FIELD AND LABORATORY ANALYSIS OF
WATER WELL DESIGN PARAMETERS

by

Christopher Robert Harich

A Dissertation Presented to the
FACULTY OF THE VITERBI SCHOOL OF ENGINEERING
UNIVERSITY OF SOUTHERN CALIFOIRNIA
In Partial Fulfillment of the
Requirements for the Degree
DOCTOR OF PHILOSOPHY
(CIVIL ENGINEERING)

May 2009

Acknowledgements

I am forever grateful for all of the professors at the University of Southern California who inspired me to pursue Water Resource Engineering. These professors shared their passion and insight in their fields of Engineering and it became contagious within me to do the same. My gratitude and honor will always be with them for their patience with me and on this project. I would also like to thank the Roscoe Moss Company for their dedication to the University of Southern California in pursuing an engineering approach to water well design with their contribution and support of the Roscoe Moss Company Well/Aquifer Model.

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Abstract

It is the goal of this research to establish fundamental principles of water well design. These principles have developed critical water well design parameters for four different types of aquifers; very coarse, coarse, medium and fine grained according to the Wentworth classification. With extensive laboratory testing utilizing the world's largest sand-tank well/aquifer model at the University of Southern California's Geohydrology Laboratory and field data from over 100 wells accompanied by 400 aquifer sieves, this research has developed a standard by which water wells can be designed.

The design of efficient water wells requires knowledge of various hydraulic factors that affect the major drawdown components of a well. Determining which design criteria are most applicable in a given aquifer will improve well efficiency and decrease energy usage which will then lead to a significant contribution to the ground water industry. A large cost to any well operator is the electrical cost of a well. A decline in specific capacity, well efficiency, and or lack of well development will increase this operational expense. Minimizing these turbulent flow losses can result in substantial cost savings over the lifetime of the well.

This research will aid engineers in developing more efficient water wells in various geohydrological settings. Its goal is to provide the largest production of water while maintaining the lowest operational costs for the well owners. This paper will design wells that are simple and strong while protecting our water resources.

Chapter 1. EXECUTIVE SUMMARY

Previous investigators over the years have applied solutions for designing efficient water wells. Some of these solutions have led to achievements in water well design while others have been oversimplified or grossly approximated. It is the goal of this research to test and develop a standard of water well design criteria by better understanding the hydraulic factors that influence water well efficiencies.

Understanding water well efficiency and well loss is the first step to develop, test, and define our design criteria. Currently there are no design criteria or standards when an engineer or geohydrologist designs a particular water well and generally they all have their own design. It is the goal of this research to understand water well efficiency and well loss and then describe some of the design criteria that is important for different types of aquifers that may be encountered.

There are several design factors that an engineer should consider when designing water wells. The most important factors that affect the hydraulic performance of a well are well screen length and diameter, filter pack material used, critical well radius and initial well development. A properly designed well considers which factors are the most important to the hydraulic performance of the well with regard to initial cost of the well and cost of the operation during its life time. This research concentrates on the hydraulics of the well screen, filter pack material, and the critical radius of the well. It also compares field data of actual operational water wells to the laboratory data in an effort to verify the Design

Criteria set forth. Design criteria for the filter pack materials used in a well have varied widely in the water well industry. It is the effort of this research to help in standardizing well design criteria by which most wells can be designed.

There will be large economic benefit from this research to many water suppliers. The savings to well operators will be two-fold; first the increase in the ability to deliver more water from newly planned wells, and second the decrease in energy costs by operating wells more efficiently. These benefits will help not only in water conservation but a large energy savings for a water agency.

The ground water basins would also benefit from this research by reducing the number of drilled wells that a well operator generally constructs. In 2007 there were over 14,000 public supply wells drilled in California alone. The cost of these wells are estimated at $1.5-$2.0 Million per well (AGWT, 2008). Often the cost of the well is small compared to the land value needed to place the well site on. Many water agencies do not have the land or are limited in its ability to have multiple well sites. The cost saving associated with more efficient wells would be tremendous. This project not only saves a precious ground water resource but is also energy efficient thus making it a truly water wise project.

Chapter 2. IMPORTANCE OF WATER WELLS

Mark Twain stated, “Whiskey is for drinking and water is for fighting over.” This has never been more pertinent than in today’s world. Nationally approximately 56% of the large public utilities obtain their water from ground water, over 80% of small public water utilities utilize ground water for their supply, and over 95% of the non-community water sources are from ground water (Helweg, 2000). California alone relies 47% on ground water for its public drinking water supply (Water Encyclopedia, 1990). Table 2.1 below shows the comparison of ground water vs. surface water usage in California last year (AGWT, 2008).

Table 2.1 California Water Usage 2006, Million Acre-ft

Source Water	Public Supply	Domestic	Irrigation	Other[1]	Total
Surface Water	3.6	0.03	21.2	1.17	26
Ground Water	3.1	0.3	13	0.6	17
Total	6.7	0.33	34.2	1.77	43

[1]Includes livestock, aquaculture, industrial, mining, and thermoelectric power

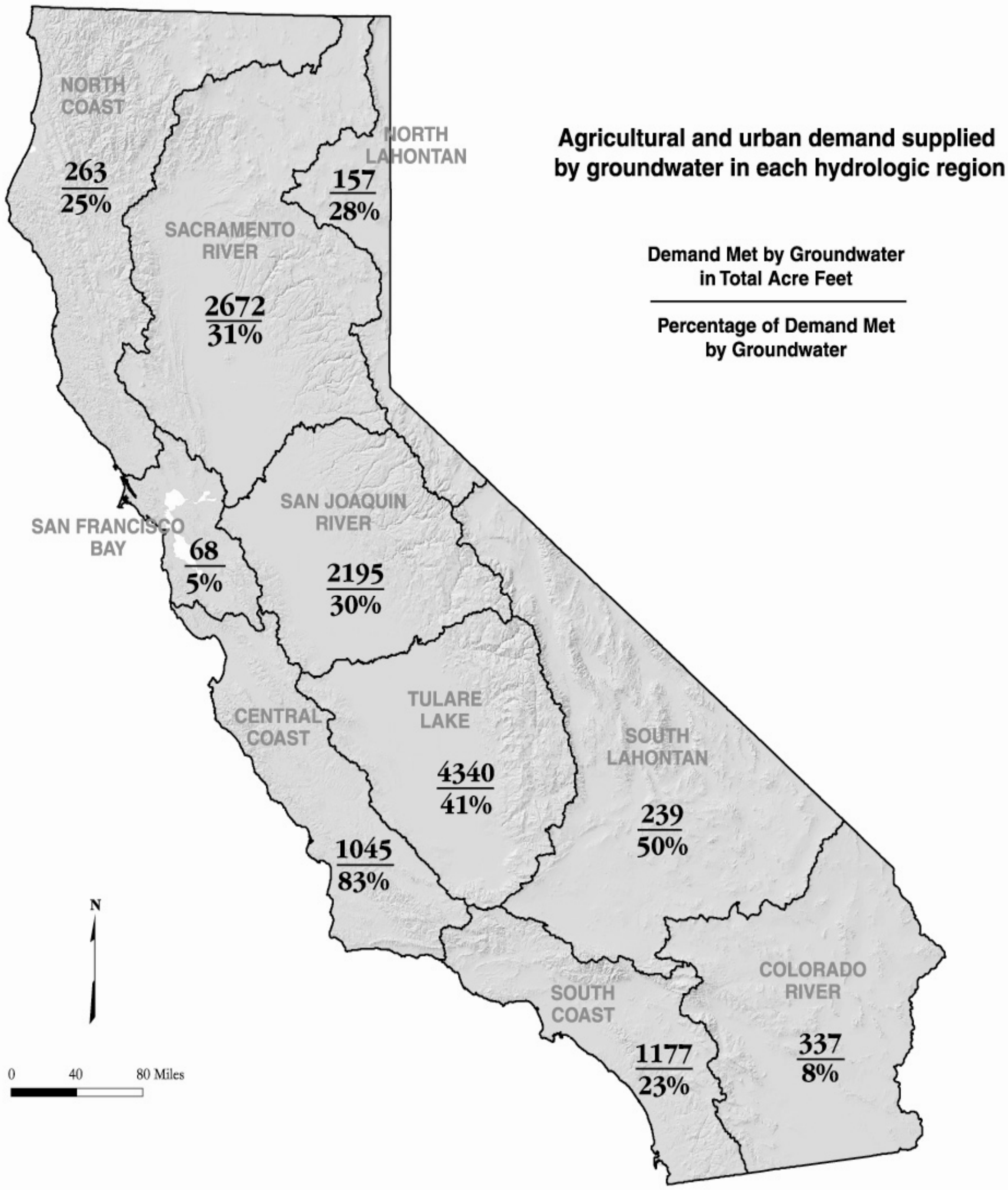
Why is ground water utilized so much in California? The American Ground Water Trust estimates that the surface water reservoirs have an estimated capacity of 43 Million Acre/Feet of water. The ground water reservoirs are in the hundreds of millions of Acre/Feet of capacity. Table 2.2 below shows the area of the ground water basins in California and the amount of wells in each basin (AGWT, 2008).

Table 2.2 California Basin Areas

Province	Total Area (mi²)	Number of Watersheds	Number of Ground Water Basins	Total Area of Basins (mi²)	Public Supply Wells in Basins	Public Supply Wells Outside Basins
Northern Coast Ranges	14,672	176	79	2,317	770	280
Southern Coast Ranges	16,216	89	74	5,019	1,740	480
Klamath Mountains	8,880	51	7	116	20	110
Modoc Plateau & Cascades	15,058	70	55	8,108	240	40
Central Valley	20,463	8	36	20,463	5,360	0
Sierra Nevada	25,483	161	22	772	330	1170
Basin & Range	13,900	56	45	6,178	260	20
Transverse & Peninsular Ranges	8,494	167	33	3,089	2,720	800
Sand Diego Drainages	3,861	163	25	4	180	120
Desert	31,274	110	96	21,622	1,240	60
Totals	**158,301**	**1051**	**472**	**67,688**	**12,860**	**3,080**

From the table above we can see the distribution of these basins as per usage of ground water in California. Figure 2.1 below is the breakdown of the ground water basins in California and each basin's reliance on ground water.

Figure 2.1 California Ground Water Demand



(Courtesy of America Ground Water Trust, 2008.)

Due to recent droughts in California and the decrease in surface water from the Sacramento Bay Delta, public supply wells in southern California are projected to increase by 20% in the upcoming years. It was estimated in 1988 that there were over 282,000 public supply wells in the nation as a whole. The nation as a whole can see 800,000 wells drilled a year (The Water Encyclopedia, 1990). In comparison, there were only 30,000 oil and gas wells drilled in the U.S. in 2004 (CAB, 2004). This research has tremendous impact not only on a ground water resource but for a community's energy consumption. The potential energy savings from an increase in specific capacity of a well could aid well operators in better decision making of how to manage their ground water supply. The ground water basins would benefit from this research by reducing the number of re-drilled wells that a well operator generally goes through. Many of these wells could benefit from an increase in specific capacity from better initial design criteria and development techniques. The cost savings associated with more efficient wells would be tremendous. By defining initial design criteria for different formations, engineers can design more efficient water wells from the start and decrease some of the need for redevelopment of poorly performing water wells. Determining which design criteria are most applicable in a given aquifer will improve well efficiency and decrease energy usage which will lead to a significant contribution to the ground water industry.

A large cost to any well operator is the electrical cost to operate a well. A decline in specific capacity, well efficiency, and or a lack of well development will increase operational costs. This additional operating cost can often lead well operators to decide if well rehabilitation or re-drilling is beneficial or not. National expenditures for pumping public supply water wells is estimated at $3.5 billion a year (Helweg, 2000), just a 10% increase in well efficiency from initial well design or well development would be an annual savings of $350 Million for just the public supply water wells, and this corresponds to only 19% of the total ground water usage. Table 2.3 below explains the ground water usage across the US (U.S. Geological Survey Circular 1268, 2004).

Another very large cost is the actual drilling of the well. Currently the costs for steel and fuel are constantly on the rise, driving the price for drilling up as well. The current cost per foot of drilling ranges from $400 to $600 (AGWT, 2008). This is constantly changing as the price of steel and fuel has become commodities.

Many investigators have proposed solutions for designing efficient water wells. Some of these solutions have led to achievements in water well design while others have been oversimplified or grossly approximated. It is the goal of this research to test and develop a standard of water well design criteria by better understanding the hydraulic factors that influence water well efficiencies.

Table 2.3 – Ground-Water withdrawals by water-use category, 2000.

(U.S. Geological Survey Circular 1268, 2004)

[Figures may not sum to totals because of independent rounding. All values are in million gallons per day. —, data not collected]

STATE	PUBLIC SUPPLY	DOMESTIC	IRRIGATION	LIVE-STOCK	AQUA-CULTURE	INDUSTRIAL		MINING		THERMO-ELECTRIC POWER	TOTAL		
	Fresh	Fresh	Fresh	Fresh	Fresh	Fresh	Saline	Fresh	Saline	Fresh	Fresh	Saline	Total
Alabama	281	78.9	14.5	—	8.93	56	0	—	—	0	440	0	440
Alaska	29.3	10.9	0.99	—	—	4.32	0	0.01	90.4	4.65	50.2	90.4	141
Arizona	469	28.9	2,750	—	—	19.8	0	81.2	8.17	74.3	3,420	8.17	3,430
Arkansas	132	28.5	6,510	—	187	67	0.08	0.21	0	2.92	6,920	0.08	6,920
California	2,800	257	11,600	182	158	183	0	21	152	3.23	15,200	152	15,400
Colorado	53.7	66.8	2,160	—	—	23.6	0	—	—	16.1	2,320	0	2,320
Connecticut	66	56.2	17	—	—	4.13	0	—	—	0.08	143	0	143
Delaware	45	13.3	35.6	3.7	0.07	17	0	—	—	0.47	115	0	115
District of Columbia	0	0	0	—	—	0	0	—	—	0	0	0	0
Florida	2,200	199	2,180	31	7.81	216	0	160	0	29.5	5,020	0	5,020
Georgia	278	110	750	1.66	7.7	290	0	7.75	0	1.03	1,450	0	1,450
Hawaii	243	4.82	171	—	—	14.5	0.85	—	—	0	433	0.85	434
Idaho	219	85.2	3,720	27.7	51.5	35.8	0	—	—	0	4,140	0	4,140
Illinois	353	135	150	37.6	—	132	0	—	—	5.75	813	0	813
Indiana	345	122	55.5	27.3	—	99.7	0	4.2	0	2.58	656	0	656
Iowa	303	33.2	20.4	81.8	—	226	0	2.49	0	11.9	679	0	679
Kansas	172	21.6	3,430	87.2	3.33	46.6	0	14	0	14.9	3,790	0	3,790
Kentucky	71	19.5	1.14	—	—	95.2	0	—	—	2.71	189	0	189
Louisiana	349	41.2	791	4.03	128	285	0	—	—	28.4	1,630	0	1,630
Maine	29.6	35.7	0.61	—	—	9.9	0	—	—	4.92	80.8	0	80.8
Maryland	84.6	77.1	29.8	7.18	4.81	15.9	0	4.21	0	1.8	225	0	225
Massachusetts	197	42.2	19.7	—	—	10.7	0	—	—	0	269	0	269
Michigan	247	239	128	10.2	—	110	0	—	—	0	734	0	734
Minnesota	329	80.8	190	52.8	—	56.3	0	6.9	0	4.17	720	0	720
Mississippi	319	69.3	1,310	—	321	118	0	—	—	43.5	2,180	0	2,180
Missouri	278	53.6	1,380	18.3	2.01	29.2	0	4.1	0	12.2	1,780	0	1,780
Montana	56.1	17.3	83	—	—	31.9	0	—	—	0	188	0	188
Nebraska	266	48.4	7,420	76	—	35.5	0	5.64	4.55	6.87	7,860	4.55	7,860
Nevada	151	22.4	567	—	—	5.29	0	—	—	12	757	0	757
New Hampshire	33	40.9	0.5	—	3.12	6.95	0	0.08	0	0.71	85.2	0	85.2
New Jersey	400	79.7	22.8	1.68	6.46	65.3	0	6.12	0	2.24	584	0	584
New Mexico	262	31.4	1,230	—	—	8.8	0	—	—	11.4	1,540	0	1,540
New York	583	142	23.3	—	—	145	0	—	—	0	893	0	893
North Carolina	166	189	65.8	89.1	7.88	25.6	0	36.4	0	0.09	580	0	580
North Dakota	32.4	11.9	72.2	—	—	6.88	0	—	—	0	123	0	123
Ohio	500	132	13.9	8.2	1.36	162	0	53.1	0	7.57	878	0	878
Oklahoma	113	25.5	566	53.6	0.29	6.83	0	2.25	256	3.27	771	256	1,030
Oregon	118	68.3	792	—	—	12.1	0	—	—	2.47	993	0	993
Pennsylvania	212	132	1.38	—	—	155	0	162	0	3.98	666	0	666
Rhode Island	16.9	8.99	0.46	—	—	2.19	0	—	—	0	28.6	0	28.6
South Carolina	105	63.5	106	—	—	50.9	0	—	—	5.83	330	0	330
South Dakota	54.2	9.52	137	16.9	—	3.16	0	—	—	1.23	222	0	222
Tennessee	321	32.6	7.33	—	—	56.3	0	—	—	0	417	0	417
Texas	1,260	131	6,500	137	—	244	0.5	129	504	60.2	8,470	504	8,970
Utah	364	16.1	469	—	116	34.3	5.08	8.6	21.5	13.1	1,020	26.5	1,050
Vermont	19.5	20.7	0.33	—	—	2.05	0	—	—	0.66	43.2	0	43.2
Virginia	70.7	133	3.57	—	—	104	0	—	—	1.5	314	0	314
Washington	464	125	747	—	—	138	0	—	—	0.92	1,470	0	1,470
West Virginia	41.6	39.6	0.02	—	—	9.7	0	—	—	0	90.9	0	90.9
Wisconsin	330	96.3	195	60.3	39.8	83	0	—	—	8.99	813	0	813
Wyoming	57.2	6.57	413	—	—	4.31	0	58.8	222	1.13	541	222	763
Puerto Rico	88.5	0.88	36.9	—	—	11.2	0	—	—	0	137	0	137
U.S. Virgin Islands	0.52	0	0.29	—	—	0.22	0	—	—	0	1.03	0	1.03
TOTAL	16,000	3,530	56,900	1,010	1,060	3,570	6.51	767	1,260	409	83,300	1,260	84,500

Chapter 3. HYDRAULICS OF GROUND WATER FLOW

3.1. Determining Hydraulic Flow Rates Through Porous Media

Geohydrologists and Civil Engineers are very familiar with Darcy's Law and its application to finding the hydraulic conductivity for a given porous media. Darcy's Law is an expression for the dominance of the viscous forces applied by a porous media on the interstitial fluid valid for a certain range. Darcy's law is a linear relationship between hydraulic gradient and fluid velocity. Post-Darcy flow or Forchheimer flow is affected by both the inertial forces and turbulence forces of a system. Forchheimer (1901) was the first to observe that there was a non-linear relationship between a pressure gradient and fluid velocity.

Understanding flow through porous media is the first step at better understanding the relationship between wells and their surrounding aquifer materials. This understanding of flow becomes particularly important when a well system has a filter pack. Thus understanding the flow through the aquifer material and filter packs can aid in the development of critical design criteria for wells and filter packs.

3.2. Background

In the 1800's Henry Darcy preformed experiments in Dijon, France where he passed water passed through a pipe packed with sand. Darcy (1856) found a relationship such that a volumetric flow rate of water through a pipe packed with sand is a function of the flow area, elevation, fluid pressure, and proportionality constant. A one dimensional flow of Darcy's column is shown in Figure 3.1,

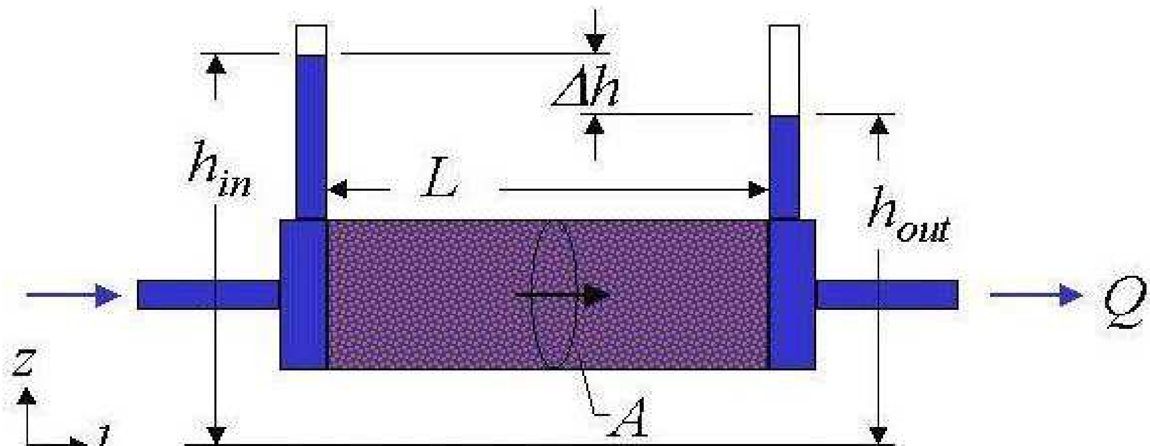


Figure 3.1 - Simple Darcy Column

Q = volumetric flow rate (m^3/s or ft^3/s), *A* = flow area perpendicular to L (m^2 or ft^2), *K* = hydraulic conductivity (m/s or ft/s), *L* = flow path length (m or ft), *h* = hydraulic head (m or ft), and *Δh* = denotes the change in *h* over the path *L*.

Therefore for 1-Dimensional flow and Darcy's Law may be stated simply as.

$$Q = -KA\frac{\Delta h}{L} \quad (3\text{-}1)$$

Where the Darcian flux, q is given by (Todd, 1980).

$$q = Q / A \quad (3\text{-}2)$$

While Darcian Flux has units of velocity, it is not the interstitial velocity of the water in the porous media. The aquifer material takes up some of the flow area and limits the water to flow only through the pore throats and pore volumes of any given media. The average pore water velocity thus becomes know as the seepage velocity, v_s, and is given by (Handbook of Ground water Development, 1990);

$$v_s = \frac{Q}{A\phi} \tag{3-3}$$

Where ϕ is the porosity of the given porous media. The Darcian flux or Darcy velocity, v_d, can thus be written as;

$$q = \frac{Q}{A} = v_d = v_s\phi = -K\frac{\partial h}{\partial L} = -KJ \tag{3-4}$$

Where J is the as the hydraulic gradient. It can therefore be said that the hydraulic conductivity of an aquifer or filter pack can be determined by the Darcian velocity and the hydraulic gradient. It is important to note that Darcy's velocity is valid within a certain flow rate for any given velocity. Darcy's Law states that discharge flux is proportional to the hydraulic gradient to the first power; similarly the velocity of a fluid in laminar flow is proportional to the first power of the hydraulic gradient, it has been reasonable to assume that the Darcy's Law in porous media is valid in laminar flow conditions. Reynolds number is used to determine whether a flow is in a laminar or turbulent state.

3.3. Flow Regimes

Thus if you use hydraulic gradients and Darcy velocities to calculate the hydraulic conductivity of a given porous material or filter pack, you must make sure that the data being used is within the laminar regime of a certain test, otherwise erroneous hydraulic conductivities maybe found. To understand a flow regime of a given system you must look at flow velocities and Reynolds's Number for that system. Reynolds's number is stated as follows (Todd, 1980);

$$Re = \frac{v_d d}{\upsilon} \tag{3-5}$$

v_d = Darcian Velocity (m/s or ft/s),

d = Particle diameter or characteristic length of a given material (m or ft),

υ = Kinematic viscosity (m^2/s or ft^2/s)

There are four demarcations of flow regimes in porous media which have been described for a very long time. In 1987 Fand determined that in completely randomly packed spheres, fluid exhibits four different regimes of flow which could be explained by Reynolds's Number. The four regimes of flow are Pre-Darcy, Darcy, Forchheimer (or Transitional), and Turbulent. Fand quantified these regimes by using a range of Reynolds's Numbers. Table 3.1 below demonstrates what Fand and others have determined as the demarcations of flow for their set of experiments (Fand, 1987).

Table 3.1 - Range of Reynolds's Numbers (Re)			
Flow Regime	**Bear (1972)**	**Fand (1987)**	**Kececioglu (1994)**
Pre-Darcy	Re<1	Re<1	Re<0.3
Darcy	1<Re<10	1<Re<2.3	0.3<Re<1
Forchheimer	10<Re<100	5<Re<80	1.6<Re<21
Turbulent	Re>100	Re>120	Re>21

NOTE; Darcian Reynolds's Number is based on diameter of the porous media

It is worth noting that the particle diameter used by each researcher above was the mean grain diameter for their set of experiments. Many researchers though use different grain diameters for the determination of Reynolds's Number. Todd (1980) uses d_{10}, that is, the diameter such that ten percent by weight of the grains are smaller than that diameter for a given sample. Bear (1972) and Williams (1985) both use mean diameter, d_{50}, for determining the particle diameter for a Reynolds number. Collins (1961) suggested using a different approach to getting a characteristic length for a certain Reynolds's Number.

$$d = \sqrt{\frac{k}{n}} \tag{3-6}$$

k = permeability (m^2 or ft^2)

n = porosity

Some researchers use the square root of the permeability as a representative grain size diameter (Ward, 1964). For the filter packs in the lab, both d_{10} and d_{50} where used in determining Reynolds's Number. It is worth noting that the characteristic length used whether it be d_{10} or d_{50}, affects Reynolds's Number.

3.4. Well Efficiency

Water well efficiency can be defined simply as follows (Handbook of Ground water Development, 1990);

$$E = \frac{Q/s_w}{Q/s_t} = \frac{s_t}{s_w} \qquad (3\text{-}7)$$

E = Well Efficiency, %

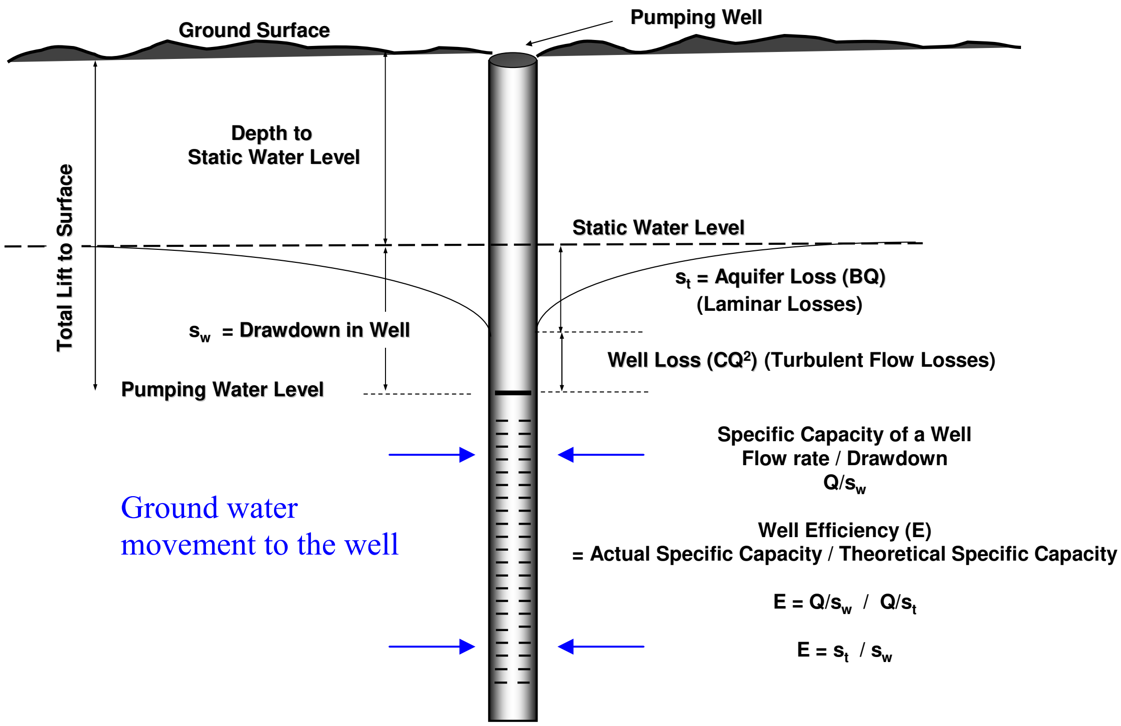
s_w = Actual drawdown (ft, m)

s_t = Theoretical drawdown (ft, m)

Q = Well discharge (gpm, L/s)

Water well efficiency is thus the ratio of the actual specific capacity to the theoretical specific capacity. Figure 3.2 below is a representation of the concepts presented above.

Figure 3.2 - Well Efficiency
(Courtesy of Dennis Williams, "Well Rehabilitation: Is It Time? Is It Worth it?" 2008.)



There are several components to a pumping well that must be understood in order to define well efficiency in hydraulic terms. First, the total drawdown of a well is composed of laminar and turbulent head loss components. Laminar losses generally occur in the aquifer as a result of the water moving towards the pumping well and generally consist of viscous forces between the water and the aquifer material. These approach velocities are generally low and are uncontrollable. As the water approaches the well its flow velocity increases and the inertial forces begin to dominate over the viscous forces. Turbulence losses generally occur in the filter pack near or around the vicinity of the pumping well. These different flow regimes and their transitions are explained to a great degree above.

The drawdown in a well can be expressed as follows (Handbook of Ground water Development, 1990);

$$s = ds + ds' + ds'' + ds''' + \text{minor losses} \quad (3\text{-}8)$$

s = Total drawdown measured in well (ft., m)

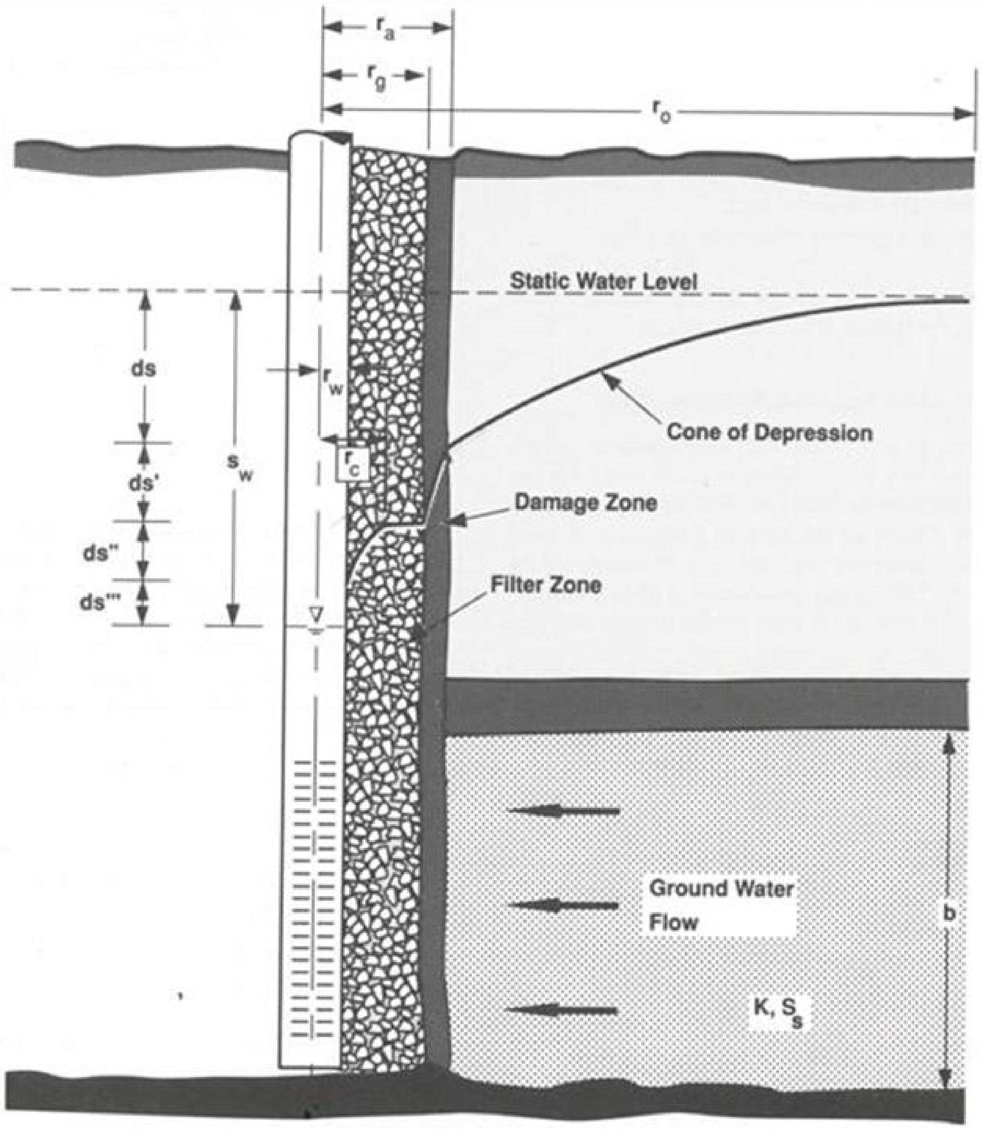
ds = Head loss in the aquifer or formation loss (ft.,m)

ds' = Head loss in the damage zone (ft.,m)

ds" = Turbulent head loss in filter pack zone (ft.,m)

ds''' = Well loss (ft.,m)

Figure 3.3 Well Head Losses



(Courtesy of Dennis Williams, “Modern Techniques in Water Well Design”, 1985.)

A figure of these losses in relation to a pumping well is seen in Figure 3.3. The formation or aquifer loss is the head loss or drawdown at the interface between the aquifer and the damage zone. The damage zone is the zone of damage caused from the drilling of the well. The aquifer loss can be quantified from the steady state Thiem equation as follows (Handbook of Ground water Development, 1990);

$$ds = \frac{528Q}{Kb}\log\left(\frac{r_o}{r_a}\right) = BQ \tag{3-9}$$

ds = Head loss in the aquifer (ft.,m)

Q = Well discharge (gpm, l/s)

K = Aquifer hydraulic conductivity (gpd/ft^2, mm/s)

b = Saturated aquifer thickness (ft.,m)

r_o = Radial distance from center of well to zero drawdown (ft.,m)

r_a = Radial distance from center of well to aquifer damage zone interface (ft.,m)

B = Formation loss coefficient (ft/gpm, m/l/s)

The head loss through the damage zone depends to what degree the drilling damaged pushed fine drilling debris, mud cake, or other low hydraulic conductivity material into the aquifer formation. The damage zone thickness depends mostly on the quality of the well construction and the initial development of the well to remove any of this low permeability material from the aquifer. The head loss through the damage zone may be expressed by (Handbook of Ground water Development, 1990);

$$ds' = \frac{528Q}{K'b}\log\left(\frac{r_a}{r_g}\right) = B'Q \tag{3-10}$$

ds’ = Head loss in the damage zone (ft.,m)

Q = Well discharge (gpm, l/s)

K’ = Damage zone hydraulic conductivity (gpd/ft^2, mm/s)

b = Saturated aquifer thickness (ft.,m)

r_a = Radial distance to aquifer damage zone interface(ft.,m)

r_g = Radial distance to the inner edge of damage zone (ft.,m)

B’ = Damage zone loss coefficient (ft/gpm, m/l/s)

The head losses in the filter pack zone are turbulent losses if the critical radius exceeds the nominal radius of the well. This concept is discussed further in Chapter 6. The turbulent losses are non-linear losses and do not obey Darcy's Law. These losses vary exponentially with flow velocity and may be a significant component of the total head loss in a well. Often times these losses are in a transitional state between linear and exponential flow. This is called transitional or Forchheimer flow. In this transitional zone the exponent of flow velocity may vary from 1 (purely laminar or linear flow) and 2 (fully developed turbulent flow). The filter pack losses may be written as follows (Handbook of Ground water Development, 1990);

$$ds'' = B''Q^n \tag{3-11}$$

ds" = Head loss in the transitional filter pack zone (ft.,m)

Q = Well discharge (gpm, l/s)

B" = Filter pack loss coefficient (ft/gpm^n, $m/(l/s)^n$)

n = Exponent ($1<n<=2$)

The well losses are the head losses associated with the entrance losses of the water through the well screen as well as the axial flow losses of the water moving towards the pump intake. The majority of these losses happen as the water jets through the well screen into the well bore which is analogous to rapid expansion losses. Examples of this happening in a well are seen in the small slot well screens in Appendix 1. These losses are turbulent losses and vary as a square of the flow velocity. The well losses are expressed as follows (Handbook of Ground water Development, 1990);

$$ds''' = CQ^2 \tag{3-12}$$

ds''' = Head loss in the well (ft.,m)

Q = Well discharge (gpm, l/s)

C = Well loss coefficient (ft/gpm^2, m/(l/s)^2)

The minor losses are those of laminar losses through the filter zone and or head losses associated with restricted well screen inlet area. These are generally much smaller losses then the other head losses mentioned above and are generally neglected.

The efficiency of a well can thus be stated as the ratio of the head loss in the aquifer formation to the head loss of the well. Well efficiencies of considerably less than 100 percent are generally caused from laminar losses in a large damage zone of the well and or high near well turbulent losses in the filter pack. A combination of poor well construction, bad filter pack design, poor screen selection, and improper well development can result in partial or completely plugged slots of a well screen opening's which in turn can cause extremely high head losses and thus very poor well efficiencies. Total well efficiency can thus be defined as (Handbook of Ground water Development, 1990);

$$E = \frac{BQ}{\left(BQ + B'Q + B''Q^n + CQ^2\right)} 100 \tag{3-13}$$

E = Efficiency of pumping well, (%)

B = Formation loss coefficient (ft/gpm, m/l/s)

B' = Damage zone loss coefficient (ft/gpm, m/l/s)

B” = Filter pack loss coefficient (ft/gpm^n, m/(l/s)^n)

n = Exponent ($1<n<=2$)

Q = Well discharge (gpm, l/s)

C = Well loss coefficient (ft/gpm^2, m/(l/s)^2)

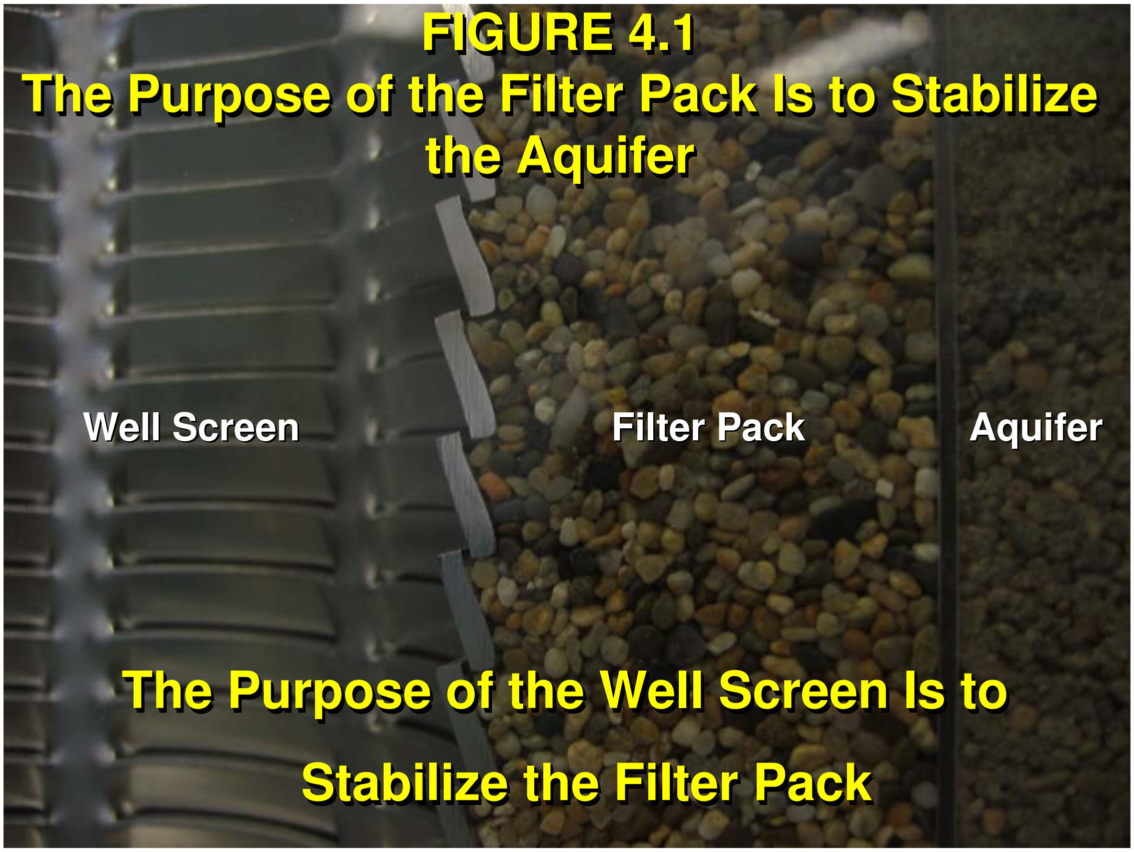
In properly constructed and fully developed wells, the damage zone losses approach zero. A pumping test called a “Step Drawdown Test” is used to determine the different loss coefficients. Thus after a series of initial development techniques and step drawdown test an engineer can determine what the initial well efficiency will be.

Chapter 4. WELL DESIGN PARAMETERS

The main design objectives of a water well is to provide a conduit from the sub-surface aquifers to the surface to yield economically significant quantities of water. This conduit or water well must be designed to;

- Match discharge requirements of a pumping plant to the aquifer characteristics.
- Achieve designed production rates with maximum well efficiency and minimum energy costs.
- Produce acceptable quality water while protecting it from contamination and over drafting.
- Maximize the well life commensurate with cost effectiveness.

These objectives are generally meet with proper well design. A diagram of a well in an aquifer is seen in Figure 3.2. Each design is site specific to each geologic setting. We therefore only have control over the filter pack design as well as the well screen design. In Figure 4.1 below we see that simplistically the fundamental principle of well design is for the filter pack is to stabilize the aquifer while the well screen is used to stabilize the filter pack. George and Rocky Moss said, “We want to design wells that are simple and strong.” This research tries to follow this type of philosophy.



(Courtesy of Dennis Williams, "Well Sighting and Design", 2007.)

To develop critical water well design criterion we must understand water well efficiency and well loss. With a complete understanding of the hydraulic interactions of the well components we will then be able to apply the fundamental principal of well design to any given aquifer. Currently there are no design standards when an engineer designs a particular water well. It is the goal of this research to first define water well efficiency and well loss and then describe some of the design criteria that is important for different types of aquifers that may be encountered. There are several design factors that an engineer should consider when designing efficient water wells. The most important factors that affect the hydraulic performance of a well are; well screen length and diameter, filter pack material used, critical well radius and initial well development. To properly design a well you need to consider which factors are the most important to the hydraulic performance of the well with regards to initial cost of the well and cost of the operations of the well during its life time. This research concentrates on the hydraulics of the well screen, filter pack material, the critical radius of the well, and the initial well development. Design criteria for the filter pack material used in a well have varied widely in the water well industry. It is the effort of this paper to standardize some criteria in which most wells can be designed for in any given aquifer. The initial design criteria to be tested are given in Table 4.1 below.

