



Preventive Well Maintenance Reduces Costs

**Neil Mansuy & Gregory P. Miller
Subsurface Technologies, Inc.**

Introduction

The starting point for all water treatment processes, and the initial cost of delivering on-specification water, is the raw water supply. Roughly, 50% of all raw water supplies are obtained by extraction from groundwater aquifers using wells. Well operation and maintenance costs exceed treatment costs for many groundwater users (1). Reduction of costs associated with wells can significantly reduce the total cost of delivered water.

Wells experience loss of production capacity, and water quality problems, as a normal process of aging. The causes are normally categorized as physical, mineral and biological. Often, bacteria growing in biofilms can filter minerals from the water as it passes over the surface. Within this biologically accumulated material, fines from the formation (clay, silt, and fine sand) can also become trapped. This trapped or accumulated material increases costs by reducing the efficiency of the hydraulic connection between the well and the aquifer. The power required to pump water grows proportionally to the lost efficiency. If allowed to proceed, well plugging can result in total loss of the well (2). Power use is not the only cost increase; the rehabilitation costs more and takes longer if deposits are allowed to accumulate and harden. Maintenance problems have become recognized as one of the most significant costs of operating pump-and-treat systems and water supply wells. Additional cost is associated with extended downtime for rehabilitation leading to the need for additional wells and the inability to achieve a design extraction rate and maintain capture. The most extreme costs come with complete loss of a capital asset, and the returns that asset would have provided. There is incredible natural variability in water chemistry and aquifer composition, requiring specialized materials and construction techniques to install wells that perform as expected. Wells are significant capital investments that require maintenance to provide the expected value.

A physical analog for an aquifer is much closer to a kitchen sponge than 'rivers of subsurface water'. It is in that environment, sponge vs. river, that we construct wells for extraction of groundwater. A well is for all practical purposes a straw in a sponge; it is not difficult to visualize that all water that is extracted from the straw must be filtered through a very small volume of sponge, close to the straw. The subsurface environment is not aseptic; it teems

with microorganisms. Because of the concentration of flow near the well, microorganisms receive a better food supply than elsewhere in the aquifer, and thrive (3). That same concentration of flow serves to mobilize the finest particles of the aquifer ‘sponge’, transporting them to the interface between the well and the aquifer, reducing open space (pore volume). Any reduction of open space in the aquifer will impede flow to the well.

In the water well industry, “rehabilitation” is a term used to reflect many different repairs, some of which have no effect on regaining well efficiency. Maintenance is the term generally used when the well repair does not involve pulling the pump, an often lengthy and expensive process. For clarity, we define rehabilitation to be a well cleaning process designed to restore lost production capacity, or solve quality problems, that requires the pump to be pulled. The rehabilitation process will generally involve iterative use of chemical, physical, or thermal treatment, singly or in combination, designed to loosen or dislodge fouling; and, physical surging, scrubbing, and pumping (work-over) to move the dislodged material into the well where it can be removed. Here, we define maintenance as well cleaning procedures that do not require pulling the pump. Preventative maintenance consist of a program of well cleaning with the pump in place that is conducted at a frequency and level of effectiveness sufficient to greatly reduce, or eliminate, the need for rehabilitation.

The routine operational procedure regarding well fouling and plugging is to wait until the well has experienced a significant problem before performing some type of rehabilitation or maintenance treatment. Often, the amount of deposited material can be very extensive, and complete removal of the deposits can be difficult. Under these conditions, it is difficult to achieve the same pore volume that existed when the well was new. Maintenance is often performed when rehabilitation is required to reduce apparent costs. Cleaning a well with the pump in place creates a significant limitation for removing material from the bottom part of the well and the surrounding aquifer. Consequently, the bottom parts of many wells are not effectively cleaned due to the lack of velocity to get deposits detached from surfaces and effectively “flush” them from the well. Traditional chemical treatments are often not capable of delivering the necessary energy to remove the deposited material and return to the original surfaces of the well screen and aquifer materials. Chemical treatments aggressive enough to clean the well screen and pore volume can be too aggressive for pumps. This causes less and less pore volume to be recovered each time a maintenance treatment is performed and the time frame between treatments becomes shorter and shorter. This historical limitation to maintenance efforts lies wholly in the inability to deliver sufficient force and chemistry into the well and the surrounding aquifer to clean the well and remove the deposits with the pump in place. We report on an effective CO₂ based preventative maintenance system that delivers the required force and chemistry to maintain original well capacity, improve water quality, reduce downtime, and cost far less than a rehabilitation or conventional maintenance program.

