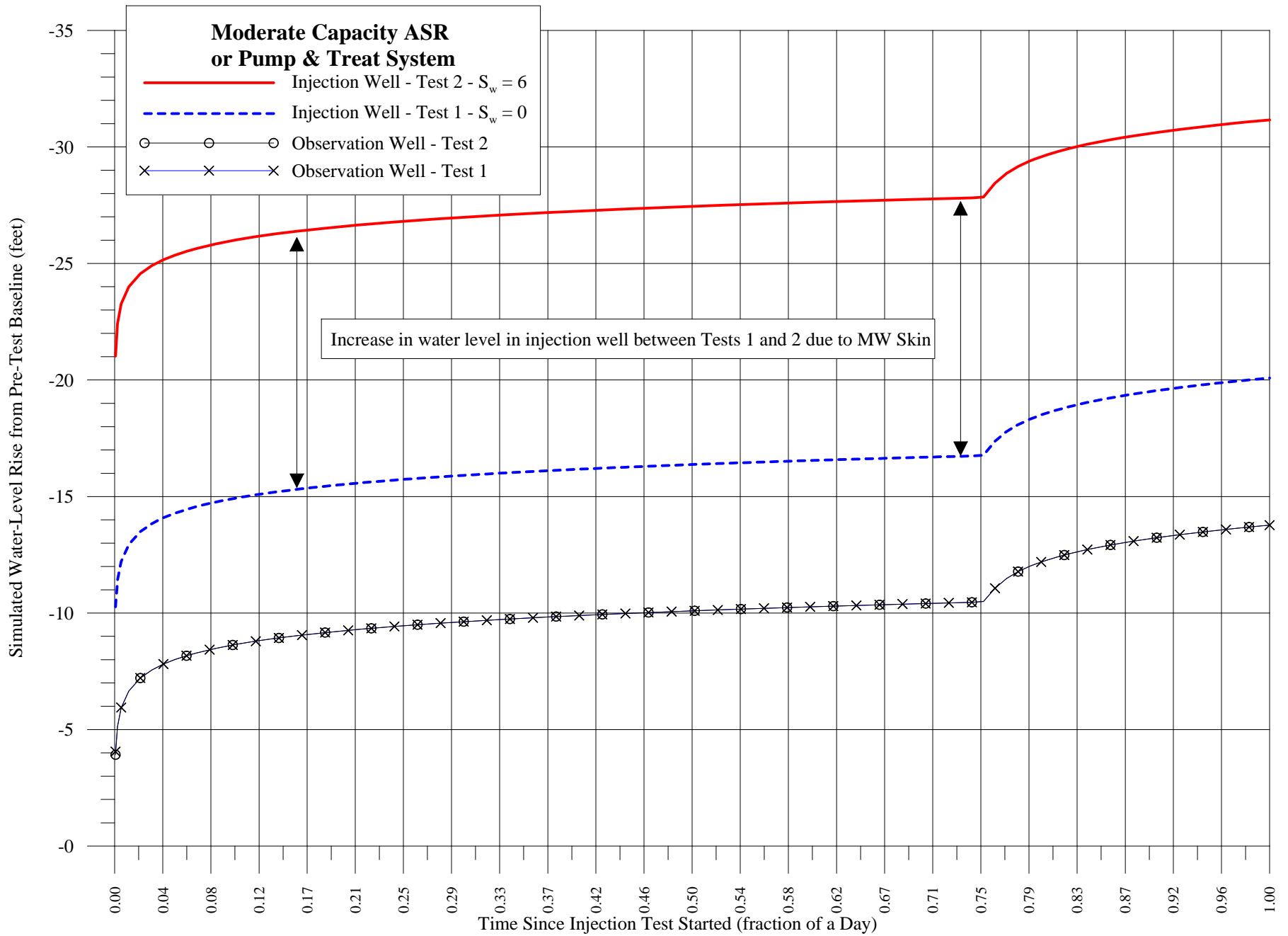


Figure 3 - Simulation for Moderate Capacity ASR Situation