Table 4.1 Water Well Industry Standards		
Standard	Critical Design Criteria	Initial Recommendations
1	Filter Pack/Aquifer Ratio (D_{50F}/d_{50A})	4-6
2	Terzaghi's Migration Factor (D_{15F}/d_{85A})	≤ 4
3	Terzaghi's Permeability Factor (D_{15F}/d_{15A})	≥ 4
4	Uniformity Coefficient, C_u (d_{60A}/d_{10A})	≤ 2.5
5	Sorting Factor, S_f (C_{uF}/C_{uA})	$0.2 \leq S_f \leq 0.5$
6	Slot Factor (d_{50A}/Slot Width)	≤ 0.5
7	Percent of Filter Pack Passing	$\leq 10\%$
8	Critical Radius, r_c	TBD

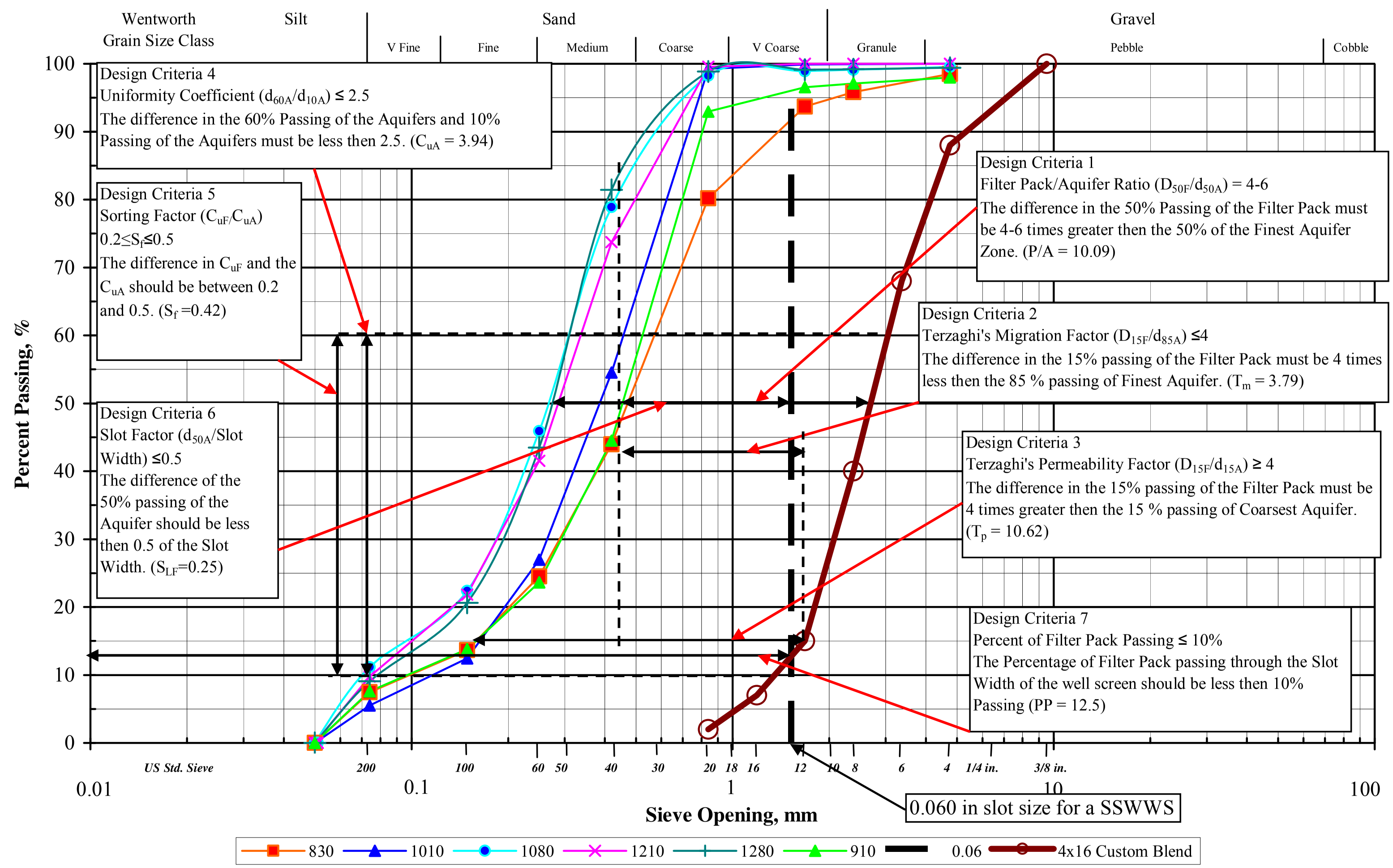
TBD- To Be Determined

D_{50F} = Diameter of the Filter pack at 50% Passing (mm)

d_{50A} = Diameter of the Aquifer at 50% Passing (mm)

Figure 4.2 below shows some of the concepts relative to actual aquifer samples. The filter pack meets the Terzaghi's Migration and Permeability Factors as well as the Pack/Aquifer ratio. Filter packs are decided on several of these different criteria as well as availability of material. Screen slots are then decided in accordance with the filter pack size. Several blends of materials were used in this research as to push these criteria to their limits as to find upper and lower bounds to the design criteria.

Figure 4.2 - Mechanical Grading Analysis
Critical Design Criteria



Chapter 5. ANALYSIS OF FIELD TESTS TO EVALUATE WATER WELL DESIGN PARAMETERS

5.1. Types of Wells Studied

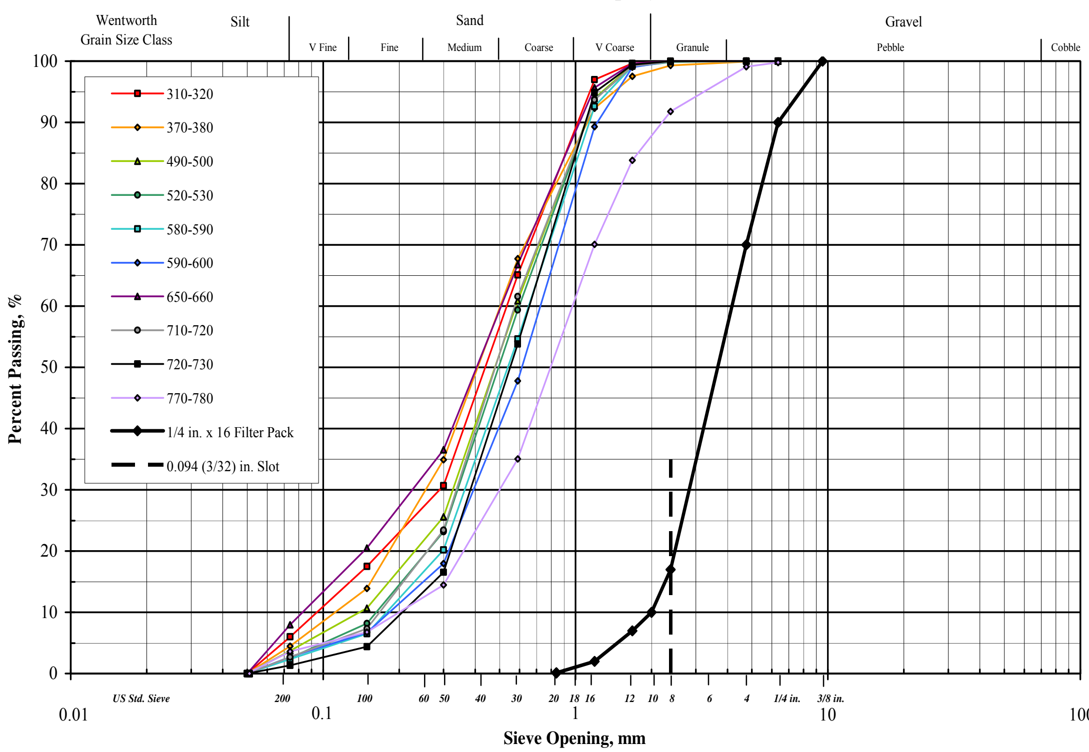
This Chapter is the analysis of field studies ranging from wells with a tremendous amount of quantitative data, to wells that had initial design criteria but only qualitative assessment of their performance. The findings in this Chapter demonstrate different wells in three different geohydrological settings. These different geohydrological settings are coarse, medium, and fine grained aquifers and their respective performances in those aquifers. The field analysis will look at the Well Design Parameters and any pumping performance that was done on the well. It will try to encompass as many different well aquifer combinations as possible.

These wells were categorized by the types of aquifers and any of the pumping tests or observations preformed on them. The analysis of over 100 wells and over 400 aquifer sieves are found in Appendix 5.0. These wells were designed by professional geohydrologists, water agencies, and water well drilling companies. The performance and efficiency of these wells vary tremendously as do the well costs. The data of each well and corresponding aquifer underlying each well, was then analyzed to develop a trend to establish a field evaluation of our critical design criteria. This analysis will then be compared to the laboratory finding in corresponding Chapters of this research.

5.2. Wells in Coarse Sand Aquifers

The first well examined was Well BKNG 220-01 in the California Water Service Company well field in Bakersfield, California. This well was designed and constructed in 2005 and was considered to be in a coarse gravel aquifer. The well met expectations and had an initial efficiency of 90% at 1500 GPM with a specific capacity of 27gpm/ft verified through step-drawdown analysis. This well had a tremendous amount of information on the design as well as pumping data. Figure 5.1 below is the sieve analysis of the aquifers and the filter pack used.

FIGURE 5.1 - Mechanical Grading Analysis
California Water Service Company BKNG 220-01



(Courtesy of Dennis Williams, Geoscience Support Services, Inc., 2008.)

The design criteria for all of the zones are shown in Table 5.1 below. The filter pack and slot size design are based from the finest aquifer which in this case was the zone from 650-660 feet.

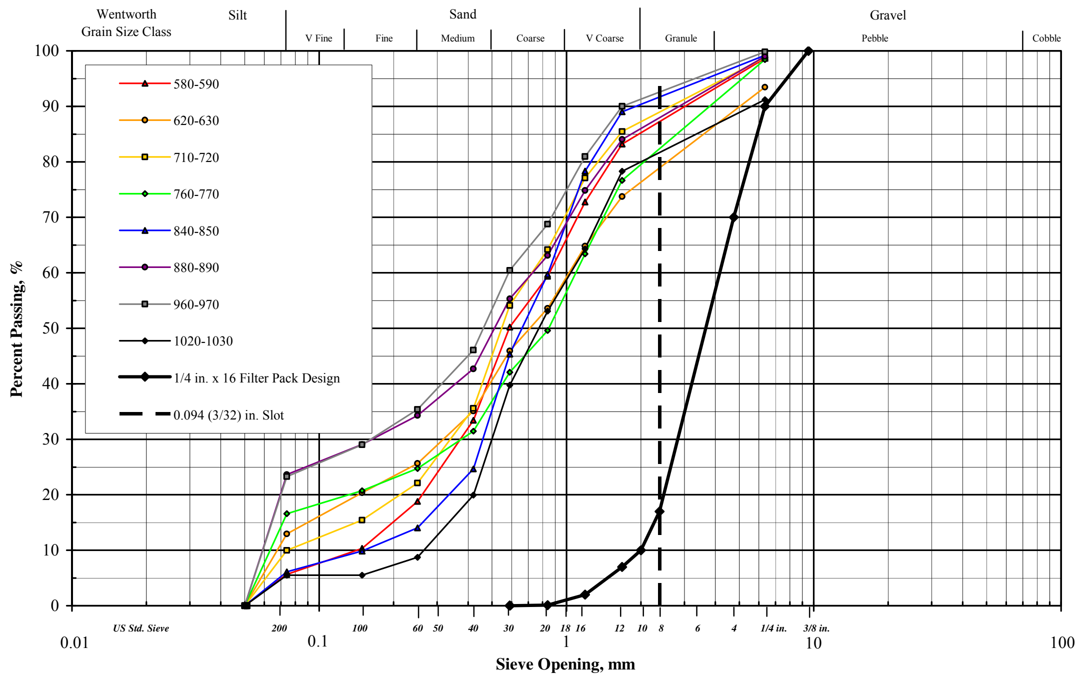
TABLE 5.1 BKNG 220-01 Design Criteria							
Depth of Sample	Pack #1 / Aquifer Ratio	Terzaghi Migration Factor for Pack #1	Terzaghi Permeability Factor for Pack #1	Uniformity Coefficient	Sorting Factor for Pack #1	Slot Factor	Percent Filter Pack Passing Well Slot
310-320	8.34	2.47	17.71	5.68	0.37	18.4%	17.0
370-380	8.95	2.34	14.68	4.53	0.46	17.2%	
490-500	7.62	2.30	12.46	4.21	0.49	20.2%	
520-530	7.36	2.27	11.10	3.72	0.56	20.9%	
580-590	6.75	2.19	9.90	3.70	0.56	22.8%	
590-600	5.93	2.05	9.14	4.00	0.52	25.9%	
650-660	9.04	2.46	20.64	6.12	0.34	17.0%	
710-720	7.59	2.30	10.95	3.47	0.60	20.2%	
720-730	6.61	2.25	8.32	3.23	0.65	23.3%	
770-780	4.58	1.28	7.48	4.90	0.43	33.6%	

The contribution of this filter pack above and the slot size was considered a typical highly effective well for that area of Bakersfield, California. The formation loss for this well was 50 feet and the well loss was 5.7 feet. The well was determined to have an initial design efficiency of 90% with little to no sand and a total of 60 hours spent on final development.

5.3. Wells in Medium Sand Aquifers

The next example of a well which performed exceptionally well was Coachella Valley Water District (CVWD) well 5625-2 Redrill. This well was in medium to coarse aquifer material but had a higher uniformity coefficient than most wells in the area. This well preformed better than expected for a typical well in that area. The well had an initial efficiency of 90% and a flow rate of 1970 GPM. Figure 5.2 below is the sieve analysis for well 5625-2.

FIGURE 5.2 - Mechanical Grading Analysis
Coachella Valley Water District (CVWD) 5625-2



(Courtesy of Dennis Williams, Geoscience Support Services, Inc., 2008.)

Looking at Figure 5.2 it was determined to only screen the zones of 750 to 1,080 ft. due to the formation in this zone were described as having the high yield, medium coarse sands with an occasional layer of silt and clay. The formation below 1,080 feet was determined to have too much clay. This is reinforced by the table below noting that the layers below 1,000 ft have 25% of the material passing through the 200 mesh sieve. Table 5.2 displays the design criteria for the all the layers of aquifer.

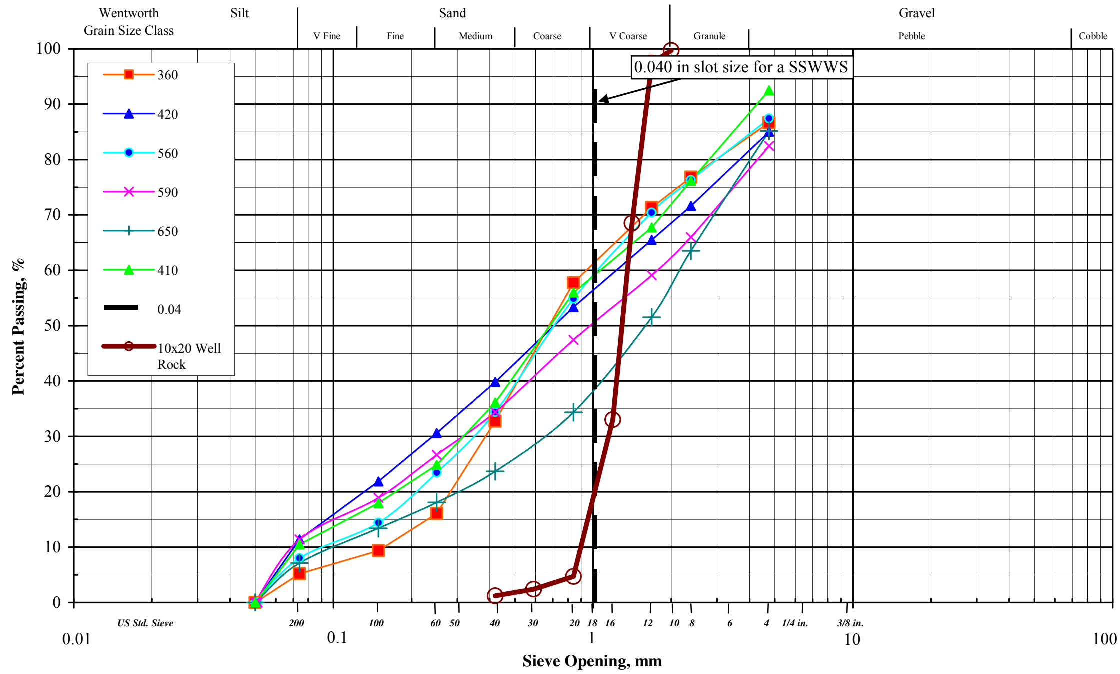
TABLE 5.2 CVWD 5625-2										
Depth	Filer Pack/Aquifer Ratio ($D50_F/d50_A$)	Terzaghi's Migration Factor ($D15_F/d85_A$)	Terzaghi's Permeability Factor ($D15_F/d15_A$)	Uniformity Coefficient, Cu ($d60_A/d10_A$)	Sorting Factor, Sf (Cu_F/Cu_A)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Critical Radius (in)	Percent Filter Pack Passing Well Slot	Slot Size (in)
580-590	4.27	0.88	8.31	6.21	0.34	0.36	82	6.840	17.17	0.094
620-630	6.19	1.30	9.15	4.23	0.49	0.25	87	4.720		
710-720	5.92	1.16	10.85	5.47	0.38	0.26	86	4.932		
760-770	5.09	0.63	23.28	20.10	0.10	0.30	77	5.738		
840-850	6.44	1.38	14.68	8.86	0.24	0.24	88	4.532		
880-890	4.48	0.81	33.00	31.95	0.07	0.34	80	6.523		
960-970	5.43	1.54	8.32	5.06	0.41	0.28	91	5.381		
1020-1030	6.89	1.24	66.08	35.15	0.06	0.22	86	4.241		
1100-1110	7.60	1.65	63.31	28.87	0.07	0.20	91	3.841		

The rows in yellow above were not screened due to the high amount of fine silts which were still in the formation. These bad zones were having about 20% of the material passing through the 200 sieve. Most of the design criteria were meet for all the zones except the uniformity coefficient was too large for every zone. The filter packs uniformity coefficient was also changed to 2.7 in effort to balance the screened zones and their high uniformity coefficients. This worked very well and this seemed to push the design criteria to some new limits of the uniformity and permeability design criteria.

5.4. Wells in Fine Sand Aquifers

CASE 1- This Chapter deals with wells built in fine sand aquifers. CVWD 6725 was constructed in 1999 in a relatively fine sand aquifer. In Figure 5.3 the sieve analysis of the aquifers and the filter pack is shown.

Figure 5.3 - Mechanical Grading Analysis
CVWD 6725



(Courtesy of Dennis Williams, Geoscience Support Services, Inc., 2008.)

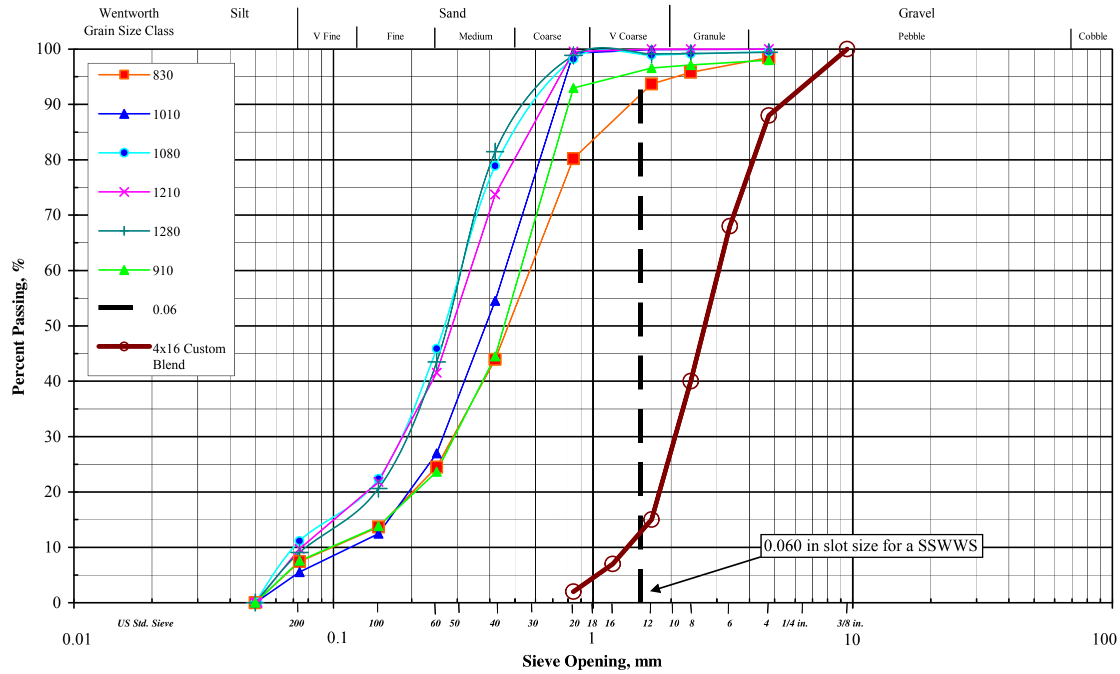
This well had step drawdown testing done on it as well as a constant rate test. The well was found to have a high efficiency of 92% at 1,500 GPM. The problem this well had was it was determined to be a "Sander", or a well that produced a tremendous amount of sand. The well was developed for 87 hours and it still produced too much sand. The sand seemed to enter from 360-410 ft zone. It was decided to patch this zone. Air development began again with some change in the sand content but for the water district, this was still too high. Table 5.3 below shows the design criteria for well 6725.

TABLE 5.3 CVWD 6725										
Depth	Filer Pack/Aquifer Ratio ($D50_F/d50_A$)	Terzaghi's Migration Factor ($D15_F/d85_A$)	Terzaghi's Permeability Factor ($D15_F/d15_A$)	Uniformity Coefficient, Cu ($d60_A/d10_A$)	Sorting Factor, Sf (Cu_F/Cu_A)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Percent Filter Pack Passing Well Slot	Slot Size (in)
360	1.91	0.23	4.14	6.04	0.25	0.67	61	18.93	0.040
410	1.89	0.28	8.46	15.99	0.09	0.67	58		
420	1.83	0.20	10.12	21.85	0.07	0.70	56		
560	1.81	0.23	6.21	11.48	0.13	0.70	58		
590	1.32	0.00	9.21	31.16	0.05	0.96	50		
650	0.82	0.20	5.38	21.09	0.07	1.56	38		

The filter pack on this well was just too small compared to the aquifer material. The pack aquifer ratio as seen above was all smaller than 4. It is recommended to have a pack aquifer ratio between 4-6. This well is not being used at the time and is waiting more redevelopment. The screen for this well had a very small slot size for the size of filter pack material used. It was projected that if this well had been in use a long time that the screen would eventually clog over time as sand entered the well.

CASE 2 – CVWD 4509 was another well drilled in a similar location as CVWD 6725 it had a better initial design and there was very little sand issues and development times were very small. The sieve analysis of the aquifers and the filter pack is seen in Figure 5.4.

Figure 5.4 - Mechanical Grading Analysis
CVWD 4509



(Courtesy of Dennis Williams, Geoscience Support Services, Inc., 2008.)

From Figure 5.4 we can see that in the same fine sand aquifer as Case 1, the filter pack was larger in comparison to the aquifers. Table 5.4 below shows the design criteria for well 4509.

TABLE 5.4 - CVWD 4509							
Aquifer Zone	Pack #1 / Aquifer Ratio	Terzaghi Migration Factor for Pack #1	Terzaghi Permeability Factor for Pack #1	Uniformity Coefficient	Sorting Factor for Pack #1	Slot Factor	Percent Filter Pack Passing Well Slot
830	5.70	1.56	10.61	5.78	0.39	31%	12.5
910	5.92	2.24	10.62	5.40	0.42	30%	
1010	6.97	2.49	10.33	3.94	0.57	25%	
1080	10.09	3.21	17.86	5.32	0.42	18%	
1210	9.39	2.96	16.74	4.47	0.50	19%	
1280	9.85	3.47	15.85	3.99	0.56	18%	

As seen in the table above the Pack Aquifer Ratio is within the initial design recommendations. This well only required 50 hours of development and the produced 1,700 GPM. This was a good design to keep the sand down with high efficiencies.

Some of the field data had extensive pump and development data associated with it while others had only qualitative results discussing the final well production and sand content. This data was compiled from many different water agencies and design firms. These wells were chosen because they were the most complete in aquifer types, construction methods, and pumping information. All of the field data is included in Appendix 5.0, even the data that look erroneous. It was the effort of this research not to evaluate the methods of data collection or pump testing methods, but rather to establish trends in aquifer types to be compared to that of laboratory research.

Chapter 6. LABORATORY TESTING OF WATER WELL DESIGN PARAMETERS

6.1. Determining Well and Aquifer Losses

This Chapter compares both screen types by running each of these screens through a series of Constant Rate Tests and Step Drawdown Tests, in an effort to determine the aquifer parameters, aquifer losses, and well losses for each well screen. From Appendix 3 & 4, various interesting observations were made regarding both the Stainless Steel Wire Wrap Screens (SSWWS) and the Stainless Steel Louver Screens (SSLS).

6.1.1. Introduction

Twelve well screens were tested in the RMC Model over the course of several months. Each screen was fully developed using the same large aquifer material with no additional filter packs. The large aquifer material was described in Appendix 2. A series of Constant Rate and Step Drawdown Tests were run and each test was repeated three times and then averaged to determine the discharge rate and change of pressure heads for each test. The findings are discussed below.

6.1.2. Background

The Stainless Steel Wire Wrap Screens (SSWWS) had a screen slot size of 0.010, 0.020, 0.040, 0.060, 0.080, 0.093, 0.125 inches. The Stainless Steel Louver Screens (SSLS) had a screen slot size of 0.040, 0.060, 0.080, 0.093, 0.125 inches. These are the commercial wire wraps and louver screens which are produced today. The screen is placed in one corner of the model and is 5 feet tall by 10 inches in diameter. The screens all had to be outfitted with a polycarbonate tube on the aquifer side of the screen such that a Borescope Camera could take pictures of the screen from the aquifers reference point.

Both the constant rate and step drawdown test were repeated on the same well screen to obtain an average set of data for a given discharge rate and pressure head. The constant rate test was used to determine the aquifer characteristics while the step drawdown test was used to determine the well/aquifer loss parameters.

6.1.3. Constant Rate Testing

The constant rate test is used to determine the aquifer parameters for each model run with a corresponding well screen. The Jacob's Straight-Line Method was applied to distance drawdown within the model to determine the Transmissivity (T) and Storativity (S) of the aquifer material. Quantitatively the distance drawdown may be expressed in general by the steady state Thiem Equation (Handbook of Ground water Development, 1990).

$$\Delta s = h_0 - h(r) = \frac{Q}{AT} Log_e\left(\frac{r_0}{r}\right) \qquad (6\text{-}1)$$

Δs = Drawdown (ft, m)

h_0 = Hydraulic head where zero drawdown occurs (ft, m)

$h(r)$ = Hydraulic head at radial distance r form the center of the well (ft, m)

A = Area of the circular well, 2π for general case (ft^2, m^2)

T = Transmissivity (gpd/ft, m^2/d)

Log_e = Log base to the exponential power

r_0 = Radius form center of well where zero drawdown occurs (ft, m)

Q = Well discharge (gpm, L/s)

Thus converting the above equation to conventional units and using 1/6th of a circular area for the RMC Model, the equation for distance drawdown in terms of Transmissivity becomes;

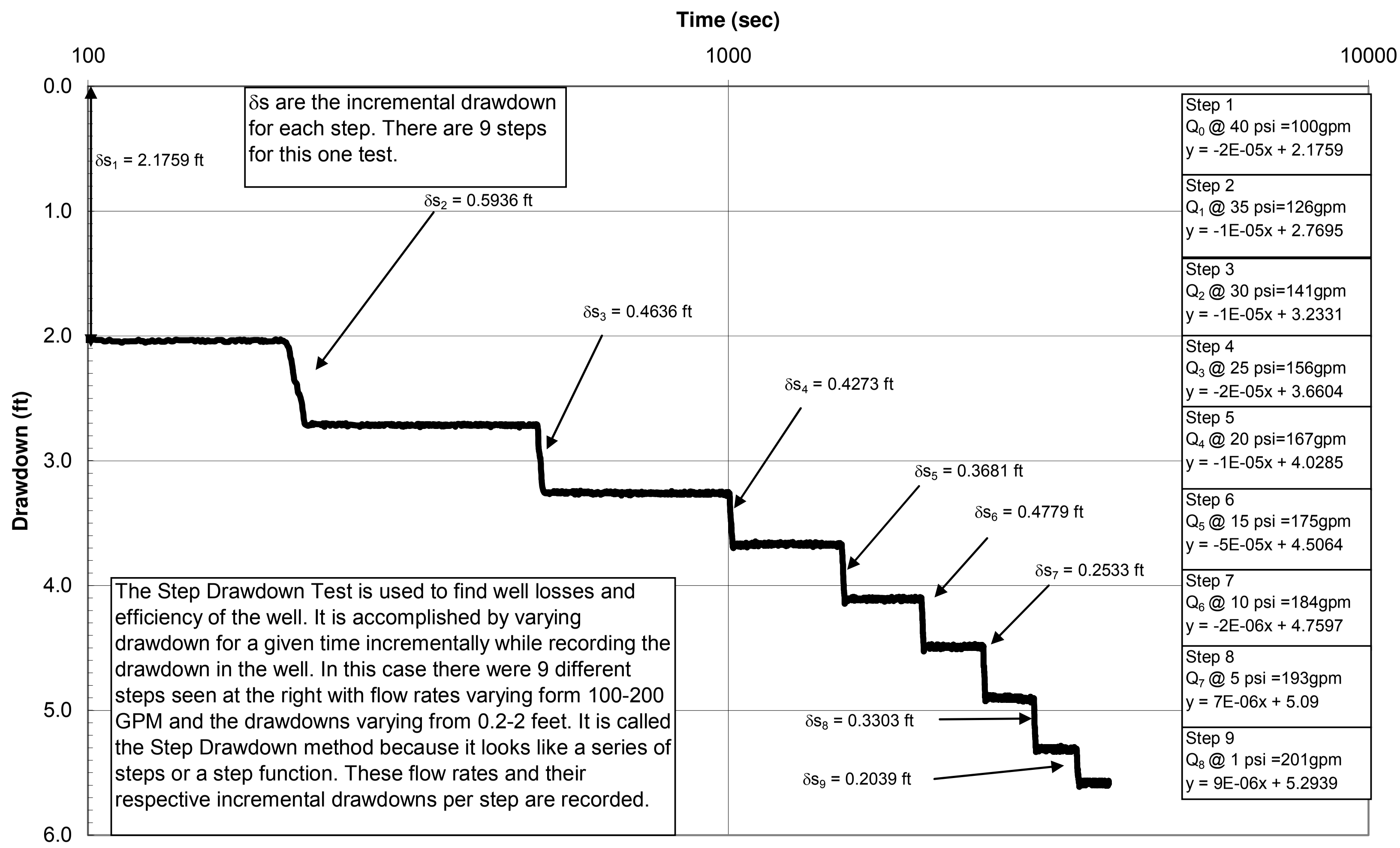
$$T = \left(\frac{(2.303)(1440)Q}{\left(\frac{2\pi}{6}\right)\Delta s} \right) = \frac{3166.9Q}{\Delta s} \tag{6-2}$$

Note: Similar to the general case of $T = \frac{528Q}{\Delta s}$ except for 1/6th of a circle in the RMC model.

6.1.4. Step Drawdown Testing

The purpose of the step drawdown test is to determine formation losses, well losses, and well efficiency. In an actively pumping well, the total drawdown in the well is composed of both laminar and turbulent head loss components. Laminar losses generally occur in the aquifer (where approach velocities are low), while turbulent losses are confined to the area in and around the immediate vicinity of the well screen and within the well bore. Step drawdown tests were also preformed multiple times on each well screen in order to determine the aquifer/well parameters in the model. These parameters are found using variable discharge rates for each well screen. Each screen is fully developed before the series of step drawdown tests. Each test is performed by varying the well discharge via the butterfly valve for a determined amount of time and thus establishing an incremental drawdown for that flow rate. Figure 6.1 is an example of a series of flow rates versus time in a step drawdown test.

Figure 6.1 - Step Drawdown Stainless Steel Wire Wrap Screen, Slot size= 0.080 in.



Analysis of the steps is then required by plotting specific drawdown, s_i/Q, versus discharge, Q. The theory behind this testing was described by Williams (1985) with the equation;

$$s_i = BQ + B^{''}Q^n + CQ^2 \qquad (6\text{-}3)$$

s_i = Incremental Drawdown measured in pumping well (ft, m)

Q = Well discharge (gpm, L/s)

B = Formation Loss Coefficient (ft/gpm, m(L/S))

$B^{''}$ = Filter Zone Loss Coefficient (ft/gpm^n, m(L/s)^n)

C = Well Loss Coefficient (ft/gpm^2, m(L/s)^2)

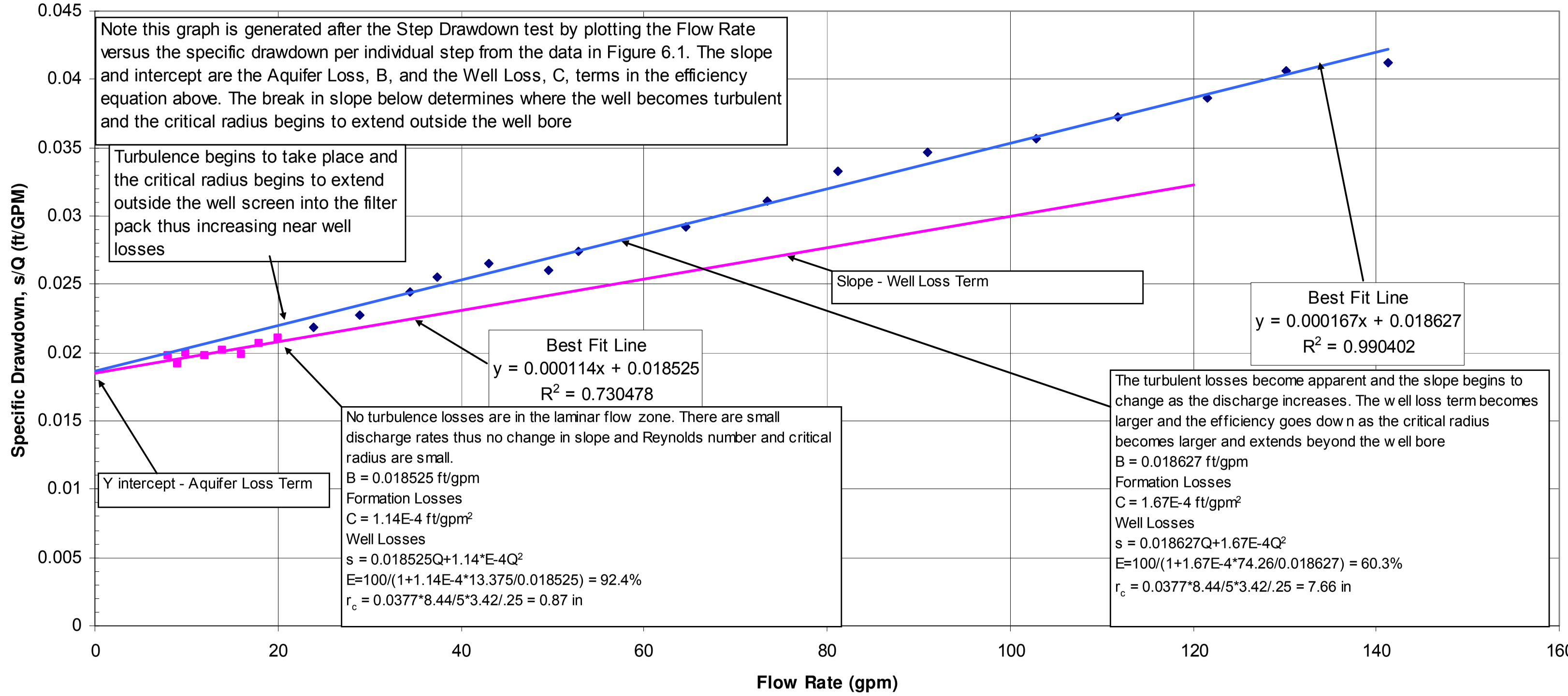
n = Exponent varying between 1 and 2

The equation above can be rewritten in terms of specific drawdown assuming fully developed flow as.

$$\frac{s_i}{Q} = B + \left(B^{''} + C\right)Q \qquad (6\text{-}4)$$

From this equation a new plot of specific drawdown versus discharge can be made as in Figure 6.2. The formation loss term, B, may be determined from the y-intercept of the best fit line of specific drawdown vs. discharge. During low discharge rates there will be no near well turbulence (i.e. $B^{''} = 0$). Consequently all the turbulent losses will be associated with the well loss. This is especially the case in the initial screen tests due to the fact that there is no filter pack used with the coarse aquifer in this Chapter. The well loss coefficient then becomes the slope of the best fit line of this data. During larger discharge rates, a change of slope will occur thus changing the well loss term. This is seen in Figure 6.2.

Figure 6.2
Step Drawdown - SSLS 0.080 in Slot Size



6.1.5. Findings

The first major finding was that of the constant rate test. From Jacob's Straight-Line Approximation using the distance drawdown approach, a hydraulic conductivity was determined for the coarse aquifer material to be in the range of 32,000 gpd/ft^2 to 61,000 gpd/ft^2 with an average of 46,500 gpd/ft^2. This correlates very well with the hydraulic conductivity test results from the CHP in Appendix 1 of 47,603 gpd/ft^2. Appendix 2 evaluated the coarse aquifer via sieve analysis to a value between 23,400 gpd/ft^2 and 64, 906 gpd/ft^2 depending on the method used.

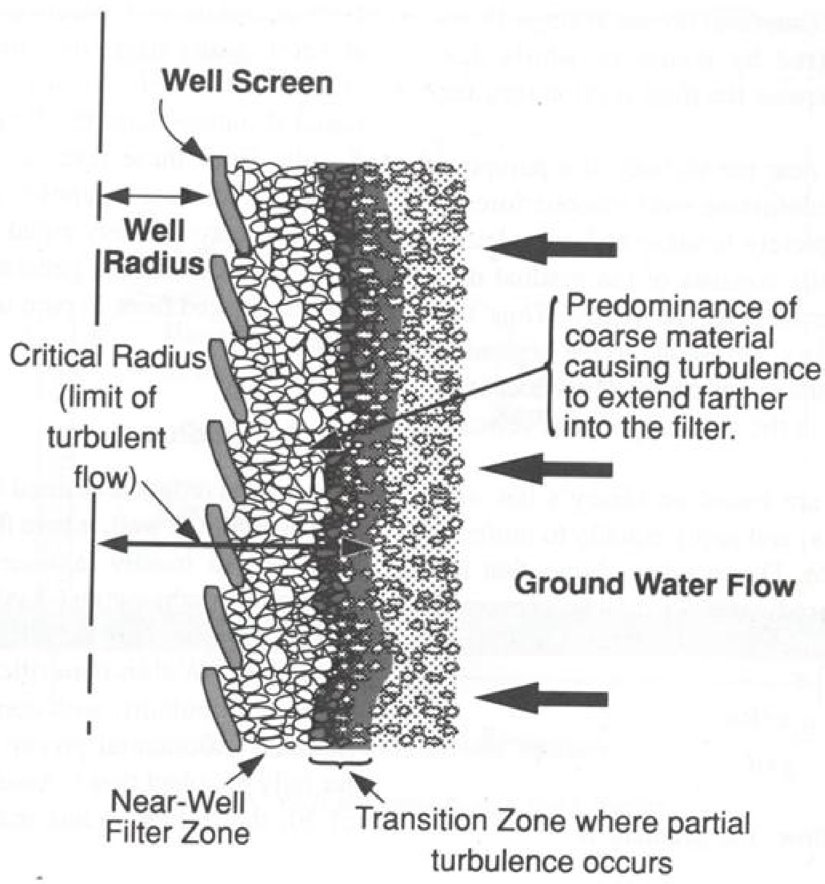
The second major finding was that of the well parameters found during the step drawdown testing. Table 6.1 is the results of the testing done for both the SSWWS and the SSLS. The aquifer loss terms are very similar for the SSLS ranging from 0.018 to 0.021 with an average of 0.019. The SSWWS has a slightly greater variance in the aquifer loss term, ranging from 0.0112 to 0.017 with an average of 0.015. The larger degree of variance in the SSWWS has a couple of reasons associated with it. Initially there was a great degree of clogging of the slots in the SSWWS as discussed in Appendix 3. This clogging plays a part in the general turbulence effect in the near well zone. Secondly, this damaged zone in the clogging of the aquifer will result in a lower aquifer loss coefficient, B, due to the well is only partially developed. This damaged zone represents laminar losses in the aquifer which decrease the aquifers efficiency. Table 6.1 below is a table of all of the loss terms associated with each well screen.

TABLE 6.1 - Loss Terms For All Well Screens Tested								
	Stainless Steel Wire Wrap Screen (SSWWS)				Stainless Steel Louver Screen (SSLS)			
Slot Size, (in)	B, Aquifer Loss Term	C, Well Loss Term	Open Area (1/2 Pipe) in^2	% Open Area (5ft screen)	B, Aquifer Loss Term)	C, Well Loss Term	Open Area (1/2 Pipe) in^2	% Open Area (5ft screen)
0.010	0.01705	0.00021	2.03	0.21%				
0.020	0.01124	0.00012	3.80	0.40%				
0.040	0.01400	0.00014	6.75	0.72%	0.01804	0.00018	1.62	0.34%
0.060	0.01570	0.00013	9.12	0.97%	0.01815	0.00015	2.42	0.51%
0.080	0.01420	0.00012	11.05	1.17%	0.01860	0.00015	3.23	0.69%
0.093	0.01510	0.00012	12.13	1.29%	0.01910	0.00014	3.76	0.80%
0.125	0.01424	0.00010	14.34	1.52%	0.02132	0.00015	5.05	1.07%

6.2. Initial Well Development and Critical Radius

An important point in understanding the head losses in a well aquifer system is to determine where the laminar flow changes to turbulent flow. The concept of critical radius is thus introduced. Critical radius is defined by Williams (1985) as the distance from the center of the well to the point where the flow changes from laminar to turbulent. Figure 6.3 below is a representation of this change in flow.

Figure 6.3 Critical Radius



(Courtesy of Dennis Williams, Modern Techniques in Water Well Design 1985.)

The equation for critical radius is derived from the continuity equation and Reynolds number. From continuity equation:

$$Q = AV_d \tag{6-5}$$

$$A = 2\pi rb$$

Q = Discharge of the well, (gpm, l/s)

A = Area of flow into well (ft^2, m^2)

V_d = Darcian flow velocity (ft/min, l/s)

r = Radius of well (ft, m)

b = Saturated thickness of aquifer (ft, m)

From Chapter 3, Reynolds Number was defined as:

$$\mathrm{Re} = \frac{V_d d}{\upsilon} \tag{6-6}$$

Re = Reynolds number

V_d = Darcian Velocity (m/s or ft/s),

d = Particle diameter or characteristic length of a given material (m or ft),

υ = Kinematic viscosity (m^2/s or ft^2/s)

Substituting for Darcian velocity and assuming uniform flow we can solve for a critical radius:

$$Q = \frac{2\pi r_c b \upsilon \mathrm{Re}}{d}, r_c = \frac{Qd}{2\pi b \upsilon \mathrm{Re}} \tag{6-7}$$

r_c = Critical radius (ft, m),

d = Particle diameter or characteristic length of a given material (m or ft),

υ = Kinematic viscosity (m^2/s or ft^2/s)

Q = Discharge of the well, (gpm, l/s)

Re = Reynolds number

b = Saturated thickness of aquifer (ft, m)

Initial well development is the process where the critical radius of the well is decreased by different hydraulic processes in which the filter pack material in the near well zone is rearranged such that the fines are removed from the filter pack and the permeability of the filter pack increases. If initial well development is not preformed, significant damage to the well can happen from a process called sand sealing. Figure 6.4 and Figure 6.5 below demonstrates this sand sealing affect on a well which was improperly developed. The initial development process is complete when the critical radius is found to be inside the nominal radius of the well screen. It cannot be over emphasized as to how important this process of initial development is. One point of caution is that clogging the well screen during this initial development can occur by having too small of a slot size which will not allow the fines to be removed from the filter pack. The well screen will begin to clog and a decrease in specific capacity of the well will occur, which will increase the operational cost of the well.