Well Performance and Capacity

There are several quantitative measures of well performance. The most commonly thought of is discharge (Q), the volume of water produced per unit time. The vertical distance between the static, non-pumping water level, and the pumping water level is called drawdown

(s). The greater the drawdown, the higher the power costs. If you try to discharge more water than can be supplied by the aquifer, or will pass the aquifer-well connection, water levels in the well decrease until the pump is exposed and the well runs dry. Drawdown is reduced by construction of higher capacity and/or efficiency wells at higher cost. Optimization of design results in a well that minimizes drawdown and construction cost while meeting the required discharge rates and intervals. When a significant safety factor is used in the well design, the well is said to have excess capacity.

Wells are often pumped at variable discharge rates, discharge varies with drawdown, and drawdown increases with the duration of pumping. A normalization of the data is needed for comparability. Specific capacity is a normalized measure of well performance (Q/s) indicating the amount of water that is available per unit drawdown. A decrease in specific capacity is a general indication of well fouling. Unfortunately, by the time that large losses in specific capacity are observed, well plugging has progressed to the point where rehabilitation, rather than maintenance, is required to restore lost capacity.

We have found that losses in specific capacity over time can be highly nonlinear. This behavior has negative consequences. First, it makes it very difficult to make a priori estimates of when a well requires maintenance, to avoid rehabilitation, without significant practical experience. Local and regional variability in hydrogeology makes a generic approach to scheduling maintenance unreliable. Second, precipitous losses in specific capacity or large increases in drawdown may make it abruptly impossible to obtain the needed raw water supply. This will have a calamitous impact on the users of that water. Third, the level of redundancy required to ensure a well-based raw water supply increases capital costs, decreasing the feasibility or profit potential of groundwater based ventures. These negatives can be offset to a substantial degree with reliable preventative maintenance programs. To understand the reasons behind the unpredictability we need to examine the governing equations and their physical basis in the well-aquifer system.

The well-aquifer system has a natural resistance to flow. Drawdown results from that resistance. Several components contribute resistance to flow. The total drawdown (s_t) under pumping conditions can be expressed by the sum (4):

$$S_t = S_a + S_{wl} + S_{pp} + S_b - S_r \quad \text{Eq. 1}$$

where:

s_a = the resistance to groundwater flow from within the aquifer;

s_{wl} = the well loss attributable to the transition from laminar to turbulent flow, at or outside the well screen;

s_{pp} = the drawdown due to a well screen only partially spanning the thickness of the aquifer, due to vertical flow components;

s_b = drawdown caused by the finite extent of an aquifer; and,

s_r = the decrease in drawdown (buildup) that is caused by local recharge to the aquifer.

Total drawdown increases with pumping duration because the aquifer is dewatered, decreasing the saturated thickness, increasing the value of s_a . With respect to well rehabilitation and maintenance, the primary term of interest is s_{wl} , the well loss. We expect the other three terms in Eq. 1 to remain relatively constant over time.

Figure 1 schematically illustrates the relationships between well loss, drawdown, and static and pumping water levels. If the well loss term is insignificant, the well is near 100% efficient, and the pumping water level is equal to the lowest level of the cone of depression. High capacity wells are rarely 100% efficient, even when new, due to a combination of factors that contribute to well loss. The most commonly cited physical reason for well loss is a transition from laminar to turbulent flow. Well plugging also contributes to the well loss term. Jacob (5) examined the differences between theoretical and observed drawdown and crafted an empirical approach to separating the drawdown due to s_a from that due to s_{wl} . There have been few advances in Jacob's approach since that time, in fact, it has been demonstrated that there are serious practical problems in the approach (2). The transition from laminar to turbulent flow has never been measured in geomedium near a production well. The groundwater flow in the near well environment is not well understood.

