Life-Cycle Economic Analysis of Water Wells

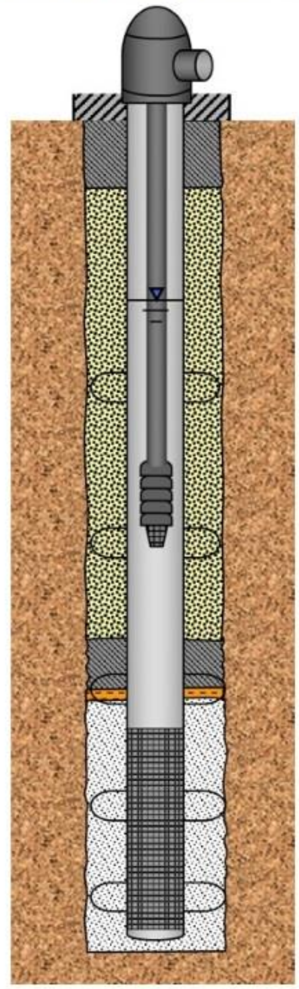
By

Marvin F. Glotfelty, R.G.*

INTRODUCTION

Water supply wells are a vital component for all entities that require a reliable water supply. This includes a broad variety of water users, such as private water companies and municipalities; power plants and industrial facilities; ranches and farms; mines; individual households; and other water users. Installation of a water well can be costly, and larger wells represent a significant capital investment that can exceed $1 million for larger municipal or industrial wells. Accordingly, many groundwater users take measures to minimize their capital expenditure for well installation by seeking less expensive construction materials and/or methods. Those cost-reduction efforts may be flawed if they result from a single-minded focus on the capital cost of the well when it is constructed, without regard to future costs that will be incurred during the remaining life of the well.

Figure 1. Life-Cycle Well Costs (Initial & Future Costs)



a) Initial well costs include the drilling contractor; construction materials; permits & waste disposal; well development & testing; and design/construction management services. Initial pump costs include the pump company contractor; pump and motor equipment; electrical and piping costs; permits; and design/construction management services.

b) Future well costs include operations & maintenance items such as energy costs; labor costs; water quality concerns; and well production concerns. Future pump costs also include repair or replacement of aging infrastructure such as pumps and motors; the well itself; and land costs for a new well location, if required.

OVERVIEW OF COST FACTORS

Depending on the design and construction techniques that are used, water wells perform differently to produce a greater or lesser flow of groundwater from the well, and variable levels of water quality. At almost any location where a well is drilled, the earth will have some degree of stratification, with some layers producing more water and some layers producing less water. Similarly, the groundwater quality will usually be stratified, with the water at some depths having good quality and with other depths producing groundwater with natural or man-made contaminants. Optimal well performance can be achieved by implementing best practices during the well construction, to identify the most favorable depth intervals for placement of the well screen.

The construction cost of a well is a one-time event, but throughout the subsequent years during which a well will be used, the well owner will continue to pay for its operation and maintenance, as detailed on Figure 1. The most important water well construction materials are the well casing and screen, the filter pack sand, and the annular seal material (bentonite clay or cement). There are multiple options for each of these materials, with varying performance characteristics and different costs. Filter pack sand and annular seal material choices are also important considerations for the performance of a water well, but this article is focused on well screen material alternatives.

For smaller-sized wells, polyvinyl chloride (PVC) well casing and screens are very effective and cost-efficient because PVC is essentially inert and low-cost. However, the structural integrity (collapse strength) of PVC is limited, and PVC loses its structural strength when exposed to temperatures over about 70°F. Therefore, steel well casing and screen materials are primarily used for larger wells. The most common steel types used for well casing and screen are ***low-carbon steel (LCS)*** (ASTM Standard A53), ***high strength low alloy (HSLA)*** steel (ASTM Standard A606 Type 4), and ***stainless steel*** (ASTM Standard A778), as shown on Figure 2. Of these three steel types, low-carbon steel (LCS) is the least expensive and also the least resistant to corrosion. High strength low alloy (HSLA) steel is more expensive than LCS, but it also reportedly provides a higher level of corrosion resistance. Stainless steel is the most corrosion resistant of the three steel types, but also the most expensive. Stainless steel well casing and screen materials are commonly composed of either Type 304L stainless steel or Type 316L stainless steel, but only Type 304L (the more frequently used and less expensive of the two stainless steel types) is considered for the economic analysis presented here.