Figure 6.4

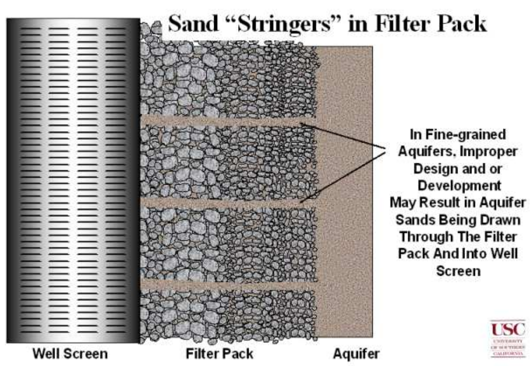
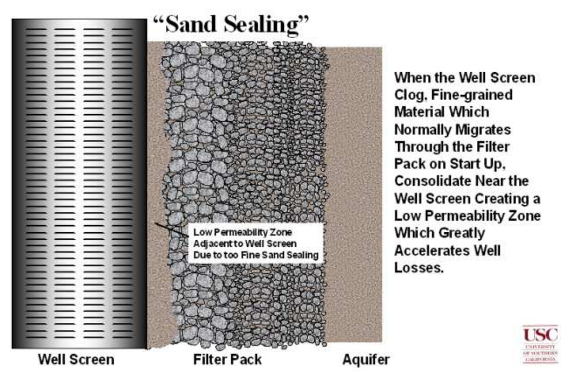


Figure 6.5



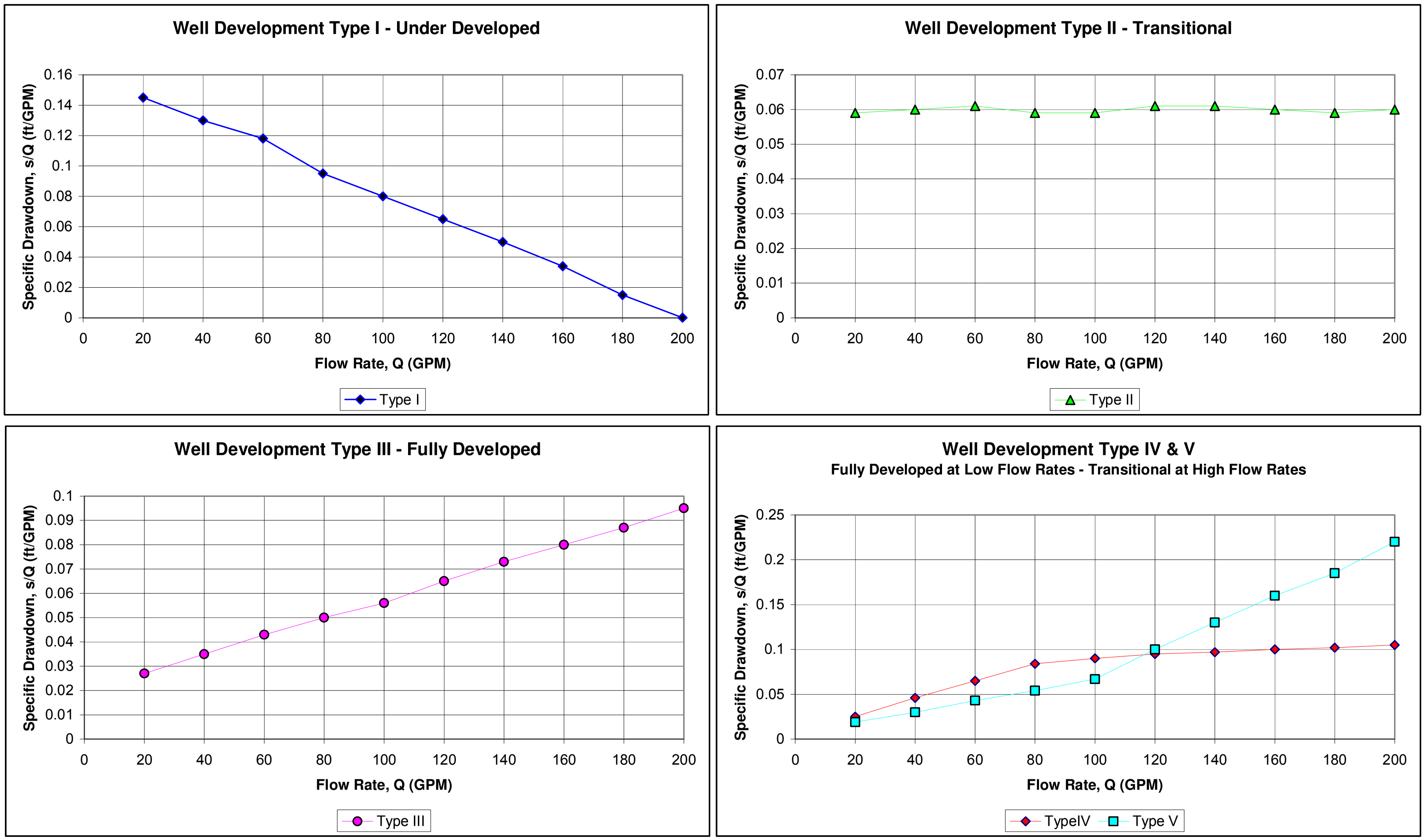
(Courtesy of Dennis Williams, Geoscience Support Services, Inc., 2008.)

The initial well development is critical in developing out the fines in the filter pack. This process can take several days to complete and sometimes if the initial design is poor, can never be completed. This was seen in Chapter 5.4 on CVWD 6725, this well never stopped producing sand. During initial development the well is pumped at different flow rates while measuring drawdown and sand content. The well is surged or raw-hided during flow rates to try to stir the filter pack up and develop out any fines that might be in the filter pack. This process will condition the filter pack such that it will have a much higher conductivity then the aquifer. The development will take on many different stages during this process.

The first stage is Type I development were the specific drawdown decreases with the flow rate and thus determined to be underdeveloped. The Type II development is a transitional stage were the specific drawdown is constant for changing flow rates. Eventually with continued development a Type III development will occur where specific drawdown will increase linearly with increased flow rate. There are two cases within this type of development, where at lower flow rates, specific drawdown will increase linear and then at higher flow rates the well will be underdeveloped. Type IV and Type V are these two cases. The Type IV development has a fully developed specific drawdown at smaller flow rates but at higher flow rates the specific drawdown becomes constant again and thus transitional. Type V is fully developed at low flow rates similar to Type IV but at the higher flow rates it starts to experience higher specific drawdowns and thus much larger well losses. Critical radius generally increases into the filter pack in Type V developed wells.

All wells generally go through the different types of development with a consummation in one of the last three categories. This must be done before any pumping test can begin for well efficiency determination. This initial development is crucial to filter pack development and in determining how the well will operate at many different flow rates. These five types of development are seen in Figure 6.6 below.

Figure 6.6 Well Development Types



6.3. Specific Capacity

Specific capacity of a well is defined as the discharge of the well divided by the drawdown. Simplistically it is the amount of water a well can provide per foot of drawdown. The initial specific capacity is a very important gauge as to how a well performs over time. A drop in well efficiency and thus a drop in specific capacity can be directly related to an increase in operational costs. Thus it is important to initially have the well complete developed to insure the highest degree of efficiency that a well will be able to provide. A simple but yet telling example of this if found in Figure 6.7 below.

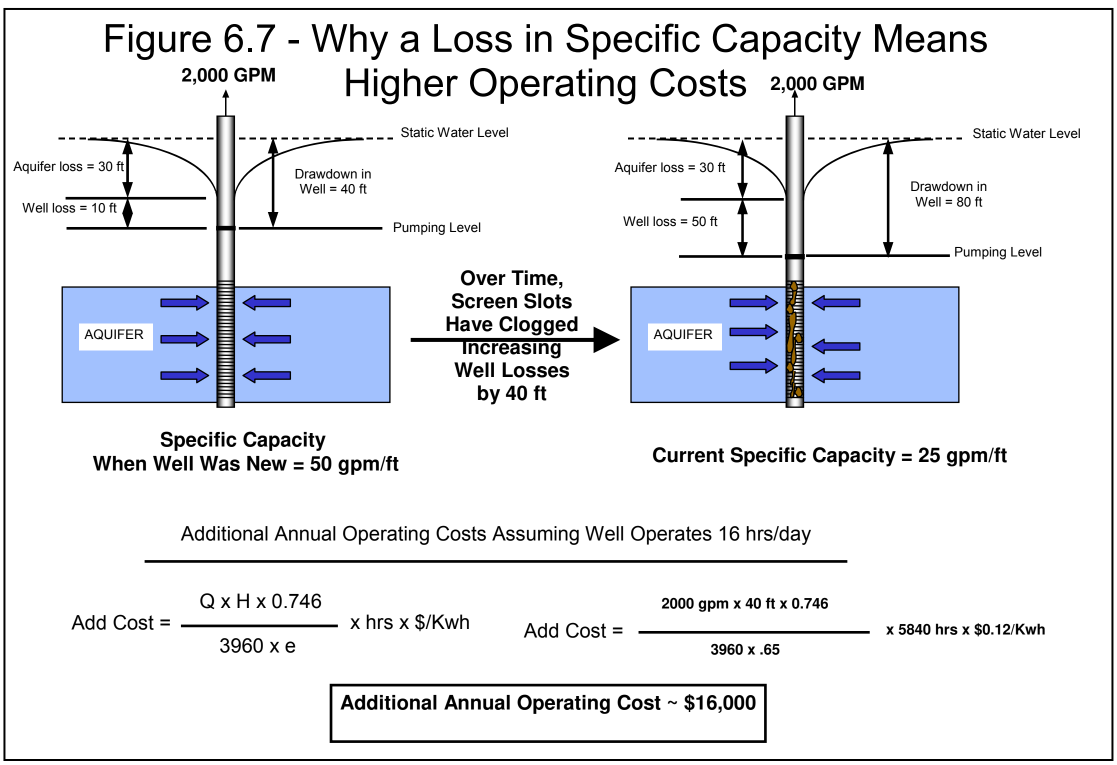


Figure 6.7 - Why a Loss in Specific Capacity Means Higher Operating Costs

(Courtesy of Dennis Williams, Geoscience Support Services, Inc., 2008.)

Chapter 7. COMPARISON OF LABORATORY, FIELD TEST RESULTS, AND THE INDUSTRY DESIGN STANDARDS

In Appendix 5, field well data is analyzed in four different types of aquifers found in southern California, very coarse, coarse, medium and fine grain sand aquifers. This data comprised of 100 wells with over 400 aquifer sieves analysis. This data was then compared to the laboratory data. What was found in the field analysis was quite interesting. In Chapter 5, Case 1, the fine sand aquifer was a great example of a well moving to much sand when the Pack/Aquifer ratio was smaller than four. Case 2, in the fine sand, was an example of the coarse aquifer have pack aquifer ratios over 6 and seem to be closer to 11.5 with no movement of fine sands, thus it is suggested that the Filter Pack/Aquifer Ratio Recommendations of 4-6 need to be changed form 4-10.

Terzaghi's Migration factor did not seem to have much of an effect on either the field data or the laboratory analysis. It also varied depending on what type of aquifer the well was drilled in. In the fine grain aquifers, Terzaghi's Migration factor were all around 4 and only in the sieves that went above 4, was there any sanding issues. In the sand invasion tests performed in the laboratory, the Terzaghi's Migration factor was 6.56 and it was stabilized by the filter pack to the point that it completely clogged the filter pack and there was no migration of the fines in the development stages. In the medium and coarse grain aquifers, the aquifer sieves were already so large that the Terzaghi's Migration factor were all well below 4. It is therefore recommended to keep it below 5 with special attention paid to fine grain aquifers.

Terzaghi's Permeability factor was initially assumed to be greater than 4. The laboratory findings were found to be all above four in order to maintain proper stability of the filter pack and aquifer. The field data showed that the Terzaghi's Permeability factor changed again depending on the aquifer type. For the fine grain aquifers the Terzaghi's Permeability factor were all well above four. As the aquifers increased in grain size the Terzaghi's Permeability factor decreased such that the very coarse grained aquifers were found to be below four. It was thus determined that the Terzaghi's Permeability factor should be above four and lower then 25 with attention paid to the larger grained aquifers. With most of the large grained aquifers, the filter pack becomes more of a formation stabilizer and thus both of Terzaghi's factors are not as important. One note would be any fine sands mixed into the large grain size formations might cause some sanding issues.

The Uniformity Coefficients varied considerably in the field findings due to the aquifers being heterogeneous from the underlying geological processes that deposited them. There were no patterns or distinctions to a Uniformity Coefficient in one grain size to another. From the laboratory testing it was found that very uniform aquifers, Uniformity Coefficients close to one, were able to be stabilized by filter packs but the likelihood of finding these in the field were small. It was also found that large Uniformity Coefficients were much harder to design a filter, but at times this was the only aquifer that was available and producing viable quantities of water. Terzaghi (1996) stated that a Uniformity Coefficient between 1.04 and12 has very little effect on permeability compared to the influence of the size of the smallest particles. Therefore attention needs to be paid to Uniformity Coefficients and how they relate to the overall filter pack design.

The Sorting Factor also varied considerably in the field findings for the same reasons stated above. In designing a filter pack around the Uniformity Coefficient, the type of aquifer plays an important part in determining the Sorting Factor. In the field findings it was determined that the sorting factor had three ranges. The coarse aquifers had sorting factors generally above 0.1, the medium aquifers were above 0.16, and the fine aquifers were generally above 0.3. The laboratory results were all above 0.3 and went all the way to 2.5. The result in the lab were misleading as there is rarely an aquifer found with a Uniformity Coefficient close to 1, therefore it was determined that the Sorting Factor should be between 0.1 and 1.0 with attention paid to the aquifer types that the well is designed in.

The Slot Factor for the field findings was below 0.35 for most conditions and efficient performing wells. In the field findings, the Slot Factor was able to be pushed up to 2.75. Care needs to be taken to ensure that the well slot is large enough to avoid the well from completely clogging during development. It was thus determined to keep the Slot Factor below 2.5.

The Percent of Filter Pack Passing the well screen has long been debated in the water well design field. Many references have stated as to not have larger than ten percent passing. The field findings showed that the percent passing ranged from 2.2 to 22 percent. In the lab findings this criteria was pushed all the way to 43 percent without moving any sand. It was thus determined to keep the Filter Pack Passing below 25 percent passing.

The final design criteria examined was that of the Critical Radius. The critical radius calculations were quite apparent in the laboratory as a controlling factor in additional head loss from turbulence extending from the well bore out into the filter pack. In the sand invasion testing in Chapter 8.0, the critical radius extended out into the filter pack 5 inches with a significant decrease in well efficiency. In the field findings, there are more than a dozen wells that had enough zone testing on discrete well screened intervals to determine the Critical Radius for each zone. Most of the wells had sufficient enough diameters that the Critical radius never extended into the filter pack. There are four wells in all three aquifer types in which the critical radius did extend into the filter pack. Three of these wells had a significant decrease in efficient as a result of this. This decrease in efficiency was found to be similar to a decrease in efficiency in the laboratory findings. It is thus determined to keep the Critical Radius inside the well bore.

In the laboratory findings of Chapter 6.0, all of the screens were run and efficiencies found. The Design Standards were examined, and the results of the field and laboratory findings are made in Table 7.1 below.

Table 7.1 Field Versus Laboratory Findings

Standard	Critical Design Criteria	Field Findings	Laboratory Findings
1	Filter Pack/Aquifer Ratio (D_{50F}/d_{50A})	4-10	4-14.4
2	Terzaghi's Migration Factor $T_m(D_{15F}/d_{85A})$	≤ 7.6	≤ 6.6
3	Terzaghi's Permeability Factor $T_p(D_{15F}/d_{15A})$	$1.4 \leq T_p \leq 96.8$	≥ 4
4	Uniformity Coefficient, C_u (d_{60A}/d_{10A})	$1.7 \leq C_u \leq 35.2$	$1.3 \leq C_u \leq 6$
5	Sorting Factor, S_f (C_{uF}/C_{uA})	$0.05 \leq S_f \leq 1.5$	$0.13 \leq S_f \leq 2.48$
6	Slot Factor (d_{50A}/Slot Width)	≤ 2.8	≤ 1.39
7	Percent of Filter Pack Passing	$\leq 22\%$	$\leq 43\%$
8	Critical Radius, r_c	-	$\leq 10 inches$

D_{50F} = Diameter of the Filter pack at 50% Passing (mm)

d_{50A} = Diameter of the Aquifer at 50% Passing (mm)

Chapter 8. MAJOR FINDINGS

8.1. Water Well Efficiency

One of the unique and independent findings of this research was verifying the Step Drawdown Method as a valid and more robust method for determining water well efficiency. We quantified the aquifer loss and well loss coefficients from this method to determine efficiencies at various operational flow rates of a specific water well pumping scenario. Over the years the water well industry has consistently used the original efficiency equation given in 3.7. The Conventional Method's efficiency is the difference of the drawdown versus the theoretical drawdown in a well. As discussed by Williams (1981) there are many more terms which can be added to the loss term of the well to get a better idea what the true efficiency of the well is at various operational flow rates. The theoretical drawdown can often times be over estimated. In Chapter 6 all of the loss terms associated with the well screens were determined for various different flow rates in several different step tests. In general the SSLS had similar efficiencies as the SSWWS for each given slot sizes. The efficiencies for the SSLS are seen in Figure 8.1 below. It is interesting to note that the 0.0125 in. and the 0.093 in. slot size for the SSLS had very similar efficiencies. There was no noticeable difference between those two screens. Figure 8.2 is the efficiencies for the SSWWS. Figure 8.3 is the comparison of the SSLS to that of the SSWWS. From Figure 8.3 it is seen that most of the SSLS have similar efficiencies to their corresponding SSWWS for each slot size except the 0.093 in. and the

0.080 in. Both of the slot sizes in the SSLS are more efficient then the SSWWS. Figure 8.4 below shows the difference in those two slot sizes for each screen.

Figure 8.1 - SSLS Well Efficiencies

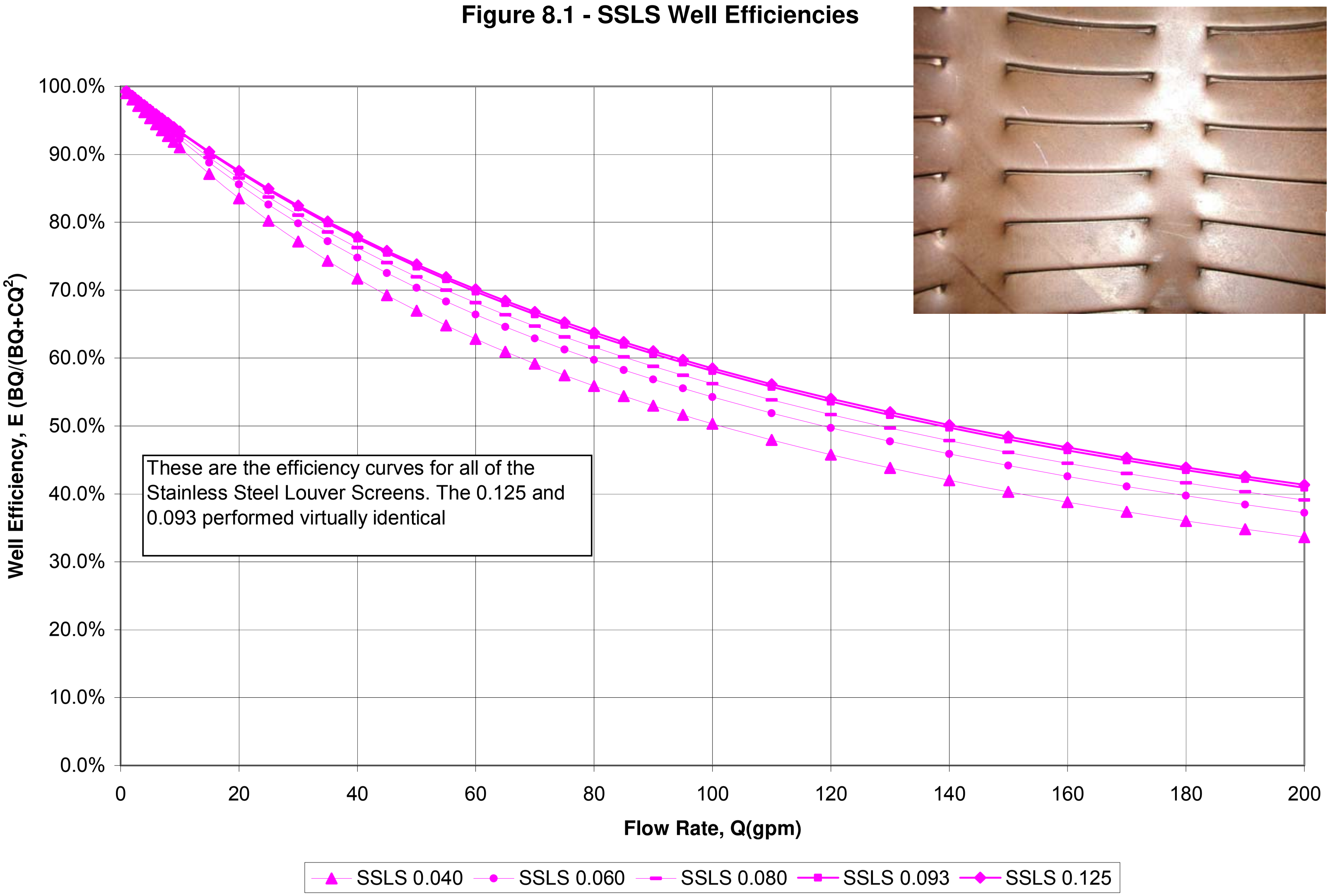


Figure 8.2 - SSWWS Efficiencies

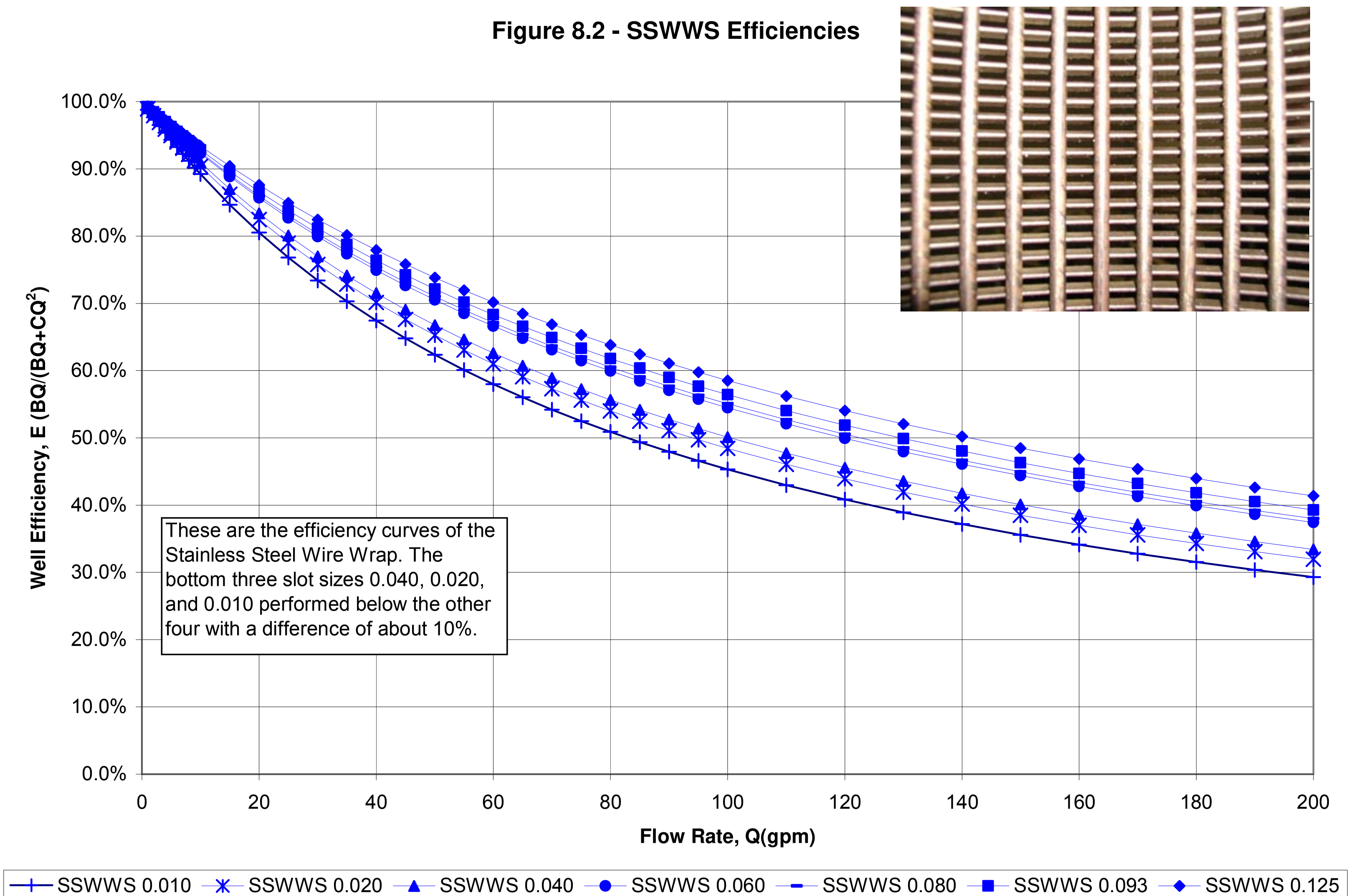


Figure 8.3 - SSWWS and SSLS Efficiencies

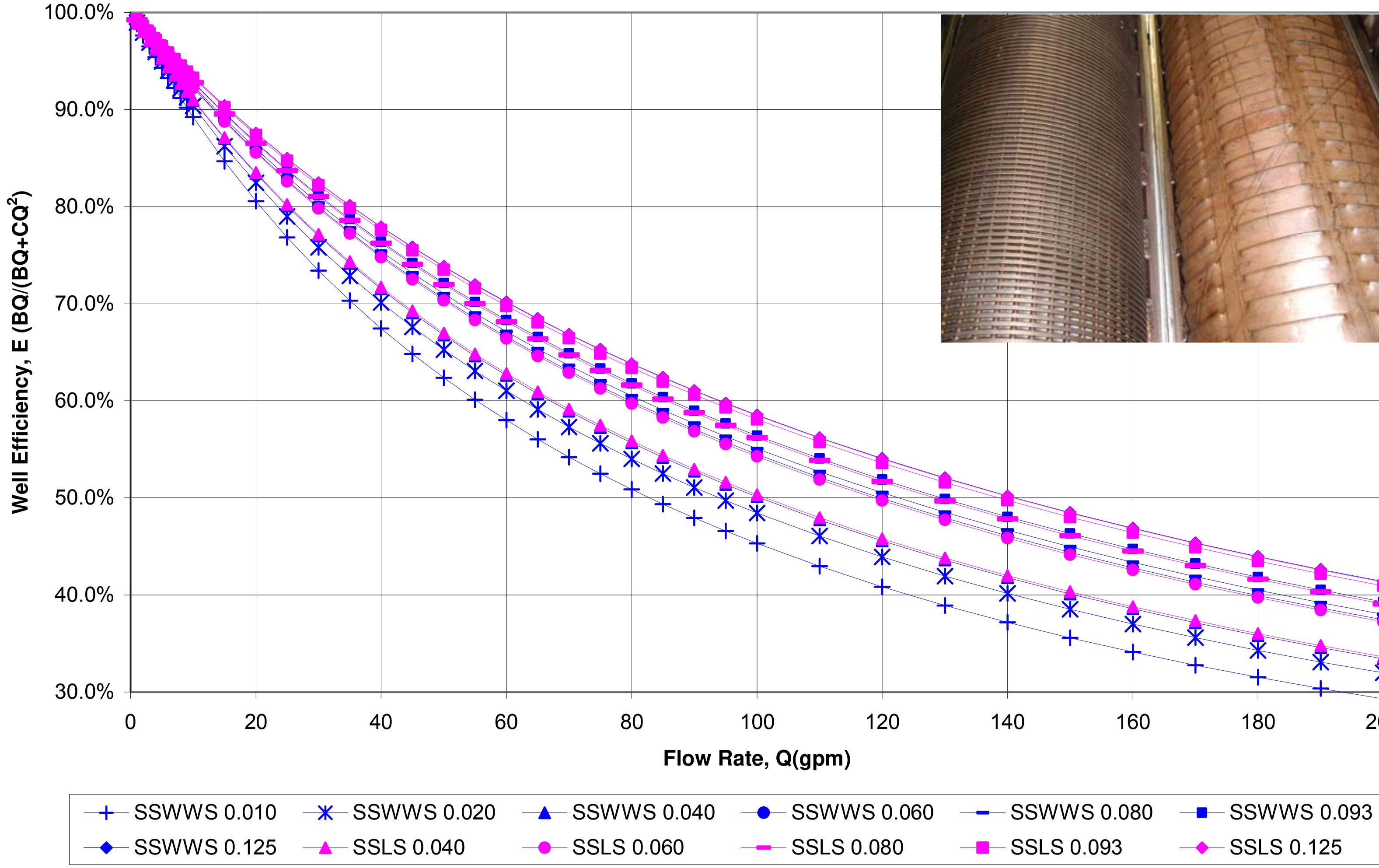
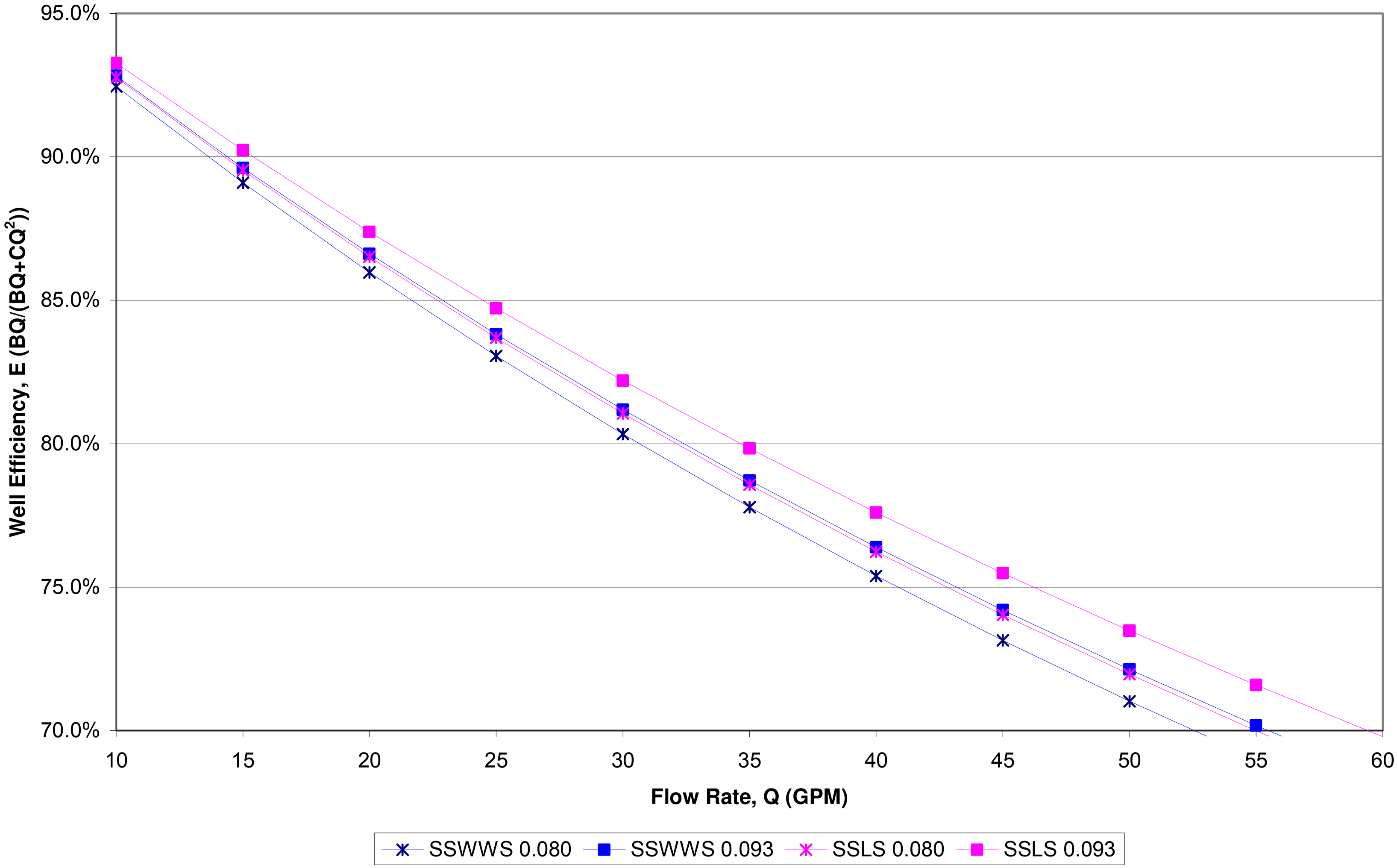


Figure 8.4 - 0.093 in. Slot Size vs. 0.080 in. Slot Size Well Efficiencies

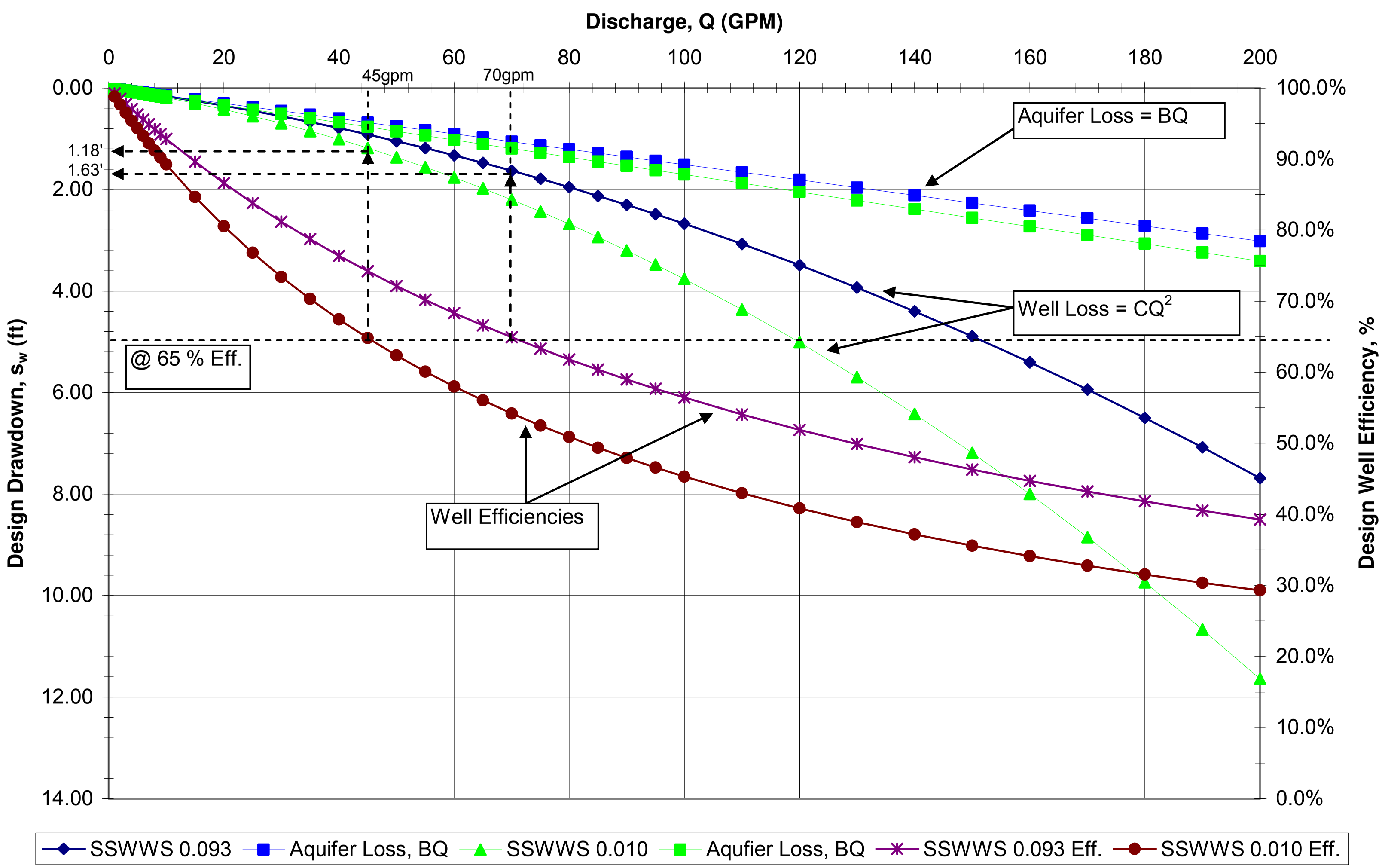


Another major finding was that of the small slot size screens in the SSWWS and how inefficient they are at higher flow rates. These small slot size screens would not perform well in a municipal type setting because of the high flow rate demands which are expected. In Figure 8.5 the SSWWS 0.093 in. is shown in comparison to that of the SSWWS 0.010 in. It is interesting to note that in Figure 8.5 the aquifer loss terms are very similar but the well loss terms vary greatly as flow rates increase. For the design well to operate at 65% efficiency, Table 8.1 below shows the difference in specific capacities one would get if they designed a well with a 0.093 in. SSWWS vs. the 0.010 in. SSWWS.

Table 8.1 Specific Capacities in Different Wire Wraps

SSWWS (in.)	Flow rate, Q (gpm)	Efficiency, %	Drawdown, s (ft)	Specific Capacity, Q/s (gpm/ft)
0.093	70	65%	1.63	43
0.01	45	65%	1.18	38

Figure 8.5 - Specific Capacity and Well Efficiency



The verification between the two well efficiency methods is seen in Figure 8.6 and 8.7 below. Figure 8.6 compares the discharge to the efficiency of the two methods, Step Drawdown and Conventional Methods, for the 0.080 SSLS and as you can see they correlate very well throughout the discharge of the well. Figure 8.7 compares the same two methods for the 0.010 SSWWS which correlate well until the higher discharge rates of the well occur. The higher order loss terms of the well begins to become apparent at these high discharge rates. As discussed in Appendix 3 and in the following, the well loss term becomes larger as the well screen begins to clog. The Step-Drawdown Method accounts for these losses better than the Conventional Method.

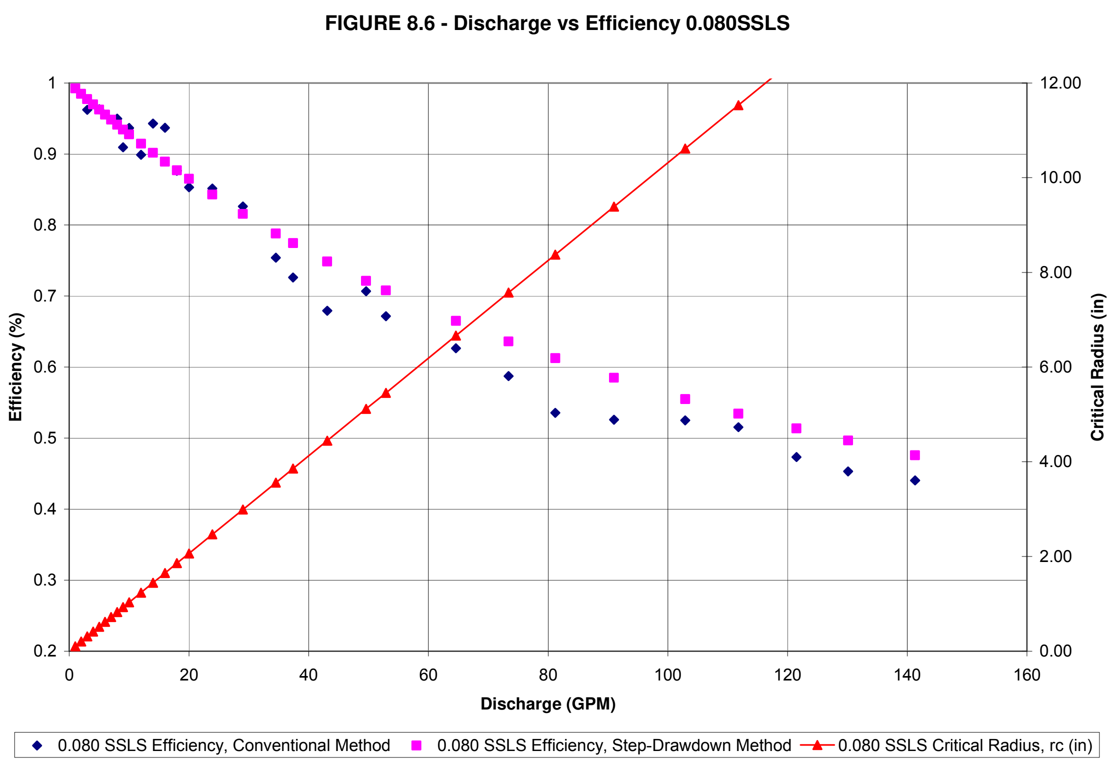


FIGURE 8.7 - Discharge vs. Efficiency 0.010 SSWWS

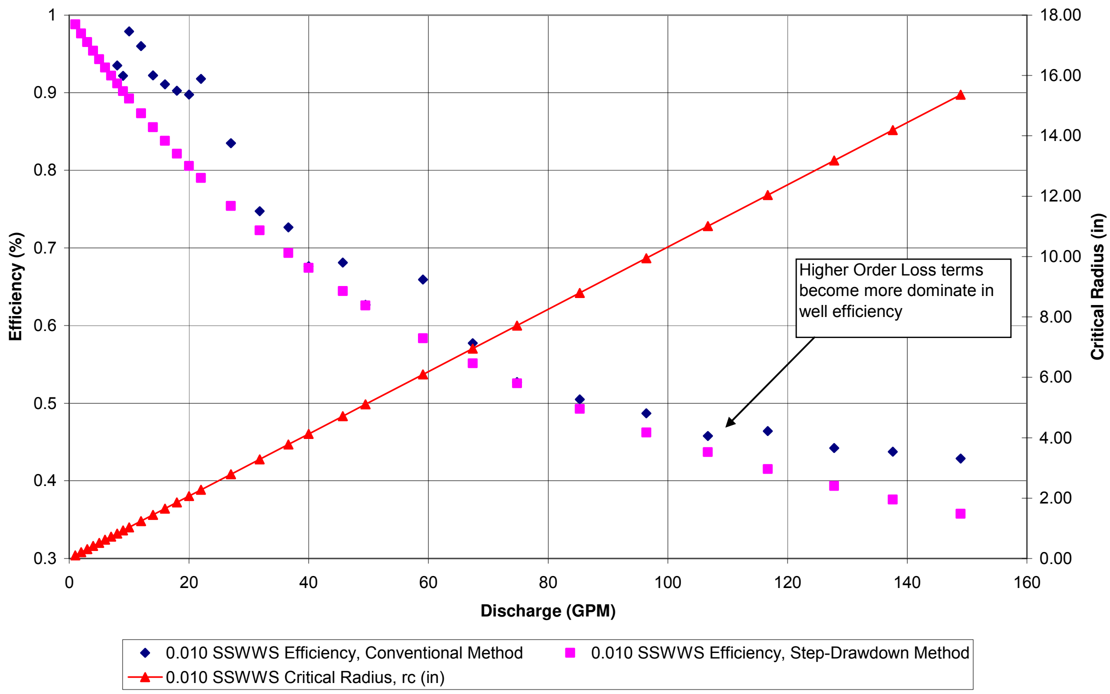


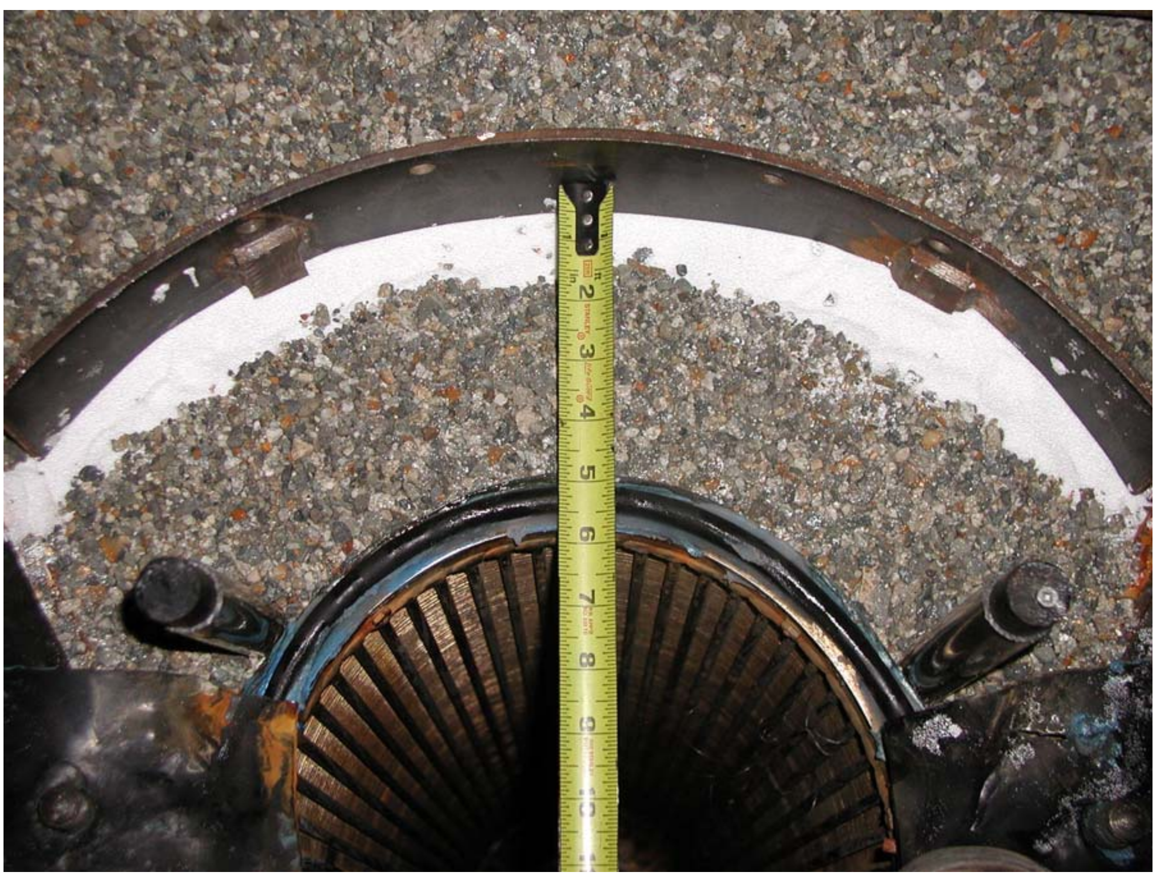
Table 8.2 below shows all of the efficiencies for the all of the well screens tested using the Step-Drawdown Method.

