



Ground Water Science

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September 13, 2007

Brian Carey, Superintendent
Chiricahua National Monument
12856 E. Rhyolite Creek Rd.
Willcox, AZ 85643

Re: Review and recommendations for Ft. Bowie NHS water supply well

Dear Mr. Carey:

At the request of Larry Martin, we have completed a review of the situation with the water supply well constructed in 2000 at Ft. Bowie National Historical Site (Well no. 2, well registration no. 55-582902). This well has been experiencing water quality and performance decline. Larry and the maintenance staff provided file information on this well and we had the opportunity to visit the site and talk with the staff August 30, 2007.

Review of well construction and testing data

The well as previously described was completed in August 2000, is 220 ft deep, cased in 6-in steel, and torch slotted from 110 to 220 ft (1/4-in 6-in roll, 6 cuts per ft) to obtain water from fractures in a fault zone (over the interval of approximately 110-160 ft) between overlying limestone and underlying siltstone. According to descriptions, the sedimentary rock beds are steeply dipping. Static water level was ~ 51-52 ft (2000) or ~ 56 ft (2006) below ground surface.

The drilling description does not describe how the well was developed to remove mechanical damage associated with drilling. The well was test pumped at various rates on August 8-9, 2000 as described and charted by Larry Martin (August 2000 memorandum).

In addition to obtaining water quality data, these tests provided usable water level data at various pumping rates for analysis, but did not constitute standard practice step-drawdown or aquifer tests. However, it is possible to assign specific capacity and associated values and to assign well efficiency (Krusemann and de Ridder, 1994) with these data and calculations. The following table is a chart of measured, calculated and extrapolated values from the August tests.

The measured flow rates (Q) were 15, 20, 22-23, and 40 gallons per minute (gpm) and drawdown (s) values were estimated using recorded pumping water levels

(PWL) and assuming a static water level (SWL) of 52 ft as reported (about 51-52 ft), with $s = \text{PWL} - \text{SWL}$. A value for specific capacity (drawdown s at a measured flow rate Q) (designated Q/s) was calculated.

Reported, calculated and estimated parameters from August 8-9, 2000 well pumping tests

Q (gpm)	10	15	20	22	40	40	
s (ft)	24*	43	66	80	140	230*	
Q/s (gpm/ft)	0.42	0.35	0.30	0.28	0.29	0.25	
s/Q	2.40	2.87	3.30	3.64	3.50	4.00	
E_w (%)	53	44	38	35	36	22	BQ/s
B	1.26						

* Extrapolated: Step test graphical analyses can be used to estimate values based on tested values. The estimated s for 40 gpm yields more normalized Q/s , s/Q , and E_w values.

