Predicting Injectivity Decline in Water Injection Wells by Upscaling On-Site Core Flood Data

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ABSTRACT

Particles suspended in water used for injection into hydrocarbon reservoirs for secondary oil recovery can result in blockage of the reservoir rock pore throats, resulting in injectivity decline of injection wells. Particles such as biomass, corrosion products, silt and scale can be present, even in the most highly treated water injection systems. On-site coreflooding is a well accepted method to directly measure the plugging effects of “live” system water on reservoir rocks and set a realistic water quality specification to minimize formation damage.

A major on-site core flooding study was undertaken on a large and complex seawater injection system in Saudi Arabia. Water from the Arabian Gulf is treated by filtration and deaeration before distribution through a long, complex, network of flowlines, some of which are bare carbon steel and some fusion

bonded epoxy lined. This results in different particle types in different areas of the system, particularly with respect to bacteria and iron. Further, the water is injected into different areas of the field, with permeabilities ranging from <10 mD to >1000 mD.

Data from the on-site coreflooding were combined with subsequent laboratory analysis of the particles and core plugs to determine the effects of the different water qualities on permeability. These data were then processed, upscaled to model injection wells and, finally, history matched to long term injectivity records. This enabled a matrix of water quality specifications to be derived for each area of the field, to give projected improvements in injection well half-lives ranging from 50% to 100%.

1. INTRODUCTION

A major on-site core flooding study was undertaken on a large and complex seawater injection system in Saudi Arabia to determine appropriate injection water quality specifications with repect to particle loading and Total Suspended Solids. The system was described by Al-Wehaimid et al. (1994), although it has expanded significantly since then, with water now being injected into areas much further south. Water from the Arabian Gulf is treated by filtration and deaeration before distribution through a long, complex, network of flowlines, some of which are bare carbon steel and some fusion bonded epoxy lined. Filtration is accomplished with sand filters, and deaeration is by nitrogen-stripping, plus oxygen scavenging by sulfur dioxide. Organic biocides are regularly dosed at the outlet of the seawater treatment plant. In order to determine the appropriate water quality specification for the injection water in the various regions of the field, on-site coreflooding was undertaken using actual core plugs taken from the reservoir and the actual injection water at various locations in the system.

Variations in pipeline materials result in differences in the nature of the suspended solids in different parts of the system, particularly in the amount of biomass and iron solids. The water quality tests, which were conducted along with the corefloods, cannot be definitely interpreted as indicating that there are deteriorations in quality along the flowlines since the tests were conducted consecutively and not simultaneously over a 6 week period. However, it is reasonable to infer that some deterioration did occur and also that there were periodically substantial upsets in water quality, with peaks of very poor quality (but of unknown duration and frequency).

The suspended solids identified in the injection water were predominantly iron oxides and sulfides, clay particles and quartz grains, with lesser amounts of plankton particles and probable biomass.

Reservoir quality decreases from north to south across the field. Consequently, it was anticipated that the water quality specification would be tighter in the south of the field, compared to the northern areas. The degree of natural fracturing in the carbonate reservoir also has an impact on the water quality specification for individual wells. Within the field there is a mix of horizontal and vertical injection wells: the larger injection surface area of a horizontal well, compared to a vertical well, results in a smaller impact of water quality on injectivity. Therefore, it may also be anticipated that a tighter water quality specification would be required for a vertical well, compared to a horizontal well.

2. ON-SITE COREFLOODING

The objective of the on-site coreflooding was to investigate the effects of potential injection waters on reservoir rock matrix permeability by passing water through core plugs prepared from reservoir material and recording the changes in measured permeability. The coreflooding was carried out at several points throughout the seawater injection system. The study began at the Seawater Treatment Plant, proceeded to the Water Supply Station, followed by Water Injection Pumping Stations and, finally, injection wellheads.

On-site coreflooding was carried out on a total of 56 core plugs at 9 different locations. Three core plugs (high, medium and low permeability) were flooded simultaneously in the on-site coreflooding rig (see Figure 1). The coreflooding was carried out in a mobile laboratory that was moved between the sampling locations. A coreflooding rig was connected directly to the water pipelines via suitable sample points and the water was flooded through the plugs as a side stream from the pipeline. This prevents the degradation of the water, for instance due to the oxidation of dissolved iron, which would occur during storage of water samples. The plugs were flooded at relatively high flow rates and very large volumes of water were flooded through the plugs. In the case of the high permeability plugs, up to 150 litres (~17,000 pore volumes) of water was flooded through an individual plug over the 2 days duration of the coreflood. The on-site coreflooding study was carried out continuously over a period of 6 weeks.