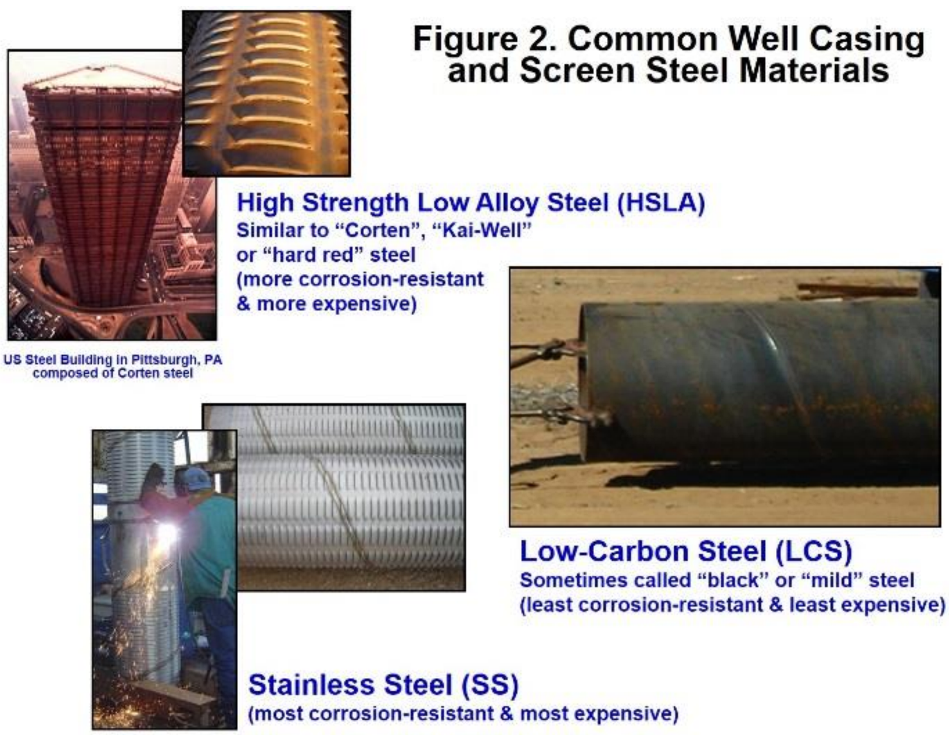
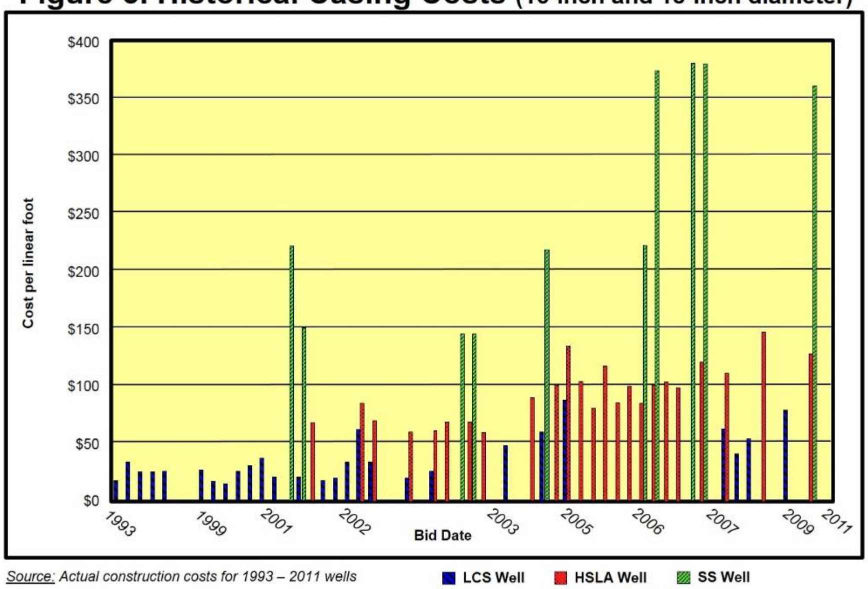


Figure 2. Common Well Casing and Screen Steel Materials

HISTORICAL WELL MATERIAL COSTS

When considering the economics of groundwater supply and wells, it is insightful to look at the fluctuations of historical well construction costs. A significant database of Arizona wells was assembled to provide such an assessment. The actual low-bid construction costs of 70 wells in Arizona were reviewed, including 60 wells from the Phoenix area, 5 wells from the Tucson area, and 5 wells from other remote areas across the state. These were all similar-sized wells with 16-inch to 18-inch diameter casings, which represent the work of 8 different drilling companies and 5 different hydrogeologic consulting firms, so this database represents a broad diversity of well design and construction sources. These wells were installed during the 18-year period between 1993 and 2011, which captures the land development boom that transpired in Arizona from about 2000 to 2008, as well as Arizona's economic decline in land development after the onset of the recession in 2008.

Figure 3. Historical Casing Costs (16-inch and 18-inch diameter)



Source: Actual construction costs for 1993 – 2011 wells

The costs for 16-inch and 18-inch diameter blank well casing ($ per linear foot) are shown on Figure 3. LCS casing costs are represented by the blue bars, which show increased costs from about $20 per linear foot in 1993 to about $75 per linear foot in 2009. High strength low alloy (HSLA) steel casing first appeared in our database in 2001 (although it had been used commonly for well construction long before that time). The HSLA casing costs are represented by the red bars, which indicate increased costs from about $70 per linear foot in 2001 to approximately $125 per linear foot in 2011. Stainless steel well casing first appears in our database around 2001 as did HSLA casing, although it had been commonly used prior to that time. The stainless steel casing costs are shown as green bars, indicating costs that are clearly much higher than the other steel types. The stainless steel costs averaged about $150 per linear foot in the 2001-2003 period, but increased to about $375 per linear foot by 2006.

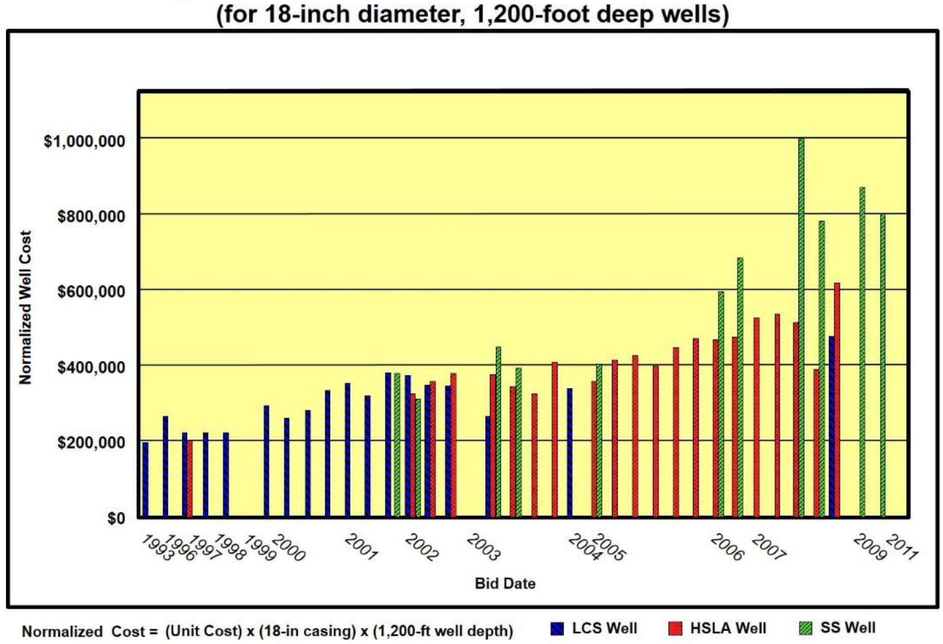
Costs for all three steel casing types generally increased over time, but a notable increase in the cost of all types of steel occurred after about 2005 (Figure 3). This abrupt increase in the cost of steel casing is not surprising, in light of the state of the global economy at that time. The years following 2005 marked a period of explosive development and economic growth in Asia and other parts of the world, which drove up the world-wide demand (and costs) for raw materials such as steel.