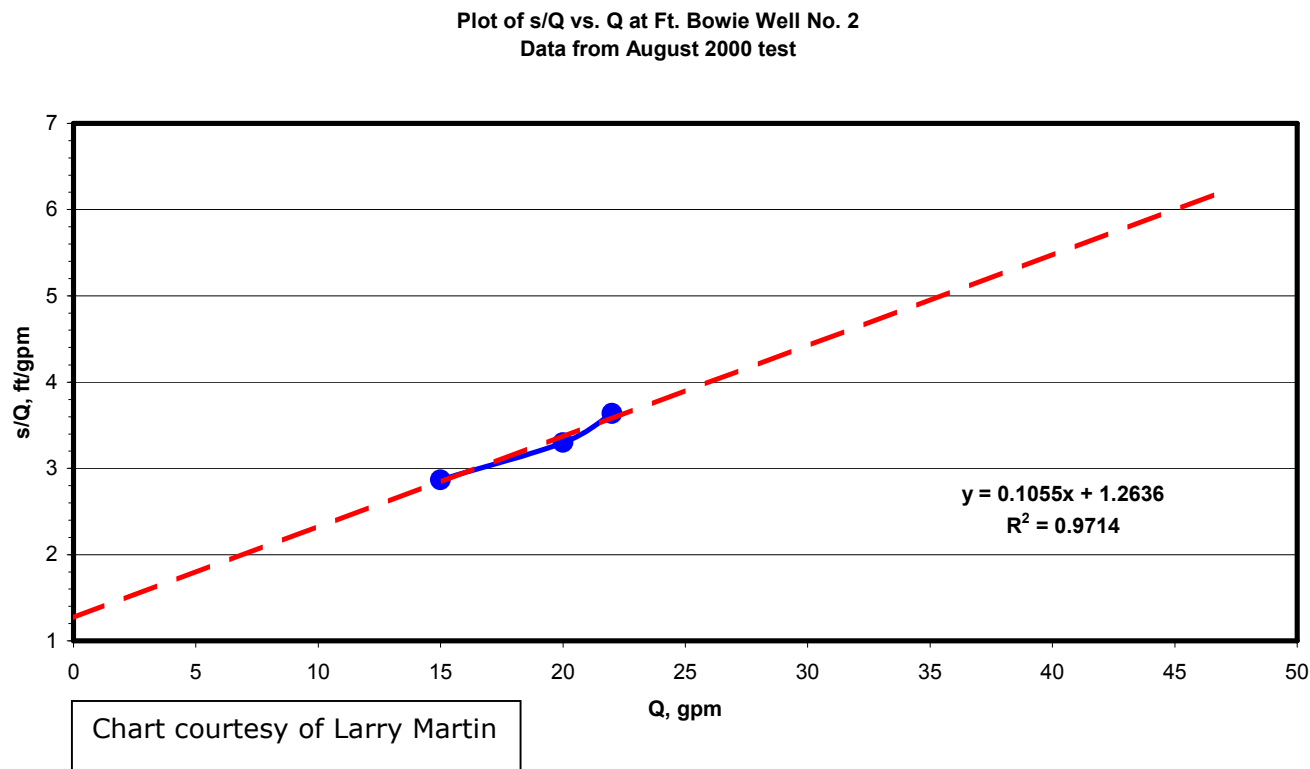
The inverse of Q/s (s/Q) is used in graphical analysis of step-drawdown pumping tests (Krusemann and de Ridder, 1994). These were not from a pro forma step test, but as the plot on the following page illustrates, they plot reasonably well on a straight line, typical of valid step test results. Using this plot, a y-axis intercept (B) can be estimated and used in the formula BQ/s to yield a well efficiency value (E_w) as shown above. This serves in the absence of calibrating values from an aquifer test.

All the values for 10 gpm were extrapolated for illustration and the $s = 230$ for $Q = 40$ gpm also estimated. The $s = 140$ ft for 40 gpm was that measured, but it is clear that it was far from being a stable PWL. Extrapolation from analysis indicates that the original 40-gpm s would exceed total well depth (about 230 ft).

In water well design, efficiencies below 70-80 % are considered poor. The other thing to note is that the Q/s values are very poor, such that drawdown is excessive. Consequently the s/Q values are very high, indicating either poor contact with the formation or very low water zone transmissivity (T). This well has been hydraulically inefficient from the beginning and began life with steep drawdown performance.

The well then was allowed to sit idle until equipped with a pump (3 HP, 25 gpm) and brought on line in February 2002. This pumping choice resulted in a system capable of drawing the PWL below the top of the slotted interval (below 110 ft), exposing these to aeration. Note also from the table that at 25 gpm, *new well* efficiency is below 35 % -- about one-half that considered acceptable in good well design and development.

Subsequent performance: As reported, reports of problems began in early 2004, starting with iron staining in fixtures and washing machines and clumps of slime in filters. Corrosion became a problem and drawdown increased.



A well cleaning was performed in December 2006, and a 15-gpm pump installed, but drawdown values remain excessive based on charts provided from the well water level recorders. Drawdown at 15 gpm in December 2006 was about 93 ft (PWL = 145 ft) for $Q/s = 0.16$ gpm/ft and $E_w = 20$ % (vs. 44 % new). By May 2007, the values were $Q/s = 0.15$ gpm/ft and $E_w = 18$ %.