Table 8.2 - Well Efficiency, $E = BQ/(BQ+CQ^2)$ via Step-Drawdown Testing												
Pumping Rate, Q (GPM)	SSWWS 0.010	SSWWS 0.020	SSWWS 0.040	SSWWS 0.060	SSWWS 0.080	SSWWS 0.093	SSWWS 0.125	SSLS 0.040	SSLS 0.060	SSLS 0.080	SSLS 0.093	SSLS 0.125
1	98.8%	98.9%	99.0%	99.2%	99.2%	99.2%	99.3%	99.0%	99.2%	99.2%	99.3%	99.3%
2	97.6%	97.9%	98.0%	98.4%	98.4%	98.5%	98.6%	98.1%	98.3%	98.5%	98.6%	98.6%
3	96.5%	96.9%	97.1%	97.6%	97.6%	97.7%	97.9%	97.1%	97.5%	97.7%	97.9%	97.9%
4	95.4%	95.9%	96.2%	96.8%	96.8%	97.0%	97.2%	96.2%	96.7%	97.0%	97.2%	97.2%
5	94.3%	94.9%	95.3%	96.0%	96.1%	96.3%	96.6%	95.3%	96.0%	96.2%	96.5%	96.6%
6	93.2%	94.0%	94.4%	95.2%	95.3%	95.6%	95.9%	94.4%	95.2%	95.5%	95.8%	95.9%
7	92.2%	93.1%	93.5%	94.5%	94.6%	94.9%	95.3%	93.5%	94.4%	94.8%	95.2%	95.3%
8	91.2%	92.2%	92.6%	93.7%	93.9%	94.2%	94.6%	92.7%	93.7%	94.1%	94.5%	94.6%
9	90.2%	91.3%	91.8%	93.0%	93.2%	93.5%	94.0%	91.8%	92.9%	93.4%	93.9%	94.0%
10	89.2%	90.4%	90.9%	92.3%	92.5%	92.8%	93.4%	91.0%	92.2%	92.8%	93.3%	93.4%
15	84.7%	86.2%	87.0%	88.9%	89.1%	89.6%	90.4%	87.1%	88.8%	89.5%	90.2%	90.4%
20	80.6%	82.4%	83.4%	85.7%	86.0%	86.6%	87.6%	83.5%	85.6%	86.5%	87.4%	87.6%
25	76.8%	79.0%	80.1%	82.7%	83.1%	83.8%	85.0%	80.2%	82.6%	83.7%	84.7%	84.9%
30	73.4%	75.8%	77.0%	80.0%	80.3%	81.2%	82.5%	77.2%	79.8%	81.0%	82.2%	82.4%
35	70.3%	72.9%	74.2%	77.4%	77.8%	78.7%	80.1%	74.3%	77.2%	78.6%	79.8%	80.1%
40	67.4%	70.1%	71.5%	74.9%	75.4%	76.4%	77.9%	71.7%	74.8%	76.2%	77.6%	77.9%
45	64.8%	67.6%	69.1%	72.7%	73.1%	74.2%	75.8%	69.3%	72.5%	74.0%	75.5%	75.8%
50	62.4%	65.3%	66.8%	70.5%	71.0%	72.1%	73.8%	67.0%	70.3%	72.0%	73.5%	73.8%
55	60.1%	63.1%	64.6%	68.5%	69.0%	70.2%	72.0%	64.8%	68.3%	70.0%	71.6%	71.9%
60	58.0%	61.0%	62.6%	66.6%	67.1%	68.3%	70.2%	62.8%	66.4%	68.1%	69.8%	70.1%
65	56.0%	59.1%	60.7%	64.8%	65.3%	66.6%	68.5%	60.9%	64.6%	66.4%	68.1%	68.4%
70	54.2%	57.3%	58.9%	63.1%	63.6%	64.9%	66.9%	59.1%	62.9%	64.7%	66.4%	66.8%
75	52.5%	55.6%	57.2%	61.5%	62.0%	63.3%	65.3%	57.5%	61.3%	63.1%	64.9%	65.3%
80	50.9%	54.0%	55.7%	59.9%	60.5%	61.8%	63.8%	55.9%	59.7%	61.6%	63.4%	63.8%
85	49.4%	52.5%	54.2%	58.5%	59.0%	60.4%	62.4%	54.4%	58.3%	60.2%	62.0%	62.4%
90	47.9%	51.1%	52.7%	57.1%	57.7%	59.0%	61.1%	53.0%	56.9%	58.8%	60.6%	61.0%
95	46.6%	49.7%	51.4%	55.7%	56.3%	57.7%	59.8%	51.6%	55.5%	57.5%	59.3%	59.7%
100	45.3%	48.4%	50.1%	54.5%	55.1%	56.4%	58.5%	50.3%	54.3%	56.2%	58.1%	58.5%
110	43.0%	46.1%	47.7%	52.1%	52.7%	54.1%	56.2%	48.0%	51.9%	53.8%	55.7%	56.2%
120	40.8%	43.9%	45.6%	49.9%	50.5%	51.9%	54.1%	45.8%	49.7%	51.7%	53.6%	54.0%
130	38.9%	41.9%	43.6%	47.9%	48.5%	49.9%	52.1%	43.8%	47.7%	49.7%	51.6%	52.0%
140	37.2%	40.2%	41.8%	46.1%	46.7%	48.0%	50.2%	42.0%	45.9%	47.8%	49.7%	50.2%
150	35.6%	38.5%	40.1%	44.4%	45.0%	46.3%	48.5%	40.3%	44.2%	46.1%	48.0%	48.4%
160	34.1%	37.0%	38.6%	42.8%	43.4%	44.7%	46.9%	38.8%	42.6%	44.5%	46.4%	46.8%
170	32.8%	35.6%	37.1%	41.3%	41.9%	43.2%	45.4%	37.3%	41.1%	43.0%	44.9%	45.3%
180	31.5%	34.3%	35.8%	39.9%	40.5%	41.8%	44.0%	36.0%	39.7%	41.6%	43.5%	43.9%
190	30.4%	33.1%	34.6%	38.6%	39.2%	40.5%	42.6%	34.8%	38.4%	40.3%	42.2%	42.6%
200	29.3%	32.0%	33.4%	37.4%	38.0%	39.3%	41.4%	33.6%	37.2%	39.1%	40.9%	41.3%

8.2. Verifying the Critical Radius Theory

The Critical Radius of a well is the point, at which the flow becomes transitional, it initially starts at or inside the well bore and as time and flow rate increase the radius grows out beyond the well screen into the filter pack. This change demarcates the point at which the efficiency of the well begins to decrease due to an increase in head loss in the near well zone. This is discussed in Chapter 6 above. To verify Williams (1985) Theory of the effect of critical radius on well efficiency, we increased the near well losses by the addition of fine sands in the near well zone. This decrease in near well loss is attributed to the fine sands not only clogging up the slots in the well but also the pore space in the filter pack making it less permeable thus less efficient. Figure 8.8 below is a photo of the setup in the laboratory to accomplish this. This method allowed us to accelerate the degradation of the well and quantify the aquifer and well loss coefficient terms in relation to different flow rates of the well using the Step Drawdown Method. This allowed us to verify the Critical Radius Theory and its relation to the demarcation of flow transition within the near well zone. Videos of this effect were also recorded showing both the sand migration through the filter pack as well as the fine sands clogging the slots of the well screen adding to the well losses.

Figure 8.8 Fine Sand Invasion Setup



This permanent decrease in specific capacity of the well lowered the efficiency from the 80 percent range all the way down to the 20 percent range. A graph of this is seen in Figure 8.9 below. The well loss component of the system started at 1E-4 ft/gpm^2 and increased to 1.6E-3 ft/gpm^2. This significant increase in well loss is one of the major contributors to a decrease in well efficiency and a change in specific capacity of the well from the initial testing of 25 gpm/ft to 5 gpm/ft or change from 80% efficiency to 20% efficiency after the fine sand migration. This change means that there would be less gallons pumped from this well per given foot of head in the well and thus a large increase in the amount of energy which would be required to operate this well at a similar flow rate from the initial flow rate established by this well.

From Figure 8.10 below, we see the distance drawdown test. At different flow rates the well losses begin to increase as time and flow rate increase. The critical radius is also plotted on this figure to show where the flow rates become turbulent and the well losses begin to increase and extend into the filter pack. This change happens to a point where the well becomes completely clogged and the efficiency of the well drops to 20 percent.

Figure 8.9 - Step Drawdown - SS Wire Wrap 0.010

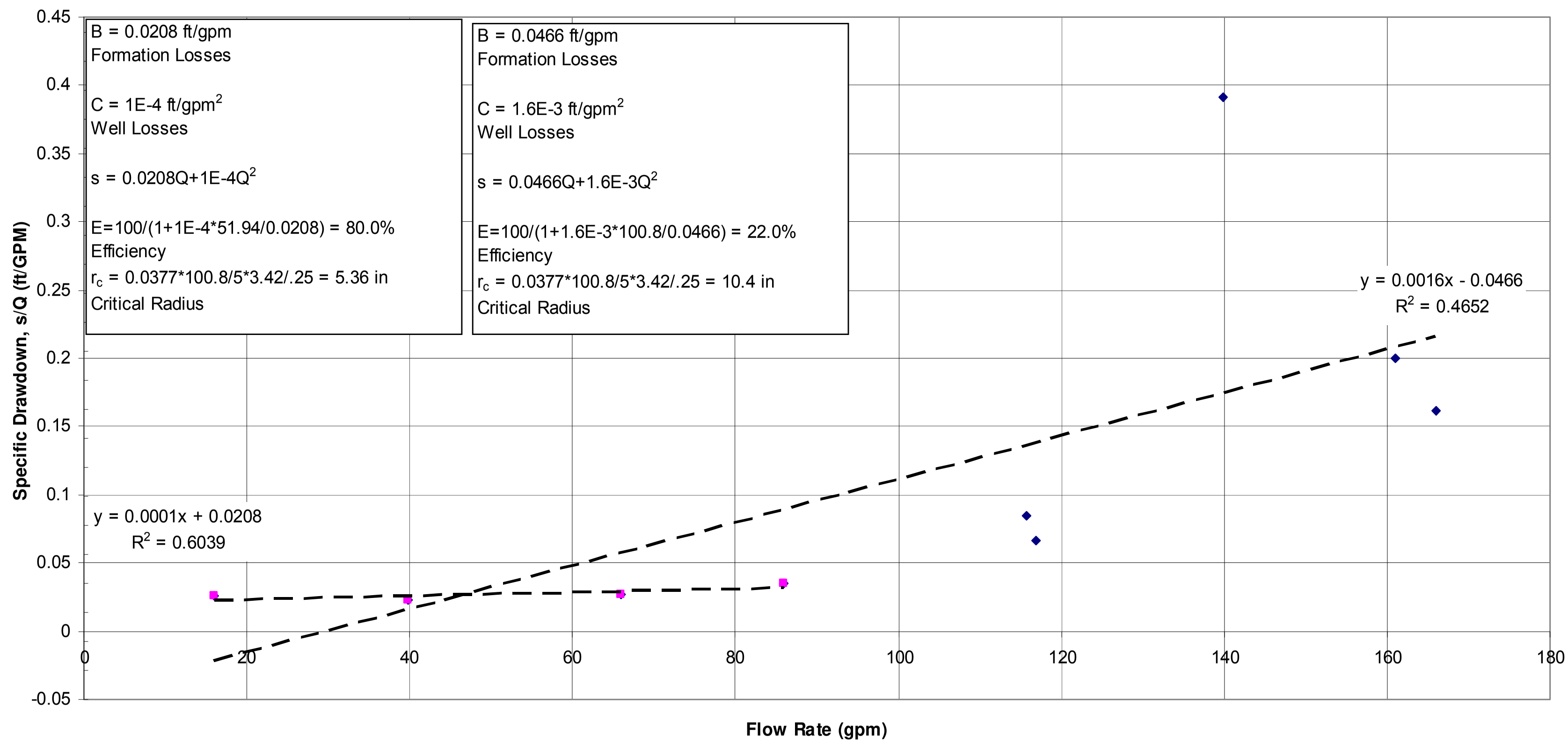
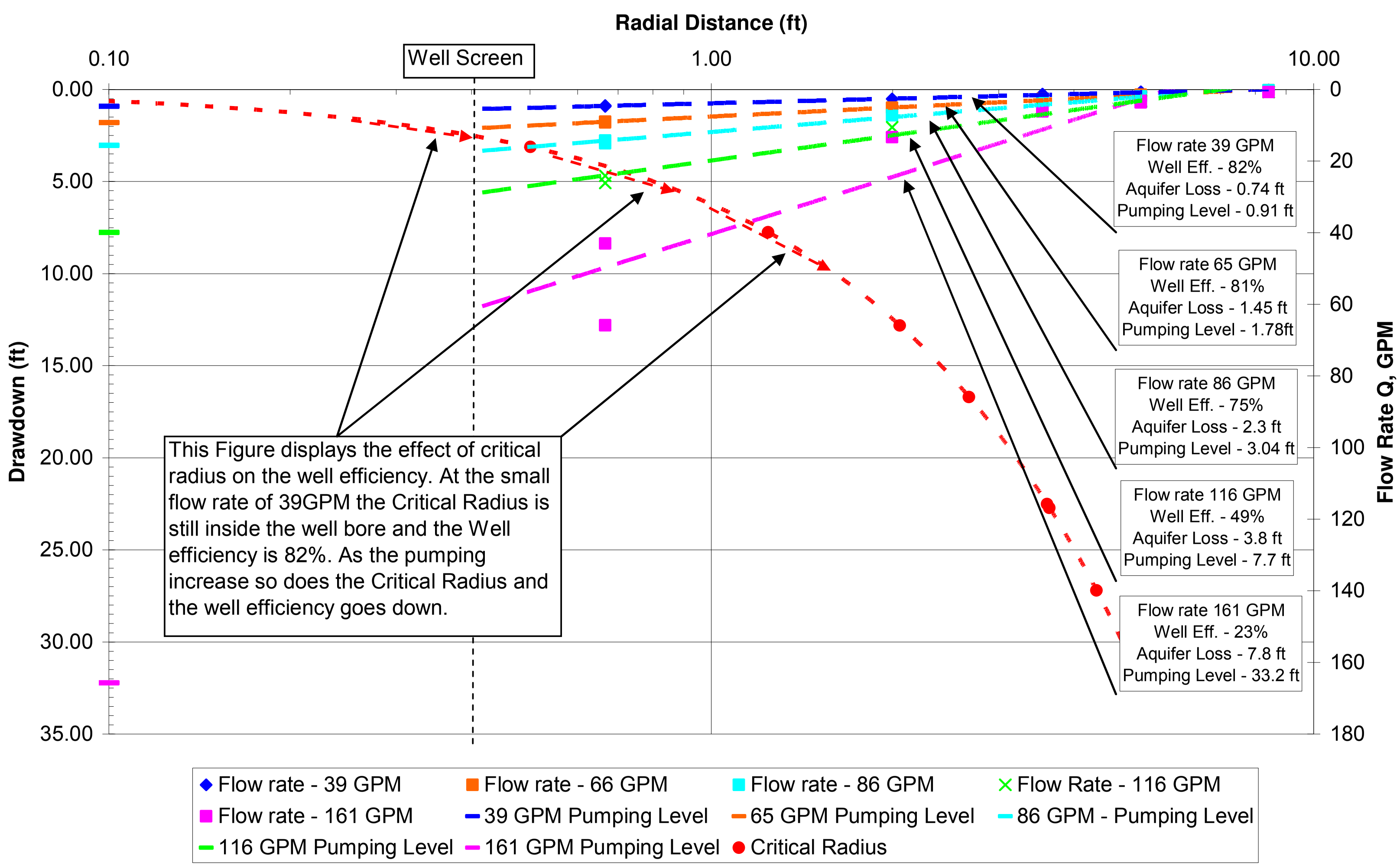


Figure 8.10 - Distance Drawdown



8.3. Verifying the Critical Design Criteria

The initial research examined only part of the Critical Design Criteria, Table 4.1. These initial tests, which were run in Appendix 3-4, were done without a filter pack so that the B' and the B" terms in the equation below are negligible thus only leaving the formation loss coefficient and the well loss coefficient to determine the efficiencies of each well screen and slot size.

$$E = \frac{BQ}{\left(BQ + B'Q + B''Q^n + CQ^2\right)}100 \qquad (1.7)$$

E = Efficiency of pumping well, (%)

B = Formation loss coefficient (ft/gpm, m/l/s)

B' = Damage zone loss coefficient (ft/gpm, m/l/s)

B" = Filter pack loss coefficient (ft/gpm^n, $m/(l/s)^n$)

n = Exponent ($1<n<=2$)

Q = Well discharge (gpm, l/s)

C = Well loss coefficient (ft/gpm^2, $m/(l/s)^2$)

When filter packs are added to a smaller sized aquifer, the ability to test other Critical Design Criteria of the well/aquifer system became more apparent. There is no drill damage zone in the laboratory testing thus all the losses are well loss and filter pack losses.

To test the design criteria, we placed outside the filter pack of the well, fine sands as shown in Figure 8.8. Both of the tubes on the left and right of Figure 8.8 allowed a camera to video the movement of the fine sands through the filter pack and the well screen itself. The 70x140 sand was selected such that 100% of it would pass through the well screen in an effort to see what the relationship between it and the filter pack would be. The filter pack is designed to stabilize the aquifer and the well screen is designed to stabilize the filter pack. This same set of experiments was duplicated with 40x60 fine sand. Sieve analysis of these two different runs is seen in Figure 8.11 below. The results were a bit unexpected in regards to the 70x140 sand, it was not expected to migrate through the entire filter pack and through the well screen. After the first set of tests it was found that the 70x140 sand was completely removed in the experiment and it had migrated through the filter pack, and passed through the well screen and into the well bore. The efficiency change in this test was negligible thus there was only raw-hiding preformed in which no change happened to the well or well efficiency. The well never dropped in its initial efficiency due to the absence of fines, but if this was a production well it would have had tremendous sanding issues.

The second set of tests is a bit different. The 40x60 sand did much less migration throughout the filter pack and most of it clogged the well screen and or the filter pack. This was visually seen in the Borescope during the test. The migration affects were much slower and all of the filter pack was clogged. Figure 8.11 shows the sieves of the filter pack before invasion of the fine sands, the fine sands, and the filter pack after the fine sand invasion. It is thus shown that the 70x140 sand passed through both the filter pack and well screen. There was no residual clogging of the filter pack by fine sands and therefore no change in the sieve curves before and after invasion by 70x140 sand. The

40x60 not only clogged the filter pack and well screen but much of it was left in the filter pack as seen the sieve after the 40x60 invasion.

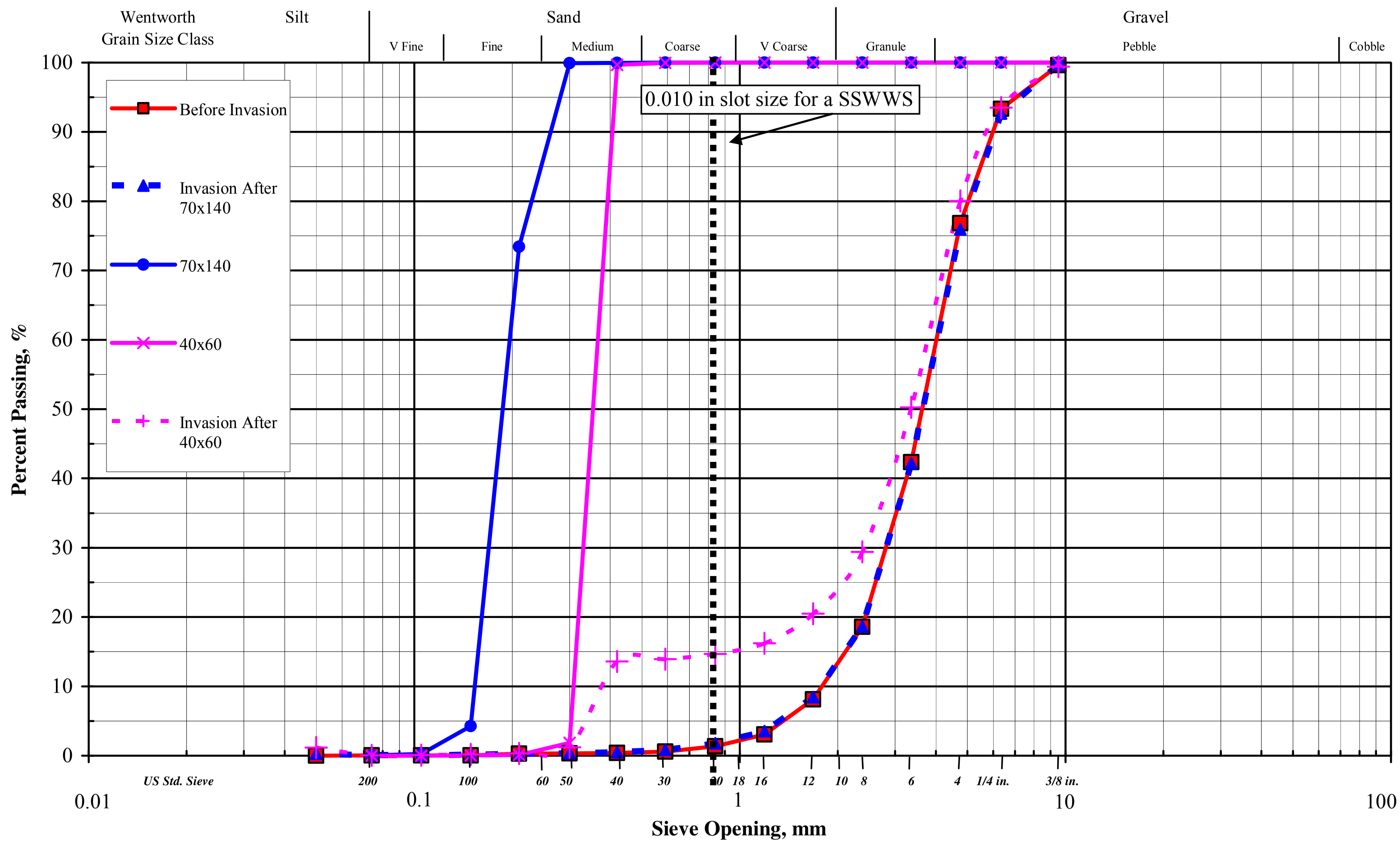
The results of these migration tests quantified some of the limits of filter packs ability to stabilize a particular aquifer. Both of the fine sands were extremely uniform and within the recommendations of the field and laboratory findings. The 70x140 fine sand had a T_m of 10.7, and it completely migrated through the filter pack. It was also smaller then the well slot size, thus it passed through the well screen and into the well bore. The 40x60 fine sand had a T_m of 6.56, and it moved through the filter pack but not completely. It also was finer then the well slot size but it bridged along the well screen clogging most of the open area. These results are seen in Figure 8.11 below. The following table is the findings of the results of the two invasion tests preformed above.

It is interesting to note that all of the tests fall within the criteria given it Table 7.1 except Terzaghi's Permeability factor. The testing of the 70x140 had no impact on the efficiency of the filter pack with the permeability factor being lower than 4. But the Invasion test of the 40x60 fine sand, efficiency's dropped off considerably and the head loss through the well screen greatly increased. This is shown above via Step-Drawdown Method as well as the Constant Rate Method.

TABLE 8.3 - Well Design Criteria for Invasion Testing

	Filer Pack/Aquifer Ratio (D_{50F}/d_{50A})	Terzaghi's Migration Factor (D_{15F}/d_{85A})	Terzaghi's Permeability Factor (D_{15F}/d_{15A})	Uniformity Coeficient, Cu (d_{60A}/d_{10A})	Curvature Coeficient, Cc ($d^2_{30A}/(d_{60A}$-$d_{10A})$)	Sorting Factor, S_f (C_{uF}/C_{uA})	Slot Factor (d_{50}/Slot Width)	Percent Aquifer Pack Passing Well Slot	Percent Filter Pack Passing Well Slot	Slot Size
Before Invasion	1.39	0.48	1.24	2.24	1.10	1.32	14.30	1.3	1.18	0.010
70x140	27.07	10.70	16.69	1.28	1.10	2.30	0.74	100		
40x60	14.35	6.56	8.41	1.19	1.10	2.48	1.39	100		
Invasion After 70x140	1.39	0.47	1.25	2.28	0.95	1.30	14.35	1.8		
Invasion After 40x60	1.51	0.50	2.90	9.91	0.97	0.30	13.19	14.7		

Figure 8.11 - Mechanical Grading Analysis Sand Invasion Test



Originally it was thought that if the slot in the well screen was too large that a large amount of the filter pack would pass through the well screen. Many well designers stated that the slot width should not allow more then 10% passing of the filter pack through the well screen, i.e. that the slots size should be no large then the 10% passing size of the filter pack being used. As seen in the Figure A3.1 the fines of the aquifer never migrated through the well screen as once expected. Even the largest screen slot size, 0.125 in., did not change the filter pack to a very large degree. The 0.125 SSWWS had a 43% passing through it but yet an insignificant amount of material, less than 1 part per million, migrated through the screen. This example had a Slot Factor, S_l, greater than 0.5.

It was there for determined that one of the initial design criteria of Chapter 4 with regards to the Slot Factor was not correctly defined thus far. The Slot Factor was originally stated as;

$$S_l = \frac{d_{50A}}{Slotwidth} \leq 0.5 \tag{4.6}$$

S_l = Slot Factor (Design Criteria from Chapter 1)

Slot width = Slot width of screen (in., mm)

In many cases the Slot Factor can be greater than 1.4 but it must be compared to the aquifer and filters being used. As seen in the tests above the 70x140 material was not stabilized by the filter pack and thus passed through the well screen. This research has verified that the filter pack design should be used to stabilize the aquifer and the well screen used to stabilize the filter pack.

From Chapter 5, the field analysis gave a much broader look at the different wells in various geological settings. From this Chapter we found that the Filter Pack/Aquifer Ratio can be much larger than once assumed. The lower limit of 4 is still very important. If this ratio is smaller than 4, in fine grain aquifers sand migration becomes a problem. We also saw in Chapter 6 that in coarse grain aquifers that the Percent Passing of the filter pack can be larger and the slot factor can be closer to 1.4.

The findings thus far have determined that the geological specifics must be taken into account before a design is to be undertaken. Most importantly proper development coupled with good well design will provide simple, strong and efficient wells providing water for many years to come.

Table 8.4 is the results of the field and laboratory findings made above. From these findings and current design practices, the conclusions and recommendations are formulated and thus represented below.

Table 8.4 Final Well Design Criteria				
Standard	Critical Design Criteria	Field Findings	Laboratory Findings	Conclusions & Recommendations
1	Filter Pack/Aquifer Ratio (D_{50F}/d_{50A})	4-10	4-14.4	4-10
2	Terzaghi's Migration Factor $T_m(D_{15F}/d_{85A})$	≤ 7.6	≤ 6.6	≤ 5
3	Terzaghi's Permeability Factor $T_p(D_{15F}/d_{15A})$	$1.4 \leq T_p \leq 96.8$	≥ 4	$4 \leq T_p \leq 25$
4	Uniformity Coefficient, C_u (d_{60A}/d_{10A})	$1.7 \leq C_u \leq 35.2$	$1.3 \leq C_u \leq 6$	$1.3 \leq C_u \leq 12$
5	Sorting Factor, S_f (C_{uF}/C_{uA})	$0.05 \leq S_f \leq 1.5$	$0.13 \leq S_f \leq 2.48$	$0.1 \leq S_f \leq 1.0$
6	Slot Factor (d_{50A}/Slot Width)	≤ 2.76	≤ 1.39	≤ 2.5
7	Percent of Filter Pack Passing	$\leq 22\%$	$\leq 43\%$	$\leq 25\%$
8	Critical Radius, r_c	-	$\leq 10 inches$	$\leq WellBore$

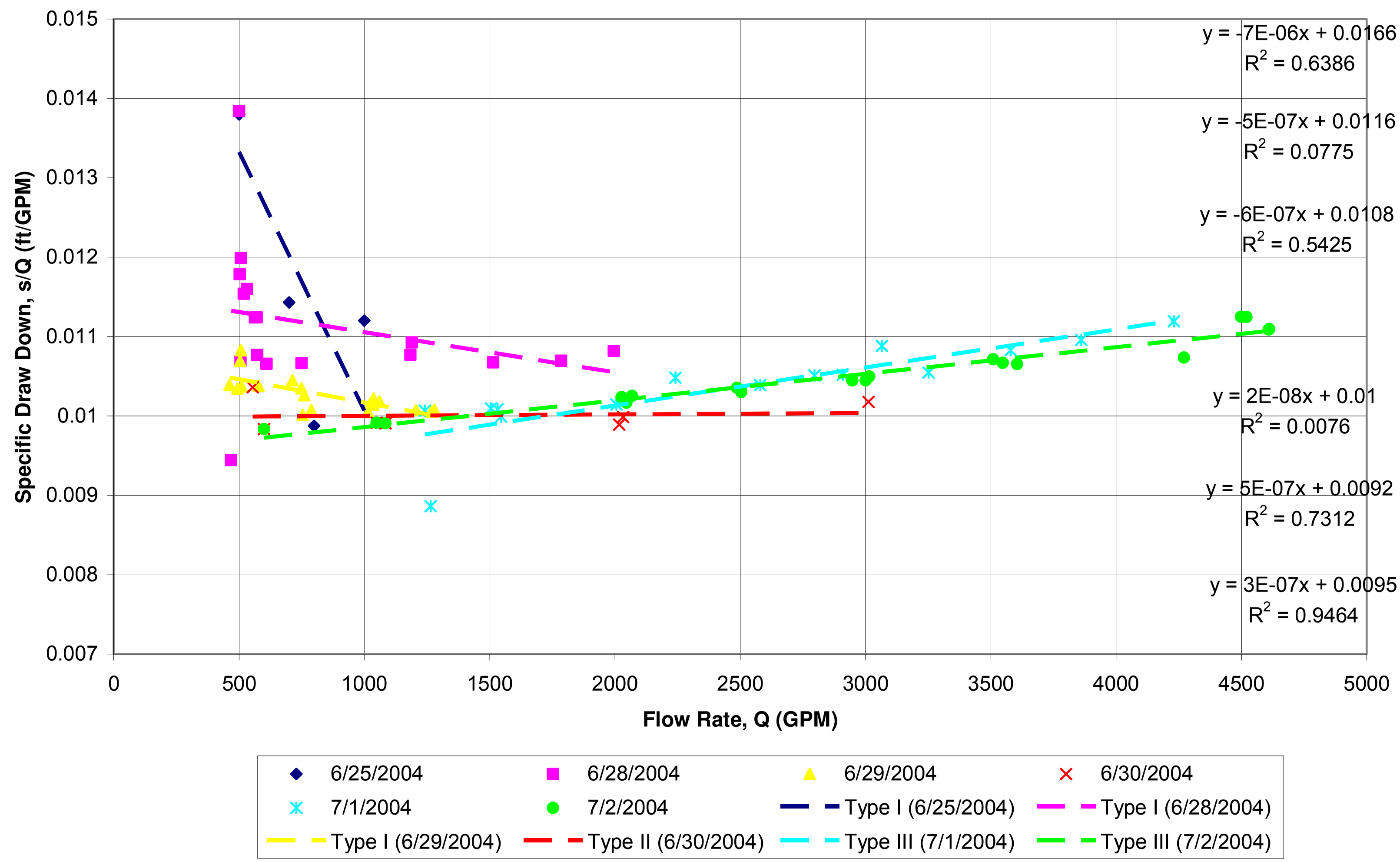
D_{50F} = Diameter of the Filter pack at 50% Passing (mm)

d_{50A} = Diameter of the Aquifer at 50% Passing (mm)

8.4. Well Development

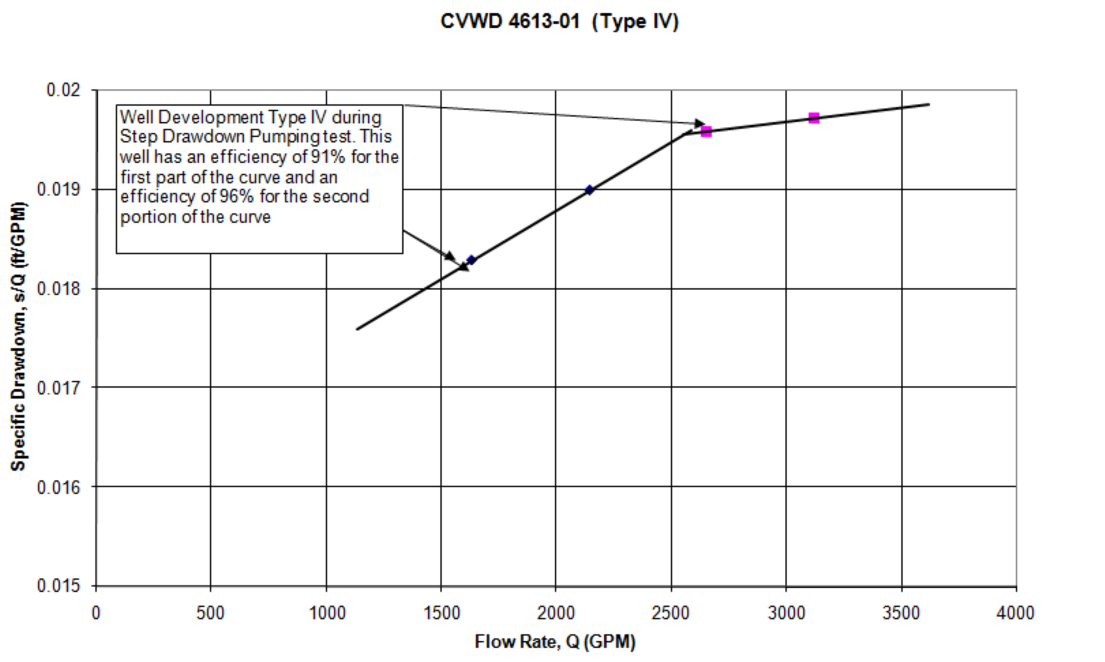
To properly determine when a well is completely developed or not, we rely on specific drawdown plots as discussed in Chapter 6.0 above. These five types of development let us determine flow rates, aquifer parameters, efficiencies, and pumping rates for that well. Well development takes place slowly, beginning at lower flow rates and slowly increasing with time while measuring sand content in the effluent of the well. A well will initially be Type I as shown in Chapter 6.0 and then transition into a Type II with surging and slowly increasing flow rates. Eventually with time and increased pumping and surging, the development will transition into a Type III. Figure 8.12 is an example of a well in the field where this development took place over six days of pumping.

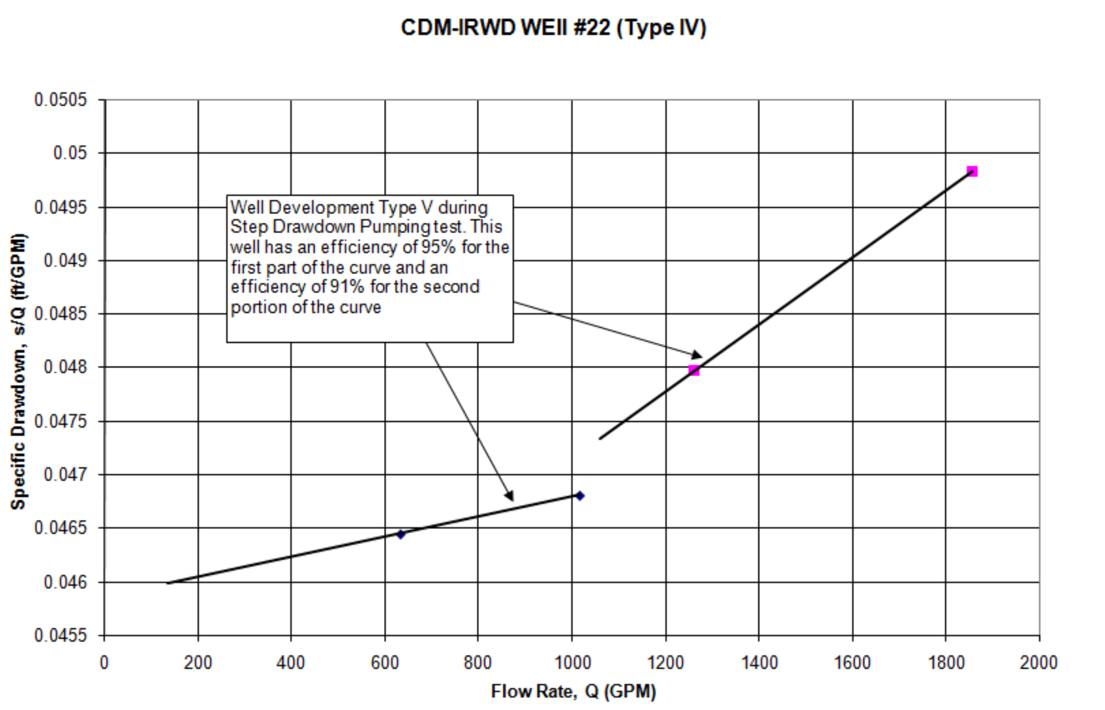
Figure 8.12 - JCSWD Well #23 Development Testing



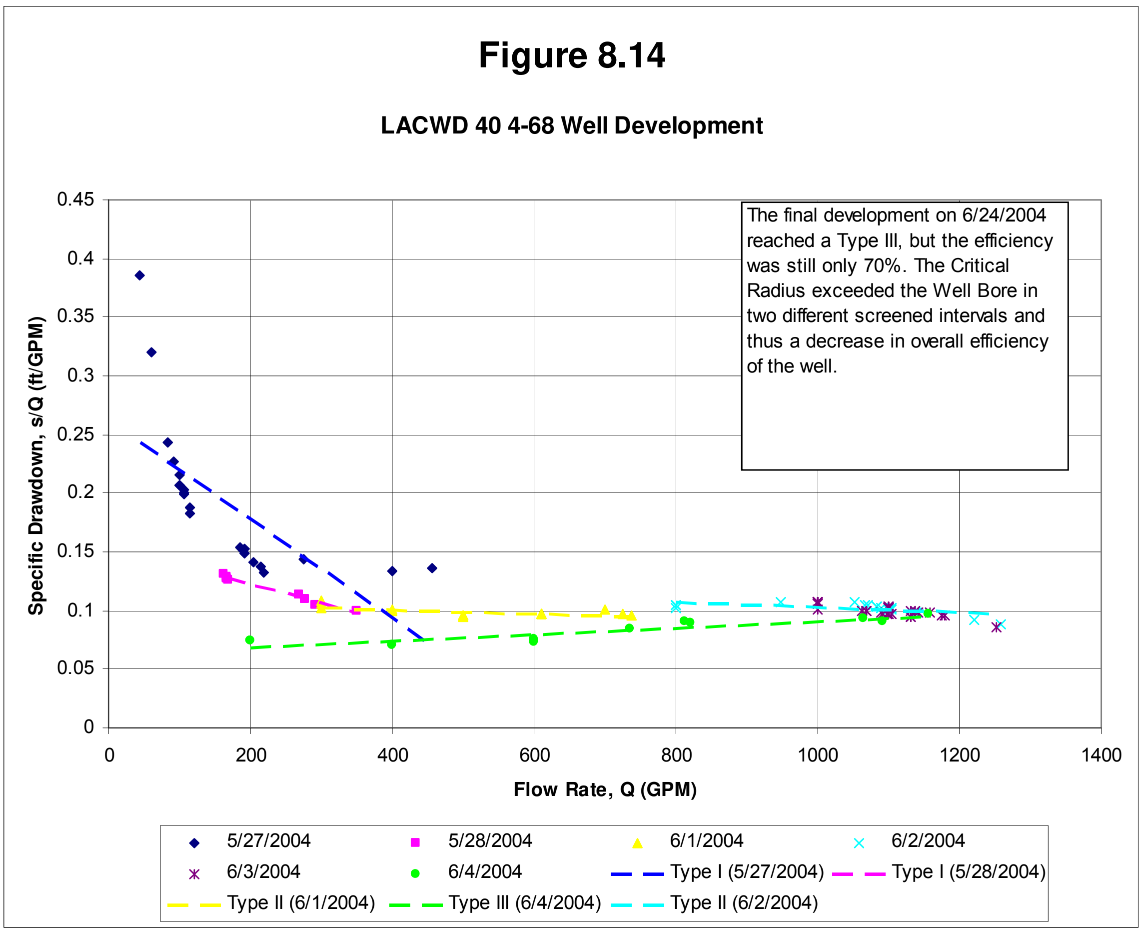
When development reaches Type III it is completed, assuming sand content in effluent stream remains low, generally below 1 parts per million (PPM). From this point one can then start pumping tests to determine the aquifer parameters, well efficiencies, and the design pumping rates for the well owner. Some wells will stay in a Type IV or V development stage. This may occur from inadequate development time, aquifer formations that will never allow complete development, stream or river recharge, or increases in critical radius at higher pumping rates. The two wells in Figure 8.13 are two wells which are examples of Type IV and V.

Figure 8.13 Field Development Types





Critical radius also plays a significant role in well development and well efficiency. From discrete flow tests performed on specific aquifer intervals, the well below went through Type I development and then into Type II development. The transition between Type II and Type III development was slow and the efficiency of the well, 70%, did not improve from the design flow rate. This well also did not exhibit strong Type III development curve. The development of this well is seen in Figure 8.14 below.



The sieves analysis of the well is seen in Figure 8.15 below. All of the design criteria were within acceptable limits except the zones of 260-270 feet and 360-370 feet had low Sorting Factors compared to the other aquifers of this well. In Table 8.5, the design criteria for all of the aquifers are shown as well as the critical radius for each zone in the well determined by a flow spinner survey. We see that the two zones, 260-270 and 360-370 feet, both have critical radii outside the well bore. The zone 360-370 feet has a tremendously large critical radius of over 5 times that of the well bore, 43 inches in a well bore of 8 in radius. This is a large contributing factor to the decrease in efficiency of this well.

Figure 8.15 - LACWD 40 Well 4-68
(Courtesy of Dennis Williams, Geoscience Support Services, Inc., 2008.)