At this time, our ability to quantify and mathematically describe the physical controls on well losses is poor, although the combined value of s_a and s_{wl} can be measured quite accurately. Part of the problem is that the well losses are assumed equal radially and vertically from the well screen, when in reality those conditions are a very rare exception. Additionally, the well loss analysis requires that we identify the radial distance of the transition from laminar to turbulent flow (r_w). This distance is poorly known, and often arbitrarily set as the well screen radius or an estimated, larger, developed zone. The physical situation depicted in Figure 2, where the boundary between s_a and s_{wl} effects lies farther from the screen cannot be discriminated from the situation in Figure 1 using discharge and drawdown measurements alone. Because the net result of plugging and fouling is large increases in well loss, in a very inhomogeneous and asymmetrical manner (1), radial approximations cannot accurately reflect reality. Figure 3 represents a simplification of field conditions; r_w will be highly variable in three dimensions and the r_w used in specific capacity evaluation will necessarily be some average of the individual values. The current limitations in evaluating the source and magnitude of well losses makes it very difficult to base maintenance programs on discharge and drawdown data.

Examination of the equation for theoretical specific capacity (Q/s_t) provides insight into how the three-dimensional variability of s_a and s_{wl} prevent the detection of incipient plugging prior to catastrophic loss of production capacity or water quality. From Walton (4) theoretical specific capacity in English units is defined as:

$$\frac{Q}{s_i} = \frac{T}{264 \cdot \log \left(\frac{T \cdot t}{2693 \cdot r_w^2 \cdot S} \right) - 66.1} \quad \text{Eq. 2}$$

where:

- Q/s_i = theoretical specific capacity (gpm/ft);
- Q = discharge (gpm);
- T = coefficient of transmissivity (gpd/ft);
- S = coefficient of storativity (dimensionless);
- r_w = nominal radius of well (ft); and,
- t = time since start of pumping (min).

Equation 2 assumes that there are no well losses and full well penetration (no s_{pp} losses). In the case of well losses, r_w is interpreted as the effective radius of the well; e.g. the radial distance from the well centerline to the transition between laminar and turbulent flow. Transmissivity is a measure of the aquifers ability to transmit water under a unit decline in head. From Eq. 2 we note that specific capacity varies with the log of $1/r_w^2$. Figure 4 schematically depicts the relationship between r_w and specific capacity for constant T and Q . Because of the inverse logarithmic relationship, specific capacity declines abruptly at some critical value of r_w .

The relationship between the r_w turbulent flow transition and specific capacity may be somewhat counter intuitive. Turbulent flow contributes to drawdown because of energy losses. The vertical zones of an aquifer with the longest r_w are transitioning to turbulent flow farther from the well screen because these are preferential flow paths. One might expect the energy losses over longer distances to cause turbulent flow zones to be less transmissive, to provide less water overall, however, high velocities are a result of the large flow volume. Plugging reduces flow, and velocity, causing r_w to be shortened. From Figure 4 it is clear that an abrupt transition in specific capacity will occur at some r_w for all flow paths. When highly transmissive, vertically discrete, production zones reach this abrupt breakpoint, accelerated and catastrophic loss of production occurs, generally without warning.

Gradually, in all wells, highly transmissive zones plug, and discharge is derived more and more from pathways of lower flow resistance than the plugged zone. Drawdown data provides no early indication of this plugging to trigger maintenance. As plugging continues, all flow paths develop shortened r_w and large changes in drawdown and specific capacity are noted. The concept of discrete production zones in wells having highly variable r_w , thus specific capacity, and the redistribution of production to pathways of lower resistance, are found in the pre and post rehabilitation data from a high capacity production well. Table 1 presents the pre and post rehabilitation data obtained from a spinner log. The subject well is screened across multiple water production zones. A spinner log measures the contribution of each production zone to the total production under pumping conditions. From Table 1 it is clear that Zones 1 and 2 had experienced significant loss of production capacity. However, the well was still supplying its needed capacity (3000 gpm) at higher drawdown. The spinner log reveals that the flow lost from Zones 1 and 2 was being supplied primarily by Zones 3 and 4. When r_w in Zones 1 and 2 decreases to below that available in other zones, the zones with the highest r_w will supply the water, at increased drawdown. If these zones differ in water quality, as most zoned aquifers do, the water quality produced by the well will be variable as plugging progresses.