Formation influences: The formation composition and structure also most likely impact the observed water quality and clogging. The log and verbal reports show a predominance of dark colors (associated with reduced depositional environment, carbon and iron content). Inclusions included pyrite (FeS_x) according to the log and a verbal report from staff of graphite being present. When exposed to flow and oxidation, pyrite can contribute abundant soluble iron (FeII), which can oxidize readily to low-solubility FeIII . Carbon supports microbial growth. The steep unit sloping allows for a large oxidation surface during drawdown, so that the oxidized clogging zone can be very large around the well.

Water quality

There is a history of water quality analysis from the new well test (Bolin Laboratories, Inc. sample date 8/9/2000) through a pre-cleaning diagnostic analysis (sampled 8/10/2004) by Water Systems Engineering (WSE), reported 8/27/2004, and finally a post-cleaning WSE report (sampled 12/11/2006 and reported 12/26/2006). Unfortunately, the original well test includes a very limited number of inorganic constituents, lacking iron (Fe) and manganese (Mn), for example. The WSE analytical suite was developed to provide information for water

treatment and well cleaning and thoroughly includes physical-chemical data useful for those purposes. These analyses also include some microscopic, microbial physiological (ATP analysis) and bacteriological analysis that the laboratory considers useful for evaluation and planning. WSE offers an analysis for "casing" and "aquifer" water, recognizing that water changes within the well and piping environment. This analysis was conducted in the 2004 testing. The 2006 testing involved a single sample analysis.

The following table provides a comparison of physical-chemical parameters that are relevant to the discussion over the analytical history (compare to the reports).

Fort Bowie Well No. 2 Physical-Chemical Data History

	Original 8/9/2000	8/10/2004		12/11/2006
	New well	WSE diagnostic		WSE post-cleaning
		Casing	Aquifer	Single sample
Total alkalinity (mg/L)	244	252	248	128
pH	7.2	7.8	7.8	6.5
TDS (mg/L)	394	460	457	520
conductivity (μS/cm)		598	594	722
Total hardness (mg/L)		256	244	244
Carbonate hardness (mg/L)	277	252	244	128
Noncarbonate (mg/L)		4	0	116
Calcium (mg/L)		252	244	152
Magnesium (mg/L)		4	0	92
Sulfate (mg/L)	63.8	71	78	92
Phosphate (as PO ₄) (mg/L)		0.2	0	195
Nitrate (nitrogen) (mg/L)	0.8	0	0.3	0.1
Total Fe (mg/L)		0.5	0.6	3.4
Dissolved Fe (Fe ²⁺)		0	0	2.3
Suspended Fe (Fe ³⁺)		0.5	0.6	1.1
Manganese (mg/L)		0	0.1	0.6
TOC (mg/L)				15.6
Tannin/lignin (mg/L)		0	0	0.7
Saturation index		0.44	0.42	-1.38
ORP (mV)		377	346	123

The water has the high hardness, alkalinity, and total dissolved solids of a carbonate aquifer water. The 2004 casing vs. aquifer results (note that these will not be totally separate – just more likely casing water in the "first flush" sample) show some slight differences typical of steel-cased wells in carbonate waters. The

environment inside the well is more oxidizing and calcite-depositing. Two possible progressions in geochemistry are highlighted in blue (TDS and sulfate) that may be due to oxidation of rock matrix minerals over time. Nitrate was somewhat higher in the initial sample (red highlight).

The sample that really stands out is the post-cleaning analysis. As the WSE analyst rightly reports, the results reflect the disturbed condition of the well post-cleaning. Persistent unpleasant odor and bursts of discoloration reported by staff up through the 8/30/2007 site visit reinforce this interpretation. A number of "outliers" or anomalous results are highlighted in red. Most of these occur in the post-cleaning report. Alkalinity is cut in half, pH down, and hardness composition and cations significantly altered. Fe (including dissolved Fe^{2+}) and Mn are much increased. We do not have original Fe and Mn values with which to compare the later tests, but the acid cleaning (see following) probably caused these alterations. Likewise, reduced (negative) saturation index goes with the acid-altered chemistry and low oxidation-reduction potential (ORP) reflects dissolution of organic material (see following) and possible access to more reduced local ground water associated with the reduced-environment rock matrix.

Of particular note are the phosphate and total organic carbon (TOC) results. Both are excessively high for ground water in the post-cleaning test. As WSE concludes, the phosphoric acid used in cleaning was not entirely removed and oxidized downhole to PO_4 . Ground water TOC is typically fractional to 1 mg/L. This TOC probably reflects dissolved biomass after the well cleaning, but it may also reflect a resurgent biofouling growth.

Biological Results of Analysis

	2000	8/2004		12/2006
Sulfate-reducing bacteria (SRB)		negative	negative	negative
ATP (cells/mL)		187,000	498,000	571,000
Total coliform		negative	negative	negative
Gallionella		many	few	negative
Leptothrix		moderate	few	negative
Protozoa		trace	few	negative
iron oxide biofilm		moderate	moderate	moderate

Biological results are sobering.

- No coliforms have been reported. That is positive.
- The SRB negative result is odd given the presence of pyrite in the formation and cleaning results reported, and may be due to near-well oxygen toxicity or sample handling issues. We usually get SRB positives regardless.
- Collecting identifiable *Gallionella* and *Leptothrix* (stalked and filamentous iron-precipitating bacteria) in a pumped grab sample so early in the well's career suggests massive filamentous biofouling. *Gallionella* are to be expected at a stark reduced-oxidized interface (e.g., deep-drawdown well in reduced-chemistry rock).

- ATP (a measure of biological activity) is something WSE analyzes that may or may not be a valid tool. Low ATP does not mean low biofouling, but high ATP means abundant biological activity. The link between ATP measured and “cells per mL” is an “it all depends” issue, but the quite high 2004 “aquifer” and 2006 results indicate that these are robustly biologically active environments and biofouling will rapidly reestablish after cleaning.
- Visible numbers of protozoa in a grab sample also suggests a biologically active environment. These are not identified, but are probably indigenous biofilm “grazers” found in many aquifers, rather than pathogenic types, if not so designated.

It appears that the well cleaning “cleaned out” visible biofouling elements collectable by grab sample at the time of the December 2006 analysis but biological activity is very high, and can be further fueled by high TOC and PO_4 .

Review of the December 2006 well rehabilitation

The specifications for this work presumably are the General Specifications included in Colleen Filippone’s July 2007 report. The work included well cleaning to improve production and water quality, pump replacement, and related plumbing and chlorination improvements. The chemistry used in the 2006 well cleaning is that recommended by WSE based on their 2004 analyses and general philosophy of well cleaning (Schnieders, 2003).

A well video was apparently not performed (no report included) and no report of pre- or post-cleaning well performance testing was provided.

The mechanical cleaning part of the specification includes scale removal and bailing prior to introduction of chemical solutions, and physical agitation during chemical introduction and purging. Such agitation is crucial to cleaning success. Debris cleaning inside the casing prior to chemical introduction improves treatment effectiveness. The contractor (Verdad Group LLC) apparently used a pump hoist rig to do this work.

Well chemical cleaning solutions specified (as noted above) are consistent with WSE’s philosophy of cleaning and their experience. Like other cleaning protocols now used, it is based around an acid and a biodispersant. WSE specifies phosphoric acid (8 %) and a polymer dispersant supplied by Johnson Screen (NW-310) at 3 % solution. The NW-310 is intended to degrade and disperse biofilms. Phosphoric acid is available in food-grade and NSF-listed forms safe for use in potable water environments and relatively safe to handle with reasonable care. As such, it is an improvement over widely used hydrochloric acid. The chemical is not especially effective against biofilm, but effective against Fe and calcite encrustations. As occurred here, its use tends to leave behind PO_4 , which is typically depleted in ground water. With a reintroduction of PO_4 , risk of active biofouling growth recurrence is increased.