Although individual material and labor costs are insightful for assessment of past economic trends, the most meaningful view of historic well installation costs would be provided by the entire cost of the well installation. Comparison of well costs from different time periods is complicated by the various depths and dimensions of wells that have been drilled over the years. Even though similarly-designed wells were selected for inclusion in our database, the variability in their depths and casing diameters require us to address those size and depth discrepancies. To resolve this, an overall "unit cost" for each well was determined using the formula:

$$\text{Unit Cost} = \frac{\text{Total Well Cost}}{(\text{well diameter in inches}) \times (\text{well depth in feet})}$$

Unit costs for the wells were then normalized to the "typical" dimensions of a municipal well in the Phoenix area, so that the historical data would be comparable for different time periods. An 18-inch casing/screen diameter and 1,200-foot depth are typical for municipal wells in the Phoenix area, and those dimensions are also common for industrial and agricultural wells in the region. Figure 4 shows the normalized costs of wells between 1993 and 2011. A 1,200-foot deep well with an 18-inch diameter casing and screen would have cost about $200,000 in 1993, but that same well would cost about $500,000 in 2008 (Figure 4). Similarly, although both HSLA and stainless steel wells had estimated costs under $400,000 in 2002, their 2008 estimated costs are about $600,000 and $800,000, respectively (Figure 4).

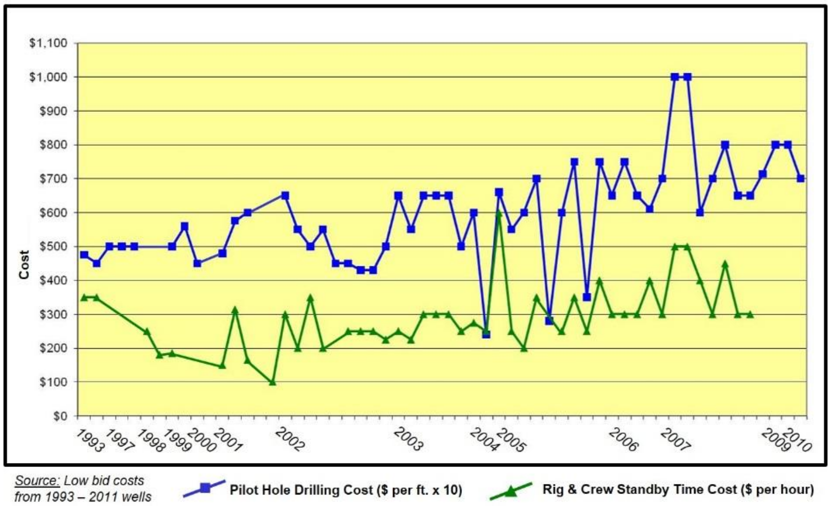
Figure 4. Normalized Historical Well Costs
(for 18-inch diameter, 1,200-foot deep wells)



LABOR COSTS

Non-material costs (such as labor, fuel, and equipment) also impact the economics of water well construction. The best representation of these costs in our well construction cost database was the unit costs for borehole drilling ($ per linear foot) and driller standby time ($ per hour). The borehole drilling costs comprise the driller's labor costs, as well as the fuel and equipment costs of the drilling rig and support equipment. Some materials are required for borehole drilling, such as drill bits and drilling fluid additives, but those materials are not represented as unit costs in a contractor's bid, so they are embedded in the linear foot costs for drilling. Standby time is charged by drillers during periods when the well construction work is suspended for such things as cement curing time, geophysical logging, or other unanticipated delays. During such periods, the driller bears the burden of overhead costs for the drilling crew and equipment, even though there is no ongoing work for which charges can be assessed. The trends of these non-material unit costs are shown on Figure 5. The pilot hole drilling costs are primarily representative of a 17.5-inch diameter borehole drilled with the reverse circulation rotary drilling method. These costs had an average trend of $50 to $60 per linear foot between 1993 and 2005, but prices increased after that time up to an average of $70 to $80 per foot by 2011 (Figure 5). Unit costs for standby time for the drilling rig and crew averaged around $250 per hour prior to 2005, but trended up to around $350 per hour in subsequent years (Figure 5).

Figure 5. Historical Labor & Equipment Costs



Hydrogeologic consultants are needed for installation of larger municipal or industrial wells to support the need for well design and permitting; geologic logging; construction management; well testing; and reporting. After the well has been installed, engineering consultants are also needed during pump infrastructure and piping installation to support the need for equipment design, permitting, construction inspection, testing, programing, and reporting. Based on recent (2011) well installations in the Phoenix municipal area, hydrogeologic consultant services (averaging about $70K/well) and engineering consultant services (averaging about $400K/well) totaled about $470K per well.

Annual operations and maintenance costs for the well owner's internal staff to perform maintenance tasks at the well sites were also included in this economic analysis. The 2011 City of Phoenix average labor cost for this work was $60/hour, with an average of about 11 to 12 hours per week (600 hours/year), for an annual cost of $36K. This well site maintenance cost is assumed unnecessary during the first year after well construction, so it was applied to the LCS, HSLA, and stainless steel wells for 72, 73, and 74 years of their life cycles. That resulted in life-cycle costs of $2.59 million, $2.63 million, and $2.66 million for the three well types, respectively.

OPERATION & MAINTENANCE COSTS

A considerable increase in the life-cycle cost of a water well will result from the growth of scale on the well screen, which will clog the screen slots and impede the flow of groundwater into the well. The accumulation of scale on the well's screen will reduce its efficiency and may degrade the quality of the pumped water. Scale buildup can be removed to improve the well's performance, but the expense of periodic well cleaning will add to the overall operations and maintenance (O&M) costs of the well throughout its operational life. Some types of scale are directly precipitated as calcite or other minerals, but most scale deposits found in water wells are the result of naturally-occurring microorganisms that form colonies on the surface of the well casing and screen. The microbes deposit incrustations of biochemical scale or biofilm on the surface of the steel. Figure 6 shows some examples of biochemical scale and biofilm on pump column pipe and on the surface of a well screen. Iron-related scale is typically composed of iron oxide or manganese oxide which accumulates from the brittle material remains (stalks, secretions, sheaths, etc.) of the biologic organisms. Biofilm may also result from microorganisms, and is produced as a buildup of soft, slimy material that results from the accumulation of biologic cells that form a protective slime layer. Both iron-related scale and slime-forming biofilm will clog the well screen and reduce its water-producing capabilities. Listed below are some well-documented facts about the naturally-occurring microorganisms that form scale or biofilm in water wells:

- **Subsurface microbes are naturally occurring, and essentially ubiquitous.** They have been found on every continent on Earth, and at depths of over 10,000 feet. Thus, we can't reasonably avoid them with well site selection or well design. Rather, we need to manage the occurrence and growth of biochemical scale and minimize its detrimental impacts on well production.
- **Water well environments in the subsurface encourage microbial growth.** A pumping well will bring groundwater from a broad radius, and the dissolved oxygen and nutrients that come with the inflow of water will augment the growth of microbial colonies and the associated scale or biofilm incrustation.

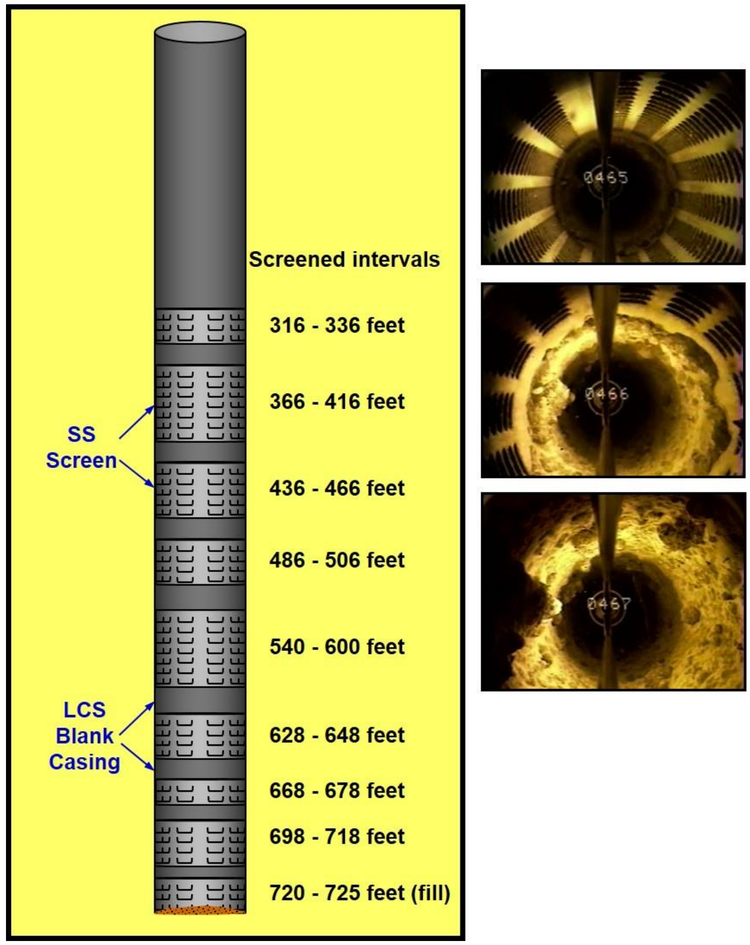
Figure 6. Scale and Biofilm Examples

Iron-related scale incrustation on pump column pipe (top & bottom-left), and biofilm accumulation on well screen (bottom-right).

- **Bacteria in water wells usually occur as interrelated colonies rather than independent entities.** There can be multiple organisms living at a single location within the well, which often support one another in a symbiotic relationship. The multiple microbial organisms can result in a variety of scale or biofilm types. In addition, just as ecosystems vary at different locations on the Earth's surface, the water chemistry and temperature will change at different depths of a well. Thus, the biochemical processes that cause scale incrustation on well screens are complex and diverse, and cannot be resolved with a single simplistic solution.
- **Bacterial scale will rapidly re-grow if well cleaning is incomplete or inadequate.** Experience indicates that if a well is only partially cleaned such that a thin layer of residual scale incrustation remains on the well screen and casing surfaces, the scale or biofilm will re-grow very rapidly due to the high surface area and the rugosity (surface roughness) of the residual scale material on the steel surface.

- **Scale and biofilm growth are related to the steel composition of the well's casing/screen.** In addition having different levels of corrosion resistance, LCS, HSLA steel, and stainless steel well screens will accumulate scale or biofilm at different rates and with extremely different degrees of incrustation. The microbial organisms seem to favor the LCS or HSLA steel over the stainless steel, likely due to the differences in metal composition. This has been observed from well videos at many locations, but because each well is located in a unique subsurface environment, it is difficult to make a direct comparison between wells at different locations. However, a well in the El Paso, Texas area with an unconventional design allowed for a direct comparison of scale accumulation on LCS versus stainless steel. The well has alternating sections of LCS blank casing and stainless steel louvered screen, as shown on Figure 7. The intervals of the well with stainless steel louvered screen have minimal scale accumulation, while intervals of LCS casing just a few inches away from the stainless steel screen show significant accumulations of scale (Figure 7).

Figure 7. Variable Scale Growth on Different Steel Types



As can be seen in the well video "screen-capture" photographs on Figure 7, there is a significant change between the minimal scale incrustation at 465 feet (top photograph) and the severe scale accumulation below 466 feet (middle and bottom photographs). The difference in scale growth is attributable to the different microbial reaction on the steel surface of the LCS below the 466-foot depth, versus stainless steel louvered screen above 466 feet (Figure 7).

The economic impact of well screen clogging from biochemical scale or biofilm can be significant. Clogging of the screen can result in a sizable increase in water-level drawdown during pumping. The energy cost to lift water to the point of use is based on the pumping water level rather than the static (non-pumping) water level, so a clogged well screen will have an immediate and detrimental economic impact. This detrimental effect can be quantified by considering changes to the total lift requirement of the water, called *total dynamic head* (TDH), while pumping at a given flow rate of *gallons per minute* (gpm) using the following formula:

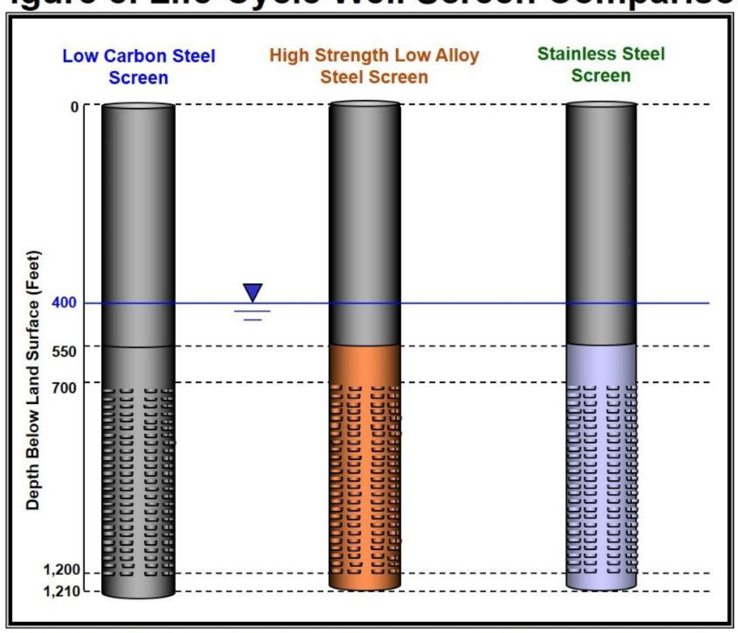
$$\text{Energy cost per hour} = \frac{(\text{gpm}) \times (\text{TDH}) \times (0.746) \times (\text{electric cost in \$/KW-Hr})}{(3{,}960) \times \underbrace{(\text{pump efficiency})}_{\text{typically 70\% to 82\%}} \times \underbrace{(\text{motor efficiency})}_{\text{typically 85\% to 95\%}}}$$

The ranges of pump efficiency (70% to 82%) and motor efficiency (85% to 95%) are applicable to new pump equipment, and the electrical cost is typically in the range of 10¢ per kilowatt-hour ($0.10/KW-Hr). So, let's consider the reasonable scenario of a large water supply well that is pumping at 1,000 gpm and operating 70 percent of the time on an annual average, with an energy rate of 10¢ per kilowatt-hour. If scale incrustation in that well causes an a 100-foot increase of water-level drawdown while the well is being pumped, then additional energy will be required to lift the water that extra 100 feet to the land surface. The resulting increase in electrical energy cost would be **$16,900 per year** – a substantial operational cost increase even for a large farm, municipality or industrial facility.

WELL LONGEVITY AND REPLACEMENT

Although the historic well cost estimates shown on Figure 4 represent reasonable estimates of well installation cost trends from previous years, current (2011) well construction data were used to determine meaningful well costs for the life-cycle economic analysis we conducted in 2011. To develop present-value costs (as of 2011) for construction of a LCS screened well, HSLA screened well, and stainless steel screened well (Figure 8), we incorporated actual construction costs from a dozen similarly-designed wells that had been installed during five recent years (from 2007 to 2011) and we coupled those construction costs with the current (2011) cost of the respective screen materials that were provided by the screen supplier, with an adjustment for contractor markup. With those considerations, the respective 2011 present-value costs (rounded) for the three wells were:

Figure 8. Life-Cycle Well Screen Comparison



All wells are 18-inch diameter and have LCS upper casing, with louvered well screen of various steel types.

Cost of LCS screened well = **$512,300**
Cost of HSLA steel screened well = **$567,000**
Cost of stainless steel screened well = **$776,400**

On the day these hypothetical wells were constructed, the stainless steel well would exceed the cost of the HSLA well by about $210,000, and would be roughly $265,000 more expensive than the LCS well. A life-cycle economic analysis enables us to address the question of whether (and when) the more expensive stainless steel well will pay for itself.

LIFE-CYCLE ECONOMIC ANALYSIS

Historical well construction costs provide us with insight on the economics of past groundwater wells, but for a look into the future cost of water wells, a life-cycle economic analysis is required. Life-cycle economic analyses provide us with a look at the long-term costs of installing and operating a water supply well, including all the *future costs* listed on Figure 1. This life-cycle economic analysis is based on well field operations data that were provided by the City of Phoenix, Arizona. The City of Phoenix is the sixth largest municipality in the United States, and since it is located in the arid southwest, water resources planning and operations are critical considerations. Thus, the City of Phoenix recognizes the importance of proper management and stewardship of its water resources in such a manner as to ensure a safe, reliable, and sustainable water supply for its citizens. The practice of forward-thinking and cost-efficient water management is paramount to the future growth and vitality of the City of Phoenix.

The design and construction attributes of water wells are driven by site-specific conditions. As hydrogeologic conditions (such as geology, depth to groundwater, etc.) vary at different locations, the well design characteristics should be adjusted in response to those local conditions. Similarly, life-cycle economic analyses of groundwater supply systems are specific not only to the local hydrogeologic conditions, but also to the purpose for which the groundwater is being used. Thus, each life-cycle economic analysis is both site-specific and system-specific, in that it is applicable only to the water use conditions and assumptions that have been rooted into that particular analysis. While the numerical results of this particular economic analysis would be applicable only to the City of Phoenix, similar results would be expected for comparable groundwater supply systems at locations with similar hydrogeologic conditions.

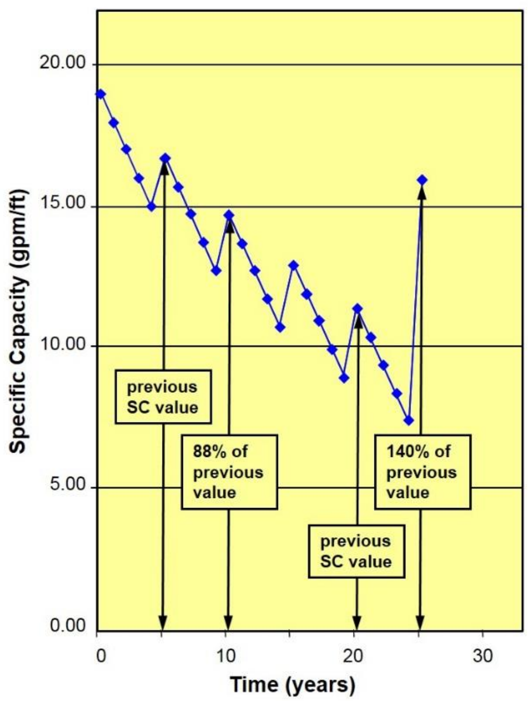
The abundance of data provided by the City enabled us to thoroughly evaluate three types of steel well screen alternatives. This life-cycle economic analysis evaluated three hypothetical wells that are essentially identical, except for having well screens composed of the different steel types. These three hypothetical well designs are shown on Figure 8. Each well is about 1,200 feet deep with an 18-inch casing diameter, and all three wells have a LCS upper blank casing (Figure 8). This enabled our economic analysis to make an apples-to-apples comparison solely of the different screen materials in the three wells.

General Assumptions: For this life-cycle economic analysis, we compared the well construction costs listed above with operations and maintenance costs that were provided by the City of Phoenix. Based on the actual reported and observed conditions of wells in the Phoenix municipal area (as of 2011), a number of general assumptions were applied to the three hypothetical wells shown on Figure 8. The following assumptions were applicable to *all three* wells:

- This economic analysis considers a 75-year well life-cycle.
- The pumping rate of each well is 1,200 gpm.
- Each well is operated 65% of the time, annually.
- *The specific capacity* value (gpm/foot of drawdown) for all new wells is 20 gpm/ft, when installed.
- The static water level is 400 feet below land surface (bls) in new wells, and that level drops 3 feet per year due to a regional water-level decline. These values are conservative, but not unreasonable for the Phoenix area.
- In addition to the pumping pressures required to lift the groundwater to the land surface, pipeline friction losses and/or land elevation changes are considered to add an extra 50 feet (about 22 psi) of lift requirement.
- The 2011 City of Phoenix electricity cost of 8¢ per kilowatt-hour was applied for all wells.
- The median pump efficiency and motor efficiency values of 78% and 87% respectively, were assumed. We assume the pumps and motors are replaced every 10 years, and new pump equipment is installed in all new replacement wells.

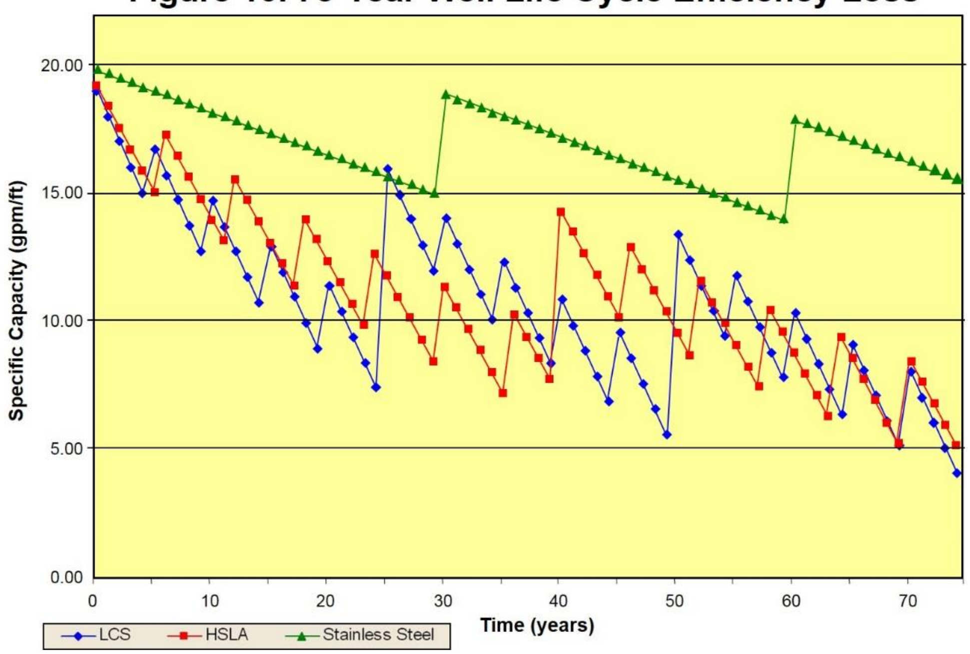
Well-Specific Assumptions: Each of the three well screen types will also have a series of unique performance characteristics. Empirical data on well performance and screen clogging in the Phoenix metropolitan area indicates that the LCS screened well would be expected to have more rapid and extensive scale accumulation in comparison to the other screen types (see Figure 7). We assume an efficiency loss (drop in specific capacity) of 25% every 5 years, so by the end of the initial 5-year period, the specific capacity will have dropped from 20 gpm/ft down to 15 gpm/ft (Figure 9). After each 5-year period, the LCS well is cleaned (alternately, by wire brushing or acid treatment), which results in an improved specific capacity. Empirical data from cleaning of numerous LCS wells in the Phoenix metropolitan area indicate that the specific capacity improvement from cleaning LCS wells averages 88% of the pre-existing well efficiency (Figure 9). That is to say, the specific capacity of the newly-cleaned well will be about 88% of the specific capacity value at the time the well was previously cleaned 5 years earlier. Local experience with LCS wells in the Phoenix area also indicates that the useful economic life of LCS wells averages about 25 years. Experience also indicates that the efficiency (specific capacity) of replacement LCS wells (at the same location) in the Phoenix metropolitan area is typically about 40% higher than the specific capacity of the old well at the time of its last cleaning (Figure 9).

Figure 9. 25-Year Life-Cycle of a LCS Well



For HSLA screened wells in the Phoenix area, experience indicates that the resistance to corrosion is superior to LCS wells, so the average longevity of these wells is about 40 years. Their propensity for scale accumulation is similar to LCS, but because of the increase of alloy metals in the HSLA steel, we consider the rate of scale growth to be slightly lower, such that a 25% drop in specific capacity will happen after 6 years instead of 5 years, as with LCS. When the well is cleaned at the end of the 6-year period, we assume a slightly better improvement in comparison to LCS wells so we assigned a 90% increase in specific capacity, rather than the 88% increase applied to LCS wells. As was the case with LCS wells, when an older HSLA well is replaced by a new HSLA well at the same location, the new HSLA well will have a specific capacity about 40% higher than the specific capacity of the old HSLA well at the time of its last cleaning.

Figure 10. 75-Year Well Life Cycle Efficiency Loss



The increased amounts of alloy metals (such as chromium and nickel) in stainless steel provide significantly higher levels of corrosion resistance, and also provide an impediment to biochemical scale growth on the surface of the steel. In the Phoenix area, wells constructed of stainless steel can reasonably be expected to last 75 years or more, and the surfaces of stainless steel well screens are not nearly as susceptible to extensive scale growth as would occur with LCS or HSLA screens (Figure 7). Accordingly, for our life-cycle economic analysis, we assigned a 75-year life cycle for stainless steel wells. Scale growth and clogging of the stainless steel well screens was assumed to result in a 25% drop in specific capacity after 30 years, after which the well would be cleaned to regain 95% of the previous specific capacity. Because the cleaning of stainless steel well screens is infrequent, we conservatively assume all cleaning of these wells to be done with acid treatment (the more expensive cleaning option)

Economic Analysis: All the costs in this economic analysis are present-value costs (as of 2011), without any projection of future costs to account for inflation/deflation. The performance characteristics of the three respective well types are supported by local observations and empirical evidence. In consideration of those performance characteristics, the declines in well efficiency during the 75-year life-cycle(s) of each well type are illustrated on Figure 10. The LCS well declines from its initial specific capacity value of 20 gpm/ft down to about 7.5 gpm/ft by the end of 25 years, when it is replaced with a second well, and later, a third well at the 50-year mark. The specific capacity of the HSLA well also drops from an initial value of 20 gpm/ft to about 7.5 gpm/ft, but for this well type that doesn't occur until just before the well is replaced at the 40-year mark (Figure 10). The stainless steel well lasts the entire 75-year period, and its initial specific capacity of 20 gpm/ft never degrades below about 13 gpm/ft (Figure 10).

The life-cycle costs for each well type are itemized in Table 1. The installation cost(s) for each well type are summarized, with the respective number of replacement wells that will be required during the 75-year life-cycle period. We also included additional well construction costs that would be expected for most well installations, which were not included in the baseline well costs. Those additional construction costs (as reported by the City of Phoenix) include: 1) sound abatement for 24-hour per day construction near residential areas (250 feet x $65/foot ≈ $16K/well); fluid disposal ($15K/well); demolition of existing facilities ($25K/well); and site re-equipping costs ($200K/well). These additional construction costs total $256K/well (Table 1).

Table 1. Life-Cycle Economic Analysis Costs

Low Carbon Steel Well Screen	High Strength Low Alloy Steel Well Screen	Stainless Steel Well Screen
Well Installation Costs $512,314 x 3 wells = $1,536,942	**Well Installation Costs** $566,974 x 2 wells = $1,133,948	**Well Installation Costs** $776,362 x 1 well = $776,362
Additional Construction Costs $256,000 x 3 wells = $768,000	**Additional Construction Costs** $256,000 x 2 wells = $512,000	**Additional Construction Costs** $256,000 x 1 well = $256,000
Consulting Costs $470,000 x 3 wells = $1,410,000	**Consulting Costs** $470,000 x 2 wells = $940,000	**Consulting Costs** $470,000 x 1 well = $470,000
O&M Labor Costs $36K/year x 72 yrs= $2,592,000	**O&M Labor Costs** $36K/year x 73 yrs= $2,682,000	**O&M Labor Costs** $36K/year x 74 yrs= $2,664,000
Well Cleaning Costs 12 cleaning events = $840,000 (includes pump removal/reinstall)	**Well Cleaning Costs** 13 cleaning events = $880,000 (includes pump removal/reinstall)	**Well Cleaning Costs** 2 cleaning events = $200,000 (includes pump removal/reinstall)
Pump/Motor Replacement Costs 9 events x $103K each = $927,000	**Pump/Motor Replacement Costs** 8 events x $103K each = $824,000	**Pump/Motor Replacement Costs** 8 events x $103K each = $824,000
Electrical Costs = $7,644,622	**Electrical Costs** = $7,591,306	**Electrical Costs** = $7,233,448

Based on City of Phoenix records, we also included the average cost for hydrogeologic and engineering consultant services during installation of a well ($470K/well), and the City's annual operation and maintenance costs ($36K/year) in this economic analysis (Table 1).

For the periodic cleaning of scale from the LCS and HSLA well screens, we assume the cleaning activities alternated between the brush-and-bail method (about 60 hours of cable tool rig time, plus pump removal and re-installation ≈ $40K/well), and the acid treatment method (chemical application/neutralization/disposal, plus pump removal and re-installation ≈ $100K/well). The sequence of brush-and-bail cleaning for the LCS and HSLA wells resulted in 6 and 7 cleaning events for the two wells, respectively. Both the LCS and HSLA wells were cleaned with an acid treatment on 6 occasions, and since the stainless steel well required only two cleanings during the 75-year life-cycle, both those cleanings were assumed to be acid treatment. Thus, the 75-year life-cycle costs for cleaning the LCS well, HSLA well and stainless steel well were $840K, $880K, and $200K, respectively (Table 1).

For all three well types, the pump and motor were replaced every 10 years, and new pump equipment was installed in replacement wells. Due to the different replacement schedules of the various well types, the LCS well had 9 pump and motor replacements, whereas the HSLA well and stainless steel well each had 8 pump and motor replacements. The 2011 cost estimates for a new pump and motor were $78K and $25K, respectively, so replacement of both pump and motor was estimated at $103K. Applying that cost to the respective number of pump and motor replacements for the LCS, HSLA, and stainless steel wells results in life-cycle costs of $927K, $824K, and $824K, respectively (Table 1).

The largest single monetary variable to be considered in a life-cycle economic analysis of water wells is the energy use. Recall from the formula presented earlier, that the energy cost is a function of: 1) the pumping rate (gpm), 2) the efficiency of the pumping equipment, 3) the cost of the electricity ($/KW-Hr), and 4) the amount of lift required to bring the water to the point of use – known as total dynamic head (TDH). Those first three items are identical for all three wells, but the TDH values are different for each well because of the variability in well efficiencies that resulted from clogged well screens during the 75-year life-cycle (Figure 10). Based on the energy cost calculations for the three well types, the LCS well, HSLA well, and stainless steel well will have 75-year energy costs of approximately $7.64 million, $7.59 million, and $7.23 million, respectively (Table 1).

CONCLUSIONS

When we sum up all the life-cycle costs listed in Table 1 for the LCS well, the HSLA well and the stainless steel well, we find that at the end of the 75-year period, the total cost expenditures for those wells are $15.7 million, $14.5 million, and $12.4 million, respectively (Table 2). This demonstrates that even though an initial cost savings would be realized by installation of the less-expensive LCS well, by the end of the 75-year life-cycle that well would cost its owner about $3.3 million <u>more</u> than the higher-priced stainless steel well. Similarly, the cumulative life-cycle costs of the HSLA well would total almost $2.1 million <u>more</u> than the stainless steel well.

The operational expenses of these wells throughout their respective life cycles are certainly non-linear, but a “broad brush” view of the overall annualized cost for each well type can be considered by simply dividing the cumulative life-cycle cost by 75. Based on this unrefined estimate, the respective average annual costs for the LCS well, HSLA well and stainless steel well are about $210K, $193K, and $166K, respectively (Table 2). This indicates that the stainless steel well would actually provide a cost savings averaging about $44K/year in comparison to the LCS well, and a cost savings averaging about $28K/year in comparison to the HSLA well (Table 2). Therefore, one could expect to recover the additional capital cost of the more expensive stainless steel well after only about 6 years when compared with the LCS well, and after only about 7½ years when compared with the HSLA well.

Table 2. Economic Analysis Results

	Low Carbon Steel $512,314 construction cost	High Strength Low Alloy Steel $566,974 construction cost	Stainless Steel $776,362 construction cost
Total Life-Cycle Cost In current (2011) dollars	**$15,718,564**	**$14,509,254**	**$12,423,810**
Differential Cost (compared to stainless steel)	**$3,294,754**	**$2,085,444**	**—**
Average Annual Cost In current (2011) dollars	**$209,851**	**$193,457**	**$165,651**
Average Annual Cost Savings from stainless steel screen	**$43,930**	**$27,806**	**—**

As previously stated, the unique hydrogeological and water system conditions of each individual water well will impact the variables that should be considered for a life-cycle economic analysis. However, well design and construction decisions that are made on the basis of a well's entire life-cycle cost rather than relying on a "low-bid mentality" that is focused solely on initial capital costs, will almost invariably benefit the well owner and in some cases, could provide savings of millions of dollars.

** Marvin Glotfelty, R.G. is a co-founder and Principal Hydrogeologist with Clear Creek Associates, a groundwater consulting firm with offices in Tucson and Scottsdale, Arizona. He is a Registered Professional Geologist in Arizona and California, and also a Licensed Water Well Driller in Arizona. During his professional career spanning over 30 years, Mr. Glotfelty has been involved with the design, installation, rehabilitation, or abandonment of over 800 water wells in the southwestern United States, and has served as Technical Director of the Arizona Water Well Association for over 25 years. Mr. Glotfelty was NGWA's Distinguished McEllhiney Lecturer in 2012, when spoke on the topic "Life-Cycle Economic Analysis of Water Wells – Considerations for Design and Construction". He can be reached at mglotfelty@clearcreekassociates.com.*