If spinner logs were conducted frequently and a model for the progression of incipient plugging to unacceptable lost capacity or quality developed for this particular well, it may be possible to detect and trigger preventative maintenance. However, spinner logs can be expensive as compared to maintenance treatments, the strategy may not be cost effective. For a groundwater user with many wells, development of a regional or local model for maintenance intervals based on intensive study of a limited number of wells may be cost effective. At this time, maintenance intervals are generally selected based on: the frequency of historically required rehabilitation; the success of those rehabilitations; local and regional data from similar wells; practical experience with the maintenance technology; and, intuition.

Table 1: Redistribution of Production Due to flow Resistance

Production Zone (ft)	Pre-Rehabilitation Production (3000 gpm total)	Post-Rehabilitation Production (3000 gpm total)
Zone 1 0-400	600	1,074
Zone 2 400-570	568	1,002
Zone 3 570-700	793	267
Zone 4 700-800	481	150
Zone 5 800-1000	314	194
Zone 6 1000-1030	244	313

In the past, a 15% to 20% loss in specific capacity was the recommended guideline to commence a rehabilitation effort. In many cases, this may already be too late to create enough disruptive action with the pump in place because significant deposition can occur prior to recognizing a loss of specific capacity. It would be better to use a time frame approach (e.g., every three months or six months or once a year) than to rely on the loss in a specific capacity, and it is clearly better to do it more frequently rather than less. Using the scheduled approach to maintenance, the time frame between maintenance would be determined geographically from experience in an area, well field or well. In cases where a well has excess production capacity, the specific capacity may not be a true measure of hydraulic efficiency. In these cases, you could actually recognize significant loss of the porous media capacity, much of the aquifer capacity or production capacity. Much of the porous media surrounding the well could be plugged without affecting the specific capacity. In the case where a well has excess capacity, then the preventative maintenance needs to be performed as soon as there are any losses in specific capacity, which can be frequent.

Critical lost capacity conditions are generally met by crisis management strategies. Maintenance operations are often ineffective because the volume, extent, and durability of the encrustations and plugging prevent effective cleaning without pulling the pump. Time and money are wasted on these efforts. A well rehabilitation is ordered, and downtime stretches into weeks of lost opportunities and escalating costs. The well is restored to operation, or replaced with a new asset, and the historic paradigm of ruin, rehabilitate, and replace continues. Effective preventative maintenance strategies clean the well during the incipient plugging phase, when the deposits are softer and easier to remove, the only time that maintenance results in effective restoration of lost capacity.

Aqua Gard™ CO₂ Based Preventative Maintenance System

In order to remove deposits from surfaces, you must deliver adequate energy into the well and aquifer. This energy can be described as energy to disrupt and dissolve, detach, mobilize, and fluidize plugging and encrustations. The energy needs to operate on the surfaces of sand, gravel, and well screen allowing the deposits to be removed more effectively during the pumping off phase. The effective removal of the detached sediments requires keeping the sediments in suspension, which is accomplished by producing energy of agitation during the pumping off phase.

Shock chlorination as a preventative maintenance chemistry is too limited in its ability to remove deposited material. The effectiveness of shock chlorination is lost once the microbes have developed their biofilm protective mechanisms. These same biofilms are associated with mineral deposits and trap migrating fines. Once protected, disinfectants are often not going to be able to impact the biofilms. We are better served looking to more broad-range chemistries, such as acids and bases with buffers and inhibitors, occasionally thermally assisted, for preventative maintenance. However, even with the best chemistries for preventative maintenance it is still very difficult to get good removal of material, in large part because of the inability to get enough energy into the bottom of the well and the surrounding aquifer for mobilization and fluidization. A separate problem for blended chemistries is that the biodegradable portions themselves can contribute to biological growth. These problems can be overcome, with the pump in place, by using a treatment chemistry and application method that can provide sufficient force and chemical activity to bring about the desired result.