Disinfection likewise followed the WSE-Johnson cleaning protocol, and is state-of-the-art in maximizing disinfection effectiveness.

In general, the specification and the work performed should be effective in principal. Some changes we would suggest based on experience with iron biofouling clogging in inefficient wells in carbonate rock:

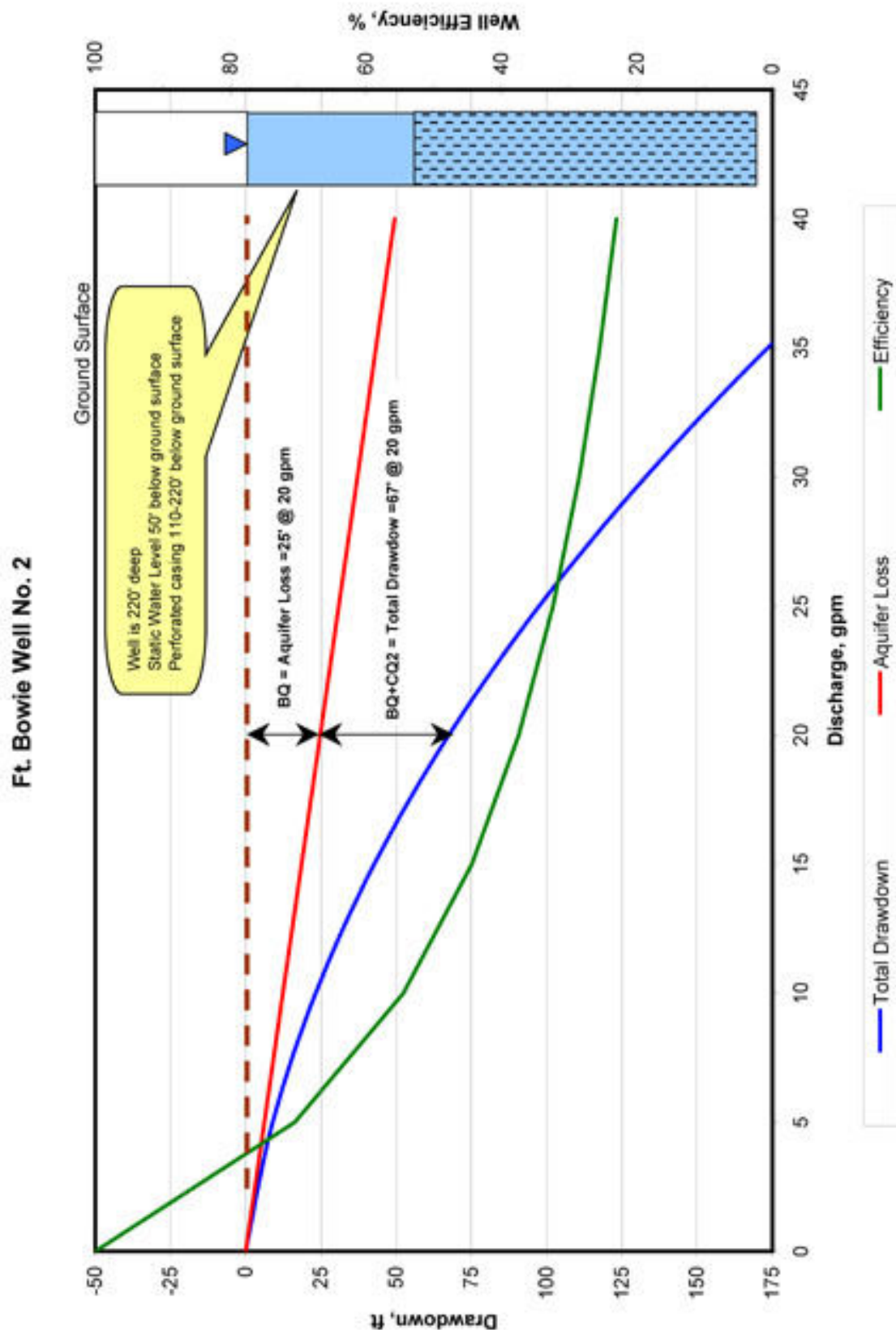
- 1) Do not use phosphoric acid again. The use of glycolic acid based solutions or blends (again with a non-P dispersant and mineral acidized) does not leave behind growth-inducing PO_4 and is similarly effective against Fe biofouling based on widespread practice.
- 2) Development was almost certainly insufficient in time and vigor. The field notes show 9 hr of swabbing and bailing, followed by pumping to purge using a 2-hp pump. Such two-part swab and bailing with a pump rig rarely generates the necessary cable velocity to move fluid in and out through such small slot openings.
- 3) Pre- and post-cleaning step-drawdown testing conclusively benchmarks hydraulic performance results.
- 4) The video would also have been illuminating and a good benchmark for the future.