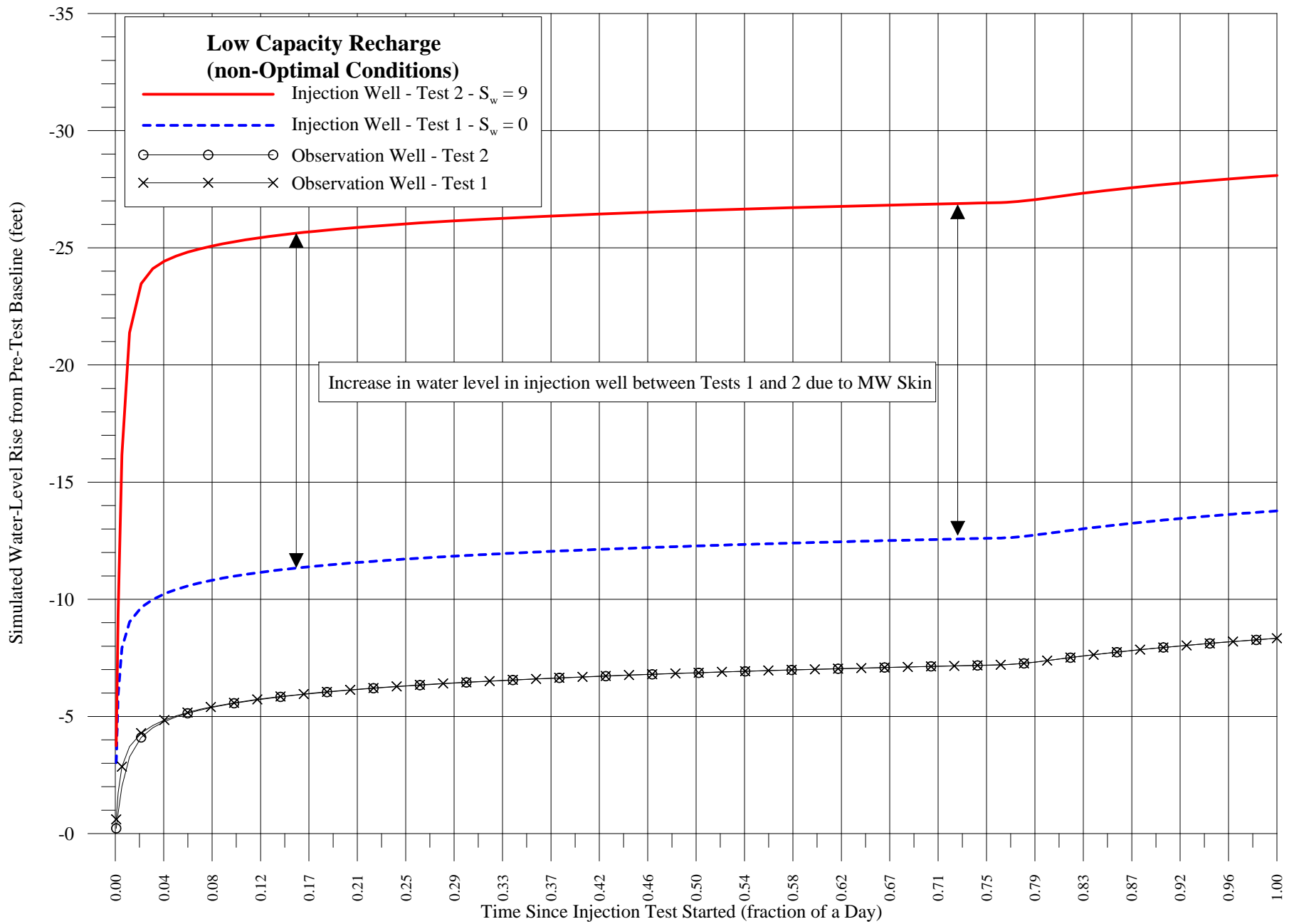


Figure 4 - Simulation for Low Capacity Recharge Situation