We have determined that application of liquid and gaseous CO₂ to well screens and formations brings about the desired result. This new concept relies on the permanent, strategic placement of energy injection equipment at various points in the well. The concept is to begin to keep surfaces clean in a well and the surrounding aquifer instead of waiting for the surfaces to become completely fouled and encrusted.

Preventative well maintenance programs can be very effective in reducing well problems and can help to maintain the well's production. As mentioned earlier, it is common practice to operate wells until they experience a significant loss of specific capacity before rehabilitation efforts are performed. At this point, it can be more difficult, if not impossible, to restore the capacity to its original condition because of the amount of plugging of the well screen. Preventative maintenance treatments offer the advantage of removing deposited material at the early stages.

The periodic removal of the deposits at the early stages of their formation may also help to slow the rate of corrosion experienced in wells. Much of the corrosion in wells is caused by "tuberculation" resulting from a symbiotic growth of iron related and slime forming bacteria with the sulfate reducing bacteria. The sulfate reducing bacteria are growing in the anaerobic zone created by the aerobic slime forming bacteria. Most of the corrosion is occurring under the tubercles. Since the surface fouling is necessary for the corrosive environment to occur, by using CO₂ well maintenance system you can prevent much of the under deposit corrosion.

The CO₂ based preventative maintenance system, with energy injection equipment installed along with the existing pump, eliminates the need to remove the pump while achieving the energy necessary to remove deposits from surfaces and mobilize them out of the well. The use of gaseous and liquid carbon dioxide offers one of the best methods of delivering energy into every part of the well and the surrounding formation without removing the pump. This periodic cleaning of the surfaces can be performed on a scheduled interval, determined by the historic rate of fouling and the current data readings. The cost of the periodic cleanings is significantly less than the cost of a major well rehabilitation. CO₂ offers the advantage of not having to neutralize or dispose of spent chemicals. Some applications may need the addition of chemical energy along with the use of liquid carbon dioxide. In some instances, this chemical energy may help to more completely detach the biomass and associated minerals. Once the material has been detached from the surfaces, it needs to be removed from the bottom part of the well and the surrounding formation. This can best be achieved with the simultaneous pumping and occasional fluidization of the sediments and deposits. This will allow more complete cleaning of surfaces and allow the original pore volume that exists around wells to be maintained more effectively. The maintenance of the pore volume and keeping surfaces clean therefore extends the timeframe between rehabilitation efforts.

Barrier wells and injection wells that are not equipped with pumps can be maintained using the CO₂ to air lift the material from the well and the surrounding formation. Once the material has been detached from the surfaces, it needs to be removed from the bottom part of the well and the surrounding formation. This, again, can best be achieved with the simultaneous pumping and occasional fluidization of the sediments and deposits.

Results

Two test cases are presented here with costs and savings calculated over a 36-month period. The first case is a facility used for breeding laboratory mice primarily for the pharmaceutical industry, shipping 10,000 mice per week. Water at the site was primarily used for facility cleaning, stock feed and domestic purposes, excluding consumption. Prior to the installation of the Aqua Gard systems all of the wells at the site tested positive for total coliform and *e.coli*, rendering it non-potable. The site was chosen based on the following criteria:

- Multiple wells (nine)
- High rate of well fouling
- Extreme biological activity (Iron Related Bacteria)
- Poor water quality, multiple levels of filtration, non-potable finished water.
- Supplemental water required to meet the needs caused by rapid yield decline.