There were some indicators that post-treatment development was not complete:

- Pumped water was not clear by mid-afternoon December 6, and really should have been prior to chlorination, as well as returned to background pH.
- Pumping to purge at various rates and depths helps, but the abundant black sludge should have triggered a return to swabbing.
- A bulk pH of 6 (10 x the background acidity at least), high chlorine demand in both chlorine treatments, and the persistence of discoloration and sulfide odor past the second chlorination also indicates that local low-pH "hot spots" remained.
- The persistence of discolored, bad-odor water to the present indicates that partially depleted acid water is still lodged in fractures, and should be further developed, as WSE recommended in the December 2006 report.
- The drawdowns recorded in 2007 remain excessive and efficiency poor and not anywhere near the already inefficient original values.

The poor formation contact allowed by torch-slotted wells of this type severely impairs development contact with the formation. Even with better and longer surging, "hot spots" likely would have remained for some time.

Summary chart of performance projections assuming calculated well efficiency and flow rates



Recommendations

- 1) Continue throttling the well to about 10 gpm output minimizes drawdown and oxidation in the slotted zone and is a good short term way to "buy time" until further treatment can be budgeted and scheduled. This output is sufficient for the water demand. At the time of construction, efficiency was probably ~ 53 % at 10 gpm. It is likely lower now.
- 2) With this and other wells, size pumps based on such step-test analysis, and follow the hydrogeologist's recommendation as provided.
- 3) Continue water level monitoring, reviewed monthly, and water quality analysis.
- 4) A repeat of the WSE-type analysis now nearly 1 year out is recommended. This can be conducted by WSE or we can do a similar analysis.
- 5) The well should be redeveloped further in the near future to complete the progress started in the 2006 cleaning.
- 6) In the meanwhile, it can be purged to waste as we did during the site visit, using the prechlorination diversion, shutting off flow to the chlorinator and tank. This diversion pumping against low head somewhat overpumps the well and seems to remove more discolored water.
- 7) Annual cleaning is probably necessary for this well. This, along with monitoring for biofouling parameters is recommended. A change to BART biofouling monitoring methods can permit monitoring by onsite or regional NPS personnel. Portable instruments can be used to effectively and inexpensively monitor Fe, Mn, pH, ORP, alkalinity and carbonate hardness – useful parameters that changed due to treatment. We can advise and train in these methods.
- 8) Do NOT install a pellet-dropping chlorinator on the well (or any other well).
- 9) As discussed during the site visit, in-line filtration is highly recommended to protect the tank, lines, and facility and house water supplies. Cartridge filters can be used on an interim basis, but backwashable sand filters or washable Harmsco filters (as allowed by state rules) would be a better permanent solution. For the water demand, these are small and simple modular installations. These should be professionally designed by a water treatment engineer.
- 10) For the future, a true cable tool rig capable of a higher sand-line transit velocity is recommended, along with an improvement in tools. They are still the favored workover rig of shallow oil and gas, and much favored by experienced water well cleaning companies. If contractors resist (this is a widespread problem), these can be purchased and operated inexpensively and kept in the National Monument inventory (useful for other hoisting needs).
- 11) If a video shows that slots are clogged with hardened mineral material, a good option is to treat the well using Sonar Jet (harmonic percussion) or Airburst (which has a similar effect) to rattle hard material loose and to open passages. A video and analysis is required to determine if this is a fruitful approach.
- 12) We discussed possibly increasing the slot openings in the well using a mills knife. This option should be explored further. The well should be inspected with color downhole video to determine where and how slots could be added (if they can) without impairing the well's structural integrity.
- 13) Record and evaluate cost of operations and maintenance (O&M) on this well. Include power, advisory and local personnel time, and treatments, and express in terms of dollars per 1000 gallons.

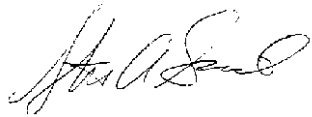
14) Compare the well no. 2 O&M costs to the cost of recommissioning and attaching to (a) the Siphon Canyon well (likely a much more efficient well) or (b) establishing another well either in alluvium or rock with a better well design. Torch slotting as a practice should be avoided in future installations. The low initial cost has not translated into long-term value.

15) It would be beneficial to the operation to have us advise further on the well-cleaning specification and chemistry to tighten up requirements and improve results. Such work is then transferable to other well work for the region.

16) This experience and lessons learned from it can be used in considering other nearby wells such as at Pinery Canyon and the Chiricahua National Monument well. The chemistry and described symptoms of the former suggests a need for cleaning that must take into consideration a difficult chemistry (high-Mn) for well cleaning.

If there are further questions, or if you wish to discuss and budget further work, please do not hesitate to contact me. This opportunity to serve the National Park Service is greatly appreciated.

Respectfully submitted,

A handwritten signature in black ink, appearing to read 'Stuart A. Smith', written in a cursive style.

Stuart A. Smith, MS, CGWP

cc: Larry Ludwig, Larry Martin, Colleen Filippone

Documents and files reviewed:

- "Evaluation of Water Supply Well Fort Bowie National Historical Site" (instructions for work)
- "Fort Bowie National Monument" (description by Larry Martin, dated July 16, 2007).
- Well Driller Report for Well Registration No. 55-582902.
- Memorandum of Trip Report, dated April 15, 1999, Larry Martin to Superintendent, Fort Bowie National Historical Site
- Memorandum of Trip Report, dated August 28, 2000, Larry Martin to Superintendent, Chiricahua National Monument
- Water level recorder data chart printouts dated 5/9/2007 and 8/27/2007 for data from December 2006 to May 2007.
- Report of analysis from Bolin Laboratories, Inc. sample date 8/9/2000 (inorganics)
- Water Systems Engineering Inc. Water Treatment Analysis and Control Report, Lab report # 16211 for Fort Bowie NHS well WSW-2-02703, 8/27/2004
- Water Systems Engineering Inc. Water Treatment Analysis and Control Report, Lab report # 17191 for Fort Bowie NHS well WSW-2PA, 12/26/2006
- Draft summary of well rehabilitation project at Fort Bowie NHS, Cochise County, AZ, by Colleen Filippone, July 12, 2007 (contains 8/27/2007 WSE report)
- Spreadsheet of well performance analyses conducted by Larry Martin September 2007.

References

Krusemann, G.P. and N.A. de Ridder, 1994. *Analysis and Evaluation of Pumping Test Data*, Publication 47, Second Edition, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Schnieders, J.H. 2003. *Chemical Cleaning Disinfection and Decontamination of Water Wells*, Johnson Screens, Inc., St. Paul, MN.