By varying the degree of filtration (using cartridge filters in the coreflooding rig) throughout the duration of the coreflood, and analysing the changes in water quality across the plugs, the causes of any permeability changes which occur during the flooding tests may be deduced. Each individual plug was flooded with up to four different water qualities (ultra filtered, fine filtered, coarse filtered and unfiltered) with respect to the water quality in the pipeline. The coreflooding methodology is based on the technique set out in the standard method ASTM D 4520-95. In the following sections, the water grade values are related to degree of water filtration as follows:

Water Grade	Degree of Water Filtration	Filtration Grade
1	Ultra filtered	1 μm
2	Fine filtered	3 μm
3	Coarse filtered	10/20 μm
4	Unfiltered, with respect to the water quality in the pipeline	None

Core plugs from three areas of the field (southern, central and northern) were flooded with water from the various sampling locations in order to investigate the impact of the varying water quality on plug permeability. A baseline permeability decline was established by flooding a full set of core plugs at the outlet of the Seawater Treatment Plant. Subsequently, additional sets of core plugs were flooded with water from further downstream in the injection system to assess how evolving water quality affects plug permeability. Core plugs were prepared from reservoir core material and were generally grainstone carbonate rocks, mostly pelletoid with some skeletal foraminifera and elongated bioclasts.

An example core flooding profile is presented in Figure 2 (medium permeability from center of field), in which it can be clearly seen that the rate of permeability decline is determined by water quality. The flooding water quality in this particular case was as follows:

Water Grade	Number of particles ≥ 2 µm diameter in 0.5 ml	Total Suspended Solids (mg/l)
1	130	0.03
2	294	0.07
3	333	0.10
4	607	0.16

The water quality of the injection water was generally good, and the additional filtration by the filter cartridges in the on-site coreflooding rig, resulted in some very clean water qualities. The particle size distribution of the water samples was measured using a Coulter Z1 particle counter, manufactured by Beckman Coulter Limited.

The total suspended solids (TSS) concentration of the flooding waters was determined using standard membrane filtration techniques (NACE Standard TM0173-99). Due to the very low suspended solids content of the flooding waters, it was necessary to filter 20 litres of water in order to obtain an accurate measurement. However, even with the very low solids content of the injection water, the permeability of the core plugs declined and the rate of permeability decline was dependent on the measured water quality. The differences in rate of permeability decline with different water qualities can be clearly seen if the initial permeability at each coreflood stage is normalized. Figure 3 presents an example of the normalized permeability plot, demonstrating increasing rate of permeability decline with decreasing water quality (normalized data from Figure 2).

3. SCALING UP OF COREFLOOD RESULTS

3.1. Treatment of Coreflood Data

Perkins and Gonzalez (1985) provide a methodology for scaling up coreflood results to determine the pressure increase across a skin due to poor water quality and this methodology was used in this study. The pressure increase across the skin damage is given by the following equation:

$$\Delta P_s = \frac{i_w \mu_w R_s}{A_f} \qquad (1)$$

Where:

$\Delta P_s =$ pressure increase as the result of skin damage due to poor water quality (psi)
$i_w =$ water injection rate, bwpd
$\mu_w =$ water viscosity, cP
$R_s =$ resistance to flow caused by skin damage, ft/mD
$A_f =$ Area over which solids from injection water are deposited, sq ft. The area calculation may take into account the perforation details of a perforated injection interval.

Of these factors, both i_w and μ_w are known for a particular injection well, while A_f can be calculated as the surface area of the open-hole or perforated section of the borehole. Only R_s is unknown, however this can be calculated from coreflooding data in the following manner.

The total pressure drop across the core can be considered to be the sum of the pressure drop across the initial core plug, plus the pressure drop across the filter cake formed at the upstream face of the core plug by filtration of suspended solids from the injection water. This relationship is summarised in the following equation:

$$\Delta P_c = \frac{i_w \mu_w L_c}{kA_c} + \frac{i_w \mu_w R_s}{A_c} \qquad (2)$$

Where:

ΔP_c = Pressure drop across length of core (psi)
L_c = Length of core (ft)
A_c = Surface area of core face (ft^2)
k = Core permeability (mD)

For a fixed water quality, growth of the pressure drop across the skin damage is directly proportional to the volume of water injected, and the concentration of total solids introduced at the upstream face of the core. It is also inversely proportional to the core area. Thus, R_s, as determined from the laboratory measurements, can be correlated vs. W_i/A_c, where W_i represents the cumulative volume of water.

The additional flow resistance caused by solids loading increases as additional water is injected. This relationship can be represented by the following linear expression:

$$R_s = \frac{\lambda W_i}{A} \qquad (3)$$

Where:

λ = Water quality coefficient (mD^{-1})

Figure 4 presents an example of the calculation of water quality coefficients using the coreflood data presented in Figures 2 and 3. In Figure 4, the R_s values (calculated using equation 2) are plotted against $\frac{W_i}{A}$ and the gradient of the fitted line through this cross-plot is the water quality coefficient (λ in equation 3). As the water quality becomes worse and the rate of plug permeability decline increases, the value of the water quality coefficient increases.

A water quality coefficient (λ) was calculated for each stage of each coreflood, except for grade 1 water. During grade 1 waterflooding the permeability varies due to factors unrelated to water quality such as the movement of fines within the plug and, therefore, it is not appropriate to use this data to make predictions of the effect of water quality on well injectivity. Therefore, grade 2 was the best water quality and grade 4 was the worst water quality used in the modelling.

Variations in the unfiltered water quality from location to location results in variations in the quality of the water at the different filtration grades. Thus, water quality coefficients were calculated for each grade of filtration at every location.

The water quality coefficients are strongly dependent on permeability, and when the water quality coefficients are plotted against maximum permeability to water, a strong negative correlation can be observed. Essentially, the lower permeability core plugs block at a higher rate than the high permeability core plugs. Therefore, the low permeability core plugs have high water quality coefficients compared to high permeability plugs, for a given water quality and coreflood location. An example of this is given in Figure 5, in which all of the coreflood data from one particular location is plotted. For a given permeability value, the water quality coefficient values increase, as water quality decreases.

3.2. Well Performance Modelling

The water quality coefficients determined from the on-site coreflooding were used in a matrix well performance model in order to predict the impact of various water qualities on the rate of injectivity decline. The modelled rates were matched to historical well injectivity declines, using the water quality coefficients for the unfiltered water from the relevant injection wellhead location. The match was achieved by varying the effective diameter of the injection zone. The naturally fractured nature of the reservoir carbonates means that the effective surface area for injection is greater than the cylindrical surface area of the well bore. The surface area was increased to correspond to fracture half-lengths of between 2 and 12 ft. There is a general positive correlation between the fracture lengths used in the model, and effective well-test permeability. This relationship helps to validate the use of variable length fractures in the model, because the increasing well-test permeability reflects more extensive fracturing within the injection zone. However, it should be noted that a similar history match could also be obtained with less extensive fractures and better wellhead water quality.

The extent of fracturing in the injection zone controls the surface area over which the water is being injected. Surface area is one of the critical factors (together with water quality coefficient and injection rate) that control the development of the skin from the suspended solids in the injection water.

Once a match was achieved to the historical data for the actual injection water quality, the impacts of different water qualities on well injectivity decline were assessed by using different water quality coefficients (see example in Figure 6 for a well at which wellhead corefloods were conducted). In this way it was possible to build up relationships between water quality and well half-life for the various regions of the reservoir areas (north, central and southern) and for vertical and horizontal wells. The well half-life is defined as the time taken for the injectivity of a well to decrease by one half.

4. RESULTS

The following table gives the recommended water quality specification determined for six typical wells across the field. The water quality specification has been set using criteria of 50%, 75% and 100% increases in well half-life compared to current well performance.

Well Location	South	Center	North

Well Orientation		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
50% increase in Well-Half Life	Number of particles ≥ 2 µm diameter in 0.5 ml	246	338	410	511	711	630
	Total Suspended Solids (mg/l)	0.07	0.08	0.09	0.14	0.11	0.10
75% increase in Well-Half Life	Number of particles ≥ 2 µm diameter in 0.5 ml	239	253	362	463	704	582
	Total Suspended Solids (mg/l)	0.07	0.07	0.09	0.13	0.11	0.10
100% increase in Well-Half Life	Number of particles ≥ 2 µm diameter in 0.5 ml	232	231	314	415	697	534
	Total Suspended Solids (mg/l)	0.07	0.07	0.08	0.12	0.10	0.10

The water quality specifications were determined by interpolating between the well half-life and water quality values for water grades 2, 3 and 4 for each well and well head core flooding location. This interpolation allows the determination of the water quality corresponding to a 50%, 75% and 100% increase in well half-life compared to the historical well half-life value.

The water quality specification becomes tighter towards the southern end of the field, reflecting the general decrease in reservoir quality in the south. In addition, the water quality specifications are generally tighter for the vertical wells compared to the horizontal wells in a particular area, reflecting the greater detrimental impact of poor water quality on the shorter injection intervals of vertical wells. The specification in a particular well is also related to the degree of natural fracturing.

Overall, the injection water quality specifications derived from this study are generally less stringent (in terms of number of particles ≥ 2 µm in 0.5 ml) than the existing specification of a maximum of 200 particles ≥ 2 µm in 0.5 ml, albeit the latter is currently interpreted as that set for treated water leaving the Water Treatment Plant, not that arriving at the injection wells. However, the TSS specifications determined during this study are approximately 50% of the initial specification value of a maximum of 0.2 mg/l. In the northern area the specification can be relaxed (in terms of number of particles ≥ 2 µm in 0.5 ml), but in the poorer reservoir quality areas of the central and southern areas, the original water quality specification still largely applies.

5. CONCLUSIONS

Well performance modelling, incorporating data from on-site coreflooding, was able to match to the historical injection rates of various wells. The matching parameter used was the extent of natural fracturing in the vicinity of the injection well, reflected in the effective well-test permeability. The well performance models enable the prediction of well-half life for various water qualities, which in turn can be used to predict the water qualities corresponding to 50%, 75% and 100% increases in well half-life.

New injection water quality specifications have been determined from on-site coreflood tests. Although these are not very different numerically from the current ones, it is clear that these should be applicable at the injection wells (ideally bottomhole) and not only in water produced at the Water Treatment Plant.

Improving the water quality to meet the specification set out in the results table will have significant benefits for the field operator. An increase in the well half-life will reduce the frequency of well work-overs (thus reducing costs), but will also increase the total amount of water injected into an injection well in a given time period. The net increase in well injection rate associated with better water quality should result in higher reservoir pressures, and possibly an increase in oil productivity. It is important to inject water at the correct rate, and in the required time period in order for reservoir performance forecasts to be accurate and to meet long-term production targets and to optimize overall oil recovery.

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Figure 1
Schematic of On-Site Coreflooding Rig

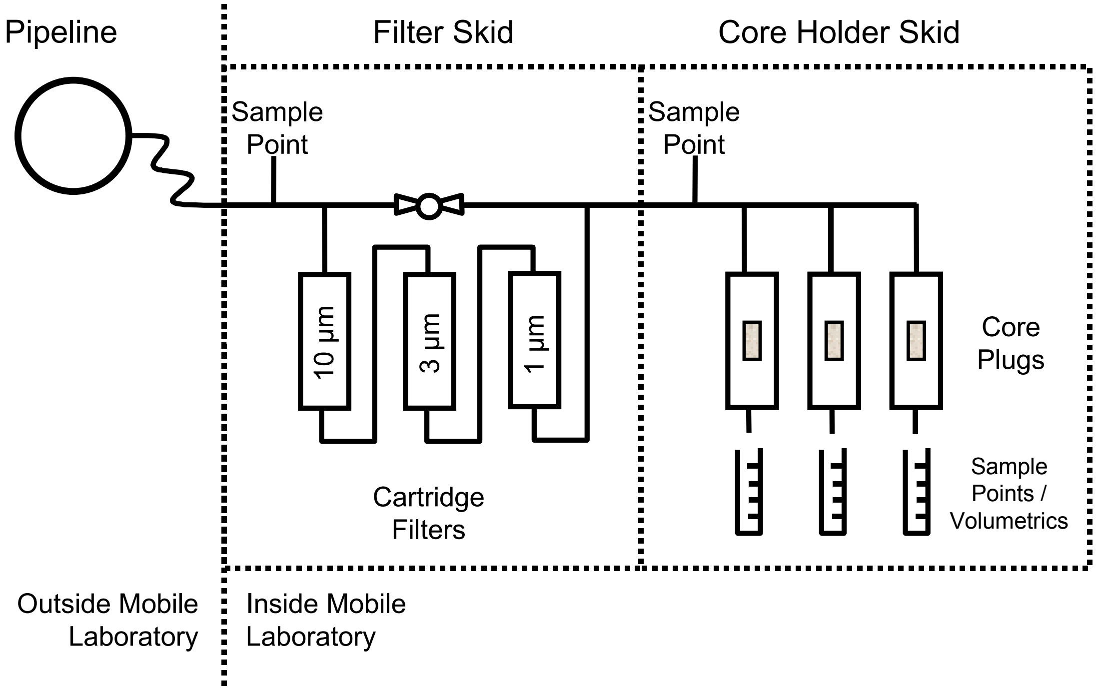

Figure 2
Example Coreflood Profile

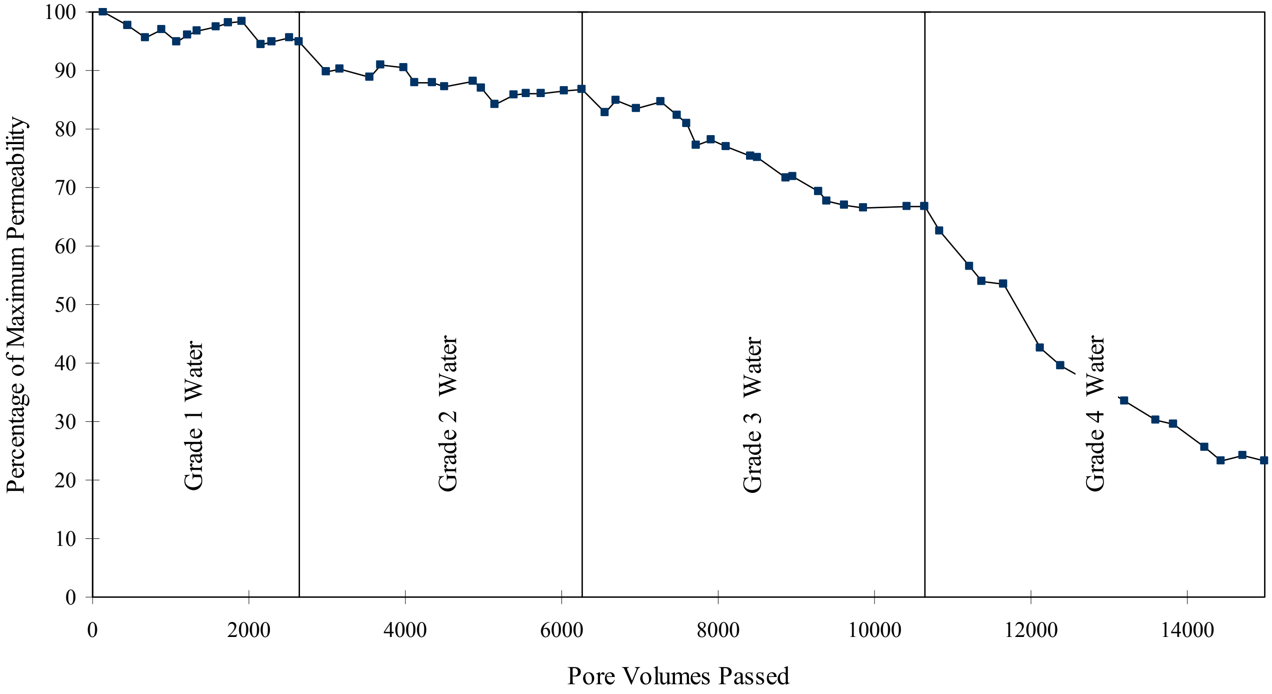

Figure 3
Example of Normalised Coreflood Data

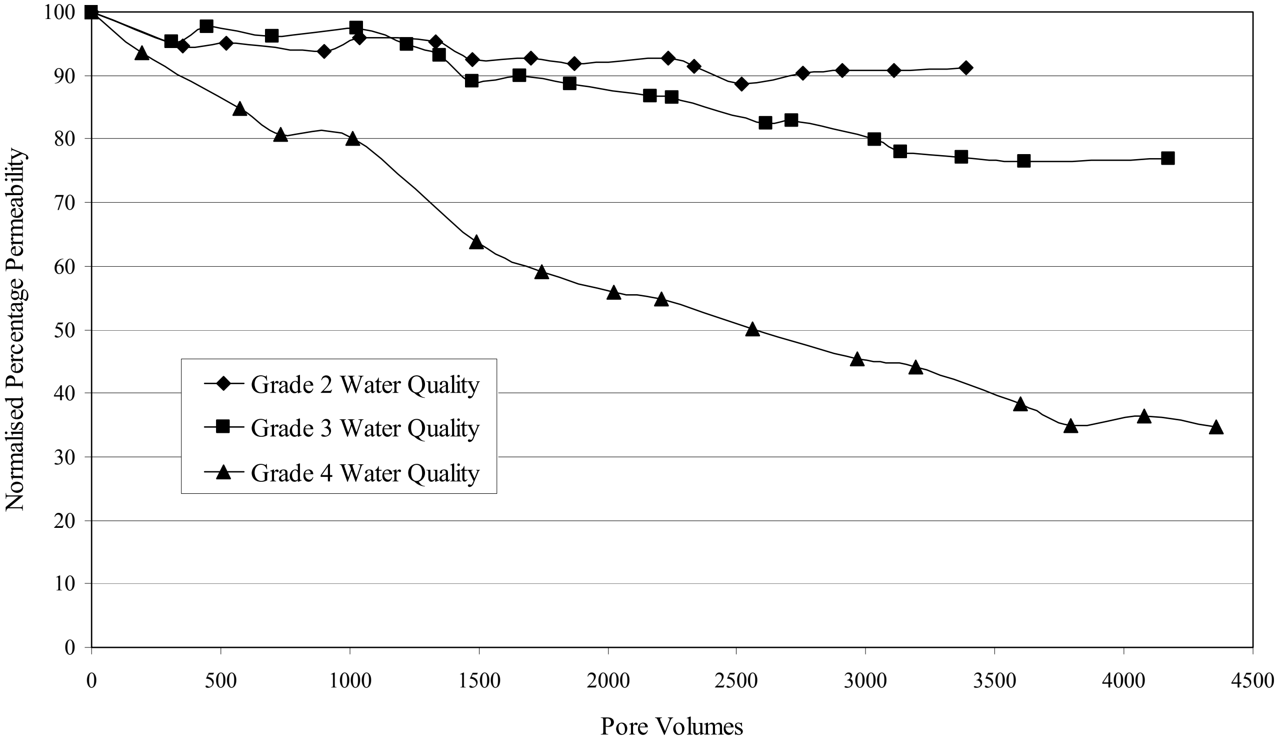

Figure 4
Example of Derivation of Water Quality Coefficients

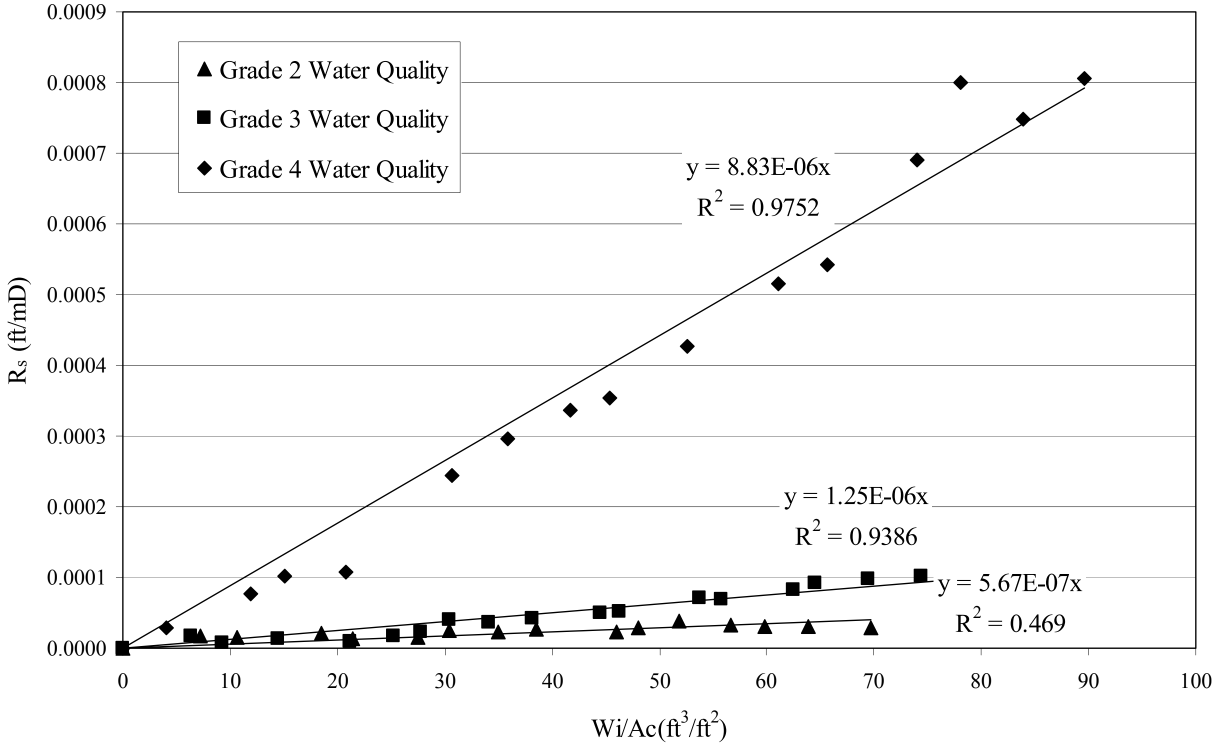

Figure 5
Example of Water Quality Coefficient versus Liquid Permeability

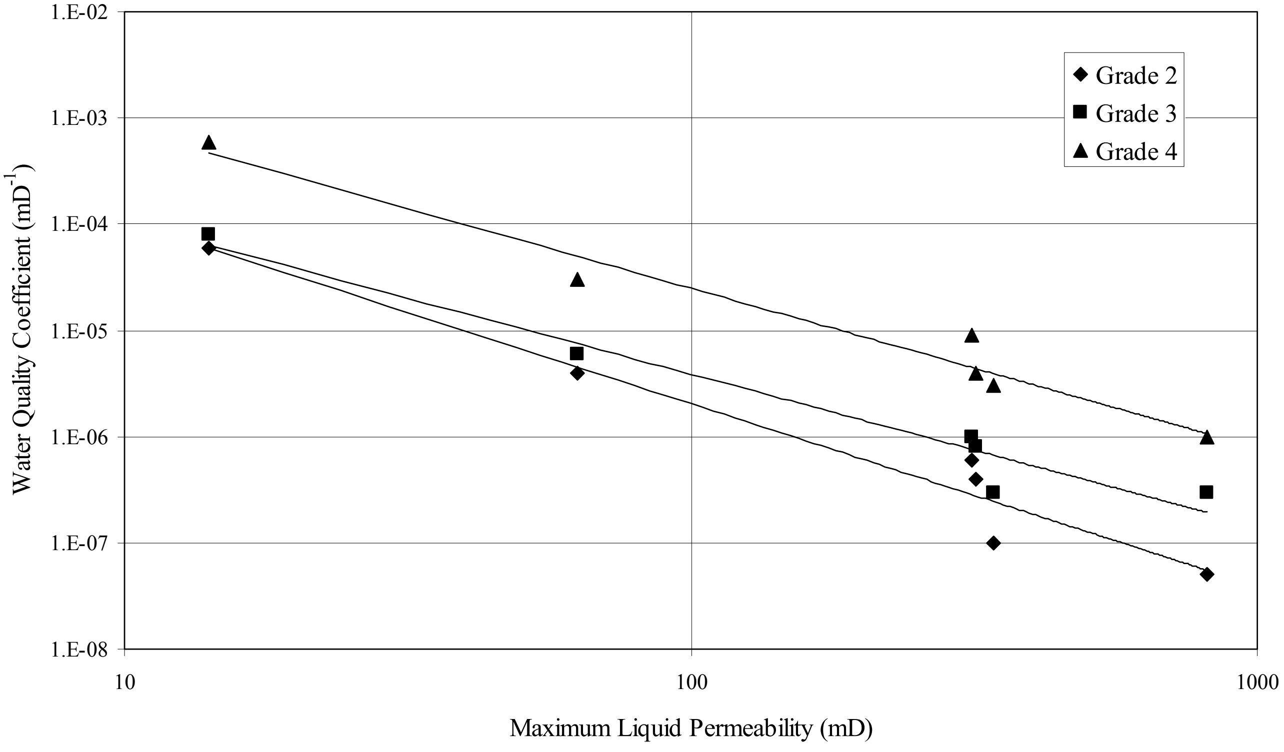

Figure 6
Injectivity Predictions and Comparison with Historical Data