All wells are installed in bedrock with +/- 50 feet of steel casing, average dimensions equaling 6"x 200' and producing an average yield of 10 gpm. Specific capacity and well yields would decline to zero within six months of prior well maintenance efforts. Severe plugging/fouling occurred not only within the well, but inside the pump, drop line and offset lines to the facility. Maintenance of the nine wells located at the site was previously performed

on each well, using non-CO₂ chemical cleaning, every six months in an effort to maintain yields and capacities. Cleanings consisted of 1.5 days (24 man hours x \$15/hr = \$360) for each well, plus \$60 in chemical cost/well/service for a total of \$420/well cleaning. Cleaning efforts resulted in marginal increase in yield and capacity, with such increases declining immediately. Poor water quality caused by very high levels of biological activity required multiple levels of filtration. Filtration cost averaged \$5,000 per month for filters. Labor to clean and change filters at the facility cost ~\$12,000/month, calculated at 20 man hours/month for each of the 38 buildings at a rate of \$15/hr for a total of \$11,400. Filtration cost totaled \$16,400, or \$1,822 per well/month. Energy costs for the pumping wells is difficult to calculate because all wells are on the same meter. The site project superintendent stated that prior to the preventative maintenance program, all nine wells were pumped constantly during 24 hour periods to meet the demand of the plant. Cost benefits are presented in Table 2.

Table 2: Cost benefit from preventative well maintenance

Task	Old Program	Aqua Gard™ Program	Savings
Well rehabilitation		\$9,200	
Aqua Gard installation		\$2,595	
Well cleaning cost	\$2,520	\$6,000	
Water treatment cost during cycle	\$65,600	\$13,600	
36 Month per well total	\$68,120	\$31,395	\$36,725
36 Month Site Total	\$613,080	\$156,975	\$456,105

Preventative maintenance installation allowed the site to pump five wells for 10 minutes each half hour, or 20 minutes per hour to meet demand because of the maintained pumping level and well efficiency's, compared to pumping nine wells for 24 hour periods prior to installation and scheduled service events. The wells now provide all of the water needed to meet site demand with improved quality. Energy costs have been reduced by ~ 82% per month during the three-year analytical period (40 minute per hour energy savings), further reduced by pumping only five of the nine wells, as a result of the wells ability to produce more water with less drawdown.

The demand on water treatment was greatly reduced because of the improved water quality. The required labor to clean and change filters after Aqua Gard installations was reduced from 760 man hours per month to 160 man hours per month for the 38 buildings, representing a labor cost reduction of ~80%. Filter costs were reduced to \$111 per month. The improved water quality is a result of effective well cleaning and the ability to keep well and formation surfaces clean, through the early and preventative scheduled service events. In addition to stable increased water production, the preceding analysis demonstrates that the client has reduced his finished water costs at the site by \$456,105 over a three year period, excluding the cost savings associated with supplemental water and actual energy costs, as a result of installing preventative maintenance.

The second case study involves a municipal water supplier. CO₂ preventative maintenance was installed in five well potable water supply wells for an eastern US facility.

Water supply was intended to meet the initial and growing local demand. The first well installed had steady decline in well yield and efficiency, almost immediately following its installation. Within 6 months of installation, the well had lost ~35% of its yield and 37% of its efficiency, thereby requiring rehabilitation (Figure 5). A well cleaning was performed and the Aqua Gard system installed. Actual well cleaning costs are represented and based on historical performance rehabilitation efforts would need to be performed every six months to restore lost yield and capacity. The cost benefit analysis assumes that cleanings would be carried out every 6 months. The subsequent wells installed at the facility were immediately equipped with Aqua Gard upon construction to avoid well cleanings on a semi-annual basis.

Table 3. Cost benefit from preventative maintenance

Task	Old Program	Aqua Gard™ Program	Savings
Well rehabilitation	\$19,000	\$19,000	
Aqua Gard installation		\$7,000	
Cleanings over 3 Years	5	11	
Cost per service	\$19,000	\$3,400	
36 Month per well total	\$114,000	\$63,400	\$50,600
36 Month Site Total	\$570,000	\$317,000	\$253,000

Summary

Preventative well maintenance programs maintain the well’s production and water quality while stabilizing and/or reducing operational costs. Historically, it is common practice to operate wells until they experience a significant loss of specific capacity before rehabilitation efforts are performed. At this point, it can be more difficult if not impossible, to restore the capacity to its original condition because of the amount of plugging that has occurred within the well and near well formation. Preventative well maintenance prevents this permanent loss of capacity by removing deposits when they are easier and less costly to remove. CO₂ based preventative maintenance treatments offer the advantage of maximizing the efficiency of the well and minimizing progressive water quality deterioration, simultaneously providing the highest currently available “pump-safe” energy levels. The annualized costs of the periodic cleanings are significantly less than the corresponding annualized cost of a well rehabilitation and replacement paradigm.