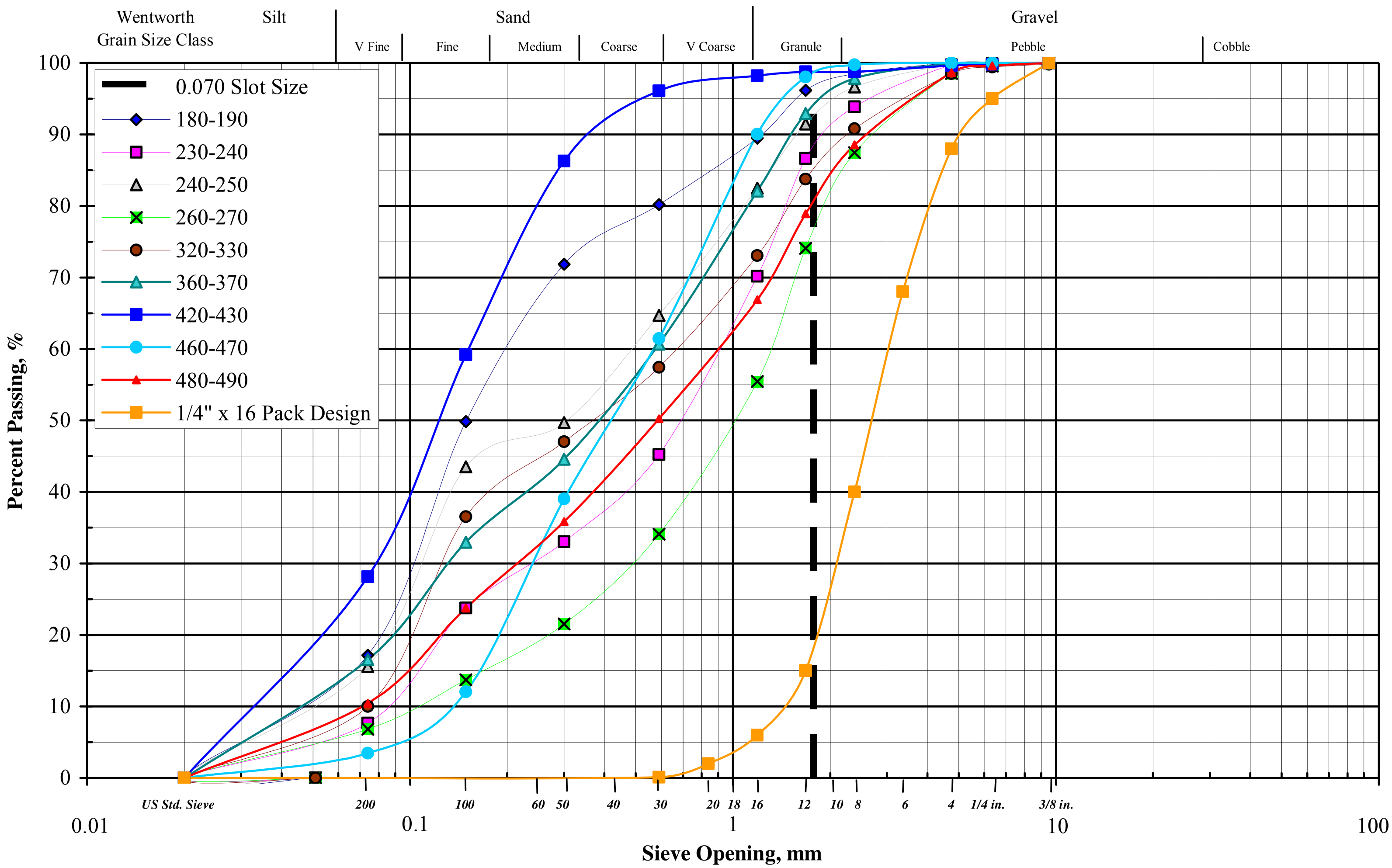


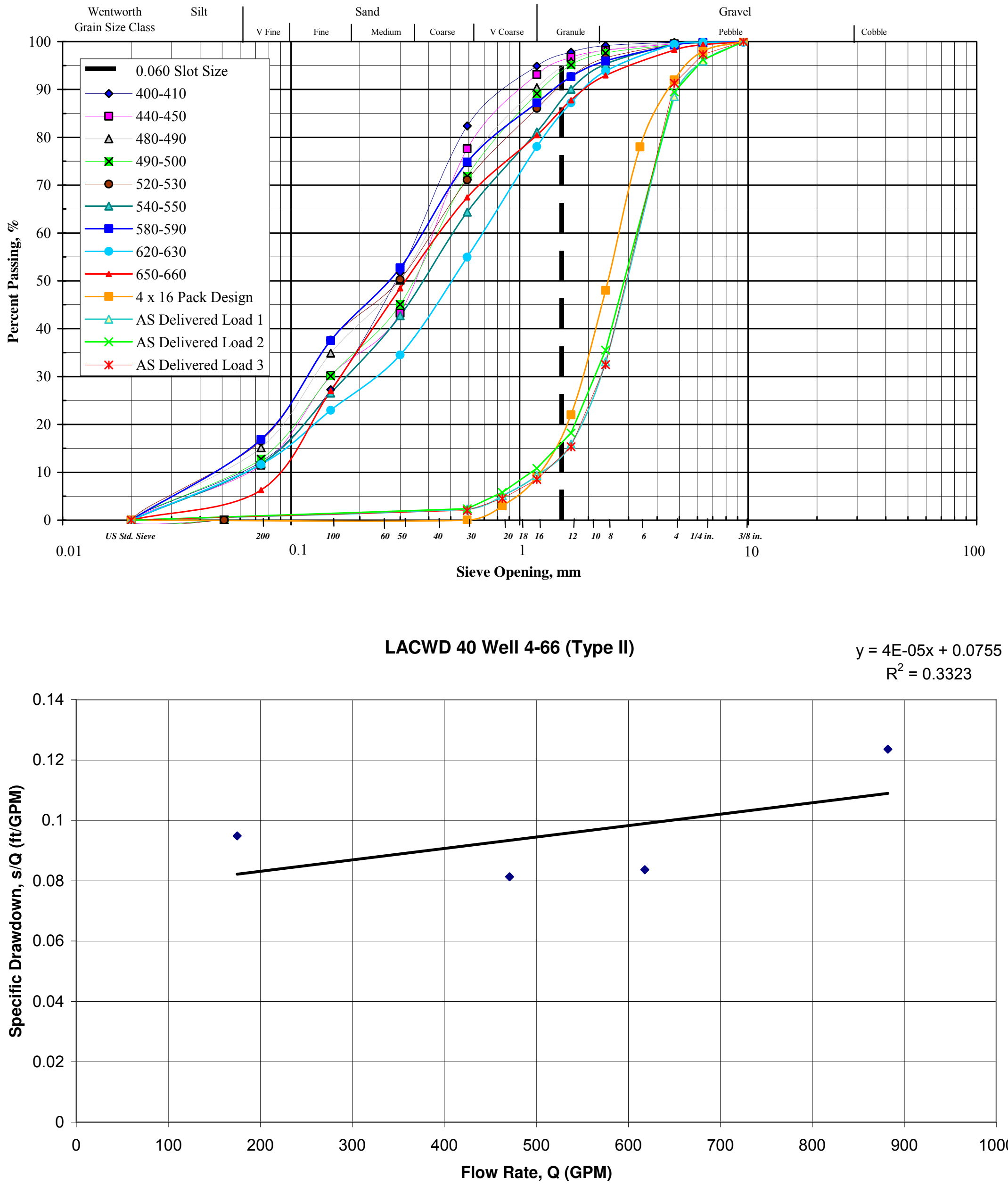
Table 8.5 - Design Criteria LACWD 40 Well 4-68													
Well	Depth	Filer Pack/Aquifer Ratio (D_{50F}/d_{50A})	Terzaghi's Migration Factor (D_{15F}/d_{85A})	Terzaghi's Permeability Factor (D_{15F}/d_{15A})	Uniformity Coefficient, Cu ($d60A/d_{10A}$)	Sorting Factor, Sf (Cu_F/Cu_A)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Critical Radius (in)	Percent Filter Pack Passing Well Slot	Slot Size (in)	Well Diameter (in)	Efficiency
LACWD 40 WELL 4-68 (Medium) Type III	180-190	18.01	1.98	30.07	7.06	0.31	0.08	96	1.62	18.50	0.070	16.000	69.7
	230-240	3.97	1.04	16.50	10.90	0.20	0.38	88	7.37				
	240-250	8.93	1.28	24.64	14.43	0.15	0.17	92	3.27				
	260-270	2.70	0.75	10.11	12.65	0.17	0.56	76	10.82				
	320-330	7.43	0.94	19.86	8.97	0.24	0.20	85	6.57				
	360-370	7.17	1.29	27.91	18.93	0.12	0.21	94	43.12				
	420-430	22.23	5.84	64.85	8.73	0.25	0.07	99	1.31				
	460-470	6.45	1.60	10.48	4.51	0.49	0.23	98	4.53				
	480-490	4.58	0.80	17.84	13.18	0.17	0.33	80	6.39				

A similar well in the same well field had a decrease in efficiency due to a critical radius outside the well bore. The sieve analysis and the development of the well are seen in Figure 8.16 below. From Table 8.6 below we see again the critical radius of 10.9 inches at 620-630 feet. This well had an efficiency of 71%.

Table 8.6 - Design Criteria LACWD 40 Well 4-66													
Well	Depth	Filer Pack/Aquifer Ratio (D_{50F}/d_{50A})	Terzaghi's Migration Factor (D_{15F}/d_{85A})	Terzaghi's Permeability Factor (D_{15F}/d_{15A})	Uniformity Coefficient, Cu ($d60A/d_{10A}$)	Sorting Factor, Sf (Cu_F/Cu_A)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Critical Radius (in)	Percent Filter Pack Passing Well Slot	Slot Size (in)	Well Diameter (in)	Efficiency
LACWD 40 WELL 4-66 Medium) Type I	400-410	10.37	2.33	18.99	7.27	0.37	0.19	97	2.294	17.86	0.060	16.000	71
	440-450	8.62	1.94	18.93	7.47	0.36	0.22	96	2.760				
	480-490	9.94	1.71	21.97	11.33	0.24	0.19	94	2.392				
	490-500	8.70	1.59	19.76	9.63	0.28	0.22	93	2.733				
	520-530	10.05	1.42	26.63	13.47	0.20	0.19	91	0.660				
	540-550	7.83	1.16	18.57	9.80	0.28	0.25	87	0.399				
	580-590	11.18	1.53	27.76	12.60	0.21	0.17	91	2.429				
	620-630	5.85	1.04	17.57	12.80	0.21	0.33	84	10.857				
	650-660	9.34	1.09	16.12	5.38	0.50	0.21	85	2.547				

Three other wells had enough data from spinner surveys to determine flow rates where the critical radius extended into the well bore. All of the wells that experienced this behavior had efficiencies below 70%. The one note to be made on both of the wells above is that over two-thirds of the water produced by the wells comes from the high critical radius zones. In that scenario water quantity is the driving criteria for the water agency in design and operation of their wells.

Figure 8.16 LACWD 40 Well 4-66 Well Development
(Courtesy of Dennis Williams, Geoscience Support Services, Inc., 2008.)



Chapter 9. CONCLUSIONS

The conclusion of this research has lead to many new criteria that an engineer can use to design a well in any given type of aquifers. From development stages to actual well design, the engineer will now have a greater understanding of the relationships that design and development have on a particular well and how ultimately the well owner can dictate a particular well operations based on these design criteria. This research has shown how step drawdown testing can now be used to determine all of the well loss components of a well. It also has shown how critical radius can decrease the efficiency of the well and thus drive up the operation cost of a particular well.

Well development has also been explored, and this research has determined the different stages a well undergoes during development. This research has shown that proper well development between the end of well construction and before pump testing begins is extremely important. Proper well development will ensure that a well is hydraulically developed and producing the highest quantities of sand free water. The well development can be extremely time consuming and thus very costly if not preformed properly. The duration of development can be even longer if the well design is poor.

This research has allowed for laboratory testing of field theories that might damage or destroy a well if tried in the field. It looked at sanding issues and how a filter pack design can either stop the sand invasion into a well or let it completely pass through the filter pack and into the well bore. With the use of the Borescope camera in the well/aquifer model, this research was able to watch what sanding issues would do from the aquifers perspective in a well that has a bad filter pack design.

Well efficiencies were determined for all of the Wire Wrap and Louver well screens which are popular on the market today. The efficiencies for various slot sizes under various pumping conditions are present in Chapter 8.0 above.

Finally all of the field data and the laboratory testing led to a critical water well design criteria given in Table 8.4 above. The average design criteria for the different types of aquifers surveyed are given in Table 9.1 below. This data coincides with the Conclusions made in Table 8.4, and it will give engineers estimates at which their parameters should be close to in designing any given well in the four different types of aquifers.

Table 9.1 - Average Design Criteria for Different Types of Aquifer Surveyed

Aquifer Types	Filer Pack/Aquifer Ratio (D50F/d50A)	Terzaghi's Migration Factor (D15F/d85A)	Terzaghi's Permeability Factor (D15F/d15A)	Uniformity Coefficient, Cu (d60A/d10A)	Sorting Factor, Sf (CuF/CuA)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Percent Filter Pack Passing Well Slot	Slot Size (in)
FINE AQUIFERS	11.20	3.07	21.30	5.72	0.48	0.18	96.70	14.38	0.06
MEDIUM AQUIFERS	8.07	1.57	16.43	7.89	0.48	0.32	87.81	16.16	0.07
COARSE AQUIFERS	6.28	1.24	14.14	8.87	0.33	0.38	83.56	14.96	0.08
VERY COARSE AQUIFERS	2.32	0.50	4.78	7.63	0.36	0.94	55.04	15.51	0.08
DESIGN RECOMMENDATIONS	4 to 10	≤ 5	$4 \le T_p \le 25$	$1.3 \le C_u \le 12$	$0.1 \le S_f \le 1.0$	≤ 2.5	≤ 100%	≤ 25%	0.05 to 0.125

Chapter 10. EXAMPLE OF A WELL DESIGN

10.1. Well Design Outline

There are many aspects that go into the design of a water well and some of which are beyond the scope of this chapter. Many times an engineer has to choose from certain properties that a water agency might have to build a water well and pumping facility which might not be the most favorable spot for the well but none the less the design must still fit the area and well owner's needs. Some important criteria that go into well sighting are;

- Ground water production potential,
- Ground water quality,
- Potential for interference with existing production wells, and
- Ability to comply with Health and Safety and or the Federal requirements.

After a sight has been chosen simple steps can be followed to insure that the well design will produce the highest quantities of sand free water with the best available water quality for that particular site.

Step 1. Drill and install a surface casing to comply with local and state requirements.

Step 2. Drill a pilot bore to target well depth taking formation samples at discrete intervals to be able to determine aquifer layers and depths as well as other geologic interfaces.

Step 3. Conduct a suite of geophysical logs in the completed pilot bore which would include but not limited to;

a. 16-inch and 64-inch normal resistivity with point resistance,
b. Spontaneous potential (SP),
c. Focused guard resistivity (Lateral-log),
d. Acoustic (sonic),
e. Gamma ray,
f. Caliper,
g. Spinner survey.

By comparing the analysis of the formation samples with the geophysical logging, discrete zones can be determined for more quantitative testing.

Step 4. Conduct an aquifer zone test in these most favorable aquifer zones to determine zone flow rates and water quality.

Step 5. Examine the geophysical logs of the pilot bore. Compare these with the sieve analysis of the formation sample taken during drilling. And compare the quality and quantity produced during the zone tests to design the final production well screen.

Step 6. Begin ream of the well to final well diameter.

Step 7. Design well screen and filter pack material.

Step 8. Install well screen and blank casing at total depth. Install filter pack via tremie pipe. Install transition sand and cement seal to surface.

Step 9. Begin pump development and pump testing on the well for a final pump flow rate determination.

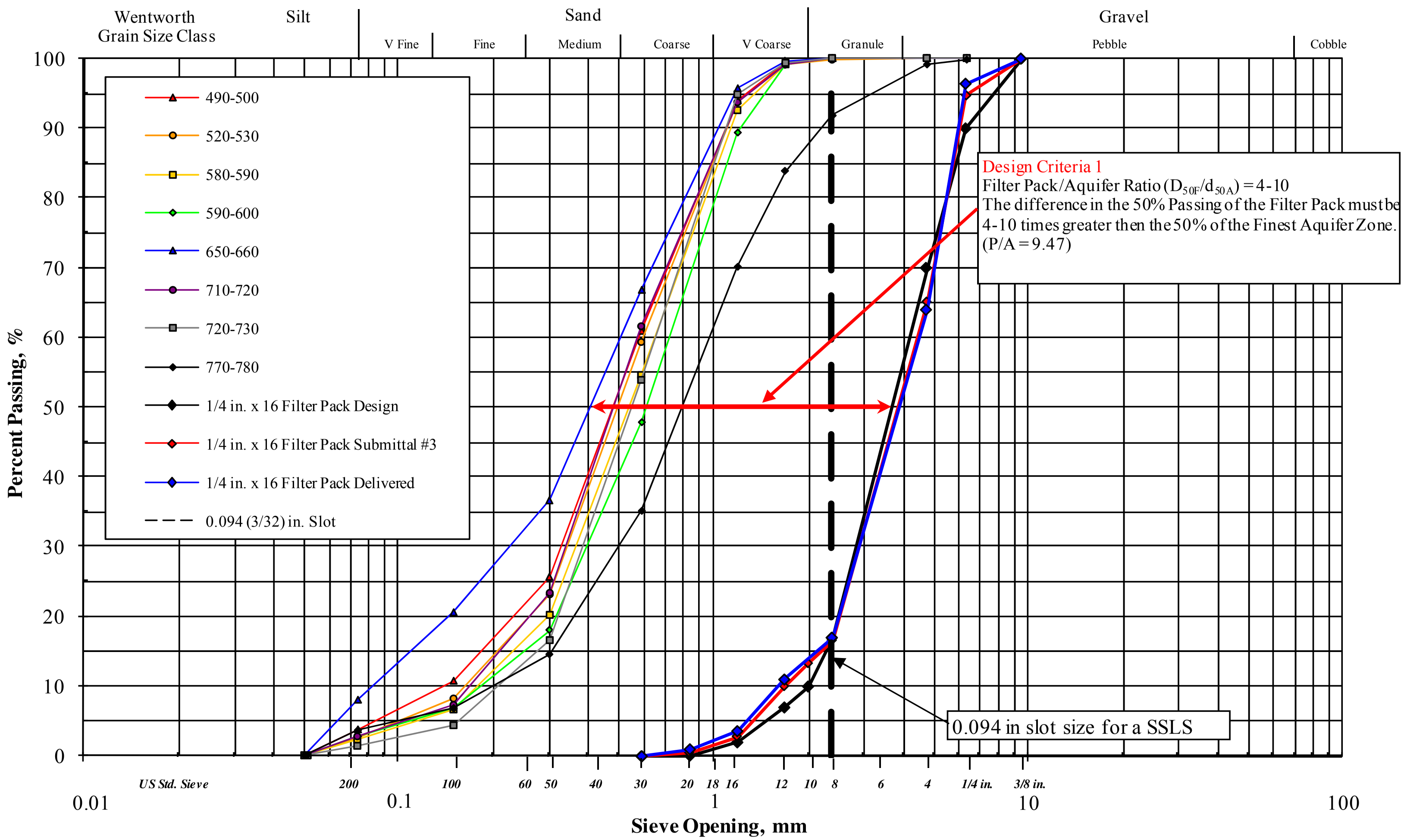
10.2. Example Well Design Steps

Below are the steps taken to design a simple filter pack and well screen for a 1500 GPM in a medium to coarse grained aquifer. It was determined from geophysical logs, zone testing, and formation sample sieve analysis that eight zones from 490 feet below ground surface (bgs) to 790 feet bgs would be sieved and a filter pack design would be based on those zones sampled.

Step 1. Analyze the different filter pack availability to the aquifer zones found. Test all the filter packs versus the aquifers sieved to the Design Criteria found in Chapter 8.

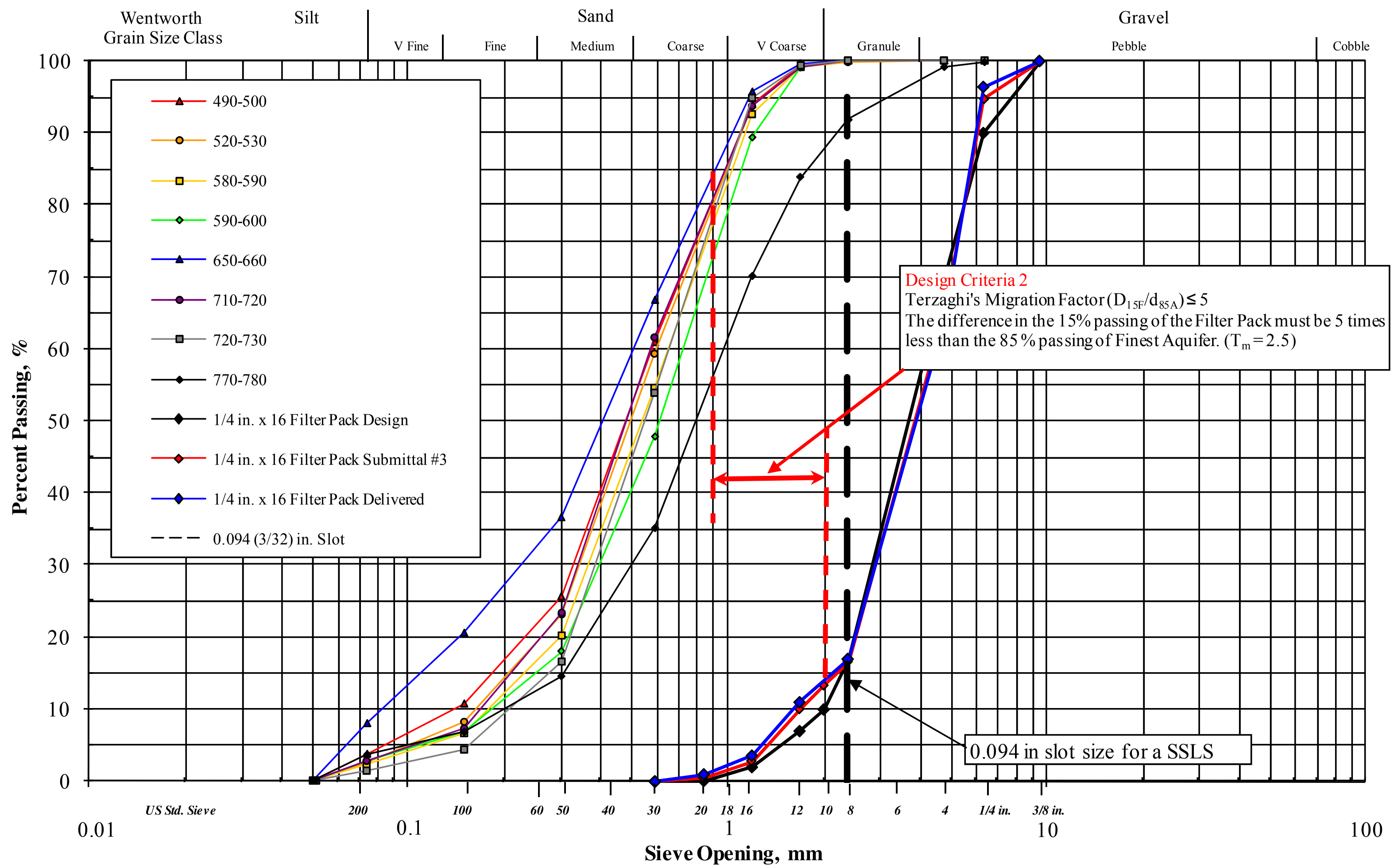
Step 2. The figure below is the First Design Criteria based on the filter pack chosen to fit within the design of the well. The difference in the 50% passing of the Filter Pack must be between 4 and 10 times greater than the 50% of the Finest Aquifer Zone. The Filter Pack/Aquifer Ratio was found to be 9.47.

Figure 10.1- Mechanical Grading Analysis
Critical Design Criteria #1 - Filter Pack/Aquifer Ratio



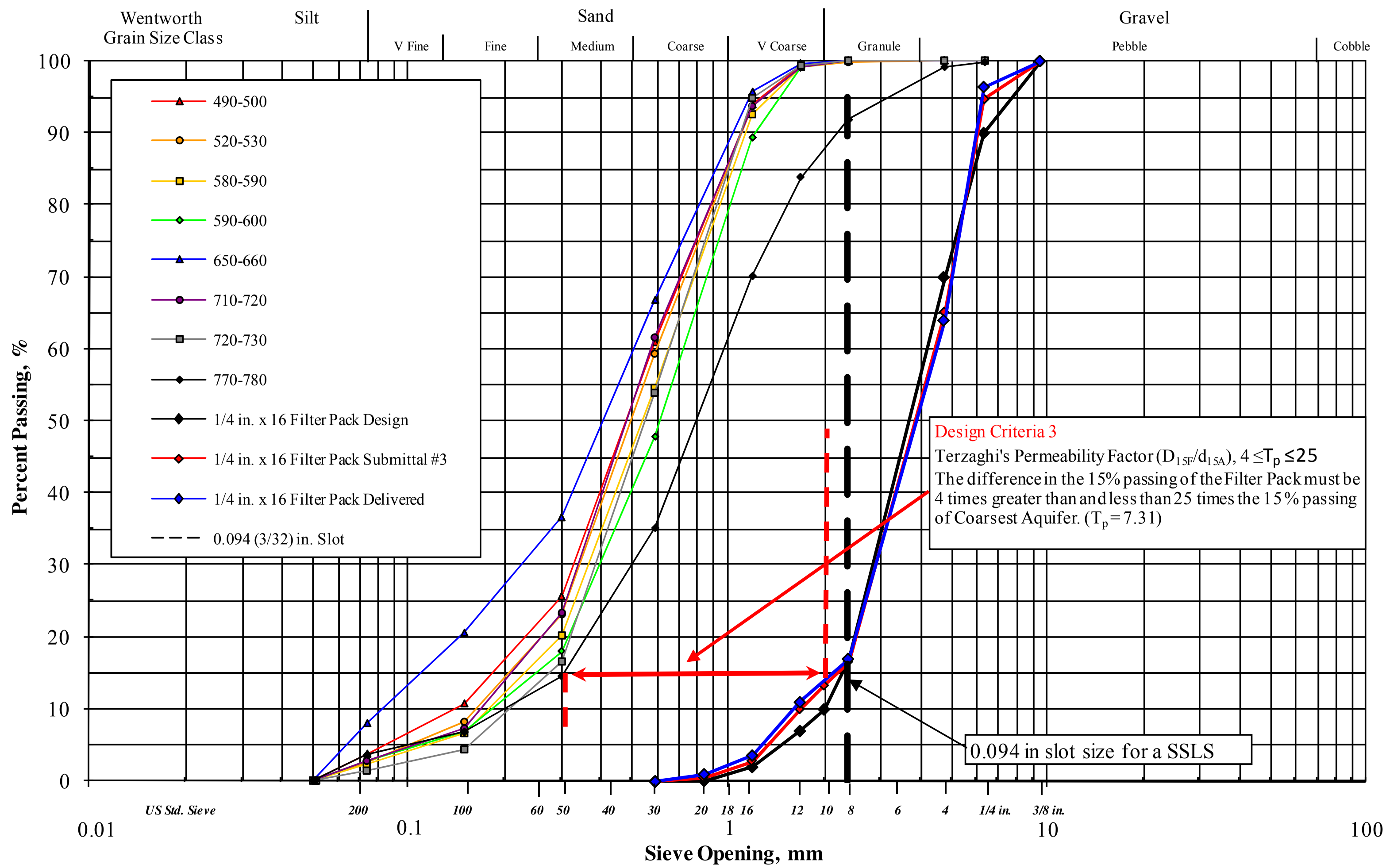
Step 3. The next figure is the Second Design Criteria to be looked at, the Terzaghi's Migration Factor. The difference in the 15% passing of the Filter Pack must be 5 times less than the 85 % passing of Finest Aquifer. The Terzaghi’s Migration factor was found to be 2.5.

Figure 10.2- Mechanical Grading Analysis
Critical Design Criteria #2 - Terzaghi's Migration Factor



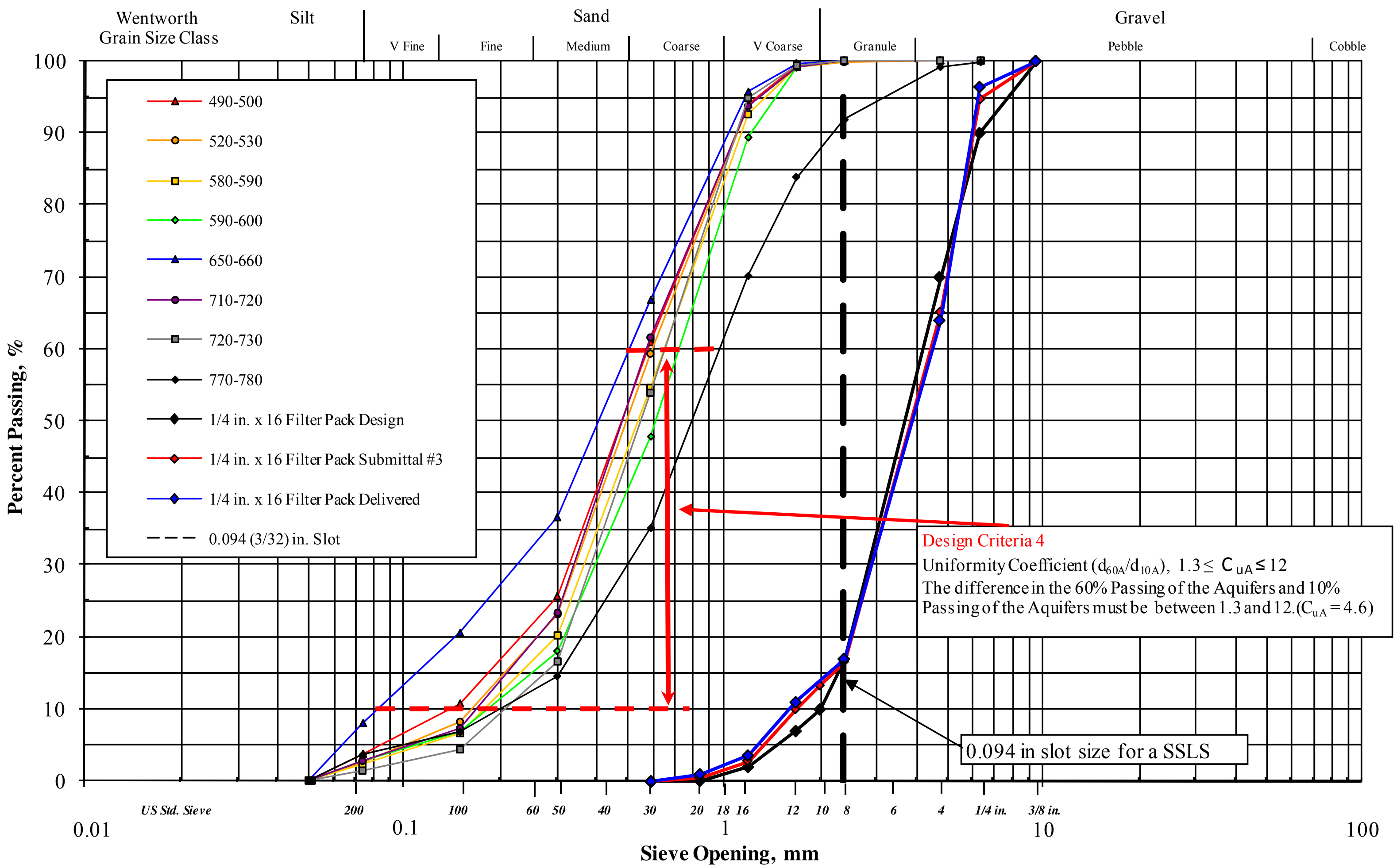
Step 4. The next figure is the Third Design Criteria to be looked at, the Terzaghi's Permeability Factor. The difference in the 15% passing of the Filter Pack must be between 4 and 25 times the 15 % passing of Coarsest Aquifer. The Terzaghi's Permeability factor was 7.31.

Figure 10.3- Mechanical Grading Analysis
Critical Design Criteria #3 - Terzaghi's Permeability Factor



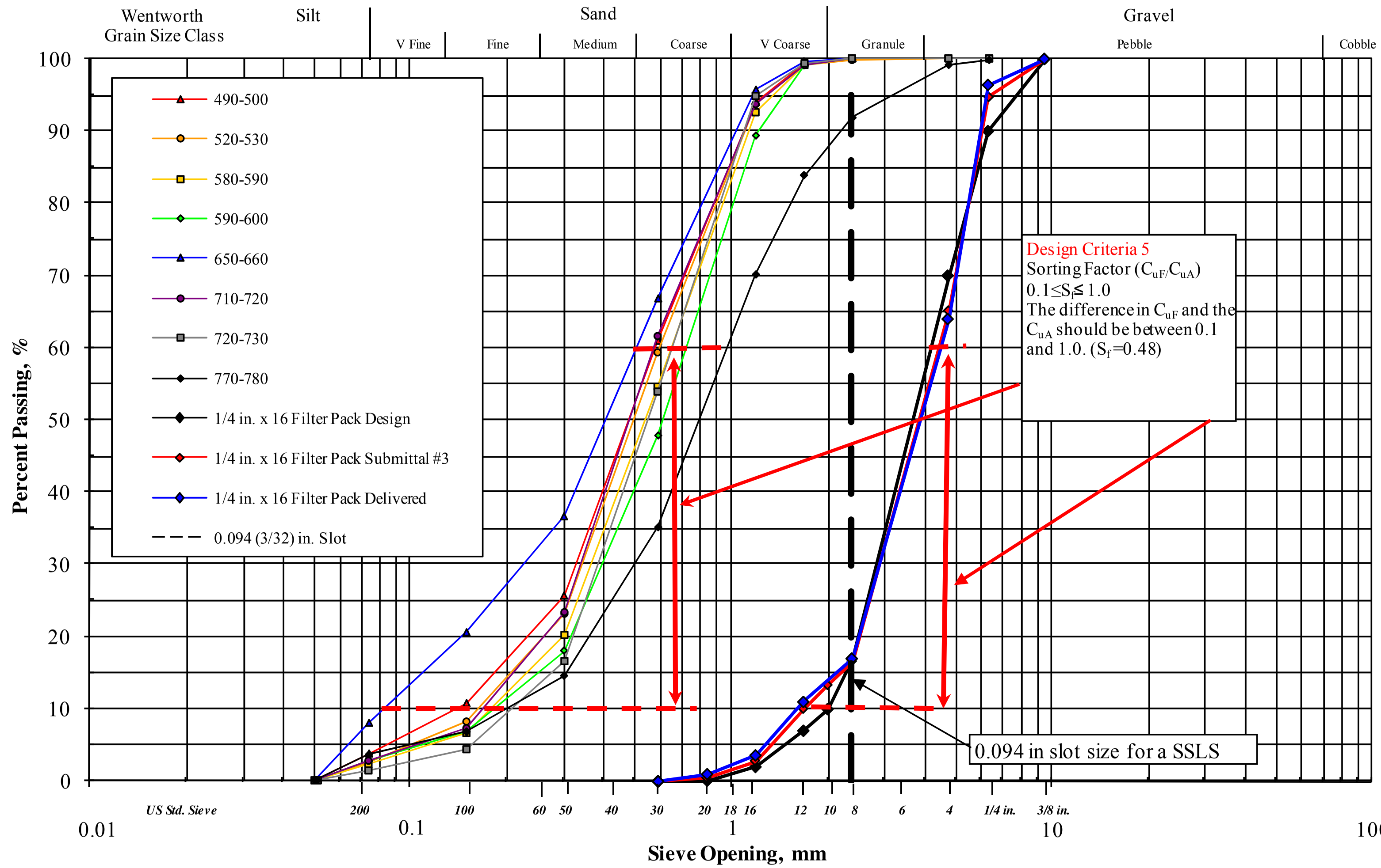
Step 5. The next figure is the Fourth Design Criteria to be looked at, the Uniformity Coefficient. The difference in the 60% Passing of the Aquifers and 10% Passing of the Aquifers must be between 1.3 and 12. The Uniformity Coefficient was found to be 4.6.

Figure 10.4- Mechanical Grading Analysis
Critical Design Criteria #4 - Uniformity Coefficient



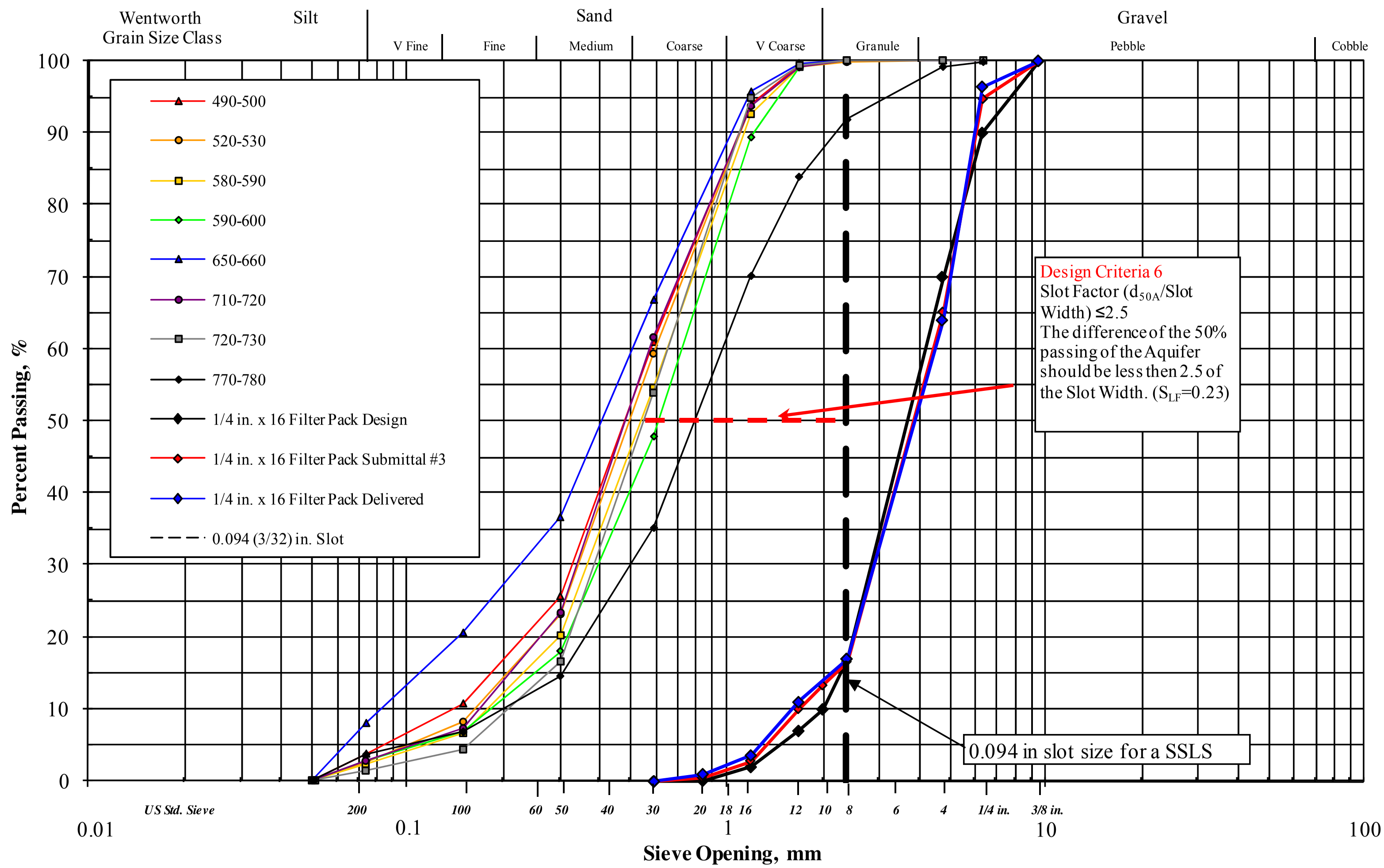
Step 6. The next figure is the Fifth Design Criteria to be looked at, the Sorting Factor. The difference in C_{uF} and the C_{uA} should be between 0.1 and 1.0. The Sorting Factor was found to be 0.48.

Figure 10.5- Mechanical Grading Analysis
Critical Design Criteria #5 - Sorting Factor



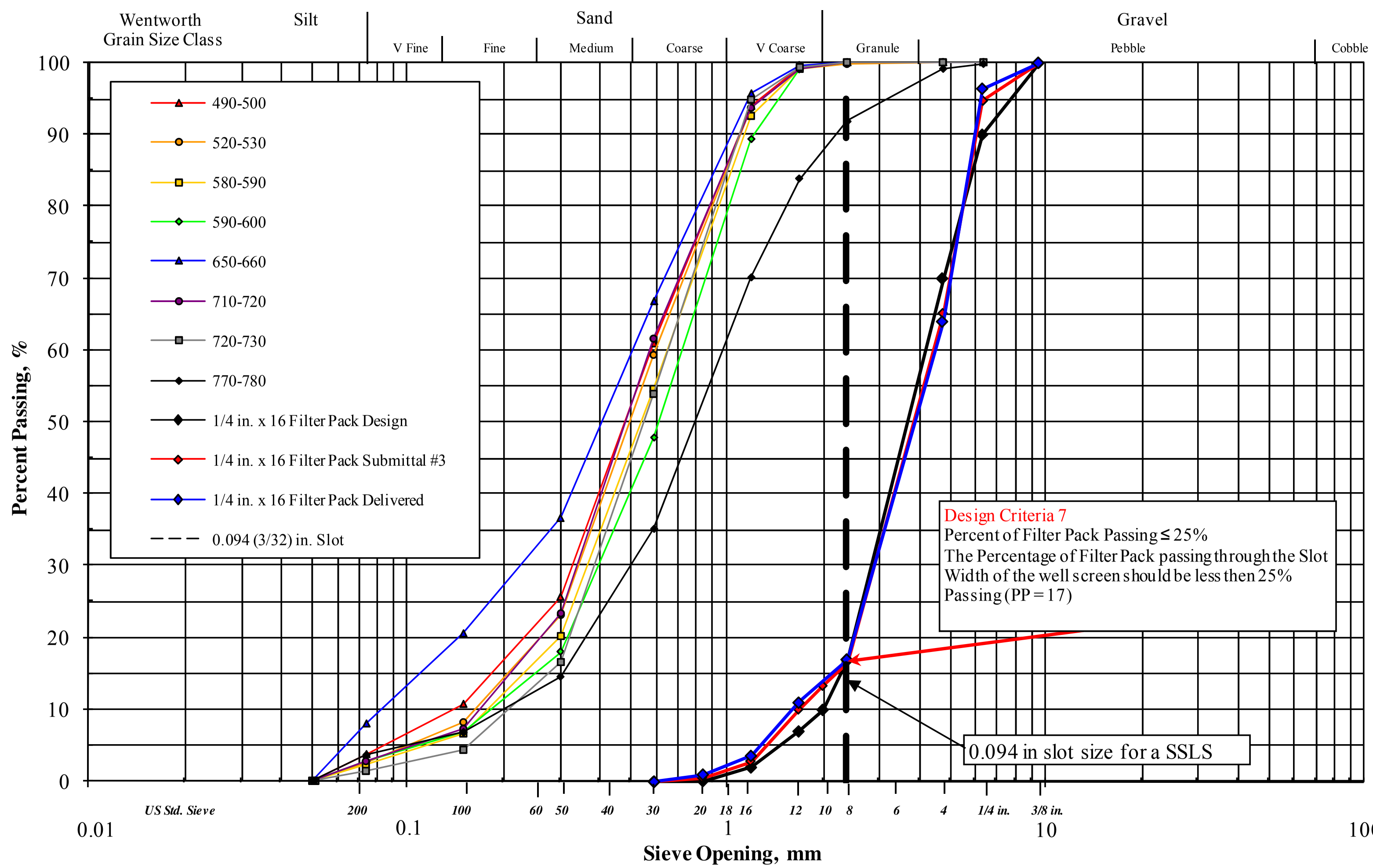
Step 7. The next figure is the Sixth Design Criteria to be looked at, the Slot Factor. The difference of the 50% passing of the Aquifer should be less than 2.5 times the Slot Width. the slot factor was found to be 0.23.

Figure 10.6- Mechanical Grading Analysis
Critical Design Criteria #6 - Slot Factor



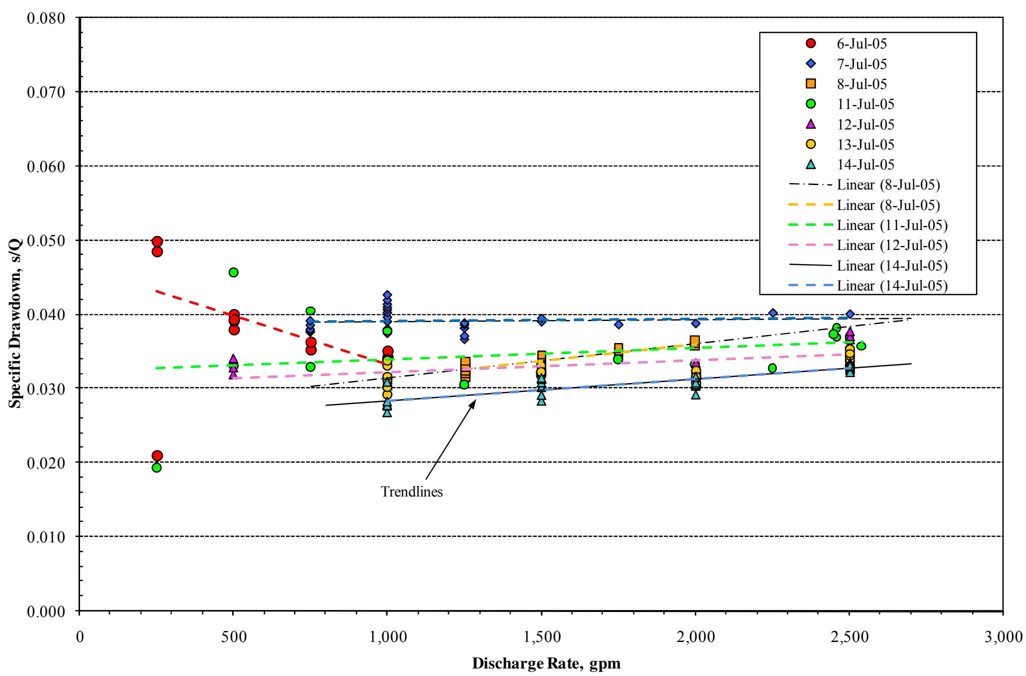
Step 8. The next figure is the Seventh Design Criteria to be looked at, the Percent of Filter Pack Passing. The Percentage of Filter Pack passing through the Slot Width of the well screen should be less than 25% Passing. The Percent of Filter Pack Passing was found to be 17%.

Figure 10.7- Mechanical Grading Analysis
Critical Design Criteria #7 - Percent Filter Pack Passing



Now that the well has been designed and all criteria meet the well can be built. In this case the well was screened from 465 feet bgs to 795 feet bgs. Blank well casing was installed from ground surface to 465 feet bgs, and again from 795 feet bgs to 815 feet bgs. Figure 10.8 below is the pump development that took place on this well over the course of seven days. From this figure we see the well start as a Type 1 development and transition into a Type II and finally into a Type III development.

Figure 10.8
Development for Example Well



The pump testing was then preformed on the example well to establish well and aquifer parameters and to determine a final design pumping rate. Figure 10.9 below is the step drawdown test for the example well. The specific drawdown plot in Figure 10.10 shows that the well is a Type III development with 90 % efficiency at the design flow rate of 1500 GPM.

Figure 10.9
Step Drawdown Test - Example Well

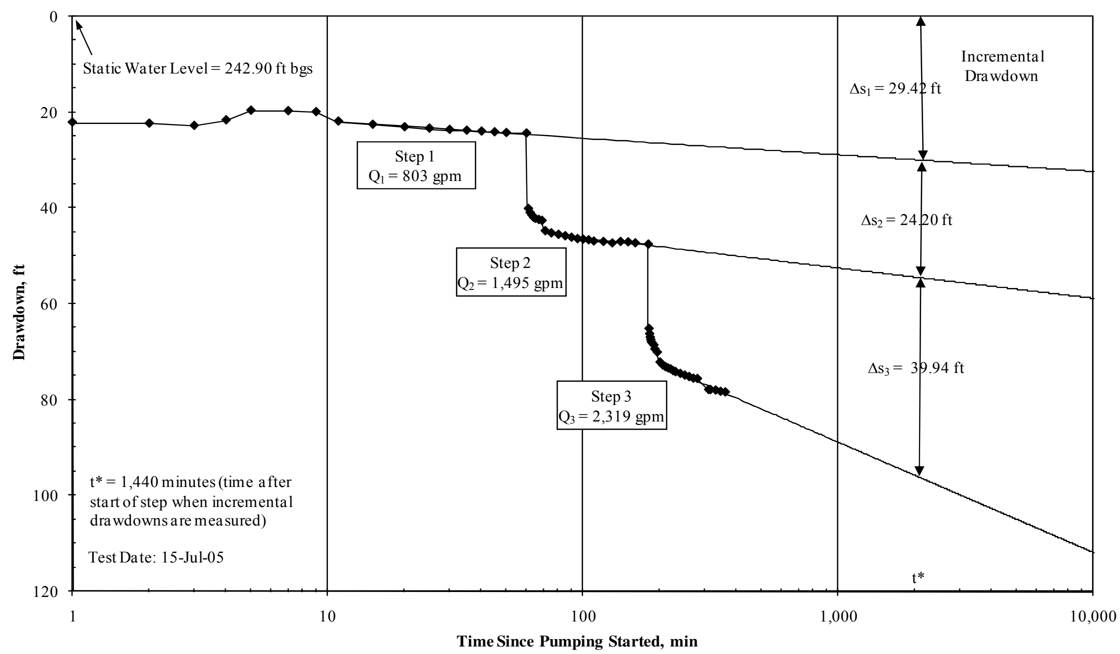
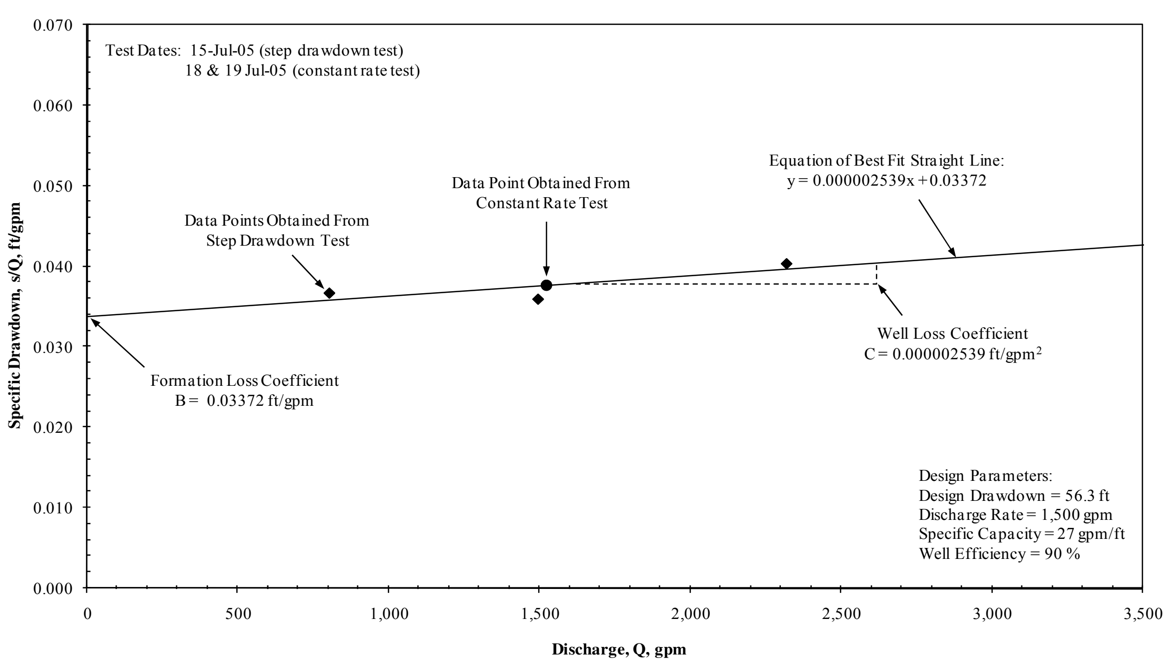


Figure 10.10
Specific Drawdown Graph - Example Well



Finally the last two figures are the flow spinner surveys that show the flow distribution into the well through the various aquifer zones. The Critical Radius is all well inside the well bore at these flow rates and aquifer sizes.

Figure 10.11 - Spinner Survey of Example Well

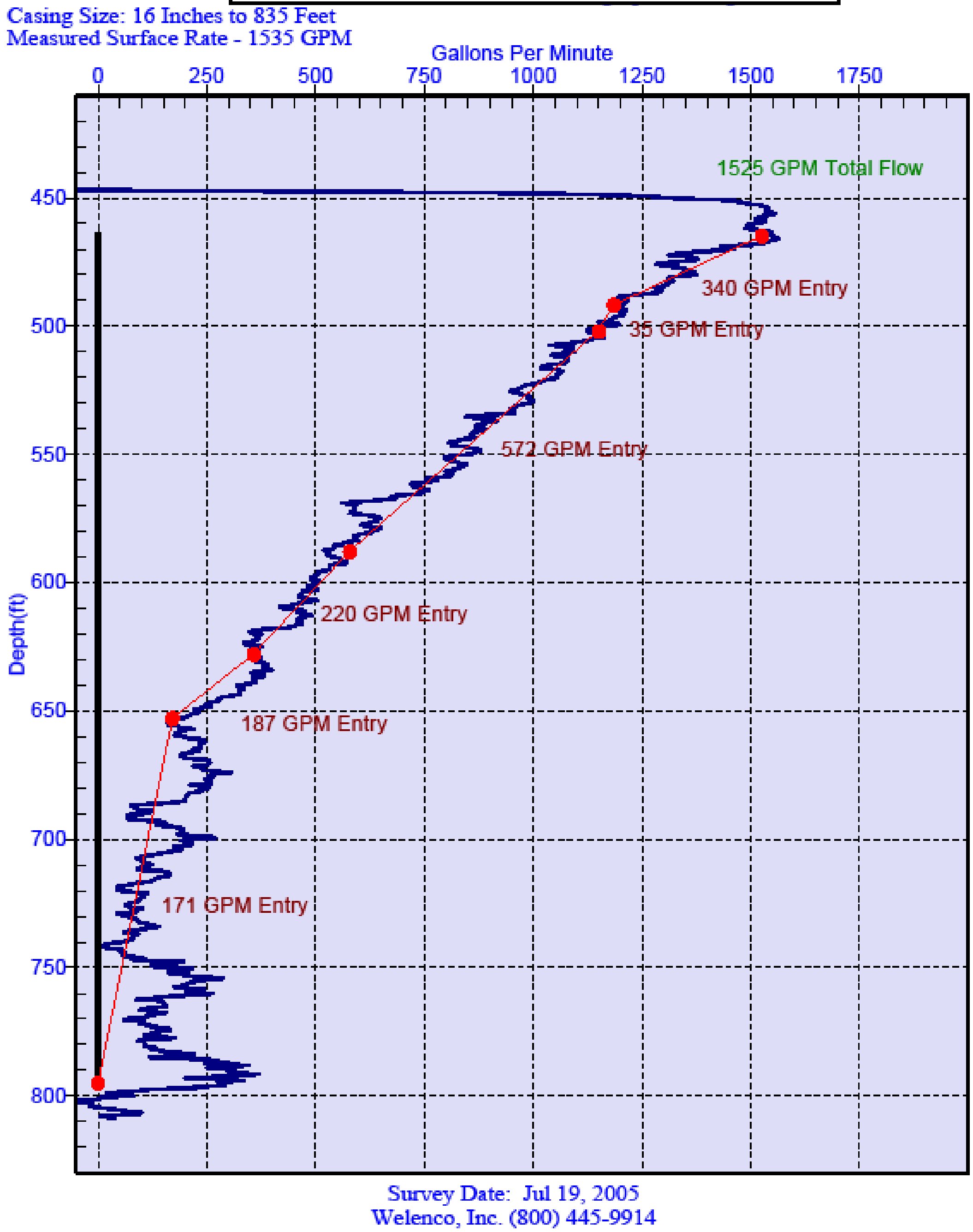
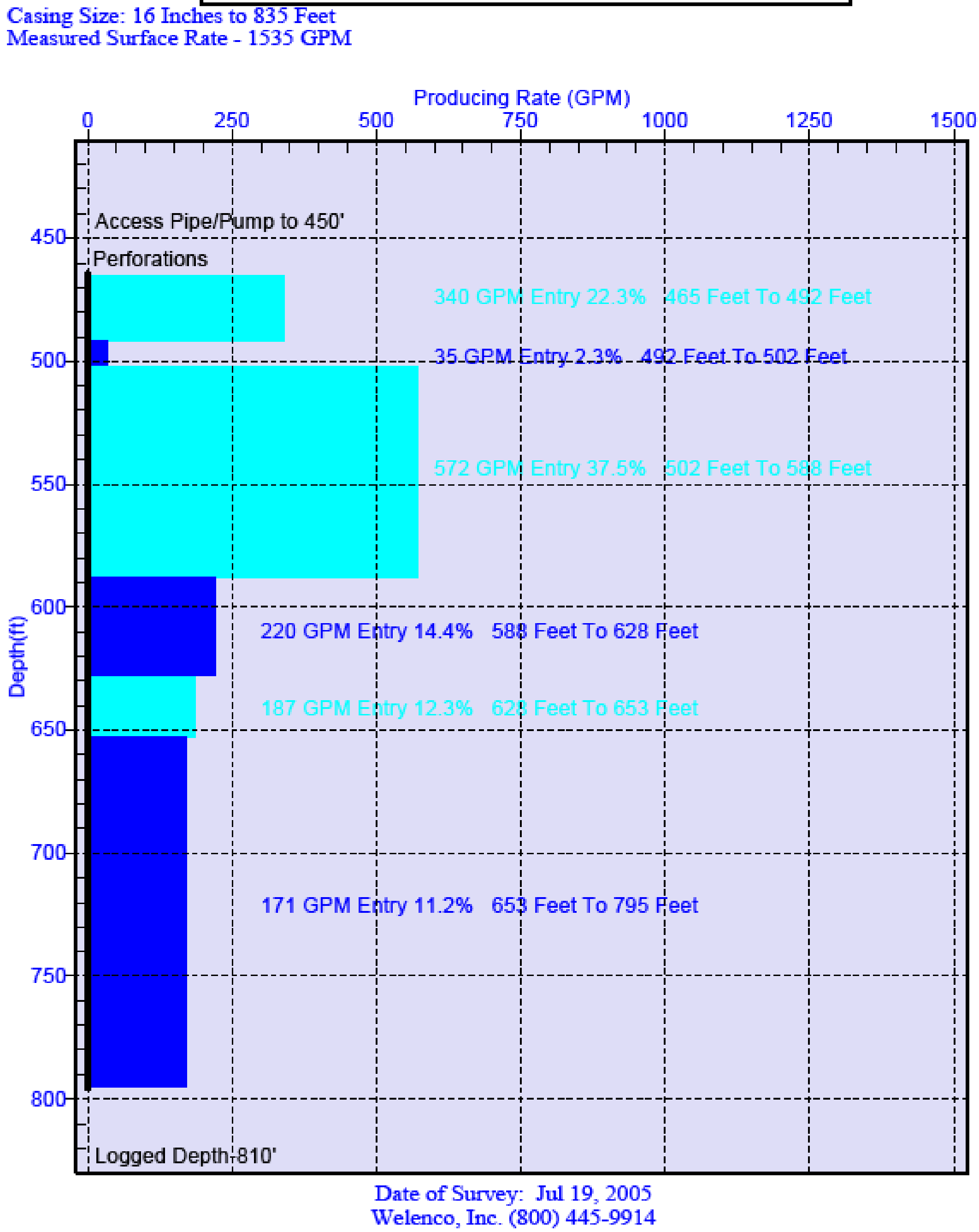


Figure 10.12 – Flow Rate Survey of Example Well



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Appendix 1. Hydraulic Properties of Filter Packs

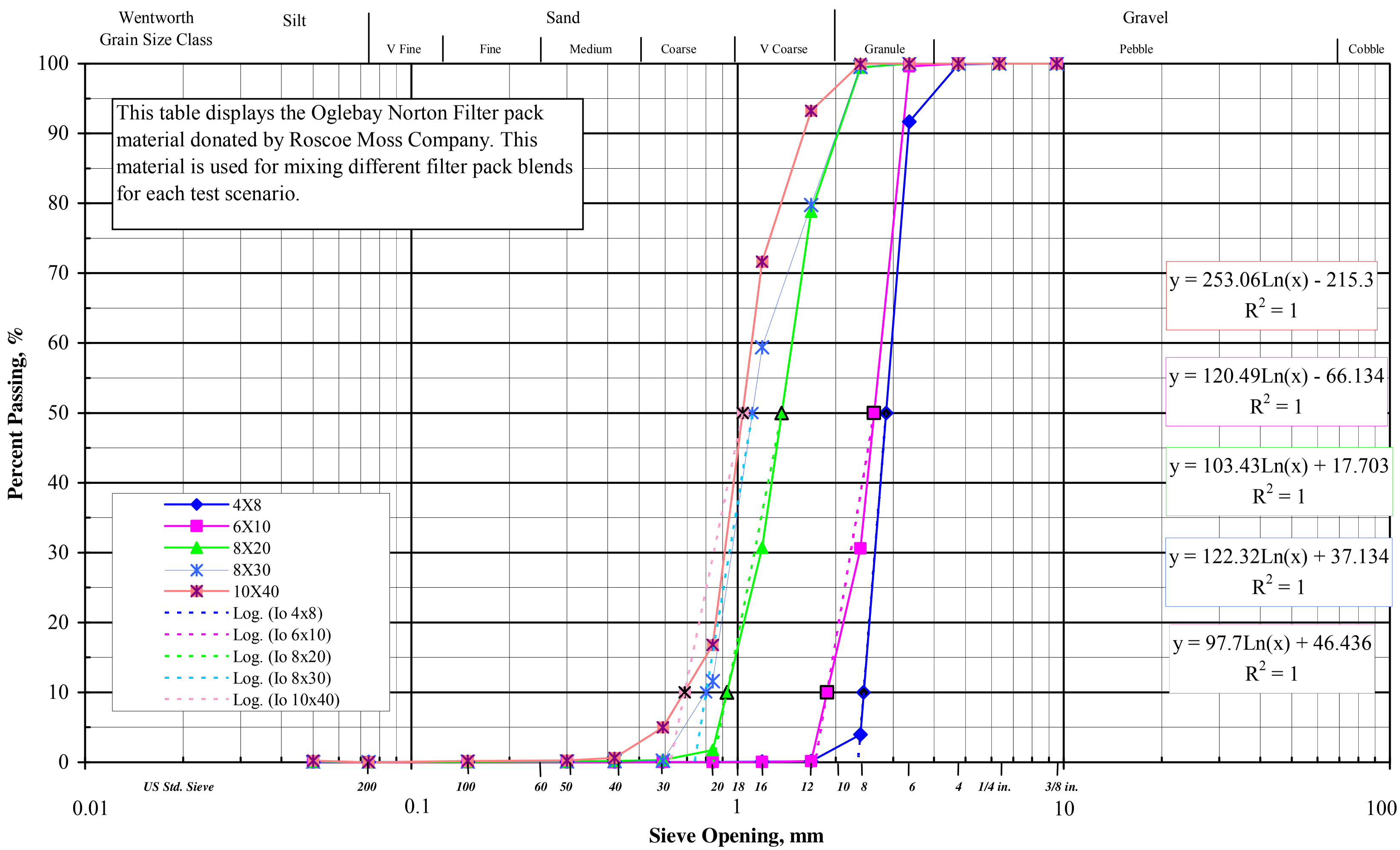
A1.1. Laboratory Filter Packs

It is the object of this Appendix to show a demarcation of the transition between Darcian Flow and Forchheimer Flow or “linear to non-linear” flow in an attempt to measure hydraulic conductivities of many different filter packs available in the lab. All five of the filter packs were tested in a Constant Head Permeameter (CHP) to accurately determine their hydraulic conductivities. These same five filter packs were also put thorough a set of sieves to determine the different percents passing for each filter pack. The results of which are seen in Table A1.1 and Figure A1.1.

TABLE A1.1 - Percents Passing D (mm) for the Given Lab Filter Packs

Lab Material	*D5*	*D10*	*D15*	*D16*	*D20*	*D50*	*D60*	*D84*	*D85*	*D95*
4X8 / Oglebay-Norton	2.39	2.44	2.48	2.49	2.53	2.85	2.97	3.26	3.28	3.87
6X10 / Oglebay-Norton	1.78	1.88	1.99	2.01	2.11	2.62	2.76	3.11	3.13	3.29
8X20 / Oglebay-Norton	0.87	0.93	0.99	1.00	1.05	1.37	1.47	1.84	1.87	2.21
8X30 / Oglebay-Norton	0.69	0.80	0.86	0.87	0.89	1.11	1.20	1.81	1.84	2.20
10X40 / Oglebay-Norton	0.59	0.69	0.80	0.82	0.86	1.04	1.10	1.45	1.47	1.84

FIGURE A1.1 - Mechanical Grading Analysis
USC GEOHYDROLOGY LAB MATERIAL



A1.2. CHP Filter Pack Results

The final step was to determine the hydraulic conductivity for each filter pack with the use of the Constant Head Permeameter, CHP. Figure A1.2 is a photo of the CHP in the lab. The CHP is a 4-inch diameter clear PVC tube, which is 4 feet in length. It has 5 pressure ports, 9 inches apart, which are connected to the Scanivalve for real time data analysis. There is a flow meter and pressure regulator, which control and monitor the CHP. The CHP has a removable top and bottom to allow for the changing of filter material easily and efficiently. The ASTM standard D 2434-68 “Standard Test Method for Permeability of Granular Soils (Constant Head)” was followed in the construction and operation of the CHP.

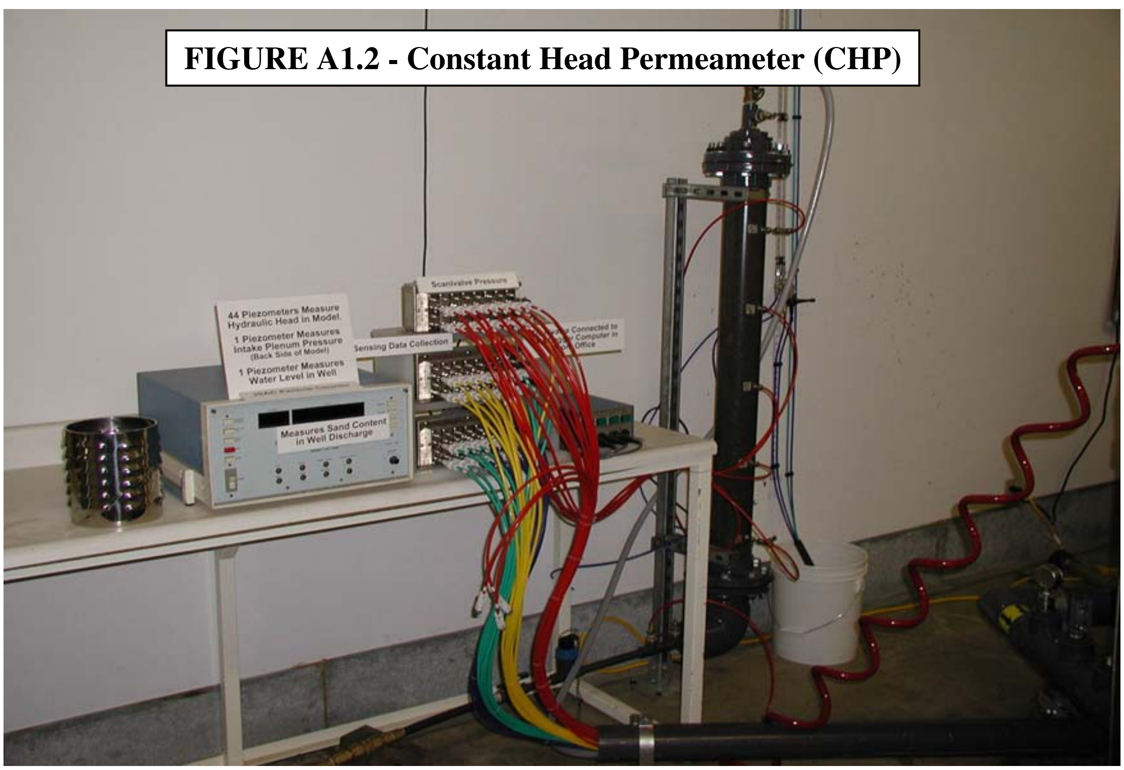


FIGURE A1.2 - Constant Head Permeameter (CHP)

The CHP was run at different flow rates in which the pressure differentials were recorded. The pressure difference (change in head) are plotted along with flow rate as to determine the hydraulic conductivity of the sample using Darcy's Equation above. An example of this can be found on Figure A1.3. The lab filter packs have been ran through the CHP and the results are seen in the Table A1.2. Also plotted are the hydraulic gradient versus the flow velocity to obtain hydraulic conductivities in Figure A1.4. These correlate very well to the results in Figure A1.4 and Table A1.2.

TABLE A1.2 - Hydraulic Conductivity [gpd/ft^2]

Lab Material	Lab Permeameter
4X8 / Oglebay-Norton	73,354
6X10 / Oglebay-Norton	50,216
8X20 / Oglebay-Norton	18,529
8X30 / Oglebay-Norton	9,126
10X40 / Oglebay-Norton	7,478
Coarse Aquifer (RMC Model Media)	47,603
Santa Ana River	716

Often times looking at the hydraulic gradient vs. flow velocity is the easiest way to determine the hydraulic conductivity of a certain material. Figure A1.4 gives a similar hydraulic conductivity for the filter pack shown. All of the filter packs, aquifer material and some local river bottoms were sieved and ran through the CHP to determine their hydraulic conductivities. Therefore by using Table A1.1 and the sieve analysis of Lab material, any Reynolds's number can be calculated for any given velocity. This will be applied latter to the actual Well/Aquifer Model and the flow regimes within the model itself. Any filter pack then added to the Model will have an upper bound of laminar flow independent of the well screen type or slot size used. The transition from laminar to Forchheimer flow and then to turbulent flow can be predetermined for a given flow rate before any testing in the model itself is even accomplished.

FIGURE A1.3 - Measured Permeameter Discharge vs. Change in Head Across Permeameter
Constant Head Permeameter 8x20 Material Test

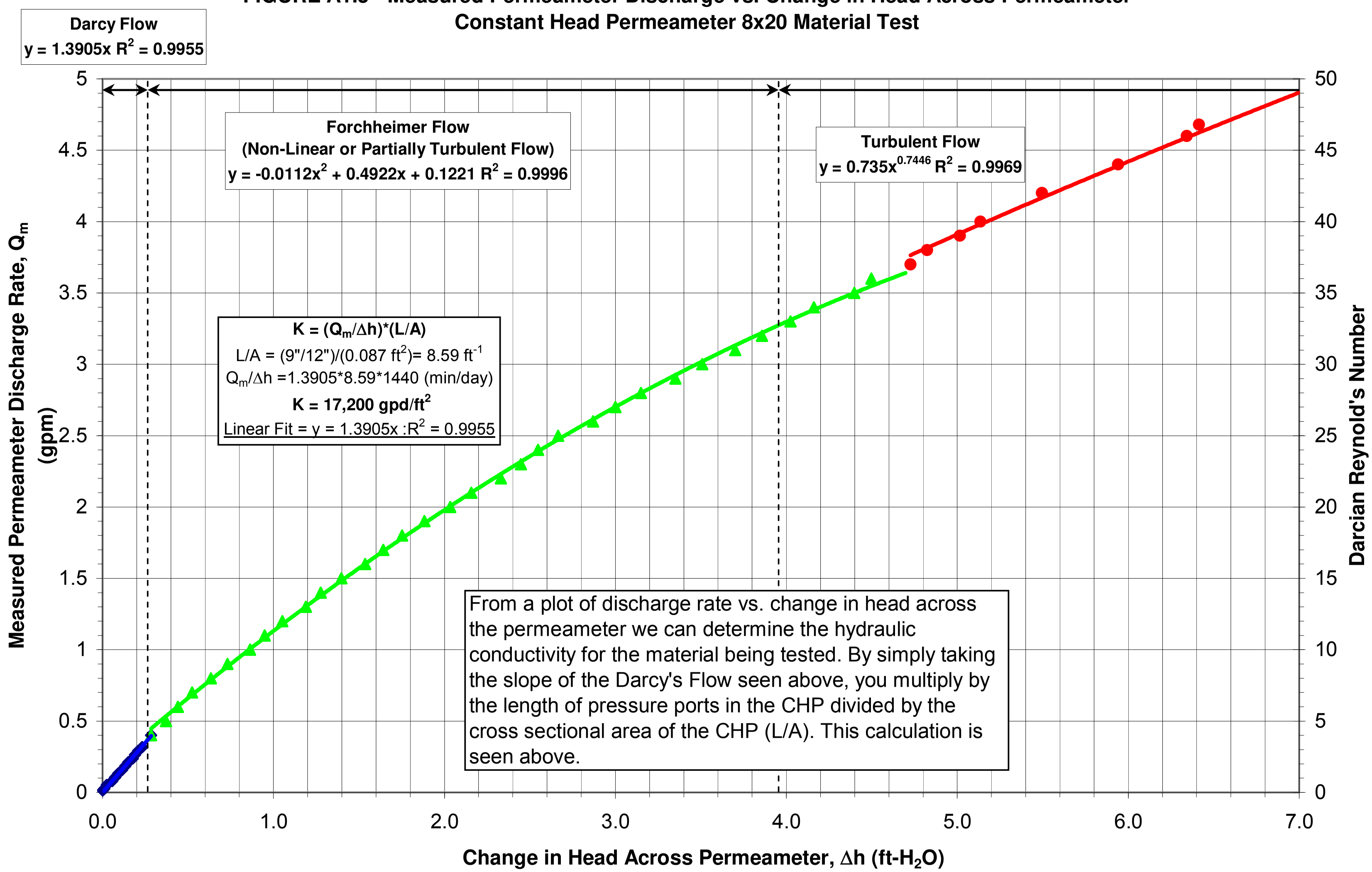
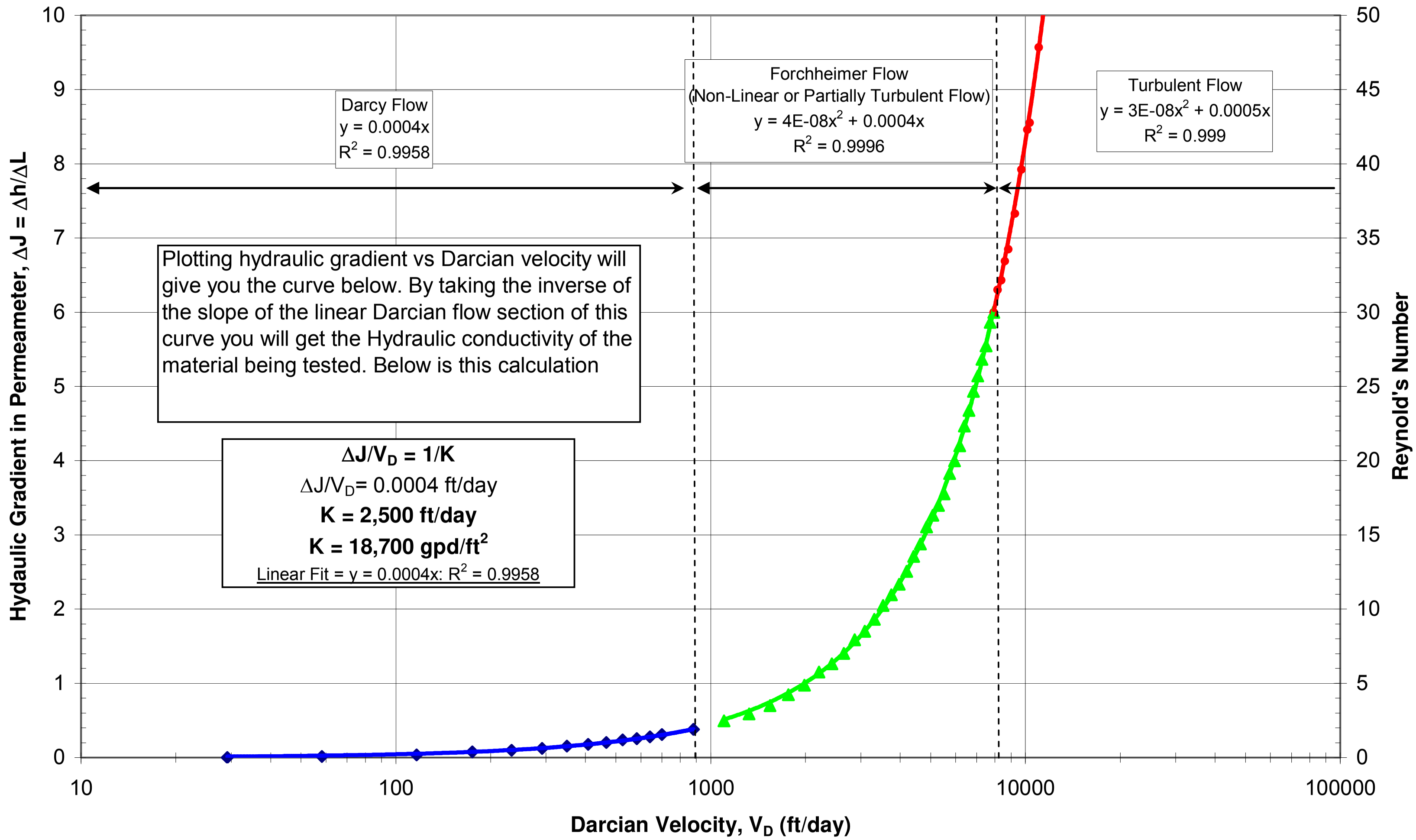


FIGURE A1.4 - Hydraulic Gradient vs. Darcian Velocity
8x20 Material Test



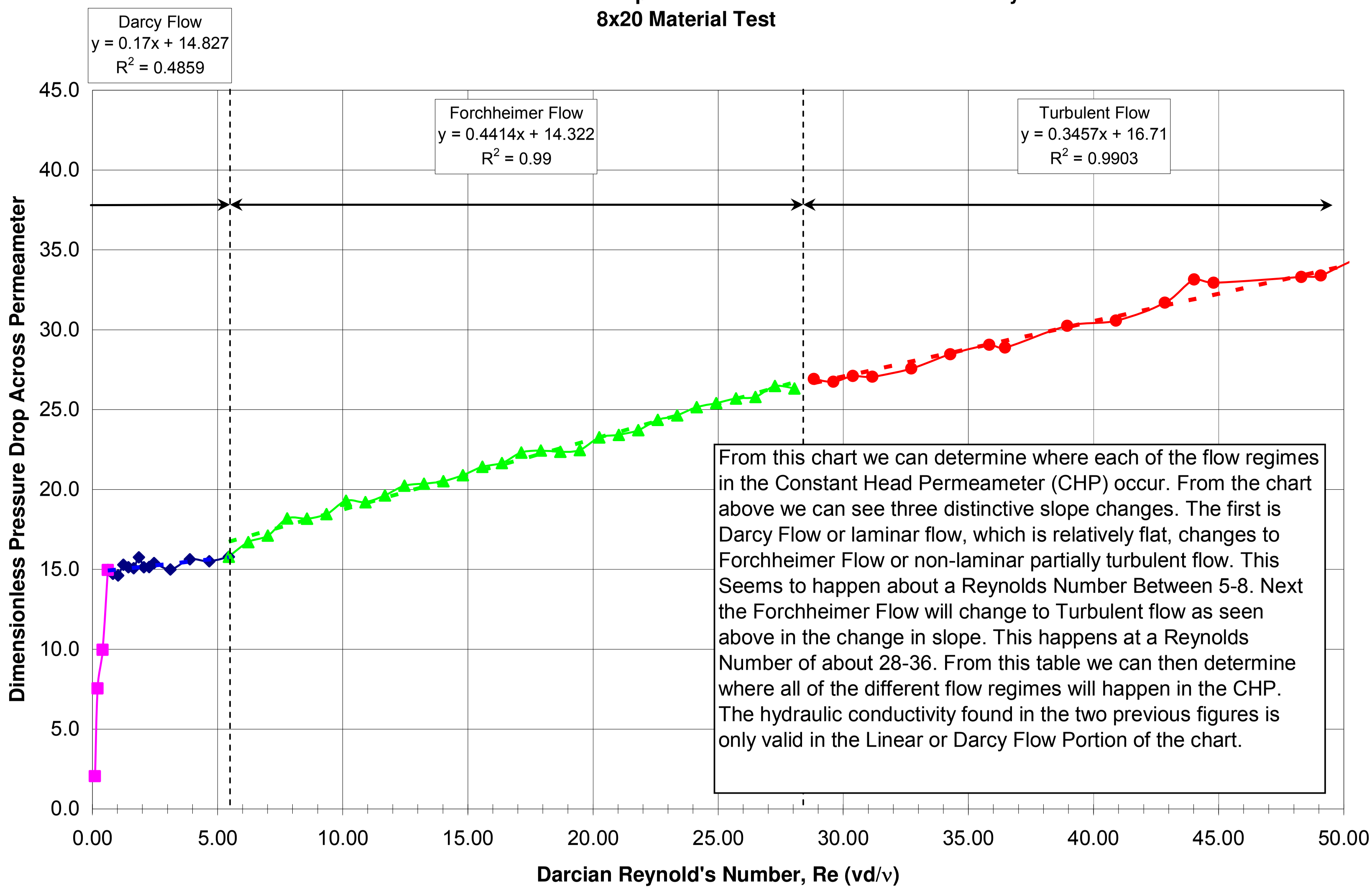
A1.3. Limits of Testing Procedure

To find the limits of the CHP testing procedure one must determine when Darcy's Law is no longer valid. Following similar procedure as Kececioglu (1994) and Ergun (1952), by plotting a dimensionless pressure drop of hydraulic gradient vs. Darcian Reynolds Number one will establish different flow regimes. Figures A1.5 clearly establishes a demarcation as to where Darcy's Law was applicable and thus a correct Hydraulic Conductivity would be calculated and where laminar conditions no longer existed and could not be included into the Darcy calculations for hydraulic conductivity. Figure A1.5 has three distinctive changes in slope from Darcy Flow (Laminar Flow), to Forchheimer Flow (Partially Turbulent), and to Fully Turbulent Flow.

A1.4. Results

The results of the testing using the CHP revealed two important factors in porous media. The first is that the materials hydraulic conductivity can only be calculated using Darcy's Law if and only if flow remains in a laminar state. Presented above are ways to calculate those demarcations of flow regime. The second main revelation was that the material tested in the lab had similar flow demarcations to Bear (1972), Fand (1987), and Kececioglu (1994). It was found that the validity for Darcy's Law had a Reynolds's Number between 0.5 and 5 to 8, and Forchheimer Flow was found between 8 and 28 to 36 depending on the material tested. The ability to test different aquifers and filter packs will aid in determining the aquifer loss terms and the filter pack terms described in Chapter 3.

FIGURE A1.5 - Dimensionless Pressure Drop Across Permeameter vs. Darcian Reynold's Number
8x20 Material Test



Appendix 2. Grain Size Distribution

Many studies have tried to characterize hydraulic conductivity by grain size distribution models. It has been found in these studies that one method over estimates a certain material while another method underestimates that same material. The reasons for this are discussed below. This Appendix uses these predictive models in a comparison to the results in Appendix 1 to show that the hydraulic conductivities found using a CHP are accurately correlated with several predictive grain size distribution models and thus valid. The engineer that uses one method over another must realize as to which method he or she is using and why. And to note that the method might over or under estimates their samples hydraulic conductivity.

A2.1. Introduction

Determining the hydraulic conductivity (K) of a porous media in a Permeameter is often not available to engineers. Often engineers only have sieve analysis for a given porous media of which they have to make a determination of hydraulic conductivity. There is no one easy method that is perfect for determining hydraulic conductivity for all types of porous media.

A2.2. Background

A large amount of effort has been made in determining hydraulic conductivity for any given porous media from just sieve analysis. Many semi-empirical methods have been determined by various authors in the past. In Appendix 1, hydraulic conductivity was found for the different filter packs available in the lab by the use of a Constant Head Permeameter (CHP). One of the first to formulate a relation between a characteristic length and hydraulic conductivity was Hazen (1892). Hazen determined that hydraulic conductivity could be expressed as a constant multiplied by the diameter of the media at ten percent passing squared.

$$K = Cd_{10}^2 \tag{A2-1}$$

K = Hydraulic Conductivity (cm/s or ft/s, Meinzer Units gpd/ft^2),

d_{10} = Particle diameter or characteristic length of a given material at ten percent passing (m or ft),

C = Dimensionless constant

Bear (1972) found that C has a range from 45 for clayey sands to 140 for pure sand. Bedinger (1961) empirically found C to be 2000. Others in more recent times use the method of thin sections to take microscopic slices of a given sample and use computer generated simulations to develop a network of pore throats and bodies to determine the hydraulic conductivity of a given media. Whatever the method might be, engineers have many alternatives to determine the hydraulic conductivity for any given media.

A2.3. Kozeny-Carman Equation

One of the most widely used equations for determining hydraulic conductivity from characteristic lengths is the Kozeny-Carman Equation. Kozeny proposed in 1927 and was later modified by Carman in 1956 a method for determining hydraulic conductivity from the following;

$$K = \left(\frac{\rho_w g}{\mu}\right)\left[\frac{\phi^3}{(1-\phi)^2}\right]\left(\frac{d_m^2}{180}\right) \quad \text{(A2-2)}$$

ρ_ω = Fluid density (kg/m^3 or ft/s^2),

d_m = Particle diameter or characteristic length of a given material (m or ft),

ϕ = Porosity

μ = Dynamic viscosity (Pa-s or lbs-s/ft^2)

g = Gravitational constant (m/s^2 or ft/s^2)

A2.4. Krumbein-Monk Equation

Krumbein and Monk (1942) described hydraulic conductivity in the form of darcies for unconsolidated sands with a lognormal grain-size distribution. Using this they used a semi empirical equation assuming forty percent porosity;

$$K = \left(760 d_w^2\right)\exp\left(-1.31\sigma_\psi\right) \quad \text{(A2-3)}$$

d_w = Geometric mean particle diameter by weight (mm or in),

σ_ψ = Standard Deviation of the ψ distribution function (mm or in)

The introduction of ψ converts the lognormal distribution function for particle diameters into a normal distribution function.

A2.5. Masch Denny

Masch and Denny in 1966 used a median grain size distribution as the characteristic length in determining a porous media's hydraulic conductivity. They did this with the intent to correlate permeability with grain size for a given media. Masch and Denny used a method of graphical statistics to statistically determine the parameters necessary to obtain a hydraulic conductivity from a mean diameter of a porous media versus its dispersion. They described the dispersion for a porous media as follows;

$$\sigma_I = \left(\frac{\phi_{84} - \phi_{16}}{4}\right) + \left(\frac{\phi_{95} - \phi_5}{6.6}\right) \qquad \text{(A2-4)}$$

ϕ = Grain size diameters expressed as the negative logarithm to the base two of the particle diameter.

σ_I = Geometric Standard Deviation

From those two parameters they developed graphs as to interpolate between different dispersion curves and grain diameters to determine hydraulic conductivities for a given porous media.

A2.6. Shepherd Equation

Shepherd in 1989 performed a similar method to Masch-Denny utilizing statistical regression on 19 sets of published data on hydraulic conductivity versus grain sizes using a simple power equation.

$$K = ad^b \tag{A2-5}$$

a,b = Empirical parameters.

d = Particle grain diameter (mm, in)

According to Shepherds findings, values for the coefficient "***a***" range from 1,014 gpd/ft^2 for river alluvium to 208,808 gpd/ft^2 for glass spheres. The values of the coefficient "***b***" were found to be 1.11 to 2.05 with an average of 1.72. Shepherd like Masch-Denny interpolates data from a plot of grain size versus different curves of different classifications of materials in an effort to determine hydraulic conductivity. The interesting difference between Shepherd and Masch-Denny is that Shepherd allows for more classification of materials from a depositional environment and thus takes into consideration the grain sizes and the degree of textural maturity.

A2.7. Alyamani and Sen Equation

Alyamani and Sen developed a different method for determining hydraulic conductivity in 1993 based on empirical data from 32 samples from Saudi Arabia and Australia. They incorporated the initial slope of the grain size distribution curve in determining hydraulic conductivity.

$$K = 1300\left[I_o + 0.025\left(d_{50} - d_{10}\right)\right]^2 \quad \text{(A2-6)}$$

I_o = X-intercept of the line formed from d_{50} and d_{10}

d = Particle grain diameter (mm, in)

In general I_o is very close to d_{10} thus it could be said that Alyamani and Sen Equation is very similar to Hazen Equation in that hydraulic conductivity is proportional to d_{10}. Alyamani and Sen have just furthered the Hazen Equation by including the dispersion of grain size into their approximation.

A2.8. Lab Material

All of the filter packs in the lab were sieved and are seen in Figure A1.1. From the sieve analysis on the lab material all of the proper percents passing were calculated and put into the various methods described above as to determine their hydraulic conductivities. The results of the testing are found in Table A2.1 below. In Table A2.1, the hydraulic conductivities found experimentally in Appendix 1 using a CHP are shown in comparison to the different empirical methods mentioned above. Many of the methods either over estimate or under estimate the hydraulic conductivity. There can be several orders of magnitude difference between one method versus another. For example, Masch-Denny and Bedinger are very similar for all the filter packs used. These two methods seem to underestimate the hydraulic conductivity found from the CHP testing. While Krumbein & Monk as well as Hazen and Shepherd predict the hydraulic conductivity values rather well compared to the CHP experimental values. Kozeny-Carman and Alymani & Sen both seem to overestimate the hydraulic conductivity values compare to the experimental values.

TABLE A2.1 - Hydraulic Conductivity [gpd/ft^2]								
Lab Material	Lab Permeameter (2002)	Masch-Denny (1966)	Hazen Approximation (1892)	Bedinger Approximation (1961)	Krumbein & Monk (1943)	Shepherd (1989)	Kozeny-Carman (1927,1956)	Alyamani & Sen (1993)
4X8 / Oglebay-Norton	73,354	17,000	125,807	16,279	86,371	75,155	170,058	176,178
6X10 / Oglebay-Norton	50,216	9,800	75,031	13,748	61,032	53,501	143,613	97,521
8X20 / Oglebay-Norton	18,529	3,500	18,269	3,735	14,655	15,448	34,986	23,209
8X30 / Oglebay-Norton	9,126	2,300	13,606	2,468	10,165	9,596	23,121	17,721
10X40 / Oglebay-Norton	7,478	2,100	10,057	2,151	8,805	8,252	20,153	12,658

A2.9. Other Materials

The filter packs tested above were very similar in that there was very little distribution of various diameters. The filter packs are said to very well sorted and thus have small correlation coefficients varying from 1.2 to 1.6. It was then decided to test more of a natural material and an example completely made up. These two new materials have one thing in common; they are poorly sorted and have a correlation coefficient of 2.63 and

8.83. The first natural occurring material was taken from the Santa Ana River bottom. The second was a constructed example was from Batu (1998). The sieve analysis along with the aquifer material in the RMC model in the lab can be seen in Figure A2.1 below. The coarse aquifer material has a well sorted distribution with a correlation coefficient of 2.27. It can be seen that once again Masch-Denny and Bedinger are very similar for three tests below in underestimating the hydraulic conductivity. While Krumbein & Monk as well as Hazen and Shepherd predict the hydraulic conductivity values rather well compared to the CHP experimental values. Kozeny-Carman and Alymani & Sen still seem to overestimate the hydraulic conductivity values compared to the experimental values. In general it can be taken from this that the hydraulic conductivity values established in Appendix 1 by the use of the CHP are well within reason to results found from grain size distribution models. Results of the Santa Ana River sand and Batu's example are seen in Table A2.2 below.

FIGURE A2.1 - Mechanical Grading Analysis
Santa Ana River & Coarse Aquifer Material

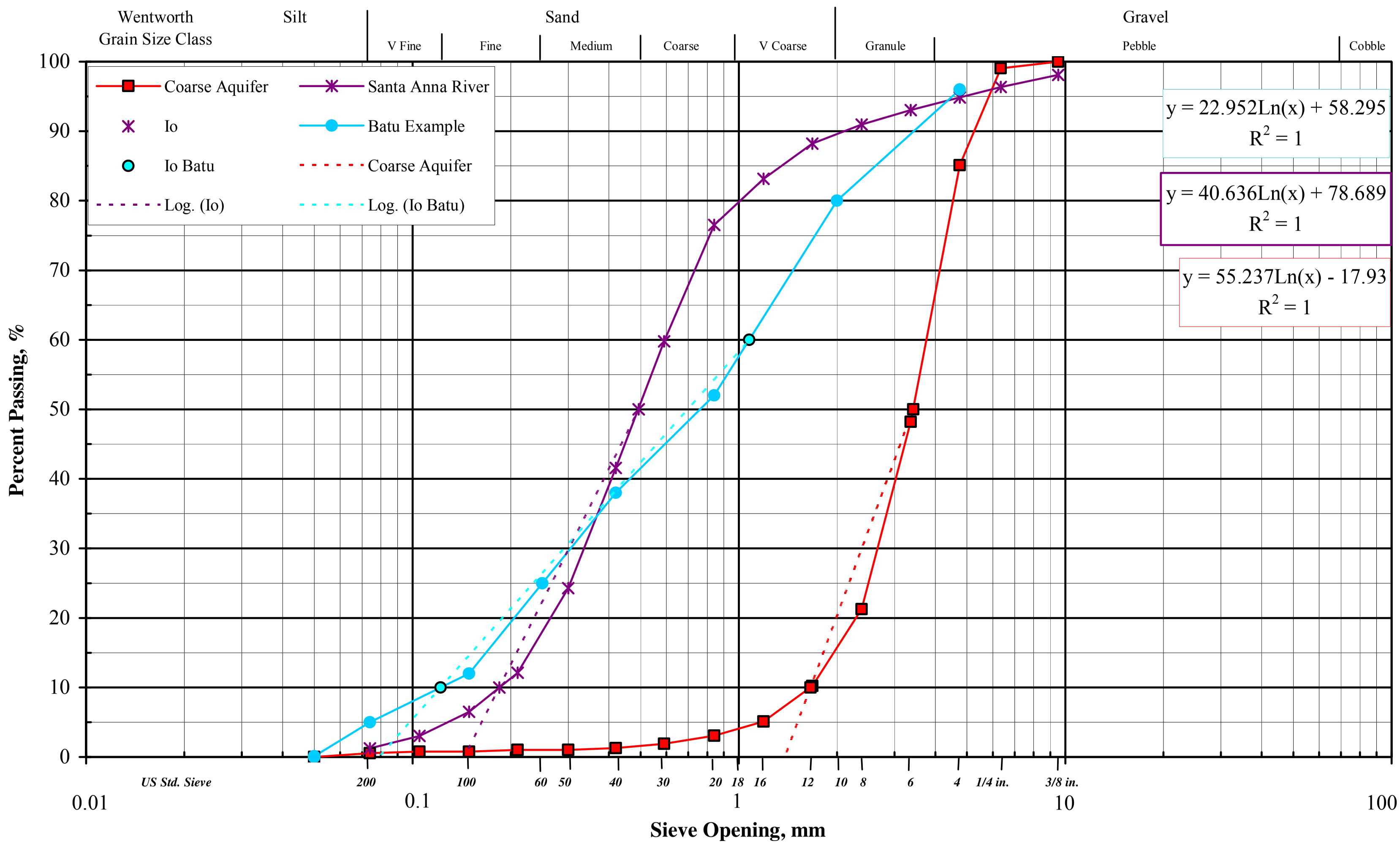


TABLE A2.2 - Hydraulic Conductivity [gpd/ft^2]								
Lab Material	**Lab Permeameter (2002)**	**Masch-Denny (1966)**	**Hazen Approximation (1892)**	**Bedinger Approximation (1961)**	**Krumbein & Monk (1943)**	**Shepherd (1989)**	**Kozeny-Carman (1927,1956)**	**Alyamani & Sen (1993)**
Santa Ana River	716	300	721	487	612	520	1,213	735
Coarse Aquifer	47,603	6,900	58,291	23,400	59,490	22,823	58,226	64,906
Batu Example	N/A	175	315	1,160	581	532	2,887	287

A2.10. Conclusion

It has been found that there are various empirical methods to estimate hydraulic conductivity from grain size distributions. It is often the case that one method over estimates a certain material while another method underestimates that same material. This can be described from Koltermann and Gorelick (1995) by the fact that geometric means in hydraulic conductivity models seem to over predict results while harmonic means seem to under predict hydraulic conductivities. The harmonic mean puts greater weight on smaller grain sizes whereas the geometric mean puts more weight on larger grain sizes. Another aspect that seems to affect one method over another is the shape of the grains. Grain irregularity often can cause one empirical model to over or underestimate a certain hydraulic conductivity.

A2.11. Further Note

One further note which is beyond the discussions of this Appendix, was a paper by Boadu (2000) titled *Hydraulic Conductivity of soils From Grain Size Distribution: New Models*. Boadu adds other parameters to form an empirical model which seems to have quite some promise.

$$\ln K = 33.09 + 0.01P - 0.18\phi + 0.33S - 7.36D - 11.09\rho \qquad \text{(A2-7)}$$

The equation above describes five additional structural descriptors which Boadu has found important in hydraulic conductivity models. These five structural descriptors are fractal dimension D, entropy S, fractal porosity ϕ, percent fines P, and bulk density ρ. By measuring some of the shape and textural properties of the soil, one can obtain better values of hydraulic conductivities from grain size distribution, porosity, and bulk densities.

Appendix 3. Initial Development and Testing Of Stainless Steel Wire Wrap Screens

This Appendix describes and details some of the testing preformed on the Roscoe Moss Stainless Steel Wire Wrap Screens (SSWWS). The screens have a slot size of 0.010, 0.020, 0.040, 0.060, 0.080, 0.093, 0.125 inches. The most interesting thing found in this testing was the high degree as to which the smaller slot sizes where clogged from fines of a coarse aquifer. This clogging will play a very interesting role in the efficiency of the screen in testing to come.

A3.1. Introduction

There were seven different sizes of well screens to be tested. All seven where constructed by the Roscoe Moss Company of Los Angeles, California. Each Screen was fitted to the model and then development and observation took place.

A3.2. Background

The Stainless Steel Wire Wrap Screens (SSWWS) had a screen slot size of 0.010, 0.020, 0.040, 0.060, 0.080, 0.093, 0.125 inches. These are the commercial wire wraps screens which are produced today. The screen is placed in one corner of the model and is 5 feet tall by 10 inches in diameter. The screens all had to be outfitted with a polycarbonate tube on the aquifer side of the screen such that a Borescope could take pictures of the screen from the aquifers reference point. There were several raw hiding and development techniques that took place during the initial development stages of each model run.

The initial model development was performed by Williams (1981). The model then tested other various well screens which are less common today. Those well screens and some of the initial testing equipment are still in the lab today.

A3.3. Model Development and Runs

When a screen is first placed into the model; the model is pumped at a constant rate for 2-3 days in order to remove all of the air which is in the model. Raw hiding is then preformed on the well screen being tested to remove any fines, air bubbles, or other debris in the near well zone. This process usually takes one day or until the water begins to clear up in the model. From here the model is turned off in order to calibrate the equipment. The Scanivalve is allowed to calibrate the model to atmosphere and all pressures are set at zero within the model. A series of tests whether it be constant rate test or step drawdown test can be ran on each screen. From the data generated by these tests on each well screen; drawdown, entrance velocities, Reynolds number, Transmissivity, aquifer loss, near well loss, and efficiencies can all be calculated.

A3.4. Observations

It was found that during some of the first raw hiding experiments, there was a tremendous amount of air bubbles that were trapped on the SSWWS which would decrease the permeability in the near well zone and the open area to flow of each screen. To alleviate this problem the model was pumped at a constant rate for two more days or until the air bubbles were no longer visible with the Borescope. Raw hiding of each well screen is performed by closing the butterfly valve on the effluent side of the model which increases the pressure head in the model to approximately 70 feet. The valve is then suddenly released open to yield a dramatic change in head and velocity in the near well zone. Some very interesting results were discovered for the SSWWS. All of the raw hiding was video logged with the Borescope in order to document fines in the aquifer passing through the each individual slot of the well screen. The material which was finer than the slot size of the screen was able to pass through the well screen while the larger material remained in place during the raw hiding. Sometimes it would take several attempts to dance the smaller grains around in order to arrange them such that they would pass through the slot size of each screen. The aquifer was sampled after each screen and a sieve analysis was preformed to see how the aquifer had changed i.e. how many of the fines were removed from each screen. Figure A3.1 details the result of this testing. The aquifer only changed from 0.020 screens to the 0.040 and the 0.060 screens. The 0.010 material was the same as the 0.020 and the 0.080, 0.093 and 0.125 were all similar to the 0.060 screen.

It was there for determined that one of the initial design criteria of Chapter 4 with regards to the Slot Factor was not correctly defined thus far. The Slot Factor was originally stated as;

$$S_l = \frac{D_{50}}{Slotwidth} \geq 1.5 \qquad (4.6)$$

S_l = Slot Factor (Design Criteria from Chapter 1)

Slot width = Slot width of screen (in., mm)

Originally it was thought that if the slot in the well screen was too large that a large amount of the filter pack would pass through the well screen. Many well designers stated that the slot width should not allow more then 10% passing of the filter pack through the well screen, i.e. that the slots size should be no large then the 10% passing size of the filter pack being used. As seen in the figure below the fines of the aquifer never migrated through the well screen as once expected. Even the largest screen slot size, 0.125 in., did not change the filter pack to a very large degree. The 0.125 SSWWS had a 40% passing through it but yet an insignificant amount of material migrated through the screen. This example had a Slot Factor, S_l, of 1.1. The Slot Factor might become more prevalent when a smaller aquifer is utilized and will be reexamined with a smaller aquifer.

A3.5. Findings

The 0.010, 0.020, and 0.040 SSWWS showed some clogging of the slots after the testing. The fines seemed to lodge themselves in between each slot. The degree to which the 0.010 and the 0.020 SSWWS were clogged was quite amazing and a bit unexpected with such a large aquifer material. A photo of this is seen in Photos A3.1-A3.3 of this Chapter. This is a significant finding due to the fact that that the open area of these screens have now been significantly reduced. It is estimated that 85% of the 0.010 and 75% of the 0.020 screens have been clogged by fines. The 0.040 SSWWS was not as plugged to the degree as the 0.010 and the 0.020 but it still lost some of its open area due to clogging. It was estimated that 20% of the 0.040 screen was permanently clogged. Photos A3.4-A3.5 are of the 0.040 screen. The 0.060 was not nearly as clogged as the others as seen in Photo A3.6. The other three screens had no clogging of the slots.

Another noticeable finding was that of the early raw hiding experiments preformed on 0.010 and 0.020 SSWWS was a jetting effect that would take place inside the well bore. Little jets would be blasting into the well bore at very high velocities where a slot was unclogged letting the water enter the well. This result was no doubt attributed to the high degree of clogging of these two well screens. The Photos A3.7-A3.10 demonstrates this jetting effect during raw hiding operations of the well screen. During normal operations of the well screen smaller jets can be seen in Photo A3.11. These jets have considerable velocities and are caused by the decrease in open area of the well screen.

Figure A3.1 - Mechanical Grading Analysis
Coarse Aquifer Material after SSWWS Testing

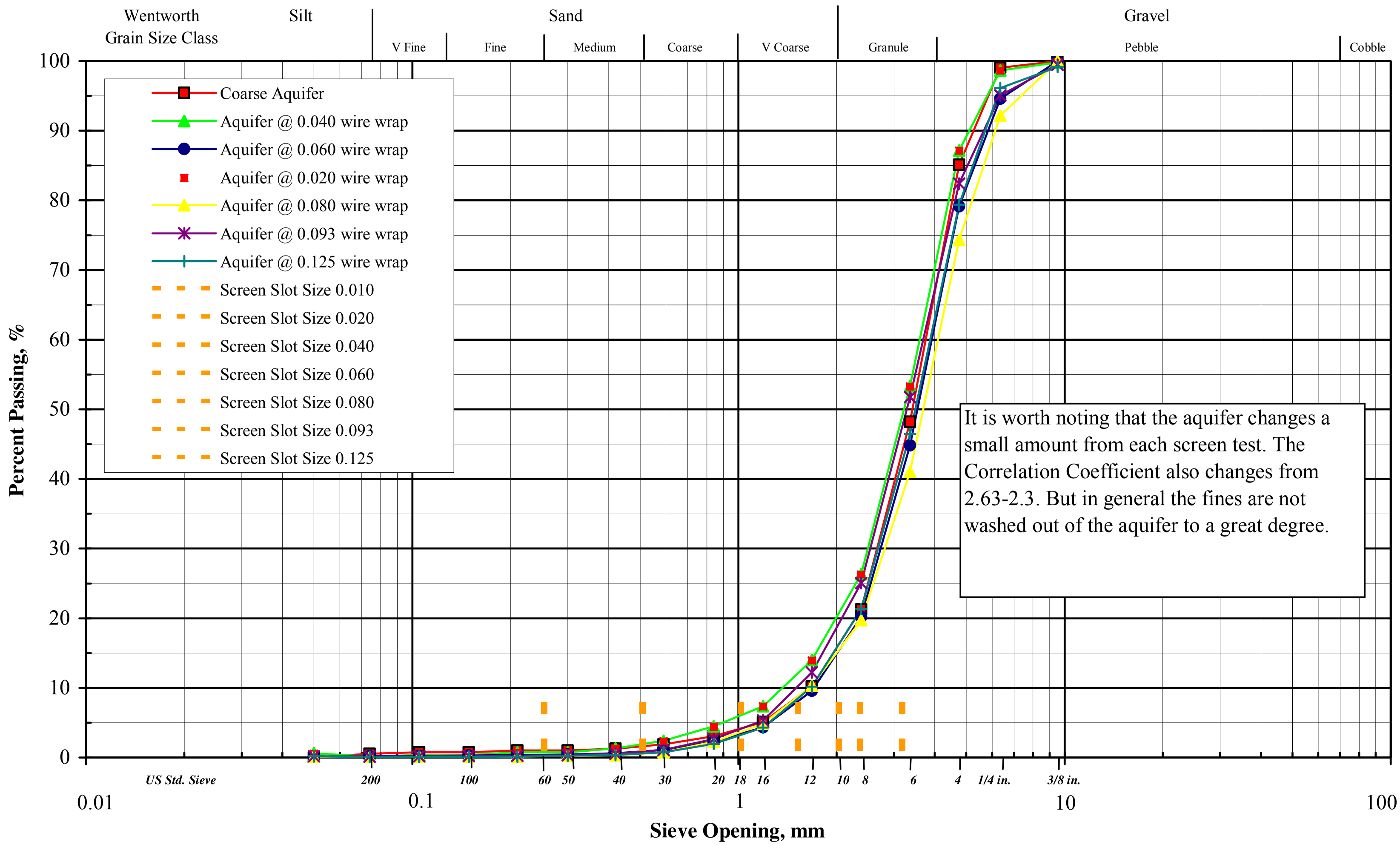


Photo A3.1 – 0.010 SSWWS After Testing With 85% Clogged

Photo A3.2 – 0.010 SSWWS After Testing With 85% Clogged

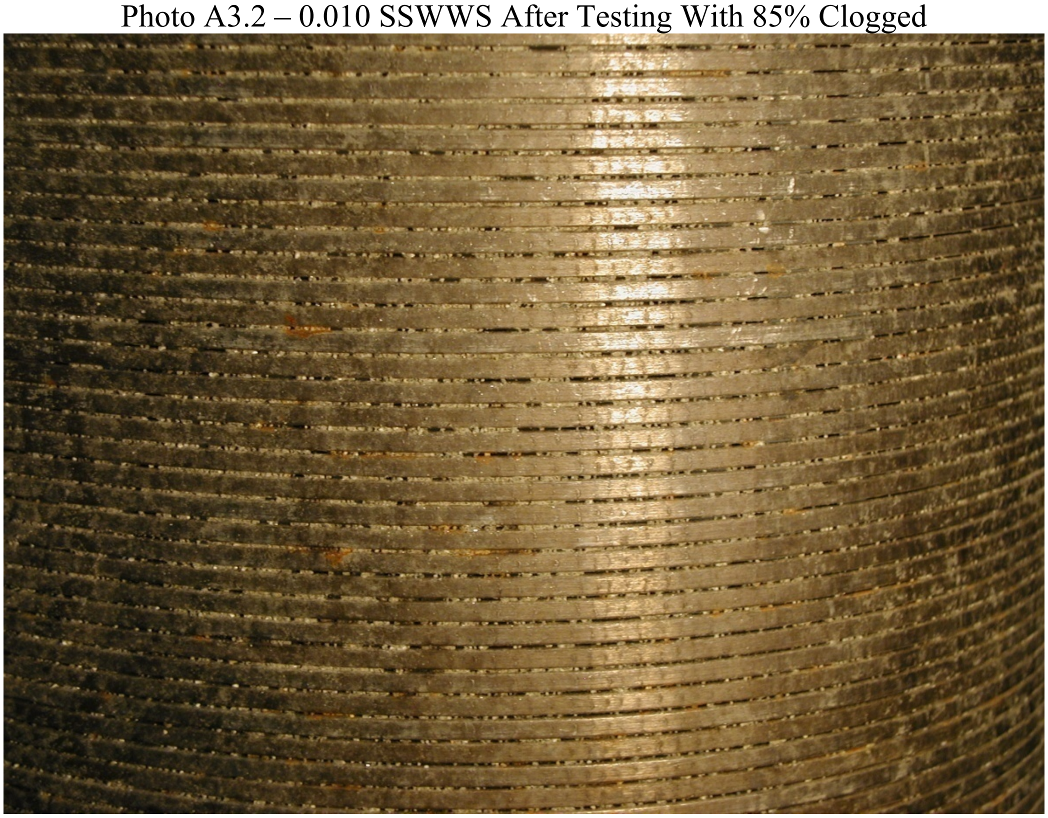


Photo A3.3 – 0.020 SSWWS After Testing With 75% Clogged

Photo A3.4 – 0.040 SSWWS After Testing With 20% Clogged

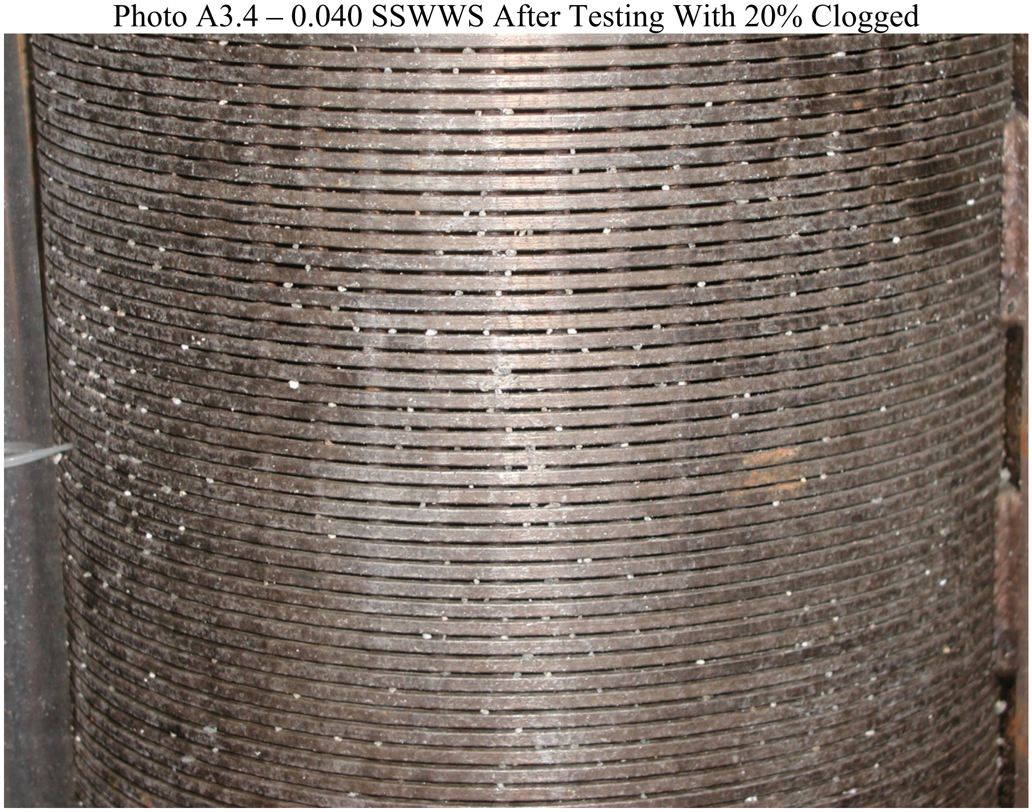


Photo A3.5 – 0.040 SSWWS After Testing

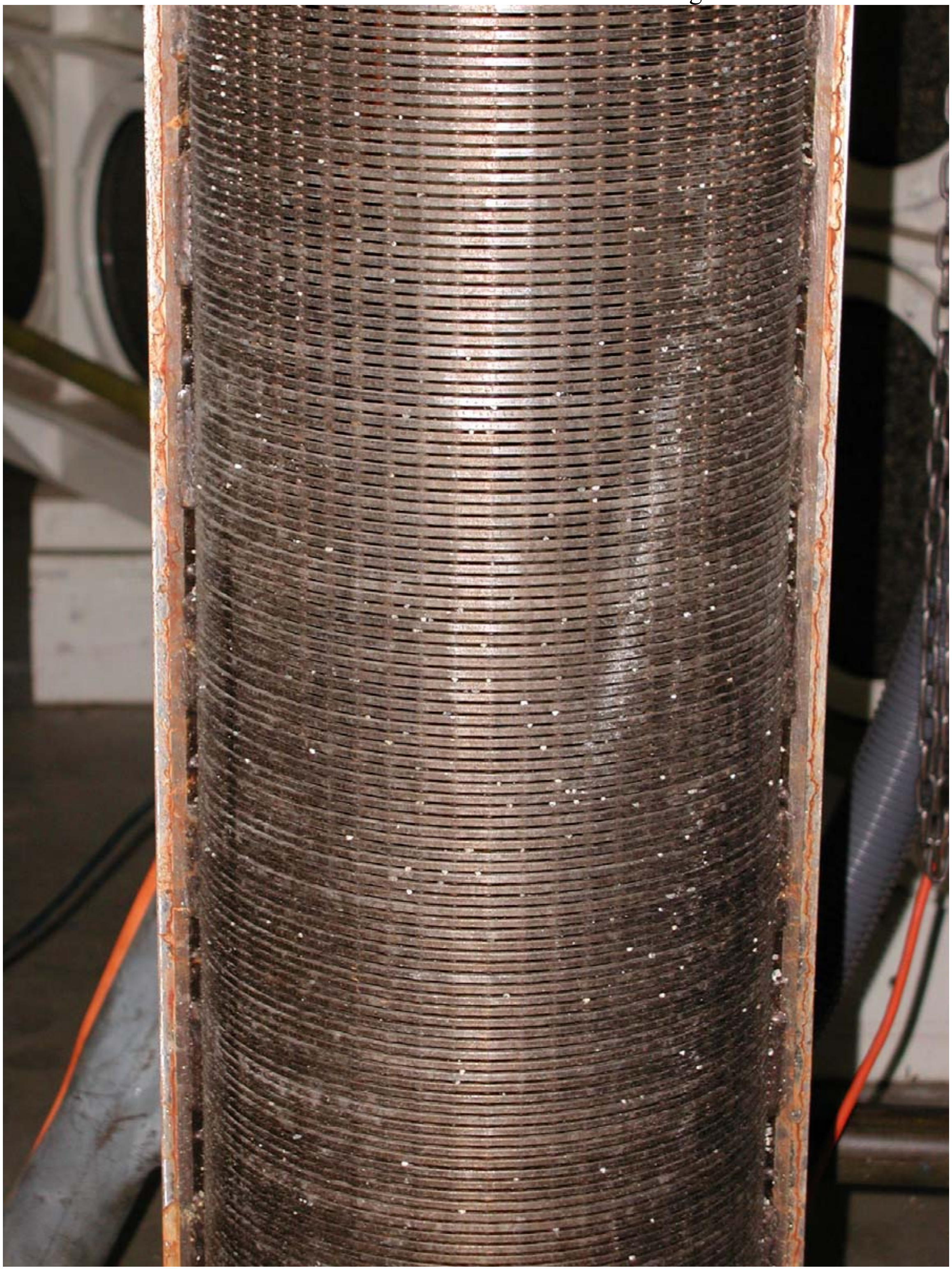


Photo A3.6 – 0.060 SSWWS After Testing

Photo A3.7 – Jetting During Raw Hiding

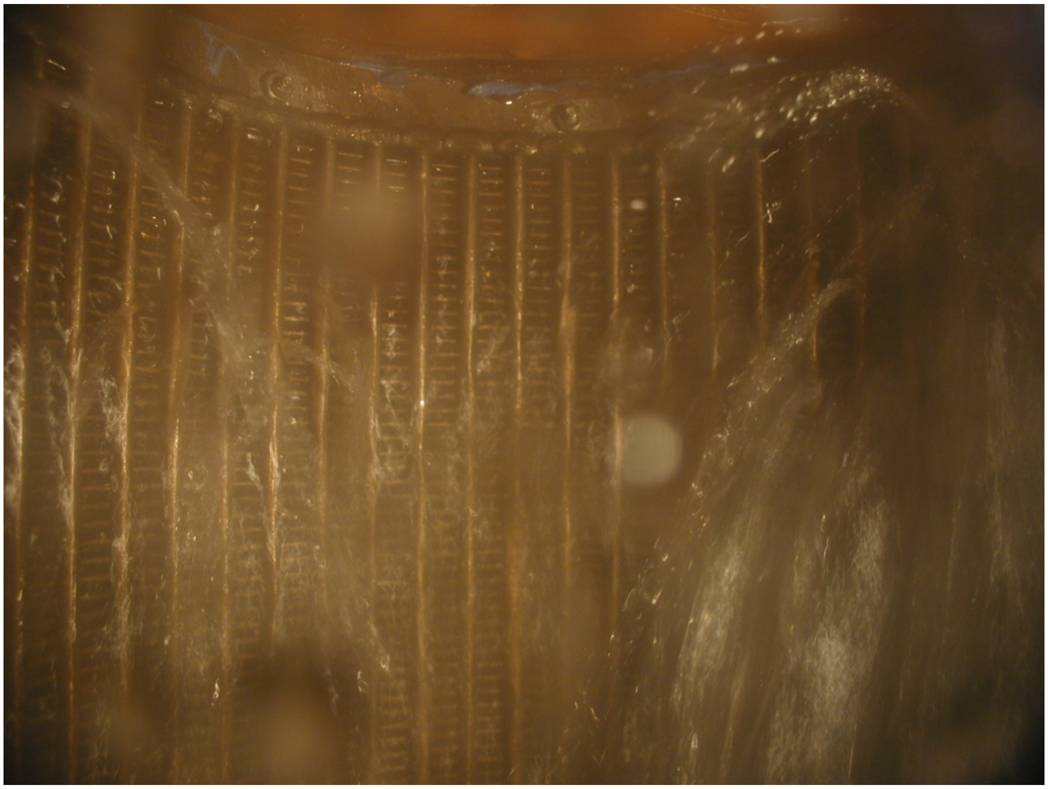


Photo A3.8– Jetting During Raw Hiding

Photo A3.9 – Jetting During Raw Hiding

Photo A3.10 – Jetting During Raw Hiding

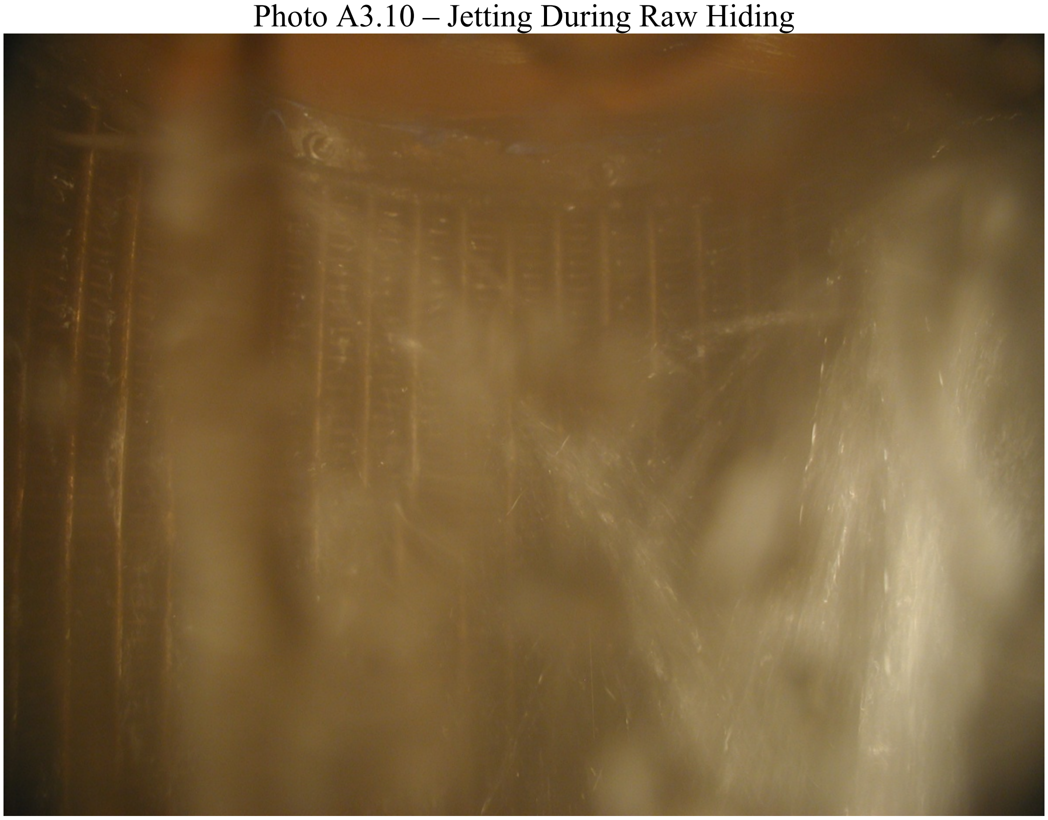
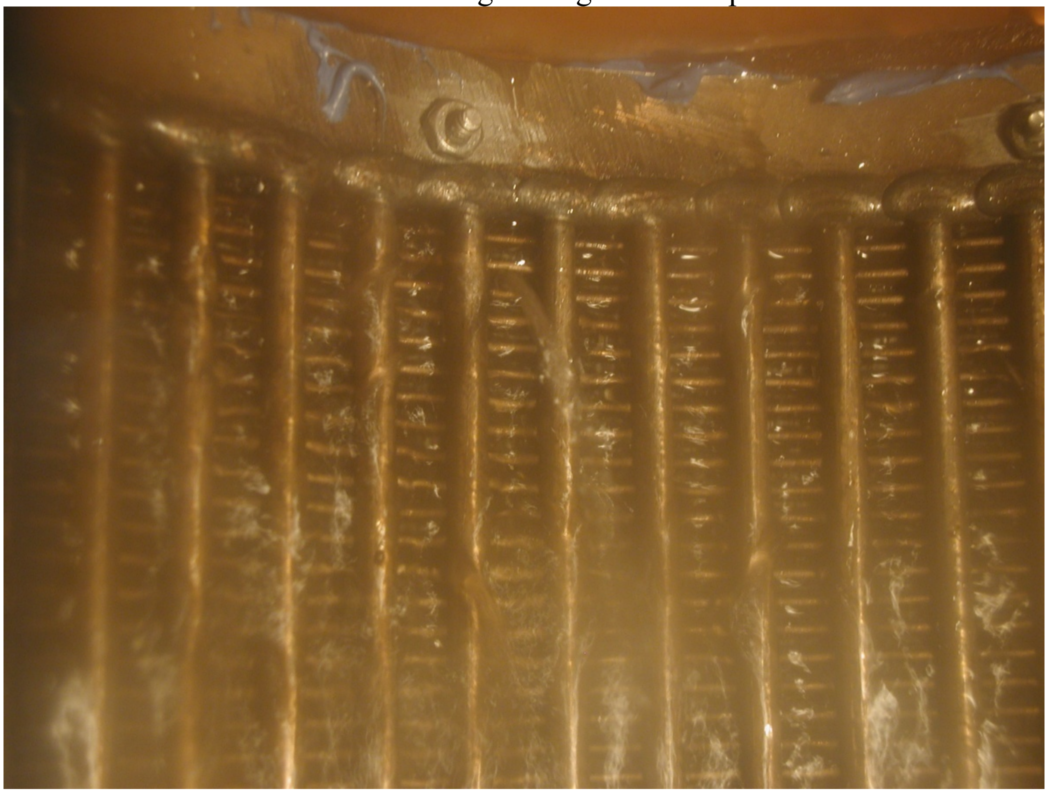


Photo A3.11 – Jetting During Normal Operation



Appendix 4. Initial Development and Testing Of Stainless Steel Louver Screens

This Appendix describes and details some of the testing preformed on the Roscoe Moss Stainless Steel Louver Screens (SSLS). The screens have a slot size of 0.040, 0.060, 0.080, 0.093, 0.125 inches. The most interesting thing found in this testing was the high degree as to which the mild steel screen was clogged from rust and bio-fouling in a coarse aquifer. There also seem to be less sand migration through the well screen. The larger particles seem to form a bit of a filter pack around each louver. All of this was recorded using the Borescope.

A4.1. Introduction

There were five different sizes of well screens to be tested. All five where constructed by the Roscoe Moss Company of Los Angeles, California. Each Screen was fitted to the model and then development and observation took place.

A4.2. Background

The Stainless Steel Louver Screens (SSLS) had a screen slot size of 0.040, 0.060, 0.080, 0.093, 0.125 inches. These are the commercial louver screens which are produced today. The screen is placed in one corner of the model and is 5 feet tall by 10 inches in diameter. The screens all had to be outfitted with a polycarbonate tube on the aquifer side of the screen such that a Borescope could take pictures of the screen from the aquifers reference point. There were several raw hiding and development techniques that took place during the initial development stages of each model run.

Appendix 4.1. Model Development and Runs

When a screen is first placed into the model; the model is pumped at a constant rate for 2-3 days in order to remove all of the air which is in the model. Raw hiding is then preformed on the well screen being tested to remove any fines, air bubbles, or other debris in the near well zone. This process usually takes one day or until the water begins to clear up in the model. From here the model is turned off in order to calibrate the equipment. The Scanivalve is then allowed to calibrate the model to atmosphere and all pressures are set at zero within the model. A series of tests whether it be constant rate test or step drawdown tests can be ran on each screen. From the data generated by these tests on each well screen; drawdown, entrance velocities, Reynolds number, Transmissivity, aquifer loss, near well loss, and efficiencies can all be calculated.

A4.3. Observations

It was found that during some of the first raw hiding experiments, there was a decrease in the amount of air bubbles that were trapped on the SSLS compared to that of the SSWWS. To alleviate this air bubble problem the model was pumped at a constant rate for two more days or until the air bubbles were no longer visible with the Borescope.

Raw hiding of each well screen is performed by closing the butterfly valve on the effluent side of the model which increases the pressure head in the model to approximately 70 feet. The valve is then suddenly released open to yield a dramatic change in head and velocity in the near well zone. Some very interesting results were discovered for the SSLS. All of the raw hiding was video logged with the Borescope in order to document fines in the aquifer passing through the each individual slot of the well screen. The material which was finer than the slot size of the screen was able to pass through the well screen while the larger material remained in place during the raw hiding. Sometimes it would take several attempts to dance the smaller grains around in order to arrange them such that they would pass through the slot size of each screen.

A4.4. Findings

The initial model testing was with a mild steel Ful-Flow louver well screen. It was noticed that when the model was left idle for more than a few weeks a tremendous amount of cementing of the aquifer material had taken place on the well screen. Photos A4.1- A4.2 shows the degree of encrustation and sealing of this well screen. Photo A4.3 is a close up of the louvers from the filter packs reference point; while Photo A4.4 is a taken from the well bore side of the model. These encrustation photos show a great degree of sealing of the well screen that can take place in a relatively short time using mild steel well screens. Photos A4.5- A4.6 shows the Filter Pack Divider (FPD) in place with a sand injection tube in the model. Finally Photo A4.7 shows the model with the FPD in place ready to be loaded with a filter pack.

Over all the SSLS performed the way they were designed to. There was nothing that was out of the ordinary observed during testing. The encrustation of a mild steel well screen was quite unexpected as to the degree which the well screen could be sealed in such a short period of idle time. None of this was noticeable with the stainless well screen.

Photo A4.1 – Encrusted Screen

Photo A4.2 – Encrusted Screen

Photo A4.3 – Encrusted Screen Aquifer Side

Photo A4.4 – Encrusted Screen Well Side

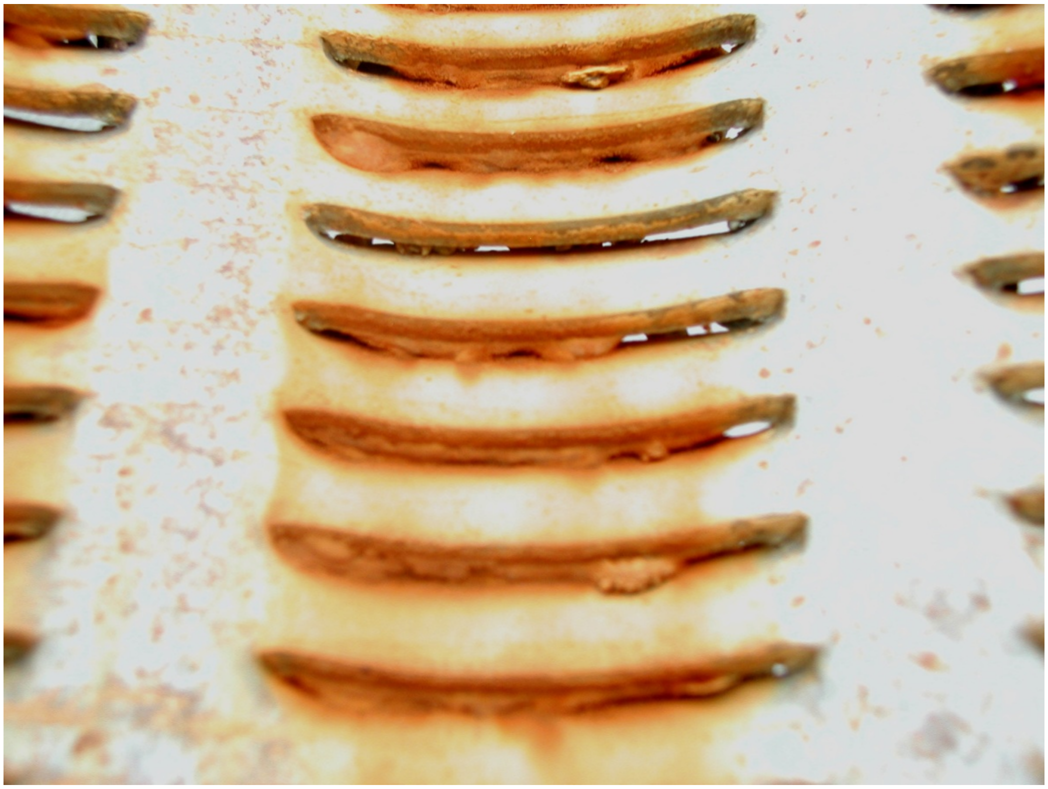
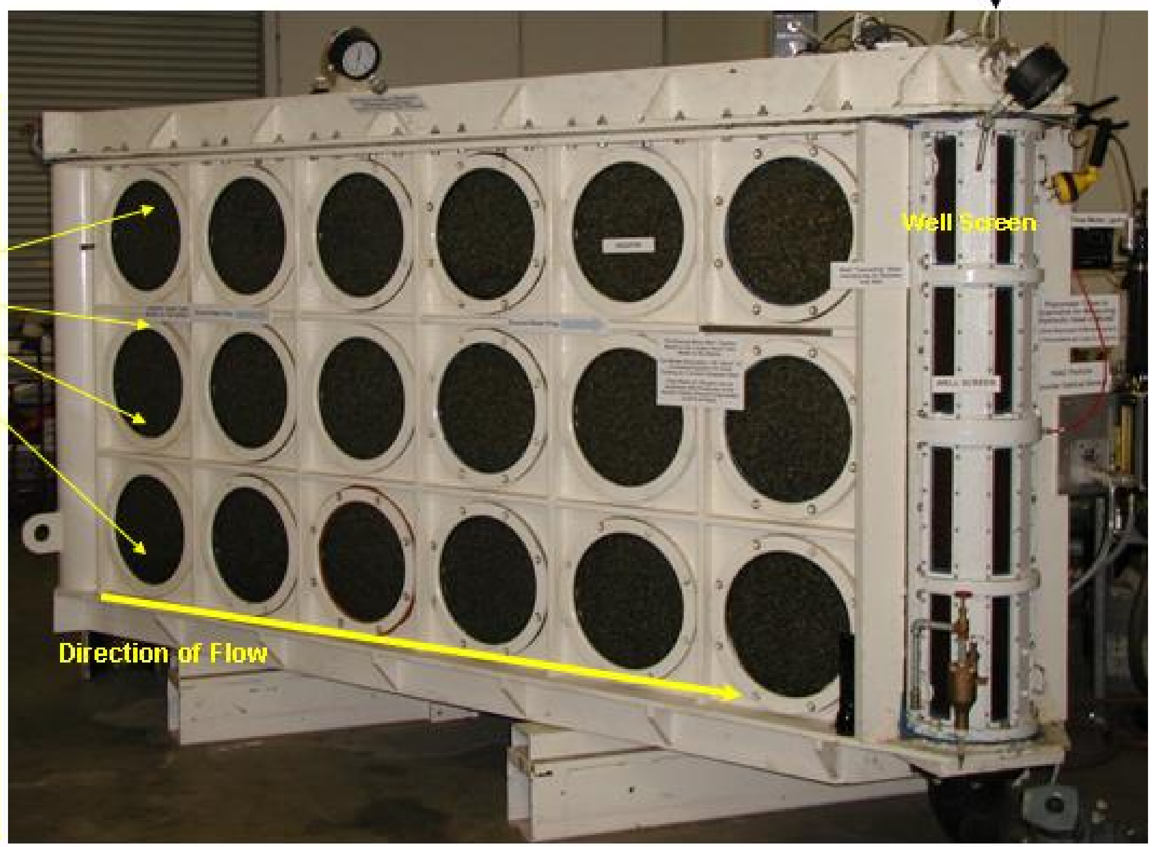


Photo A4.5 – Filter Pack Divider

Photo A4.6 – Filter Pack Divider Close Up

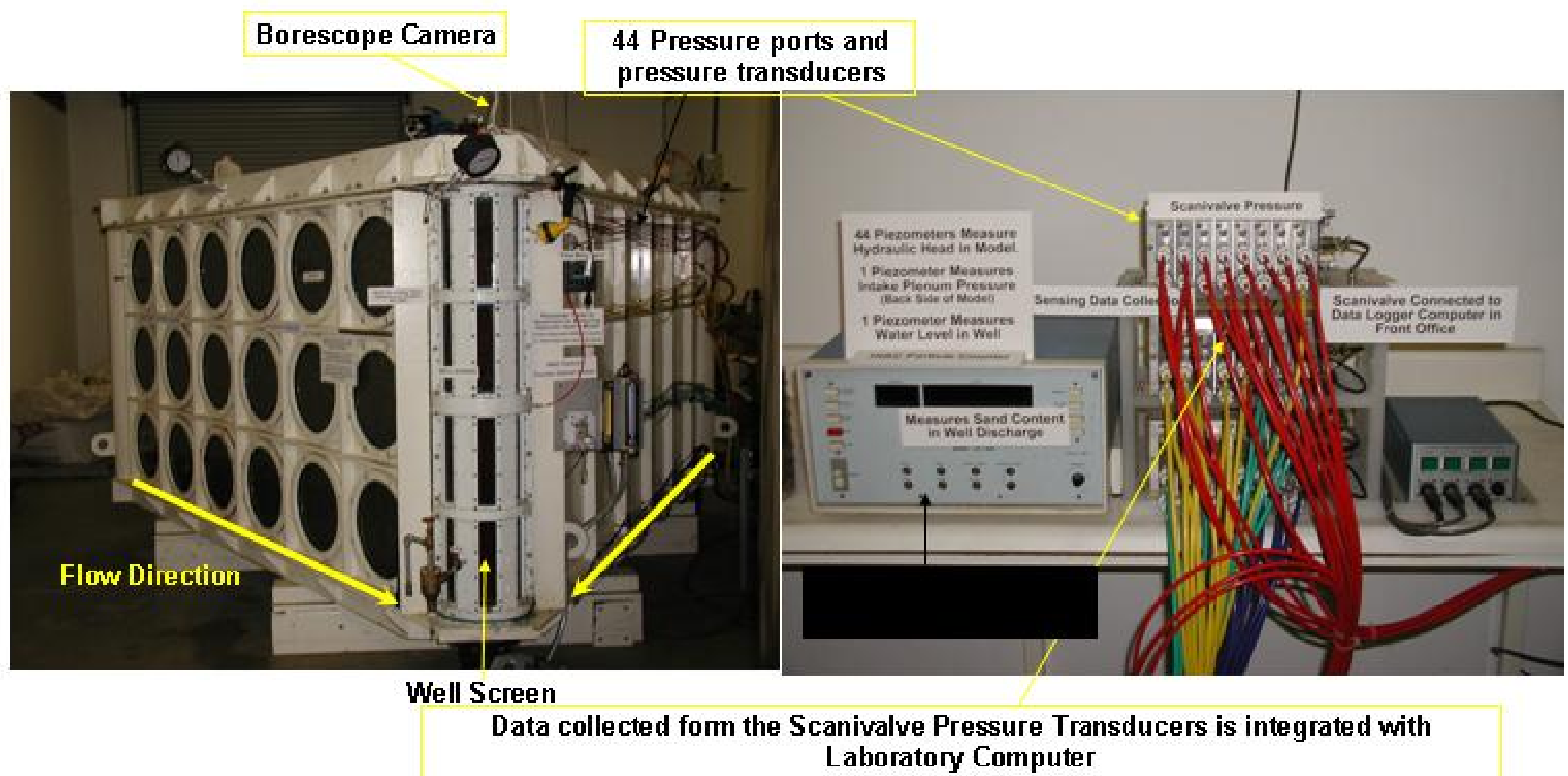
Photo A4.7 – Screen Removed

Photo A4.8 – Aquifer Model Layout



- 4 Layers extending radial outward form the well screen.
- 44 port's per layer reading real time pressure measurement.
- Re-circulates water via pump and holding tank.
- Addition of camera's and computer to collect data.

Photo A4.9 – Aquifer Model and Scanivalve



Appendix 5. Field Findings

Aquifer Type	Well Name	Depth	Filer Pack/Aquifer Ratio (D50F/d50A)	Terzaghi's Migration Factor (D15F/d85A)	Terzaghi's Permeability Factor (D15F/d15A)	Uniformity Coefficient, Cu (d60A/d10A)	Sorting Factor, Sf (CuF/CuA)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Critical Radius (in)	Percent Filter Pack Passing Well Slot	Slot Size (in)
FINE AQUIFERS	BCVWD Well #26 (Fine)	570-580	14.00	1.43	59.88	17.12	0.14	0.12	91		17.11	0.060
		620-630	30.45	4.34	88.66	9.34	0.26	0.05	97			
		760-770	15.08	1.87	46.99	12.23	0.20	0.11	93			
		800-810	19.52	2.08	67.32	12.77	0.19	0.09	94			
		910-920	13.54	1.99	18.32	5.71	0.43	0.12	93			
		1050-1060	20.45	2.81	64.12	10.85	0.22	0.08	95			
		1230-1240	22.34	2.91	62.21	8.95	0.27	0.07	96			
	CVWD 4506 Redrill (Fine) 10x20 Kelpac	880	5.20	1.84	15.27	9.74	0.16	0.26	98	2.8	16.28	0.040
		980	6.34	2.39	10.42	3.19	0.50	0.21	99	2.3		
		1070	7.73	2.34	15.27	6.87	0.23	0.17	96	1.9		
		1180	4.79	2.06	6.49	2.79	0.57	0.28	98	3.0		
		1280	7.78	3.80	10.80	2.43	0.65	0.17	99	1.8		
	CVWD 4510 (Fine) 4x12 Custom Blend	880	10.51	3.27	27.15	9.74	0.21	0.15	99		15.50	0.070
		940	12.83	4.25	18.53	3.19	0.64	0.12	99			
		960	15.63	4.17	27.15	6.87	0.30	0.10	98			
		1050	9.68	3.66	11.55	2.79	0.73	0.16	99			
		1120	15.74	6.76	19.21	2.43	0.84	0.10	100			
		1270	11.82	4.37	12.86	3.06	0.67	0.13	99			
	CVWD 4612-01 (Fine)	970	9.33	1.73	14.26	7.45	0.36	0.20	94		17.43	0.050
		1050	10.96	1.90	13.96	5.15	0.52	0.17	94			
		1140	12.57	2.66	14.55	4.82	0.55	0.15	96			
		1200	12.22	3.81	12.24	2.69	0.99	0.15	99			
		1220	10.28	2.26	9.24	2.65	1.00	0.18	100			
		1340	3.58	0.74	7.80	7.23	0.37	0.43	76			
	CVWD 5721 (Fine) 8x12	1010	9.72	3.27	27.15	9.74	0.18	0.17	99	5.1	9.77	0.060
		1040	11.86	4.25	18.53	3.19	0.56	0.14	99	4.2		
		1170	14.45	4.17	27.15	6.87	0.26	0.12	97	3.4		
		1210	8.95	3.66	11.55	2.79	0.64	0.19	99	5.6		
	CVWD 5676-01 (Fine) 6x12	500	9.98	3.67	30.49	9.74	0.15	0.15	99	3.0	6.00	0.070
		620	12.18	4.77	20.81	3.19	0.47	0.12	99	2.5		
		750	14.84	4.68	30.49	6.87	0.22	0.10	98	2.0		
		820	9.19	4.11	12.97	2.79	0.53	0.16	99	3.3		
		1000	14.95	7.59	21.57	2.43	0.61	0.10	100	2.0		
		1140	11.22	4.91	14.44	3.06	0.49	0.13	99	2.7		
		1260	4.72	1.53	7.03	2.66	0.56	0.31	100	6.4		
		Sand Produce	13.08	5.33	18.60	2.49	0.60	0.11	100	2.3		
	CVWD 5676-02 (Fine) 4x16	940-950	7.42	2.26	18.73	9.74	0.23	0.21	99	3.1	17.43	0.050
		1050-1060	9.05	2.93	12.78	3.19	0.69	0.17	99	2.5		
		1110-1120	11.04	2.88	18.73	6.87	0.32	0.14	97	2.1		
		1210-1220	6.83	2.53	7.97	2.79	0.79	0.22	99	3.3		
		1280-1290	11.11	4.66	13.25	2.43	0.91	0.14	100	2.1		
		1040-1050	8.34	3.01	8.87	3.06	0.72	0.18	98	2.7		
		1160-1170	1.74	0.33	3.08	4.96	0.44	0.88	100	13.1		
		1230-1240	5.63	1.95	6.20	2.44	0.90	0.27	100	4.1		
	BBCSD Greenway Park Well (Fine)	250-260	16.16	2.81	16.70	5.36	0.48	0.10	97		15.48	0.060
		290-300	12.40	2.62	16.56	6.54	0.40	0.13	98			
		350-360	10.02	1.74	16.23	7.97	0.33	0.15	94			
		470-480	5.96	0.83	9.15	5.64	0.46	0.26	85			
		490-500	11.80	2.75	14.06	3.12	0.83	0.13	98			
		500-510	4.91	0.73	7.73	6.20	0.42	0.32	81			

Aquifer Type	Well Name	Depth	Filer Pack/Aquifer Ratio (D50F/d50A)	Terzaghi's Migration Factor (D15F/d85A)	Terzaghi's Permeability Factor (D15F/d15A)	Uniformity Coefficient, Cu (d60A/d10A)	Sorting Factor, Sf (CuF/CuA)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Critical Radius (in)	Percent Filter Pack Passing Well Slot	Slot Size (in)
MEDIUM AQUIFERS	CBD MW II-7(Medium)	160	7.03	1.25	15.24	14.69	0.16	0.30	87		10.51	0.060
		250	8.60	1.23	21.12	15.18	0.16	0.24	86			
		300	6.40	1.03	13.66	15.64	0.15	0.33	81			
		370	6.30	1.07	13.63	15.70	0.15	0.33	82			
		420	6.24	1.05	13.33	15.69	0.15	0.33	81			
	CBD MW II-19 (Medium)	210-220	8.14	1.37	11.57	7.51	0.32	0.26	88		10.51	0.060
		300-310	7.51	1.41	11.39	7.40	0.33	0.28	89			
		320-330	8.45	1.73	11.85	8.00	0.30	0.25	93			
		380-390	8.61	1.80	11.83	7.73	0.31	0.24	95			
		400-410	9.56	1.64	15.77	9.43	0.26	0.22	92			
	CVWD 4613-01 (Medium)	950	8.54	1.93	14.89	5.94	0.43	0.21	98		17.86	0.060
		1050	10.34	2.77	12.43	3.52	0.73	0.18	98			
		1150	8.27	2.21	9.43	3.52	0.73	0.22	99			
		1230	5.32	0.80	9.25	6.30	0.41	0.34	80			
	CVWD 4614-01 (Medium)	890	10.81	3.35	11.22	2.65	0.94	0.14	100		17.86	0.060
		1000	8.02	2.61	7.75	2.24	1.11	0.19	100			
		1080	4.71	1.61	4.80	2.64	0.94	0.33	98			
		1220	1.59	0.00	3.00	6.82	0.37	0.96	50			
		1250	9.09	2.62	10.61	3.12	0.80	0.17	99			
	CVWD 4628 Redrill (Medium) 1/4 x16	830	5.71	1.57	10.62	5.81	0.39	0.31	91	7.8	12.45	0.060
		910	5.92	2.24	10.64	5.42	0.42	0.30	96	7.5		
		1010	6.98	2.50	10.34	3.95	0.57	0.25	100	6.4		
		1080	10.09	3.22	17.89	5.36	0.42	0.18	99	4.4		
		1280	9.85	3.47	15.88	4.00	0.71	0.18	100	4.5		
		1210	9.37	2.94	16.74	4.49	0.64	0.19	76	4.7		
	CVWD 5677 (Medium) 10x20 KelPac	570	3.65	1.49	3.94	2.59	0.61	0.37	98	4.1	16.28	0.040
		780	4.72	1.68	7.69	3.40	0.46	0.28	98	3.2		
		860	3.25	1.28	10.05	8.26	0.19	0.41	92	4.6		
		1000	6.66	1.59	12.52	5.99	0.26	0.20	93	2.3		
		1150	4.99	1.79	8.98	3.61	0.44	0.27	97	3.0		
		1290	5.84	2.46	7.23	3.06	0.52	0.23	97	2.6		
	CVWD 5719-01 (Medium) 4x20	580-590	5.52	0.79	33.08	26.34	0.08	0.29	81		17.54	0.060
		730-740	6.25	1.27	21.82	15.75	0.14	0.26	90			
		800-810	35.41	2.31	94.26	13.38	0.16	0.05	97	0.7		
		930-940	2.88	0.57	13.43	22.10	0.10	0.56	71	3.3		
		980-990	10.96	2.18	17.39	6.02	0.47	0.15	96	1.8		
		1020-1030	2.69	0.46	11.32	16.81	0.17	0.59	66	11.6		
		1100-1110	6.06	1.39	9.67	5.31	0.57	0.26	92	2.7		
		1120-1130	4.01	0.94	7.38	5.91	0.51	0.40	84	1.6		
		1160-1170	7.81	2.17	9.87	3.77	0.80	0.20	99			
		1180-1190	5.78	1.72	8.26	3.68	0.82	0.28	95			
		1240-1250	7.83	1.95	17.11	9.28	0.32	0.20	98			
	CVWD 5725-01 (Medium) 4x12	890-900	9.24	1.02	16.18	7.30	0.31	0.17	86	2.3	17.86	0.060
		980-990	12.01	2.56	15.85	3.24	0.69	0.13	96	1.7		
		1020-1030	5.75	1.75	7.90	3.48	0.64	0.28	96	3.6		
		1060-1070	11.98	1.64	37.33	12.43	0.18	0.13	91	1.7		
		1150-1160	22.09	2.14	73.73	11.22	0.20	0.07	94	0.9		
		1280-1290	8.73	2.05	11.81	3.99	0.56	0.18	97	2.4		
		1300-1310	18.87	2.07	66.50	12.56	0.18	0.09	95	1.1		
		1320-1330	12.67	2.23	39.54	11.82	0.19	0.13	96	1.6		
		1360-1370	3.80	0.56	7.30	5.81	0.38	0.42	75	5.5		

MEDIUM AQUIFERS	CBD I-13 (Medium)	100-110	10.76	1.20	13.14	3.18	0.75	0.16	87		17.03	0.094
		130-140	9.62	2.58	11.77	3.11	0.77	0.18	98			
		160-170	9.40	2.84	13.42	3.73	0.64	0.18	96			
		200-210	8.09	2.76	10.13	3.12	0.76	0.21	99			
		230-240	7.22	1.72	10.43	3.94	0.60	0.24	94			
		290-300	8.10	0.96	11.67	4.54	0.52	0.21	85			
		320-330	12.95	3.75	15.31	3.42	0.70	0.13	100			
		340-350	8.96	1.96	11.54	3.42	0.70	0.19	97			
	CBD I-14 (Medium)	100-110	1.88	0.53	7.35	7.38	0.19	0.51	77		7.03	0.094
		220-230	5.05	1.34	9.08	3.13	0.45	0.19	91			
		240-250	6.38	1.64	11.75	3.91	0.36	0.15	91			
		300-310	4.17	0.49	8.99	4.71	0.30	0.23	80			
		360-370	4.99	1.00	9.82	3.54	0.40	0.19	88			
		400-410	5.15	0.51	9.91	3.45	0.41	0.19	82			
		450-460	4.92	1.61	9.85	3.64	0.39	0.19	94			
	CBD I-15 (Medium)	160-170	4.17	0.99	8.08	5.54	0.42	0.39	86		13.61	0.094
		190-200	7.68	2.28	9.93	3.13	0.74	0.21	98			
		210-220	5.04	1.07	7.81	4.42	0.52	0.32	88			
		250-260	5.18	0.75	9.53	5.56	0.41	0.31	81			
		300-310	5.09	0.53	8.78	5.09	0.45	0.32	79			
	BBCSD Palomino Well (Medium)	120-130	6.50	0.50	4.10	3.26	2.36	0.26	86		33.06	0.063
		160-170	11.31	1.50	9.15	6.99	1.10	0.15	97			
		210-220	6.71	0.35	6.65	8.77	0.88	0.26	80			
		230-240	7.15	0.43	4.61	3.76	2.05	0.24	84			
		320-330	5.33	0.31	3.58	3.97	1.94	0.32	77			
		340-350	5.82	0.50	3.65	3.24	2.37	0.30	86			
	LACWD 40 WELL 4-62 (Medium)	260-270	10.05	2.17	17.27	6.61	0.45	0.17	98	0.8	19.27	0.070
		280-290	16.44	3.18	28.47	8.92	0.33	0.10	100	0.5		
		310-320	18.38	1.90	18.90	5.12	0.57	0.09	95	0.4		
		340-350	13.26	1.57	30.15	13.39	0.22	0.13	97	7.4		
		350-360	6.18	1.20	12.06	7.54	0.39	0.27	94	3.0		
		480-490	7.92	1.43	12.02	5.62	0.52	0.21	96	0.2		
		490-500	9.39	2.01	15.05	4.88	0.60	0.18	99	0.5		
		540-550	9.29	1.43	17.61	8.91	0.33	0.18	94	0.9		
		550-560	19.24	2.91	20.26	6.28	0.47	0.09	99	0.4		
	LACWD 40 WELL 4-65 (Medium)	70-80	11.39	2.26	23.32	7.16	0.31	0.13	98		20.19	0.094
		80-90	8.75	2.04	14.13	4.75	0.47	0.17	99			
		90-100	9.41	2.46	13.35	3.84	0.58	0.16	100			
		100-110	13.40	2.39	19.47	3.95	0.57	0.11	100			
	LACWD 40 WELL 4-66 Medium)	400-410	10.37	2.33	18.99	7.27	0.37	0.19	97	2.3	17.86	0.060
		440-450	8.62	1.94	18.93	7.47	0.36	0.22	96	2.8		
		480-490	9.94	1.71	21.97	11.33	0.24	0.19	94	2.4		
		490-500	8.70	1.59	19.76	9.63	0.28	0.22	93	2.7		
		520-530	10.05	1.42	26.63	13.47	0.20	0.19	91	0.7		
		540-550	7.83	1.16	18.57	9.80	0.28	0.25	87	0.4		
		580-590	11.18	1.53	27.76	12.60	0.21	0.17	91	2.4		
		620-630	5.85	1.04	17.57	12.80	0.21	0.33	84	10.9		
		650-660	9.34	1.09	16.12	5.38	0.50	0.21	85	2.5		
	LACWD 40 WELL 4-68 (Medium)	180-190	18.01	1.98	30.07	7.06	0.31	0.08	96	1.6	18.50	0.070
		230-240	3.97	1.04	16.50	10.90	0.20	0.38	88	7.4		
		240-250	8.93	1.28	24.64	14.43	0.15	0.17	92	3.3		
		260-270	2.70	0.75	10.11	12.65	0.17	0.56	76	10.8		
		320-330	7.43	0.94	19.86	8.97	0.24	0.20	85	6.6		
		360-370	7.17	1.29	27.91	18.93	0.12	0.21	94	43.1		
		420-430	22.23	5.84	64.85	8.73	0.25	0.07	99	1.3		
		460-470	6.45	1.60	10.48	4.51	0.49	0.23	98	4.5		
		480-490	4.58	0.80	17.84	13.18	0.17	0.33	80	6.4		
	WSBCWD #23A (Medium)	160-170	2.37	0.40	7.14	10.09	0.19	0.86	53		8.59	0.094
		190-200	19.44	0.43	96.80	18.97	0.10	0.11	76			
		250-260	1.10	0.36	3.70	11.01	0.17	1.85	37			
		350-360	1.75	0.36	6.47	16.46	0.12	1.17	48			
		420-430	1.27	0.36	3.85	10.99	0.18	1.61	38			
		480-490	1.85	0.39	5.18	10.91	0.18	1.10	47			
		560-570	3.11	0.45	7.13	7.20	0.27	0.66	61			
	Baldy Mesa (Medium)	540-550	2.72	0.60	5.32	6.36	0.44	0.58	81		14.93	0.050
		570-580	1.82	0.36	4.09	18.67	0.15	0.87	94			
		700-710	11.36	2.27	42.31	12.88	0.22	0.14	90			
		780-790	12.88	3.28	37.68	10.44	0.27	0.12	91			
		850-860	0.57	0.12	2.17	20.92	0.17	2.76	38			
		920-930	1.19	0.30	0.95	1.85	1.96	1.32	47			

Aquifer Type	Well Name	Depth	Filer Pack/Aquifer Ratio (D50F/d50A)	Terzaghi's Migration Factor (D15F/d85A)	Terzaghi's Permeability Factor (D15F/d15A)	Uniformity Coefficient, Cu (d60A/d10A)	Sorting Factor, Sf (CuF/CuA)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Critical Radius (in)	Percent Filter Pack Passing Well Slot	Slot Size (in)
COARSE AQUIFERS	CBD MW II-1 (Coarse)	190	5.93	1.07	13.56	13.57	0.16	0.30	86		13.54	0.080
		300	6.75	1.22	15.03	15.97	0.14	0.26	89			
		340	6.73	1.21	14.84	15.90	0.14	0.26	89			
		380-400	7.35	1.26	18.11	16.72	0.13	0.24	89			
		490	6.07	1.11	13.86	15.34	0.15	0.29	87			
	CBD MW II-2 (Coarse)	190	9.01	1.49	21.73	14.75	0.15	0.20	93		13.54	0.080
		310	6.69	1.15	14.91	16.07	0.14	0.26	87			
		460	8.61	1.57	19.34	14.14	0.16	0.20	95			
		520	8.52	1.51	19.60	14.52	0.15	0.21	94			
	CBD MW II-3 (Coarse)	170	6.39	1.05	13.71	14.26	0.16	0.28	85		13.54	0.080
		250	7.74	1.32	13.39	8.96	0.25	0.23	90			
		270	9.86	1.47	25.24	14.95	0.15	0.18	92			
		390	8.01	1.31	19.23	15.85	0.14	0.22	90			
		520	8.27	1.35	19.22	15.34	0.15	0.21	91			
	CBD MW II-4 (Coarse)	180	6.01	1.05	12.30	15.34	0.16	0.35	81		10.51	0.060
		230	7.08	1.20	15.95	14.61	0.17	0.29	85			
		370	8.96	1.41	21.74	14.30	0.17	0.23	89			
		410	8.27	1.40	18.99	14.17	0.17	0.25	90			
		450	7.09	1.19	17.17	16.07	0.15	0.29	85			
	CBD MW II-5 (Coarse)	200	6.63	1.16	13.93	14.91	0.15	0.24	91		18.25	0.090
		230	6.77	1.15	15.86	16.65	0.13	0.23	90			
		310	8.14	1.30	18.71	15.32	0.15	0.19	93			
		380	8.12	1.37	19.16	15.43	0.14	0.19	94			
		450	7.23	1.30	15.89	15.42	0.15	0.22	93			
	CBD MW II-12 (Coarse)	170	10.68	1.93	25.24	12.97	0.17	0.17	98		13.54	0.080
		250	10.64	1.84	26.32	13.55	0.17	0.17	97			
		330	13.68	2.53	34.57	11.89	0.19	0.13	100			
		620	7.15	1.24	13.63	11.72	0.19	0.25	89			
		690	17.14	3.55	48.34	11.37	0.20	0.10	100			
	CBD MW II-16 (Coarse)	170-180	7.10	1.19	12.60	7.14	0.31	0.22	91		18.25	0.090
		210-220	7.36	1.25	12.94	7.93	0.28	0.21	91			
		260-270	8.13	1.31	13.29	8.34	0.27	0.19	92			
		340-350	7.43	1.21	12.88	7.73	0.29	0.21	91			
		390-400	8.98	1.43	13.35	7.57	0.30	0.17	94			
	CBD MW II-18 (Coarse)	180-190	6.81	1.10	11.16	7.39	0.33	0.31	83		10.51	0.060
		260-270	8.01	2.30	5.79	1.69	1.43	0.26	96			
		280-290	6.67	1.03	11.20	8.10	0.30	0.31	81			
		330-340	7.81	1.22	11.86	9.26	0.26	0.27	86			
		390-400	7.36	1.26	11.43	7.89	0.31	0.28	86			
	CBD MW II-22 (Coarse)	180-190	8.08	1.37	11.43	6.78	0.36	0.22	91		14.45	0.070
		190-200	7.39	1.22	11.11	6.06	0.40	0.24	89			
		220-230	8.34	1.22	13.27	10.07	0.24	0.21	89			
		230-240	7.45	1.11	11.49	8.16	0.30	0.24	87			
		250-260	7.71	1.22	11.24	6.39	0.38	0.23	89			
	VVWD WELL 30 (Coarse)	230-240	3.09	0.84	5.72	4.32	0.44	0.49	81		14.93	0.094
		360-370	14.61	2.05	95.05	22.38	0.09	0.10	94			
		380-390	3.06	1.14	3.76	2.51	0.76	0.49	90			
		450-460	4.65	1.30	9.53	5.70	0.34	0.33	91			
	VVWD WELL 32 (Coarse)	370-380	4.21	1.38	6.54	3.33	0.58	0.36	92		14.93	0.094
		480-490	5.34	1.25	7.38	3.14	0.61	0.28	89			
		540-590	3.03	1.17	3.72	2.41	0.79	0.50	90			
	HUNNIGTON LIBRARY (Coarse)	270-280	3.31	0.50	6.92	8.24	0.35	0.55	69		15.84	0.080
		320-330	4.88	0.92	9.25	6.82	0.42	0.38	83			
		400-410	4.11	0.45	12.00	19.01	0.15	0.45	70			
		480-490	5.95	0.91	12.46	12.64	0.23	0.31	83			
		630-640	2.99	0.00	7.42	10.87	0.26	0.61	63			
		700-710	3.98	0.64	6.12	5.14	0.56	0.46	78			
		770-780	5.17	0.84	12.09	13.95	0.21	0.36	80			
	LACWD 40 WELL 4-67 (Coarse)	190-200	4.87	0.80	9.81	6.60	0.37	0.27	86		20.19	0.094
		260-270	6.63	1.35	18.47	8.53	0.28	0.20	98			
		270-280	3.61	1.18	4.38	3.06	0.79	0.37	98			
		380-390	4.03	0.86	12.81	12.05	0.20	0.33	88			
		420-430	4.77	1.10	19.09	14.38	0.17	0.28	93			
		450-460	2.85	0.84	6.47	7.50	0.32	0.47	88			

COARSE AQUIFERS	BBCSD Booster Station Well (Coarse)	200-210	7.10	0.63	14.23	9.24	0.26	0.30	74		5.72	0.070
		220-230	8.28	0.83	18.27	8.28	0.29	0.26	79			
		240-250	10.10	0.82	22.67	6.90	0.35	0.21	79			
		260-270	12.54	1.13	23.02	5.40	0.45	0.17	83			
		280-290	10.59	1.11	19.18	5.81	0.42	0.20	83			
		560-570	11.95	2.43	24.86	7.28	0.33	0.18	96			
		570-580	14.61	2.79	29.36	9.35	0.26	0.15	95			
		600-610	10.54	2.35	18.99	6.07	0.40	0.20	97			
		610-620	10.69	2.19	23.35	8.21	0.29	0.20	96			
	CDM Well #21-IRWD (Coarse)	334.5-347.5	0.68	0.40	2.35	5.92	0.23	1.98	32		17.44	0.060
		363-368	4.09	1.60	6.87	2.75	0.50	0.33	88			
		382-405	0.78	0.40	3.53	9.13	0.15	1.72	36			
		420.5-425	0.82	0.40	4.23	11.03	0.13	1.63	41			
		573-583	1.40	0.44	3.16	4.44	0.31	0.96	52			
		710-720	0.64	0.40	0.96	2.26	0.61	2.10	9			
		1038-1042	0.64	0.47	1.35	5.48	0.25	2.25	15			
		1105-1109	2.86	0.55	7.17	4.60	0.30	0.50	68			
	CDM Well #26 (Coarse)	708-718	3.60	0.54	9.82	5.91	0.21	0.36	74		2.22	0.055
		738-748	2.53	0.48	6.48	5.49	0.23	0.51	69			
		763-766	3.79	0.44	9.96	6.43	0.19	0.34	71			
		766-770	2.05	0.44	5.18	5.48	0.23	0.63	63			
		830-840	1.84	0.38	5.28	8.96	0.14	0.70	55			
		918-928	2.50	0.43	5.14	4.42	0.28	0.51	67			
		948-958	1.92	0.39	4.91	6.94	0.18	0.67	58			
		978-988	3.45	0.79	8.86	5.10	0.24	0.37	80			
		1010-1020	2.70	0.44	6.58	5.13	0.24	0.48	69			
		1040-1080	3.65	0.84	9.80	5.24	0.24	0.35	81			
		1158-1168	4.59	1.23	12.33	5.30	0.23	0.28	86			
		1180-1190	1.81	0.55	4.68	5.37	0.23	0.71	61			
	CDM Well #27 (Coarse)	680-686	2.82	0.67	5.91	3.98	0.31	0.49	72		2.51	0.080
		696-706	6.08	1.66	18.75	5.66	0.22	0.23	90			
		716-726	2.63	0.71	6.36	5.07	0.24	0.53	71			
		747-757	3.73	1.12	9.15	4.91	0.25	0.37	83			
		777-817	3.51	1.23	7.09	3.59	0.34	0.40	85			
		847-857	2.74	0.80	5.76	4.37	0.28	0.51	73			
		887-927	2.69	0.86	5.44	4.17	0.29	0.52	76			
		957-997	2.47	0.69	5.32	4.65	0.26	0.56	70			
		1037-1047	2.75	0.87	8.39	6.73	0.18	0.51	74			
		1097-1137	1.68	0.61	3.95	5.09	0.24	0.83	56			
		1157-1167	1.94	0.63	5.30	5.79	0.21	0.72	62			
		1187-1197	3.27	0.98	8.29	4.94	0.25	0.42	82			
	BCVWD Well #24 (Coarse)	520-530	7.47	1.23	18.71	8.98	0.23	0.25	88	5.9	20.16	0.094
		660-670	10.56	1.57	29.81	13.05	0.16	0.18	92	4.9		
		780-790	5.89	1.01	27.41	21.37	0.10	0.32	83	13.0		
		940-950	10.38	1.85	29.27	11.64	0.18	0.18	94	1.0		
		1040-1050	15.31	2.09	33.26	10.69	0.19	0.12	94	0.8		
		1100-1110	18.74	2.71	42.05	10.71	0.19	0.10	96	1.1		
		1170--1180	12.93	1.58	34.29	14.63	0.14	0.15	92	1.6		
		1270-1280	18.40	1.83	32.79	7.88	0.26	0.10	94	1.1		
		1330-1340	20.04	2.45	50.95	11.76	0.18	0.09	96	1.0		
	CVWD 8995-02 (Coarse)	290-300	6.09	1.56	9.05	4.85	0.43	0.25	95	1.4	17.17	0.094
		340-350	4.00	0.92	6.42	4.24	0.49	0.38	84			
		380-390	6.62	1.32	10.99	5.39	0.39	0.23	90	2.2		
		390-400	4.70	1.16	8.46	5.90	0.35	0.33	90			
		430-440	4.03	0.72	7.86	6.07	0.34	0.38	79	3.3		
	City of Tustin - Pasadena Ave Well (Coarse)	460-470	4.73	0.91	15.43	10.64	0.19	0.32	87		17.17	0.094
		520-530	5.66	0.80	17.74	10.69	0.19	0.27	83			
		590-600	2.39	0.59	4.34	5.33	0.38	0.63	68			
		650-660	4.59	0.83	14.34	10.82	0.19	0.33	84			
		830-840	10.72	1.83	21.22	5.62	0.36	0.14	95			
		900-910	11.92	2.09	24.99	5.45	0.38	0.13	95			
		940-950	3.80	0.82	13.23	12.57	0.16	0.40	81			
		970-980	6.13	1.07	14.19	7.73	0.27	0.25	89			
		1060-1070	2.99	0.72	8.19	10.32	0.20	0.51	77			
		1200-1210	2.80	0.74	3.22	2.94	0.70	0.54	80			

COARSE AQUIFERS	CVWD 5625-2 Redrill (Coarse) 1/4x16	580-590	4.27	0.88	8.31	6.21	0.34	0.36	82	6.8	17.17	0.094
		620-630	6.19	1.30	9.15	4.23	0.49	0.25	87	4.7		
		710-720	5.92	1.16	10.85	5.47	0.38	0.26	86	4.9		
		760-770	5.09	0.63	23.28	20.10	0.10	0.30	77	5.7		
		840-850	6.44	1.38	14.68	8.86	0.24	0.24	88	4.5		
		880-890	4.48	0.81	33.00	31.95	0.07	0.34	80	6.5		
		960-970	5.43	1.54	8.32	5.06	0.41	0.28	91	5.4		
		1020-1030	6.89	1.24	66.08	35.15	0.06	0.22	86	4.2		
		1100-1110	7.60	1.65	63.31	28.87	0.07	0.20	91	3.8		
	CVWD 6725 (Coarse)	360	1.91	0.23	4.14	6.04	0.25	0.67	61		18.93	0.040
		410	1.89	0.28	8.46	15.99	0.09	0.67	58			
		420	1.83	0.20	10.12	21.85	0.07	0.70	56			
		560	1.81	0.23	6.21	11.48	0.13	0.70	58			
		590	1.32	0.00	9.21	31.16	0.05	0.96	50			
		650	0.82	0.20	5.38	21.09	0.07	1.56	38			
	CBD II-1 (Coarse)	150-160	5.23	1.29	6.61	3.68	0.68	0.29	91		19.26	0.094
		170-180	3.93	0.70	5.35	3.59	0.70	0.39	82			
		210-220	1.24	0.00	4.19	16.05	0.16	1.24	46			
		260-270	6.33	1.94	8.01	3.50	0.72	0.24	98			
		300-310	4.64	0.73	8.70	6.24	0.40	0.33	83			
		360-370	2.14	0.00	6.86	15.96	0.16	0.72	55			
		380-390	1.39	0.00	4.42	12.76	0.20	1.11	48			
	CBD II-2 (Coarse)	150-160	14.17	2.32	29.89	10.25	0.22	0.10	99		22.85	0.094
		170-180	8.54	1.72	18.10	6.42	0.36	0.17	97			
		190-200	4.18	0.98	10.77	8.85	0.26	0.35	89			
		220-230	5.25	1.25	13.34	9.06	0.25	0.28	93			
		260-270	8.47	1.98	12.93	4.31	0.53	0.17	97			
		270-280	7.66	2.09	11.41	3.74	0.61	0.19	99			
		300-310	8.75	1.98	14.26	5.00	0.46	0.17	96			
	CBD II-3 (Coarse)	170-180	6.48	2.29	10.25	3.87	0.52	0.24	99		14.18	0.094
		190-200	5.05	1.61	11.85	6.97	0.29	0.31	96			
		220-230	5.94	2.15	8.72	3.60	0.56	0.26	99			
		260-270	5.80	1.90	9.47	4.08	0.49	0.27	98			
		300-310	7.33	2.16	11.93	3.86	0.52	0.21	97			
	CBD II-4 (Coarse)	160-170	7.13	1.86	13.06	5.01	0.47	0.22	96		15.77	0.094
		180-190	9.48	2.30	17.28	5.20	0.45	0.16	98			
		210-220	10.02	2.54	15.96	4.46	0.53	0.15	99			
		230-240	6.65	1.61	13.12	5.43	0.43	0.23	94			
		240-250	6.78	1.66	13.38	5.37	0.44	0.23	96			
		280-290	9.62	2.40	20.82	6.17	0.38	0.16	100			
		300-310	10.21	2.44	20.29	5.49	0.43	0.15	99			
		330-340	6.20	1.53	12.15	6.19	0.41	0.25	98			
	CBD II-6 (Coarse)	120-130	6.59	1.93	8.70	3.49	0.71	0.23	97		17.17	0.094
		140-150	5.93	1.94	7.24	3.28	0.75	0.26	99			
		170-180	7.05	2.15	9.07	3.32	0.75	0.22	100			
		200-210	7.00	2.15	9.25	3.43	0.72	0.22	100			
		230-240	6.75	1.97	8.48	3.38	0.73	0.23	98			
		280-290	4.85	1.16	9.11	5.73	0.43	0.32	90			
	CBD II-7 (Coarse)	140-150	9.36	2.94	12.01	2.94	0.78	0.17	100		17.17	0.094
		160-170	6.95	1.86	11.98	4.58	0.50	0.23	96			
		180-190	9.18	2.30	14.35	4.39	0.52	0.17	99			
		210-220	5.61	1.71	8.91	4.31	0.53	0.29	96			
		220-230	5.93	1.73	9.38	4.15	0.56	0.27	96			
	CBD II-8 (Coarse)	130-140	5.81	0.90	6.72	3.54	0.82	0.35	84		17.03	0.094
		150-160	10.21	1.58	12.49	3.83	0.76	0.20	92			
		180-190	3.87	0.47	6.90	6.99	0.42	0.52	69			
		210-220	3.75	0.54	4.42	4.06	0.72	0.54	73			
		220-230	4.98	0.72	6.75	4.77	0.61	0.41	79			

Aquifer Type	Well Name	Depth	Filer Pack/Aquifer Ratio (D50F/d50A)	Terzaghi's Migration Factor (D15F/d85A)	Terzaghi's Permeability Factor (D15F/d15A)	Uniformity Coefficient, Cu (d60A/d10A)	Sorting Factor, Sf (CuF/CuA)	Slot Factor (d50/Slot Width)	Percent Aquifer Pack Passing Well Slot	Critical Radius (in)	Percent Filter Pack Passing Well Slot	Slot Size (in)
VERY COARSE AQUIFERS	CBD II-9A (Very Coarse)	180-190	1.52	2.28	3.36	8.67	0.27	1.12	47		17.03	0.094
		210-220	2.84	0.37	4.64	4.37	0.54	0.60	70			
		240-250	0.99	0.00	2.74	10.10	0.23	1.73	38			
		260-270	1.13	0.00	2.42	7.28	0.32	1.51	38			
		280-290	1.07	0.00	6.56	30.88	0.08	1.59	42			
	Chino Hills Well #20 (Very Coarse)	220-230	1.79	0.25	5.69	17.86	0.17	1.24	45		17.11	0.094
		340-350	4.57	0.36	9.65	10.20	0.30	0.49	64			
		420-430	2.01	0.24	4.62	10.20	0.30	1.11	47			
		470-480	5.66	0.45	9.58	7.31	0.42	0.39	70			
		600-610	1.38	0.24	4.02	12.95	0.24	1.61	36			
		650-660	2.39	0.31	8.57	17.68	0.17	0.80	54			
		710-720	4.57	0.28	8.46	7.47	0.41	0.42	67			
		780-790	3.28	0.28	6.56	8.78	0.35	0.68	57			
		890-900	2.11	0.24	9.68	21.23	0.14	1.05	49			
		960-970	2.71	0.26	6.66	11.53	0.26	0.82	54			
		1040-1050	2.43	0.31	4.34	8.60	0.35	0.92	52			
	CDM Well #22-IRWD (Very Coarse)	290-294	2.52	0.47	3.69	2.70	0.54	0.59	64		5.80	0.060
		306-314	0.67	0.41	1.95	5.00	0.29	2.22	24			
		432-442	0.60	0.40	0.66	1.74	0.84	2.49	5			
		515-524	1.61	0.45	3.30	4.44	0.33	0.93	53			
		560-563	2.00	0.46	3.47	3.90	0.38	0.75	57			
		563-573	1.17	0.45	2.06	3.61	0.41	1.28	37			
		669-673	2.18	0.50	4.02	5.34	0.27	0.69	62			
		673-680	1.28	0.44	2.71	4.40	0.33	1.17	45			
		718-722	5.61	2.18	9.66	3.98	0.37	0.27	94			
		735-740	4.70	2.21	7.07	2.60	0.56	0.32	96			
		816-831	1.96	0.44	5.00	8.00	0.18	0.77	54			
		916-925	2.39	0.69	4.90	3.53	0.42	0.63	77			
	CDM Well #28-Monte Vista (Very Coarse)	640-644	1.29	0.45	3.48	7.26	0.20	0.97	51		17.42	0.070
		664-674	1.91	0.54	3.16	3.77	0.38	0.66	64			
		717-727	0.82	0.42	1.79	3.87	0.37	1.53	33			
		791-799	2.09	0.51	3.80	4.12	0.35	0.60	66			
		839-849	2.00	0.46	5.22	7.32	0.20	0.63	60			
		918-924	1.21	0.44	2.93	6.31	0.23	1.05	48			
		996-999	3.42	1.06	6.95	4.24	0.34	0.37	87			
		1017-1027	1.43	0.45	3.07	4.80	0.30	0.88	55			
		1104-1106	2.35	0.51	10.72	12.20	0.12	0.54	65			
		1119-1123	1.28	0.44	3.77	8.14	0.18	0.98	50			
		1128-1170	0.83	0.41	2.18	5.45	0.27	1.53	38			
		1212-1216	1.91	0.45	5.67	8.32	0.17	0.66	59			
	JCSD Well #23 (Very Coarse)	180-190	3.20	0.42	4.37	5.03	0.64	0.56	70		20.19	0.094
		190-200	1.75	0.24	2.37	5.18	0.62	1.02	49			
		210-220	3.05	0.34	3.54	4.63	0.69	0.58	67			
		220-230	2.53	0.30	2.91	4.82	0.66	0.70	61			
		290-300	8.11	0.46	8.45	4.09	0.78	0.22	81			
		300-310	1.41	0.21	2.29	6.76	0.47	1.26	42			
		390-400	1.23	0.17	2.19	7.97	0.40	1.45	41			