References

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Figure 1:

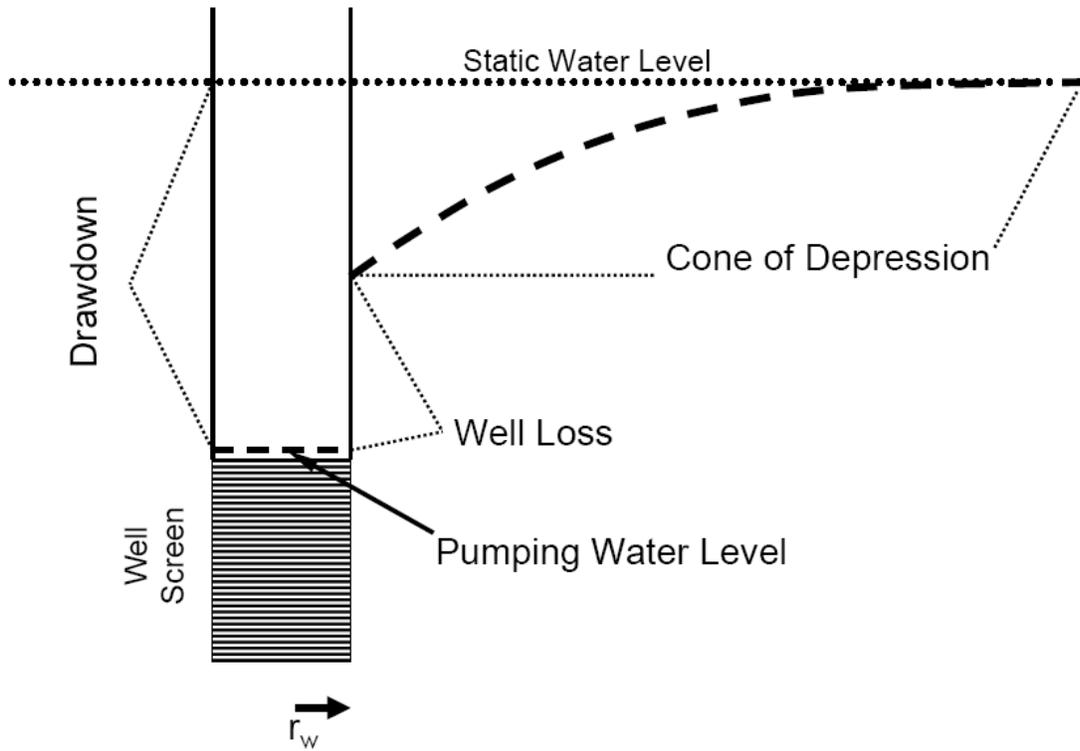


Figure 2:

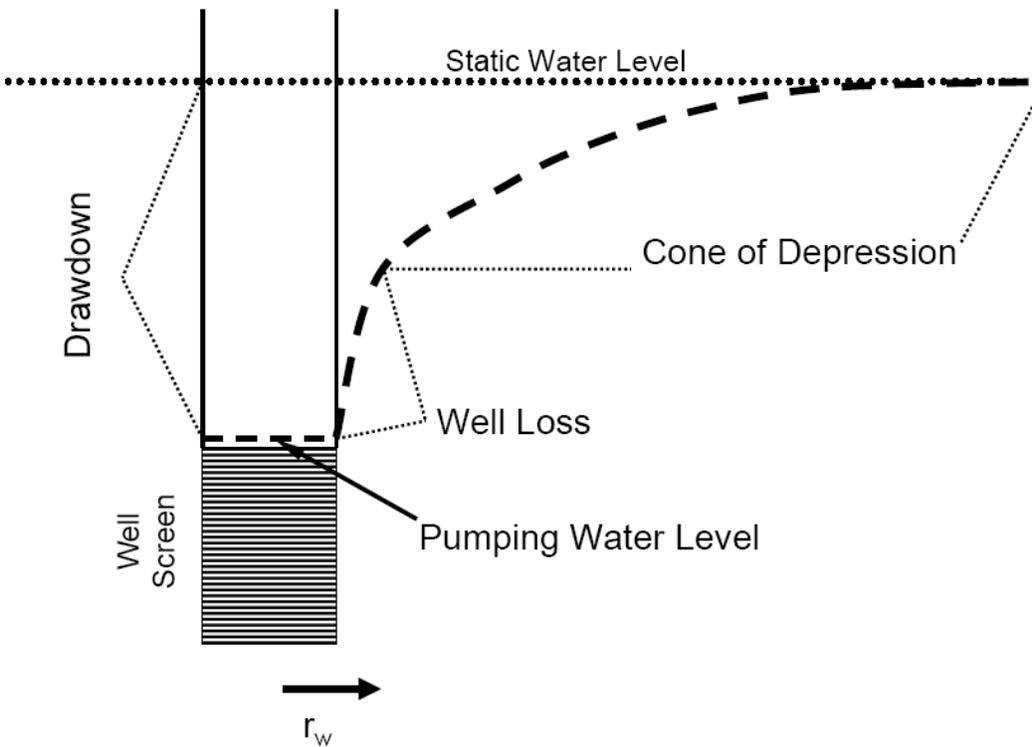


Figure 3:

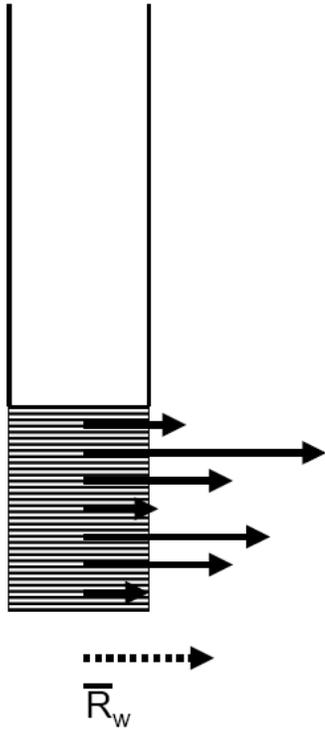


Figure 4:

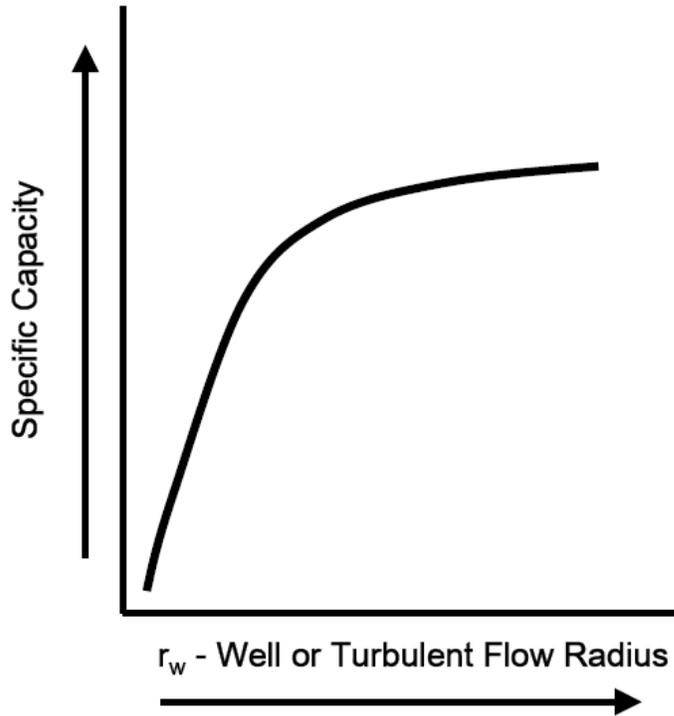


Figure 5:

