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EVALUATION OF PRODUCTION-WELL PERFORMANCE IN RESPONSE TO FORMATION CLOGGING AND REHABILITATION FOR THE KEWEENAW BAY TRIBAL FISH HATCHERY

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EVALUATION OF PRODUCTION-WELL PERFORMANCE IN RESPONSE TO FORMATION CLOGGING AND REHABILITATION FOR THE KEWEENAW BAY TRIBAL FISH HATCHERY

By

Brock O. Howell

A REPORT

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Abstract

Temporally, the KBIC (Keweenaw Bay Indian Community) Hatchery wells have manifested general trends of declining specific capacity and higher energy consumption due to mineral precipitation in and around the production wells. Monitoring data, laboratory water analyses, and downhole video logging have confirmed that naturally occurring minerals are precipitating and clogging the screens and, likely, the surrounding formations. The reduction in fluid pressures in and around the well-screens from active pumping wells is typical but, ultimately alters the geochemical and physical conditions such that dissolved minerals precipitate on and around the well-screens, therefore, effectively clogging the well. The clogging from mineral precipitation results in increased drawdown causing more pressure losses and clogging, and so on. Consequently, the pumps work harder and ultimately increase energy consumption and reduce production efficiencies.

The Hatchery's SCADA system now provides the ability to monitor flows and drawdowns, which reflect important information regarding well field performance. To be more economically strategic in managing the well field operations it is apparent that the performance data from the SCADA system must be utilized to conserve well-field-related costs. The analysis of the SCADA data clearly shows that the production well's performance diminishes with use over time due to well-screen plugging because of mineral precipitation in and around the well-screen. The observed regained performance from well rehabilitation efforts (mechanical scrubbing and/ or acid treatment) demonstrates their effectiveness, and with the use of the spreadsheet tool (developed for the KBIC Hatchery production well field), the frequency of rehabilitation efforts can be assessed on a more financially sound basis by forecasting a relative breakeven cost-benefit analysis for a particular well and associated rehabilitation. The economic analysis of power consumption and treatment costs suggests that well-treatment costs can be recovered in approximately 6-9 years based on the treatment's effectiveness in offsetting the performance declination due to mineral precipitation from pumping and relative drawdown. In other words, the magnitude of the regained well performance will be proportional to the rehabilitation method's effectiveness in removing the mineral precipitation buildup and unclogging the well screen. The SCADA system is invaluable for monitoring, understanding, and managing the well field. The continued use of the SCADA system and implementation of the other recommendations in this report will be financially beneficial as more informed flow-management decisions can be made with confidence. Furthermore, to improve life on our planet through more sustainable approaches to groundwater management, the continued development of computational tools that utilize field monitoring data in making strategic decisions for well rehabilitation and minimizing drawdown will be essential for groundwater optimization and energy cost reduction now and in the future.

1 Introduction and Background

Effective optimization of groundwater extraction is vital in terms of minimizing energy use and water consumption. Water resources, particularly groundwater resources, are becoming increasingly more sensitive to anthropogenic impacts and the trends in climate changes (longer dry periods, more intense precipitation events). It is becoming more imperative to manage water resource usage efficiently by lessening energy needs and minimizing impacts.

Production wells exhibit performance reduction over time for various reasons: either the well/pumping system is deteriorating (e.g., plugging or sedimentation) and/or aquifer levels are dropping. In either case, as it gets more difficult to pump the water from a well, production diminishes. Reduction in performance due to plugging is caused by mineral precipitation, biofilm growth, and/or screen collapse. Sedimentation (infilling) of the well can occur if fines are drawn from the surrounding formation into the well and settle out, reducing the effective screen length (Deed and Preene, 2015). Mineral precipitation occurs due to a change in the hydrogeochemistry within and near a pumping well (Briggs, 1949); (Sterrett, 2007). Biological plugging results from microorganisms biproducts that form biofilms or biomats, which is also known as bio-fouling. “The primary cause of bio-fouling, or biological clogging, of well screens and rock fractures is attributed to iron bacteria. These and other similar bacteria create a slimy, voluminous biomat.” (Rizzo and Swistock, 2022). Screens can collapse vertically due to improper design, installation, or operation. Diagnosing the causes for reduced production for a particular well will help with identifying potential rehabilitation actions and, potentially, preventative measures (Sterrett, 2007).

The Keweenaw Bay Indian Community (KBIC) Tribal Fish Hatchery well field located northeast of the intersection of Pequaming Road and Aura Road in Baraga County, Michigan, as shown in Figure 1 below, has experienced reduced production performance over time. The causes for the reductions were not obvious. Downhole video logging (E. Kleiman, personal communication) has suggested that mineral precipitation around the well screens is the most likely cause. Accordingly, rehabilitation measures (scrubbing the inside of the screens and acid treatment) have returned some of the performance. This report outlines the performance changes with time and the impacts of rehabilitation efforts.

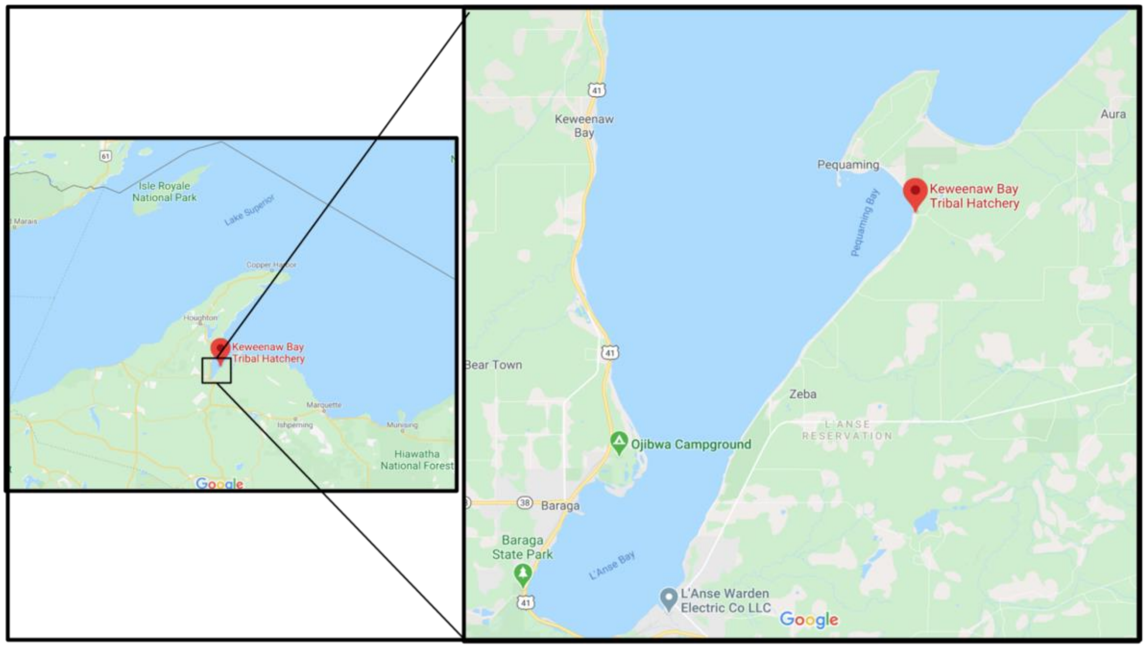


Figure 1. Site location map of the KBIC hatchery and associated well field. The red balloon pin depicted in the image above marks the location of the KBIC hatchery.

The KBIC hatchery well field has a history of performance reduction for all of the production wells. Wells 3, 4, and 5 all exhibit performance deterioration with use and the data shows that it is related to the amount of water pumped (see Results). Downhole video logging (see Appendix A) and the nature of the production decrease and responses to rehabilitation all point to mineral precipitation in and around the well screen as the likely cause.

Mineral precipitation is likely to occur in response to changes in hydrogeochemistry. These changes are due to pressure drops resulting from drawdown around the wells. Pressure drops can cause dissolved CO_2, a component of carbonic acid, to bubble out of solution and raise the pH, which, in turn, makes the geochemical conditions more favorable for mineral precipitation (Briggs, 1949; Sterrett, 2007). The blockage of pores and screen slots results in more drawdown and pressure drop, which exacerbates screen and formation plugging around the well screen. The synergistic behavior of pressure drop leading to plugging, which leads to more pressure drop, is the underlying reason for optimizing well field operations to minimize drawdowns and to develop periodic maintenance to remove the plugging that occurs (Theis, 1957).

Ascertaining the rate of plugging and the optimal timing of rehabilitation interventions is challenging because well-performance data represents a combination of factors, including inter-well effects (often called interference), seasonal changes on recharge, variable total instantaneous discharge from well field, and the nature of the plugging over time. Moreover, the improvement of rehabilitation methods cannot be predicted in advance and the impacts of acid treatment on neighboring wells is a major concern for the fish in the rearing facilities.

Wells 3, 4, and 5 are connected to a supervisory control and data acquisition (SCADA) system, which has been collecting data since December 2016. Even though Wells 3, 4, and 5 were completed in 1993, 2008, and 2011, respectively, comprehensive data on well performance has only been available since the SCADA system has been operating. The current SCADA system provides information regarding the flows and input power for each production well to their respective final discharge locations, head tanks 1 and 2 (see Figure 2).

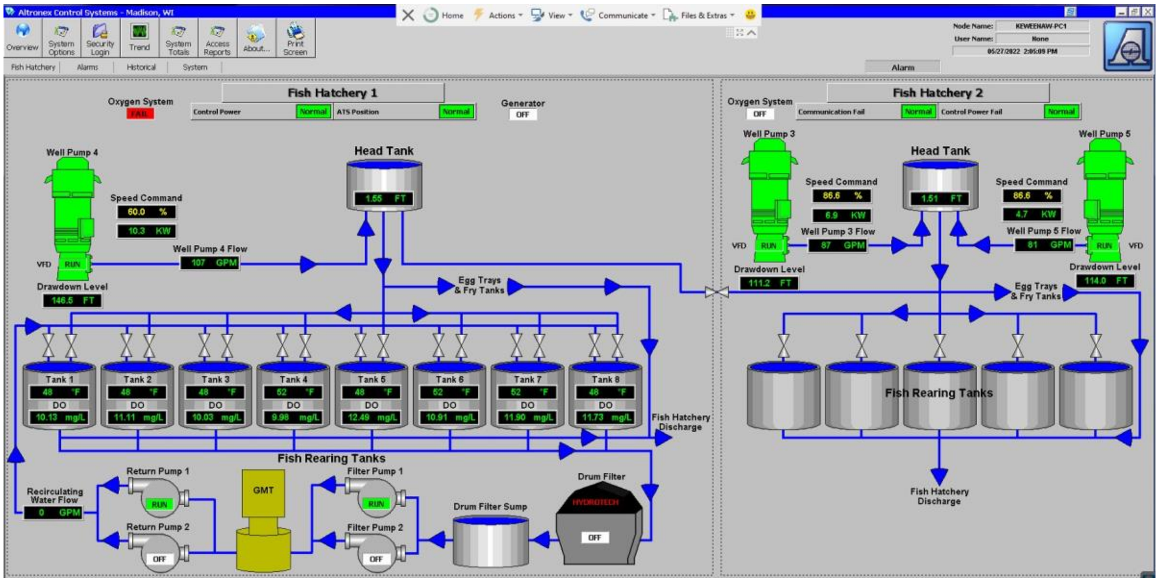


Figure 2. Current KBIC hatchery SCADA system overview displaying flow paths and values from Wells 3, 4, and 5 to their respective final discharge locations, head tanks 1 and 2. Even though the head tanks are connected for leveling purposes, Wells 3 and 5 discharge into head tank 2, and Well 4 discharges into head tank 1.

Historically, Well 2 was a production well for the hatchery until the pump was removed due to critical performance reduction. Well 2 was repurposed as a monitoring well in August of 2021 by installing a new Levelogger probe 100-feet below the top of the well cap and collecting data on one-hour intervals. The water level of the aquifer beneath the KBIC hatchery well field has been collected from Well 2 and analyzed in conjunction with the available well performance data from Wells 3, 4, and 5. This is the first collective analysis of that data.

The data analysis is complicated by the pumps operating with variable speed motors, which leads to variable flows and, concomitantly, frequently changing drawdowns. Wells 3 and 5 discharge to the head tank in (the North) Building 2, and Well 4 discharges to the head tank in (the South) Building 1, see Site Plan referenced below as Figure 3. To maintain balanced water levels among the head tanks, a supply pipe connects them. Maintaining balanced head-tank levels are used for managing tank flows, but the balancing causes more variations in flows and drawdowns, which adds to the complexity of the data analysis.

The data analysis will confirm what the hatchery staff know from their observations: (1) Well 3 performance has greatly diminished from its initial performance in 1997, and (2) Well 4 exhibits similar trends of performance loss since its initial performance in 2008. This analysis of Well 5, which was installed in 2011, data is also showing behaviors that resemble the performance degradation of Wells 3 and 4. These trends are consistent with screen/formation plugging.

Wells 3 and 4 were scrubbed mechanically, which resulted in modest performance improvements. Well 3 underwent additional treatment with a descaling agent, which more than doubled the performance, relative to the observed performance prior to treatment.

The results presented in this report clearly show the trends in performance and the impacts of the rehabilitation interventions. Until the SCADA data was analyzed over multiple-year trends, the periodic, almost seasonal, trends in well performance were unknown. The seasonal trends are different in magnitude each year and further complicate the analysis of the performance data to obtain conclusive results. However, when compared to the water levels in the monitoring well (Well 2), the apparent "seasonal" variation in well performance was more closely correlated with variation in total discharge from the production well field to accommodate the required flow for healthy fish rearing throughout an annual year, rather than the appeared seasonal aquifer recharge. This report details these findings and demonstrates a spreadsheet-computational tool for monitoring and managing well-field production.

Figure 3. Site Plan of the KBIC hatchery. The map view of the Site Plan depicts the production wells, piping connecting the wells to the two head tanks (north and south head tanks), and structures currently present at the KBIC hatchery site. The full-size map image is provided in appendix B.

2 Data Analysis: Specific Capacity and Well Performance

Water well performance is often characterized by the specific capacity (flow per unit drawdown) and the laminar and overall efficiencies (Sterrett, 2007). Efficiencies are calculated from step-drawdown tests, which were conducted for Wells 3 and 4 when each were installed, but not since, so the efficiencies are not applicable to changing performance without recent step drawdown tests. However, specific capacities of the wells can be calculated frequently now that flows and drawdowns are observable in real-time and the measurements are archived nearly continuously by the SCADA system.

Theoretically, equilibrium drawdown is directly proportional to the pumping rate (Theis, 1957). Since the Hatchery well pumps are equipped with variable frequency drives that allow adjustments to the motor and pump speeds, then variations in flows resulting from changing speeds and drawdowns change concomitantly. Despite these variations, however, the ratio of flow to drawdown will trend with respect to time, season, and neighboring-well effects.

During times when pumping rates are relatively constant, the drawdowns stabilize and calculating specific capacity (S.C., flow/drawdown) is applicable. Drawdowns typically stabilize in a few hours after flow adjustments, making conditions appropriate for calculating specific capacity.

We compiled and analyzed hourly observations of flows and drawdowns for Wells 3, 4, and 5 for the five calendar years (2017-2021, inclusive) to explore trends in the specific capacities of each well. Specific capacities were calculated from the hourly data without consideration of temporal trends after flow adjustments. Flows are not adjusted frequently, typically less often than daily, so trends over multiple days and weeks tend not to be affected by short-term (few-hour) trends occurring after a flow adjustment.

Interferences between wells were observable but not quantifiable because of the changing combinations of pumping rates among the wells and lack of definitive static water level making it impossible to distinguish interferences from the other natural fluctuations. Interferences did not seem to significantly affect the long-term trends in specific capacity. So, interferences were ignored. The time after a change in pumping rate does affect the specific capacity temporarily but continued pumping at a near-constant rate will eventually, within a day, lead to stabilized (equilibrium-like) conditions for which the specific capacity applies. There seems to be “seasonal” effects in the specific capacity data, and these effects are discussed further in Section 2.1 of this report.

2.1 Static Water Levels

The SCADA-recorded drawdowns for each well reflect the pumping water levels (PWLs) in the wells relative to the ground surface. This is not a true drawdown, except when the static (unpumped) water levels (SWLs) in the wells are at the ground surface. Although the SWLs for some wells were at or near ground surface when drilled, there has been no methodical monitoring of SWLs to assure an accurate representation of static conditions.

Although it is feasible for SWLs of confined aquifers to be as high as (or higher than) the ground surface, it is not common in this region. It is more common locally that SWLs are 10-50 ft below ground surface or deeper (Sweat and Rheaume, 2000; Wellogic Home. State of Michigan Department of Environmental Quality).

Establishing the SWL for the wells is important to accurately calculate drawdowns for the specific capacity calculation. The proper approach to establish SWL conditions would be to shut off all wells simultaneously for a few days, which is not feasible for the Hatchery operations. Because of the quantity of SCADA data and some intentional changes in February 2020, we were able to calibrate current estimates of the SWLs for Wells 3, 4, and 5 that would reflect the conditions during the flow manipulations. The calibrated values were used as the baseline SWLs for this analysis.

Well 2 was repurposed as a monitoring well in August of 2021 by installing a new Levelogger (Model 3001 LTC Levelogger Edge, M30/C80, Solinst Canada Ltd., Ontario, Canada) probe 100-feet below the top of the well cap that has been continually collecting data on one-hour intervals. The relative static water level of the aquifer beneath the KBIC hatchery well field collected from Well 2 has been analyzed in conjunction with the available well performance data from Wells 3, 4, and 5. This is the first collective analysis of that data.

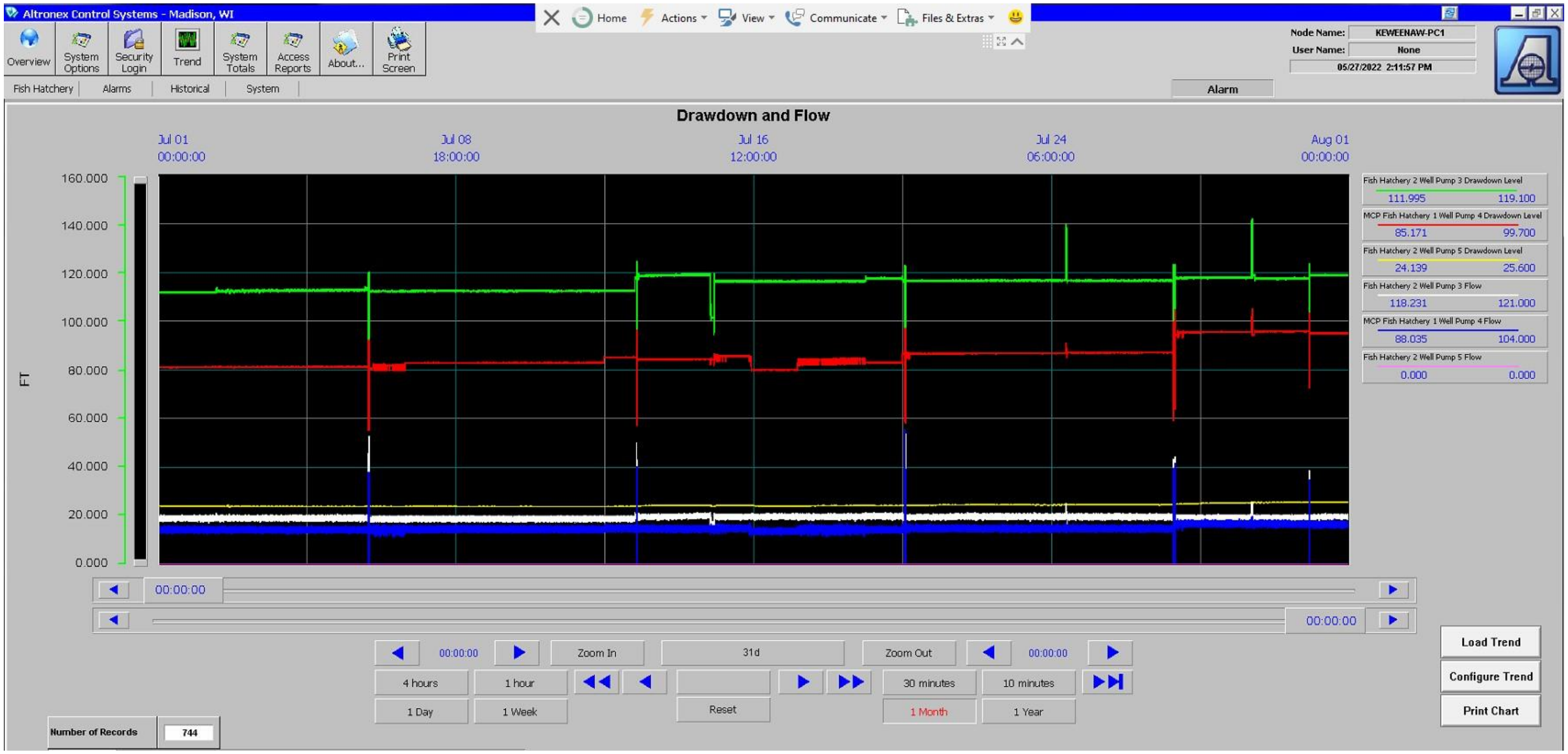
Neighboring wells that overlap in each other's region of influence will cause associated drawdowns that should be accounted for when calculating specific capacities and ascertaining well performance. For well fields like the Hatchery, it is challenging to isolate the effects one well has on its neighbors without shutting off all but one well, which is not practical for most pumping conditions at the Hatchery. Instead, we used intentional changes to one well while keeping the others operating at a constant rate. This is not ideal to ascertain interference effects because the changes are incremental and in the case of this field, smaller than the natural variability in the data. Accordingly, we assumed the well interference effects were negligible and analyzed the data from each well separately. However, the observations from Well 2 proved to be useful and provided a clearer understanding of the "seasonal" groundwater fluctuations as it relates to the variation in well performance observed historically.

As total flow increases, the equipotential surface lowers, which is reflected in the depth to water in Well 2. Well 2 is located within the region of influence of the total active pumping well field. As a result, the total well-field interferences are observable in the relative change in water level associated with Well 2.

2.2 SCADA Data Selection Rational

From remote access to the SCADA system via TeamViewer (teamviewer.com), hourly data for each well were downloaded in monthly intervals from January 2017 through December 2021, which encompasses the past five years of SCADA operation. The extent of data to be downloaded is first queried by date and time and second the number of records to be downloaded is calculated based on the number hours fall between the extent of queried data. Lastly, a trend is selected, which for this report and research consisted of drawdown and flow (see Figure 4), or power and speed command (see Figure 5). The raw data sets were reviewed and checked for anomalies and potential errors as a result of the downloading process. All anomalies and/or potential errors from downloading the data were identified and resolved.

SCADA system outages were also identified, and the data analysis skipped those time periods. Various periods of well maintenance and unconventional operations, such as during the well tracer tests, yielded inconsistent drawdown-flow data that were not included in this analysis. The periods of erroneous data, from a well performance perspective, that were ignored will appear as gaps in the data analysis. Also, periods during when a well was not pumping does not provide a relevant specific capacity as the flow is zero during those periods. Non-pumping periods also appear as gaps in the time-series data.



Node Name: KEWEENAW-PC1

User Name: None

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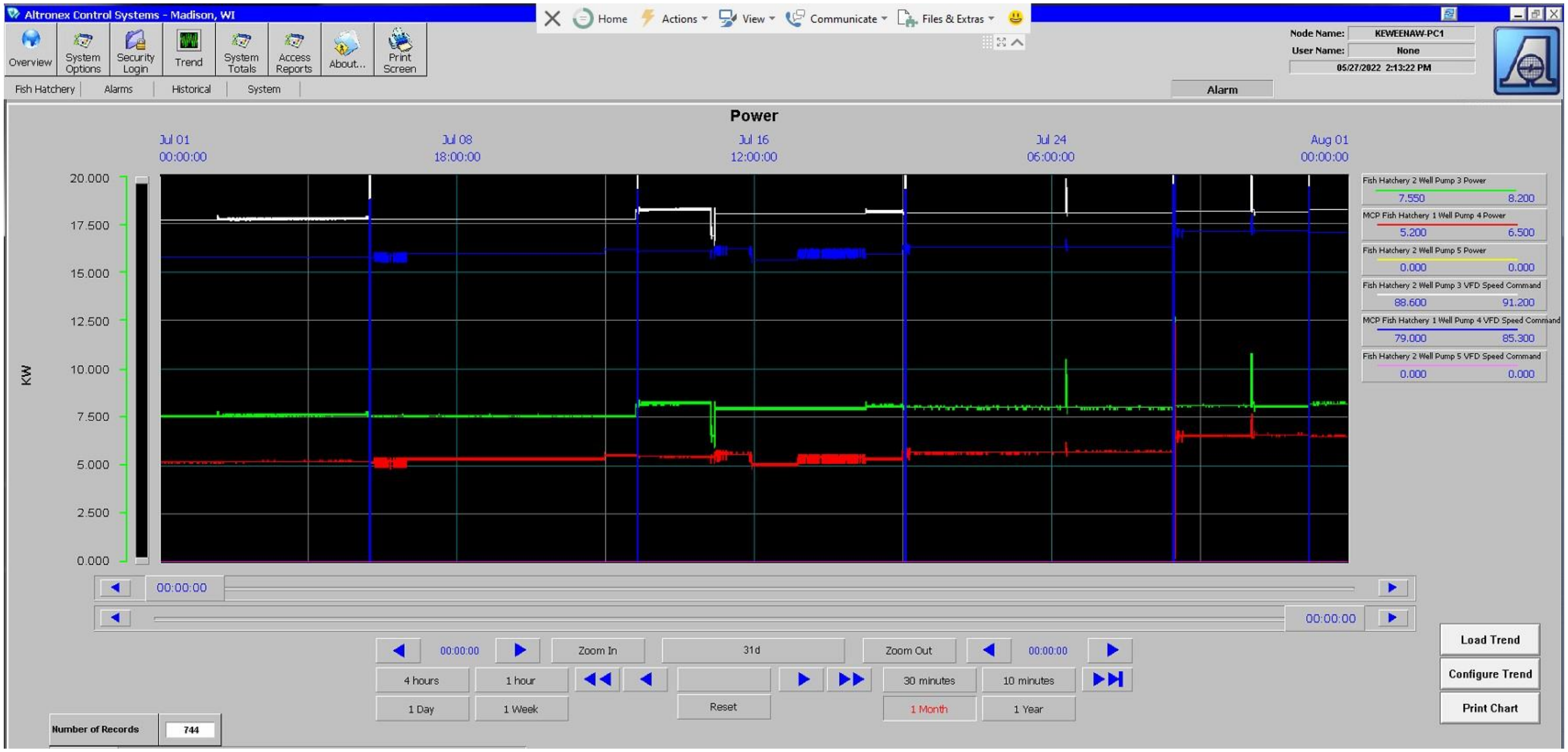
Number of Records: 744

Figure 4. SCADA data displaying the KBIC Hatchery well field drawdown and flow trend for July 2021 with 744 hourly data points. See Figure 5. Below for the same date and extent of data but displaying the power and speed command trend rather than the drawdown and flow trend.



Node Name: KEWEENAW-PC1

User Name: None

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Fish Hatchery 2 Well Pump 3 Power 7.550 8.200

MCP Fish Hatchery 1 Well Pump 4 Power 5.200 6.500

Fish Hatchery 2 Well Pump 5 Power 0.000 0.000

Fish Hatchery 2 Well Pump 3 VFD Speed Command 88.600 91.200

MCP Fish Hatchery 1 Well Pump 4 VFD Speed Command 79.000 85.300

Fish Hatchery 2 Well Pump 5 VFD Speed Command 0.000 0.000

Number of Records 744

Figure 5. SCADA data displaying the KBIC Hatchery well field power and speed command trend for July 2021 with 744 hourly data point

3 Results

Temporally, the Hatchery wells have manifested general trends of decreased production and higher energy consumption due to mineral precipitation in and around the wells. Monitoring data, laboratory water analyses, and downhole video logging have confirmed that naturally occurring minerals are precipitating and clogging the screens and, likely, the surrounding formations. The clogging from mineral precipitation causes more drawdown, which, in turn, makes the pumps work harder, increasing energy consumption, and reducing production rates due to declining specific capacity.

3.1 KBIC Active Well Field Evaluation

With the addition of monitoring Well 2, which is no longer in production service, in August of 2021, the periodic spikes in specific capacity observed in the production wells (Well 3, 4, and 5) were definitively characterized as well-to-well interferences. When the depth to water in Well 2 and total flow (sum of Well 3, 4, and 5 flows) were plotted together with respect to time, it became apparent that the overall well-field interferences are observable in the relative change in water level in Well 2 (See Figure 6).

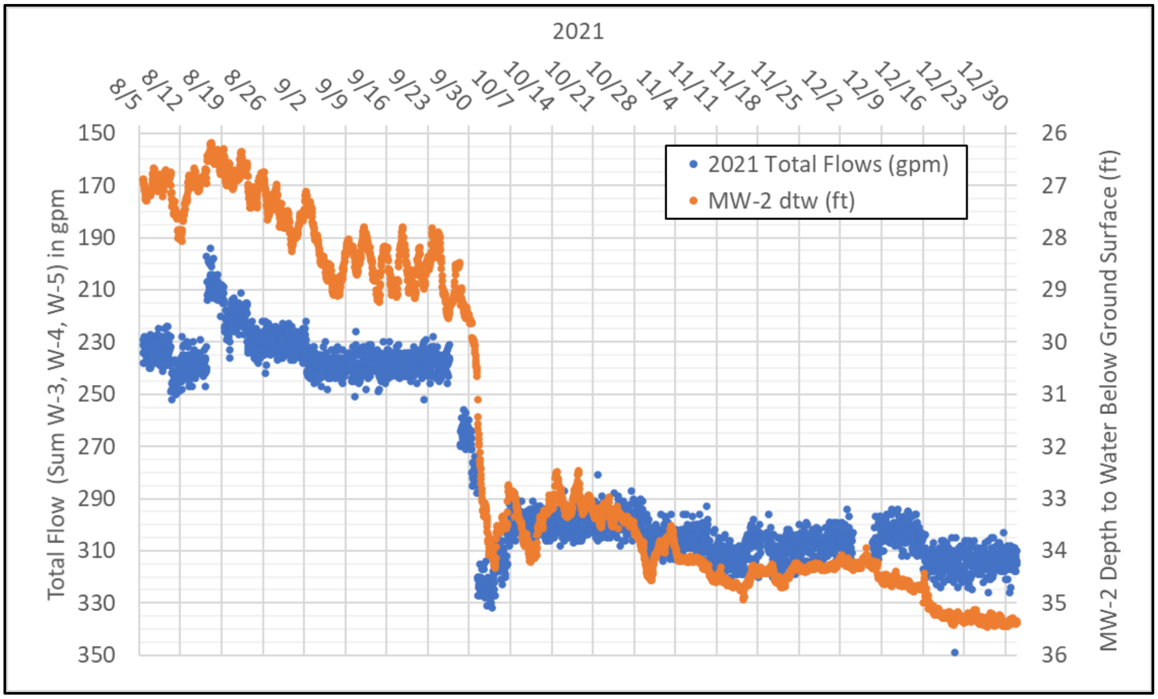

Figure 6. The data collected by the Levelogger (Model 3001 LTC Levelogger Edge, M30/C80, Solinst Canada Ltd., Ontario, Canada) in Well 2 suggests that the static water level in Well 2 is directly proportional to the total flow from the production well-field. As total flow increases the depth to water in Well 2 also increases.

Since specific capacity is flow per unit drawdown, then this relative fluctuation in potentiometric-surface elevation would effectively influence the specific capacity of any production well within the hatchery well field. Particularly when the total flow is reduced, which can limit the magnitude of well-to-well interferences and decrease the measured drawdown values in the KBIC production wells. Ultimately, if not accounted for, higher SWLs due to lower overall pumping can result in artificially inflated specific capacities that could be misinterpreted as natural "seasonal" aquifer recharge. Since the water-level depth in Well 2 and total flow seemed correlated (at least qualitatively, see Figure 7), the specific capacity equation for each pumping well was modified to account for the dynamic nature of the well-to-well interferences when estimating the relative static water levels for the KBIC production wells. By utilizing the equation of the best fit line displayed in Figure 7 below to calculate the relative static water level, a more accurate and dynamic approximation of the specific capacity for each well was achieved.

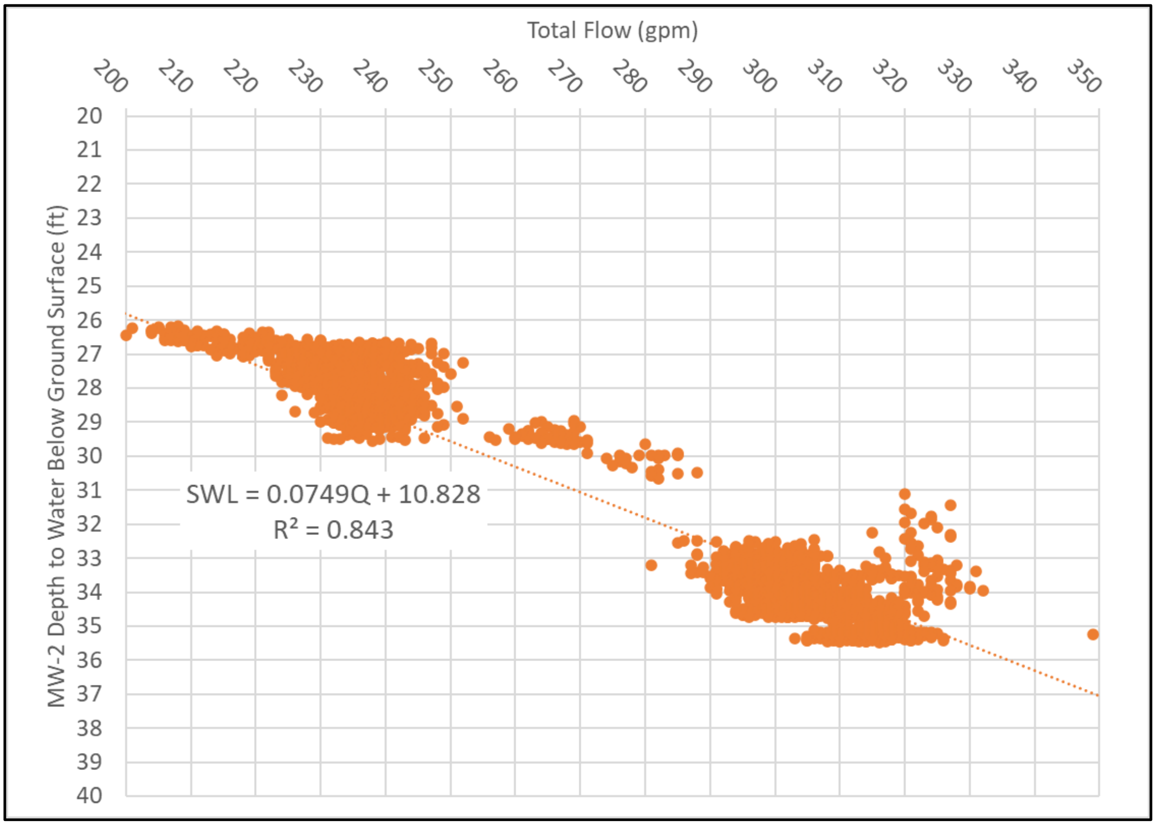

Figure 7. Scatter plot of the water level below ground surface in Well 2 (MW 2) as a function of total flow (sum of Wells 3, 4, and 5 flows) in gallons per minute. The R^2 value of 0.843 suggests a reasonable correlation between total flow and drawdown in the non-pumping well (Well 2). The equation for best fit line was used to approximate a more dynamic, yet realistic static water level in the three pumping wells. Ultimately providing a more realistic drawdown in a particular production well resulting in more accurate specific capacity values.

Using the static water level (SWL) equation obtained from the Well 2 depth-to-water data as a function of total flow (displayed on Figure 7) provides a better approximation of specific capacity for each of the KBIC production wells. Provided below is the specific capacity equation used for the performance evaluation of the KBIC production wells utilizing the previously mentioned SWL calculation.

$$S.C. = \frac{Qi}{(PWL - SWL)} \qquad \text{(Equation 1)}$$

- $S.C. = Specific\ \ capacity$
- $Q_i = Well\ specific\ flow\ rate$ (gpm)
    - $(i\ =$ well 3, 4, or 5)
- $PWL =\ Measured\ pumping\ water\ level$ (ft)
- $SWL\ (static\ water\ level)\ =\ 0.0749Q + 10.828$
- $Q = Total\ Flow\ (gpm)$

While time affects the performance efficiencies of the production wells, the more relevant variable is “volume of water pumped” by each well because it is this water volume that is bringing a fresh supply of water with dissolved minerals that can precipitate in the surrounding formation and well screen.

The SCADA data were used to integrate the flows over time to translate time into volume. It is typical for the total flow from the KBIC well-field to fluctuate throughout an annual year based on the current demand required for fish rearing. As such, the specific capacity for each production well compared to the total flow clearly shows that the observed short-term peaks in well performance are due to reductions in total flow rather than the appeared seasonal aquifer recharge (see Figure 8). The total flow changes seasonally because of changes in water demand for rearing operations and apparently not because of seasonal changes in recharge, which is unknown. Therefore, the relative specific capacity of a production well is partially dependent on the total flow at any given time. Furthermore, it is clear that the performance of the production wells are decreasing with use (see Figure 8), which ultimately negatively affects the cost to operate.

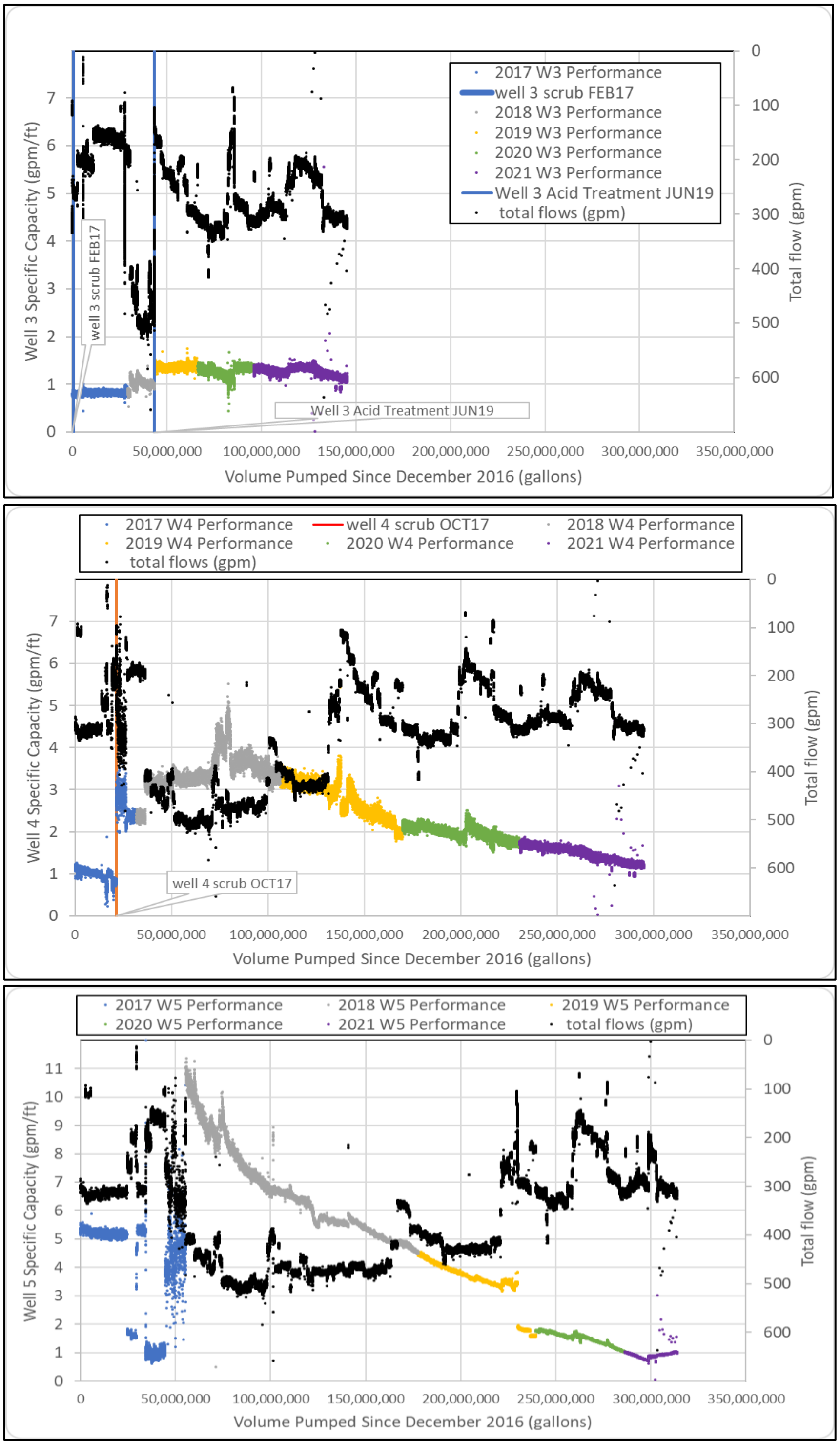

Figure 8. Performance from 2017 through 2021 for Wells 3, 4, and 5 based on specific capacity compared to the total flow as a function of total volume pumped in gallons since December 2016. Short-term peaks in performance are due to decreases in total flow. Individual full-page figures for each of the three wells displayed above are provided in Appendix C.

Unfortunately, the gaps in production performance data between well-installations (1997, 2008, and 2011 for Wells 3, 4, and 5, respectively) and SCADA instrumentation (December 2016) do not allow a more comprehensive analysis of performance reduction rates than what is outlined above. Translating the declining performance and the impacts of events (treatment(s), increased total flow demand) to energy costs and ultimately dollars are better observed using specific input power (see Figures 9, 10, and 11), but understanding the rate of precipitation and plugging is better observed using specific capacity per volume pumped (Figure 8). Specific input power is the ratio between the input power in kilowatts (kW) to the resulting flow rate in gallons per minute (gpm) from a submersible pump in a given production well. The specific input power for each of the KBIC production wells exhibits increasing trends in specific input power (See Figures 9, 10, and 11), meaning the energy required to pump a volume of well water is increasing. This increasing energy demand can be partially reset with well rehabilitation efforts, such as descaling with an acid injection treatment and/or mechanical well-screen scrubbing (see Figures 9, 10, and 11). In particular, the amount of energy reduction due to the acid treatment of Well 3 in June 2019 can be quantified as a percent difference in specific input power by using the general formula for evaluating a percent difference, provided below.

$$\%\Delta SC_i(t) = \frac{SC_i(t) - SC_i(t_0)}{\left(\frac{SC_i(t) + SC(t_0)}{2}\right)} \cdot 100\% \qquad \text{(Equation 2)}$$

- $SC_i(t_0) = initial\ specific\ input\ power\ value$
- $SC_i(t) = final\ specific\ input\ power\ value$

Using the average specific input power from Well 3 for the months preceding the acid treatment (December 2017 through August 2018) as the initial value (0.1013 kW/gpm), and the average specific input power from Well 3 immediately after acid treatment (July 2019) as the final value (0.0619 kW/gpm), the cost (in energy) to pump on Well 3 was reduced by approximately 48% because of the acid treatment in June 2019. Using the same general equation to quantify the increase in energy costs post acid treatment using the July 2019 average specific input power (0.0619 kW/gpm) as the initial value and using the August 2021 average specific input power (0.0714kW/gpm) as the final value; the energy cost to pump on Well 3 has increased by approximately 14% since the acid treatment performed in June 2019. By 2021, the energy cost to pump on Well 3 is still approximately 34% less than the energy cost to pump on Well 3 prior to the acid treatment in June 2019.

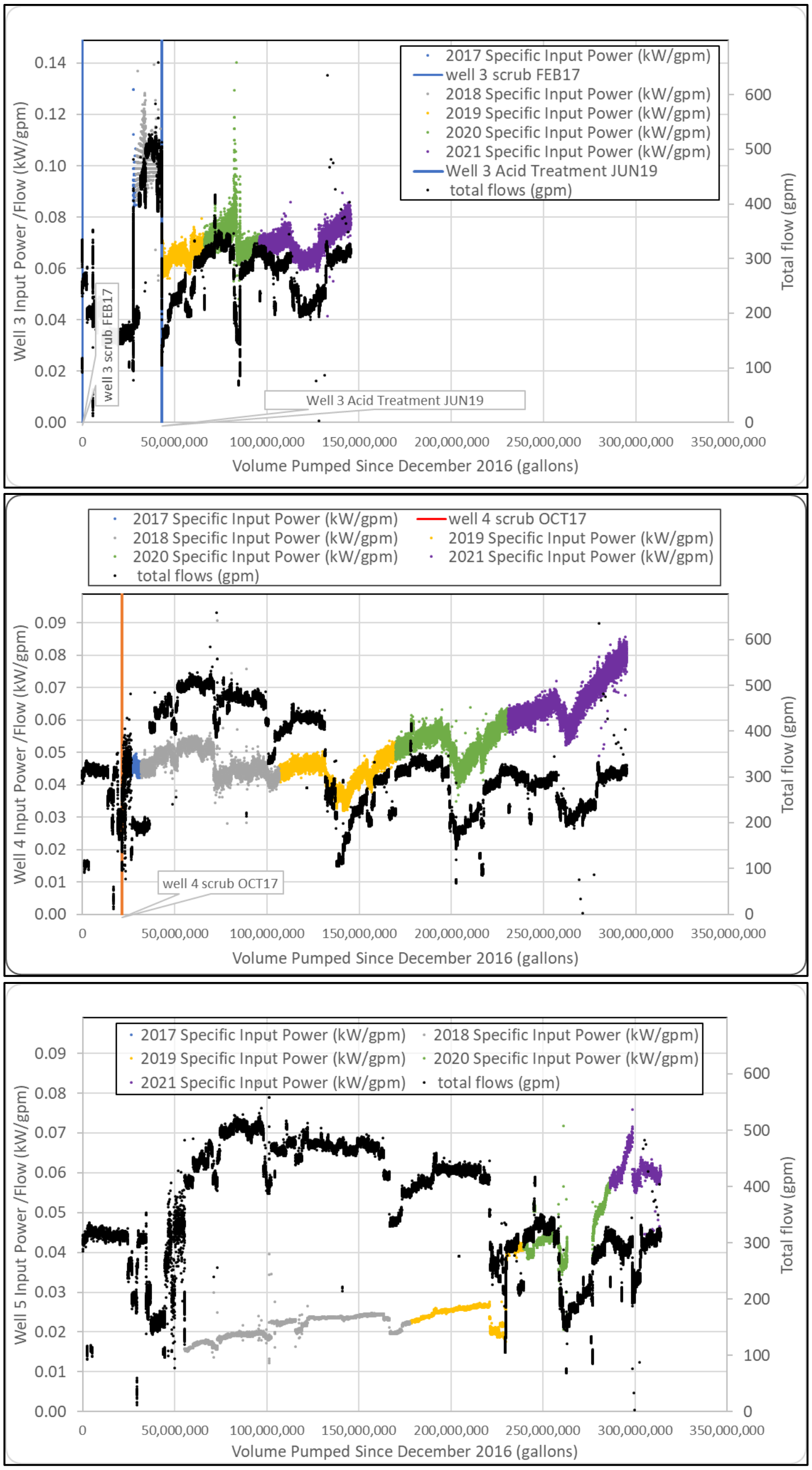

Figure 9. Specific input power trends for Wells 3, 4, and 5 from 2017 through 2021 based on the specific input power (kW/gpm) for each well compared to the total flow as a function of total volume pumped in gallons since December 2016. Short-term drops in specific input power are due to decreases in total flow. Individual full-page figures for each of the three wells displayed above are provided in Appendix C.

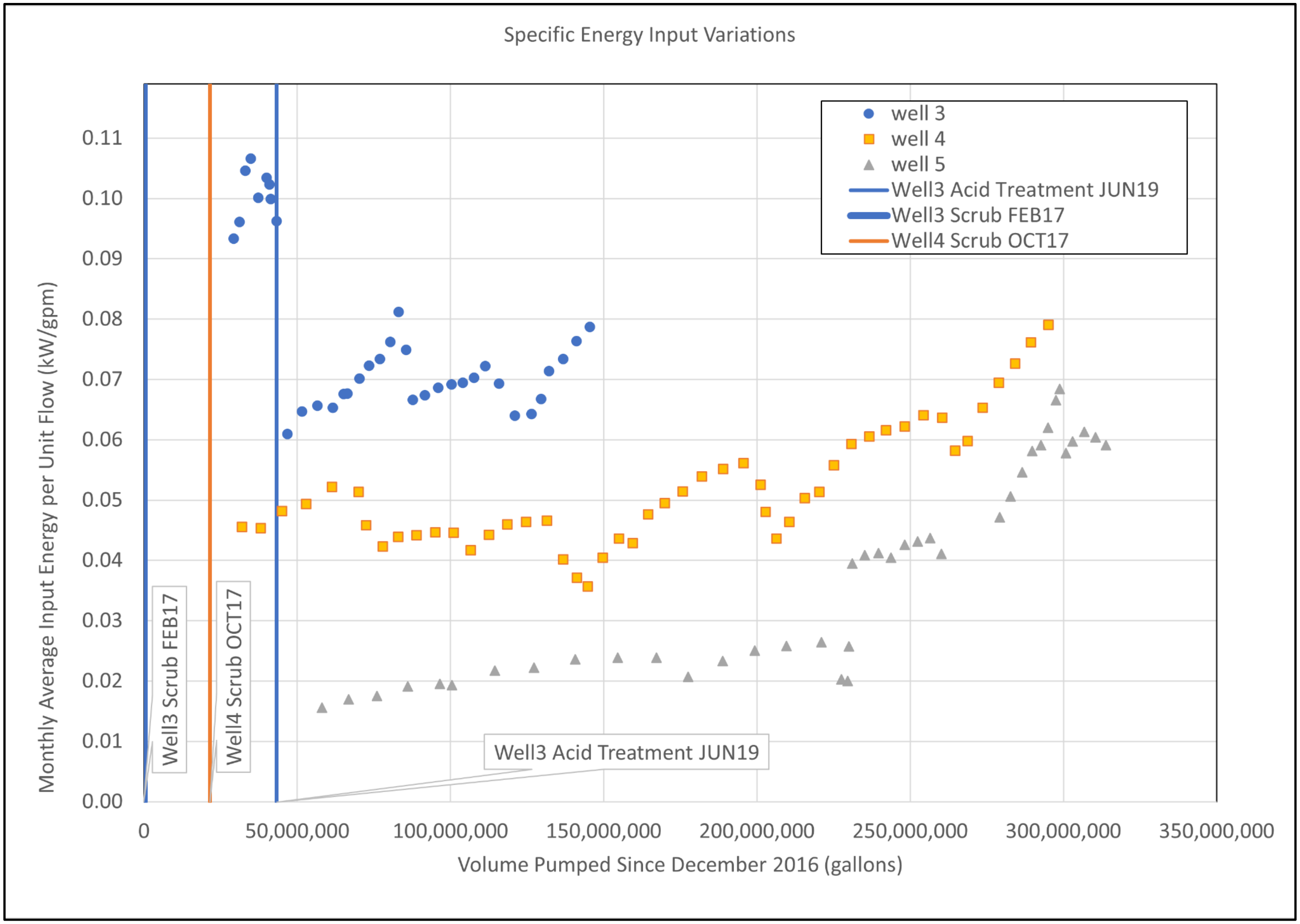

Figure 10. Specific input power trends for Wells 3, 4, and 5 from 2017 through 2021 based on the monthly averages in specific input power (kW/gpm) for each well collectively as a function of total volume pumped in gallons since December 2016. Short-term drops in specific input power are due to the decreases in total flow observed in Figure 9.

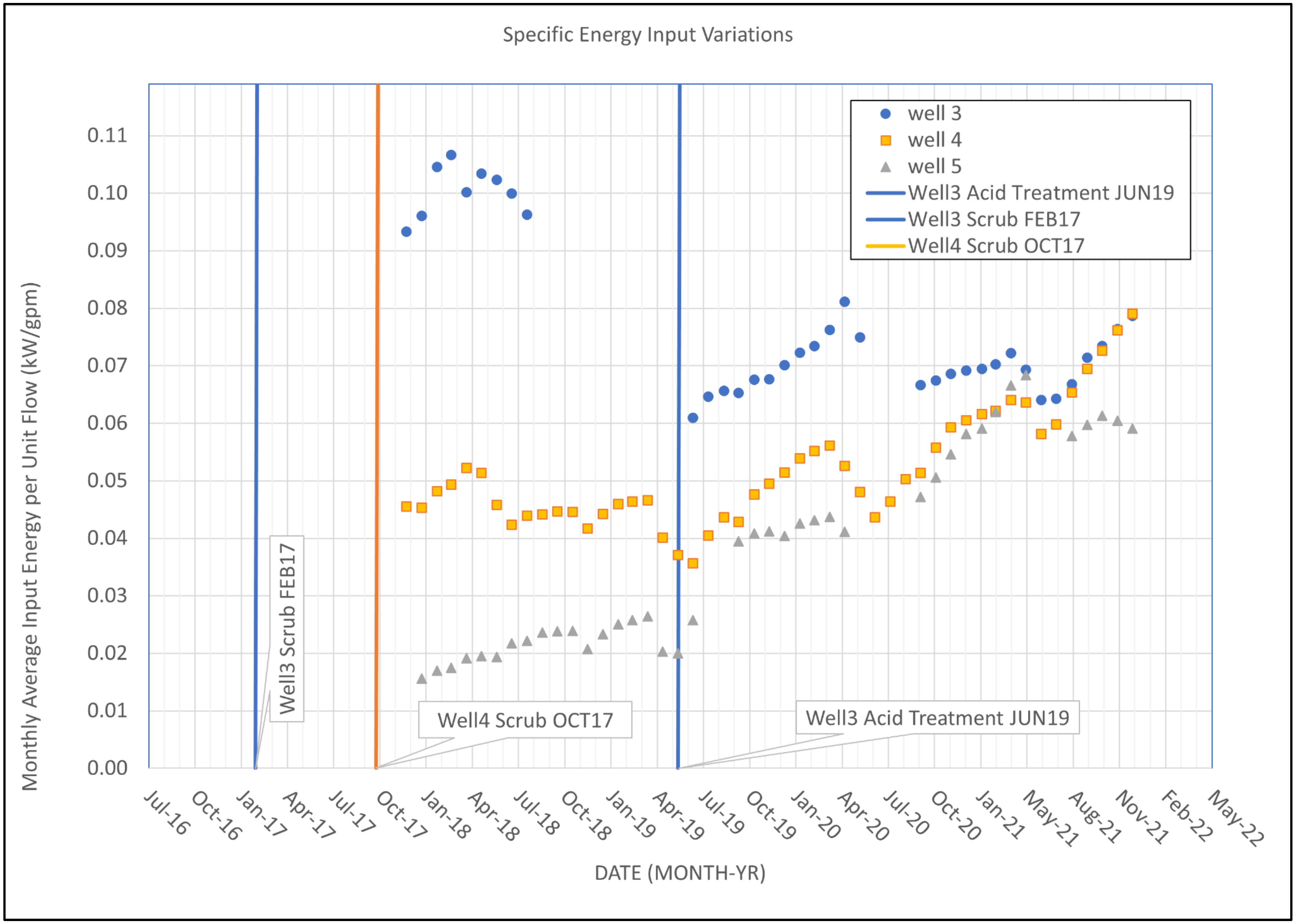

Figure 11. Specific input power trends for Wells 3, 4, and 5 from 2017 through 2021 based on the monthly averages in specific input power (kW/gpm) for each well collectively as a function of time (monthly) since December 2016. Short-term drops in specific input power are due to the decreases in total flow observed in Figure 9.

Further confirmation of performance reduction due to well encrustation from mineral precipitation is observable in the changes in production well efficiency, which is an empirical value of output power per input power $\left(\left[\frac{output\ power\ (kW)}{input\ power\ (kW)}\right]\right)$ (see Figure 12). Additionally, the regained performance from well rehabilitation efforts is also observable in the production well efficiency when evaluating pre-rehabilitation and post-rehabilitation efficiency values (see Figure 12). The results in this report confirm that clogging from mineral precipitation causes more drawdown, which, in turn, makes the pumps work harder, increasing energy consumption, and reducing production rates due to declining specific capacity.

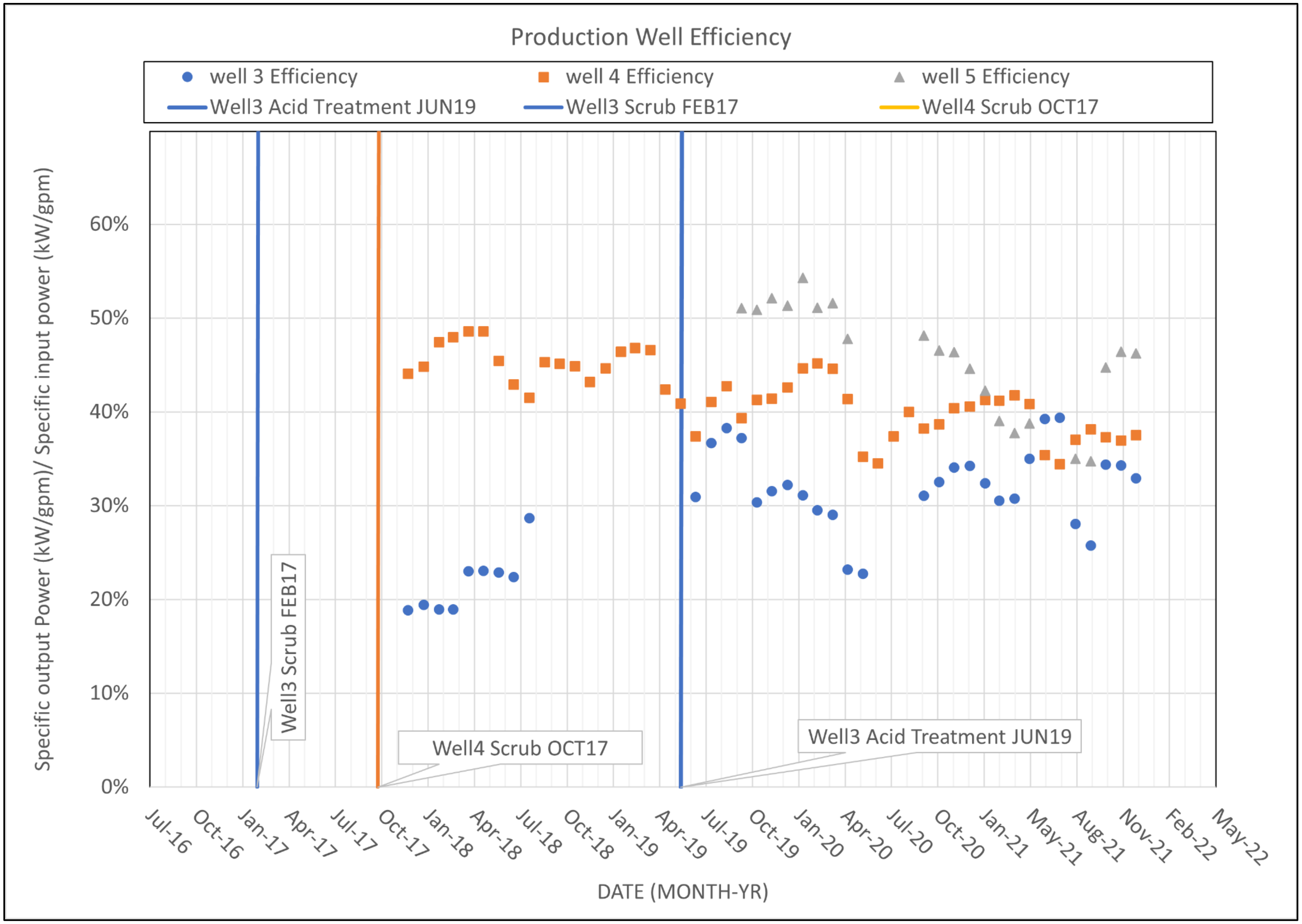

Figure 12. Power efficiency trends for Wells 3, 4, and 5 from 2017 through 2021 based on the quotient value of monthly averages in specific output power (kW/gpm) per specific input power (kW/gpm) as a function of time (monthly). Short-term drops in power efficiency are due to the decreases in total flow observed in Figures 9, 10 and 11.

3.2 Tracer Test and Rehabilitation Interventions of Wells 3 and 4

Conventional remedial practices to rehabilitate a well include costly and disruptive acid treatments. Downhole acid treatment could harm fish if the treatment agents were captured by production wells during treatment. The potential for this hazard was evaluated using salt tracer tests; the results of which are summarized below.

In 2018, students from the Geological & Mining Engineering & Sciences (GMES) department at Michigan Technological University conducted a salt tracer test in Well 3 to mimic the acid treatment in terms of in-well water density (specific gravity of 1.02) and duration (36 hrs.), while monitoring for salinity (using an electrical conductivity probe) in Wells 4 and 5. This was done twice with no observed salinity (electrical conductivity) increases in either of the pumping wells (Wells 4 and 5). As a result, Well 3 was treated with a strong-acid treatment solution in the summer of 2019. During and following treatment, no acid was produced by either Wells 4 or 5, and so the treatment was considered successful in terms of not harming the Hatchery operations during the rehabilitation. The well performance improved by at least a factor of two from the pre-treatment, however that is still only half of the original performance observed after Well 3 was completed in 1997. We are unsure if a stronger solution or longer treatment would yield better results.

Similarly, as done in Well 3, Michigan Tech conducted a salt tracer test in Well 4 to ensure that Well 4 can also be treated with an acidic descaler without Wells 3 and 5 capturing significant amounts of the descaler solution. Given the results from the 2020, Well 4 tracer test, it appears that an acid solution treatment in Well 4 will likely not be captured by simultaneously pumping Wells 3 and 5. Therefore, it is recommended that Well 4 be rehabilitated with an acidic descaler solution treatment.

4 Discussion: Well Field Performance Management and Rehabilitation

The SCADA system provides valuable data on a frequent basis that can be processed to clearly show performance trends in terms of energy consumption and specific capacity, including the production-well responses from rehabilitation efforts. Continuous monitoring and analysis as outlined here will eventually allow the staff to separate the impacts of events (treatment(s), increased total flow demand) from longer-term plugging-induced trends.

The addition of the unpumped monitoring well (Well 2) has provided valuable information regarding the magnitude of the well-to-well interference as it relates to the total flow and relative SWLs from the three pumping wells. Additional monitoring (non-pumped) wells amid the wellfield would also provide more valuable information for increasing the accuracy of the relative SWLs for the active production wells. By utilizing the Well 2 data to refine the SWL value in the production wells through the removal of the total well-to-well interferences, a more accurate specific capacity estimate was obtained for each production well. However, the SWLs for each of the production wells could be refined further and more accurately from additional monitoring well data. In doing so, the performance trends will more clearly reflect the health of a well and when planning and managing well-field operations and maintenance better economical expectations can be achieved.

Knowing that rehabilitation efforts can increase well performance and reduce energy costs to operate, forecasting when it is most economical to do so becomes important. Forecasting a relative breakeven cost-benefit analysis for acid treatment in Well 3 (Figure 13) and for mechanical well scrubbing of Well 4 (Figure 14) has been done using the SCADA data analysis along with some moderate assumptions. Provided as a spreadsheet tool, various parameters can be adjusted to forecast the breakeven cost of similar rehabilitation efforts as shown in Figures 13 and 14. For example, the initial cost of the rehabilitation method can be adjusted to reflect whatever the actual bid price comes to for future rehabilitation efforts. Additionally, the forecasted cost of plugging due to mineral precipitation should be continually updated in the spreadsheet tool as new SCADA data becomes available. By updating the spreadsheet tool with new SCADA data, the accuracy of the forecasted projections will increase. It will be vital to continually update the spreadsheet tool because the current projections are based on one acid treatment (Well 3 June 2019) and one mechanical well scrubbing (Well 4 October 2017). As presented and outlined in this report, the rehabilitation efforts along with the SCADA data, and monitoring well (Well 2) data have provided a great start for estimating performance and energy consumption values and their respective trends. Similarly, as observed in the graphical figures in this report, these trends in performance and energy consumption are likely to change with time, and therefore, when forecasting future economic decisions that pertain to the hatchery wellfield, the most current SCADA, and monitoring data should be included in the spreadsheet tool.

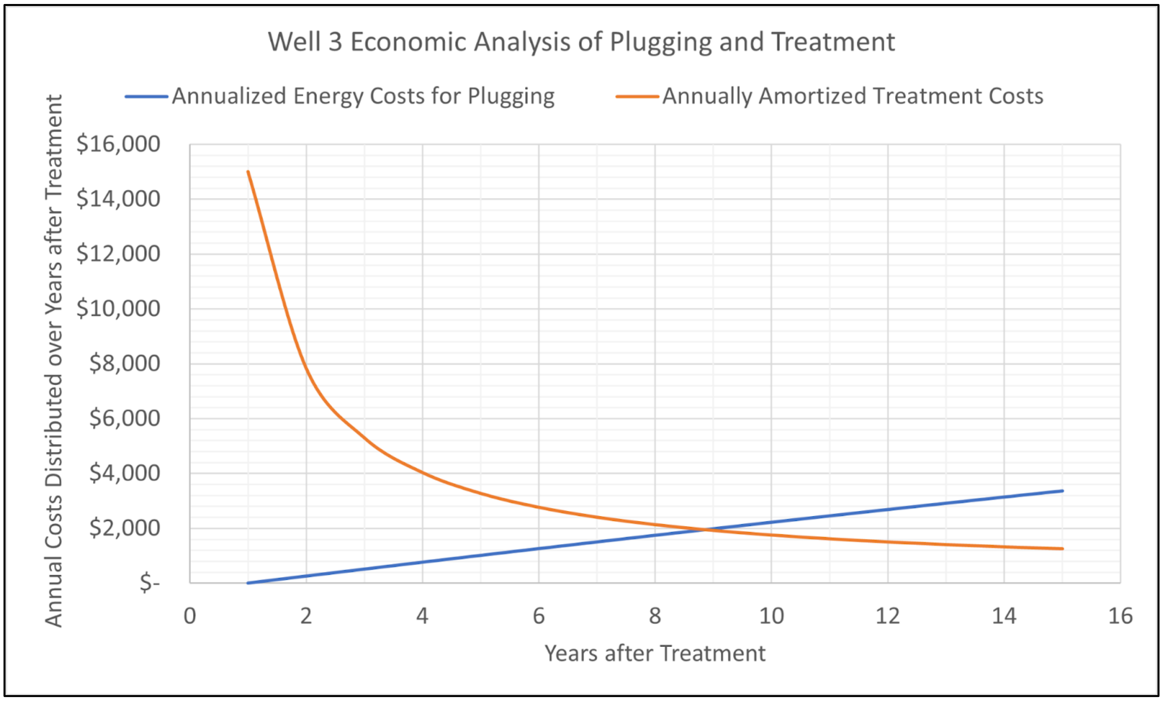

Figure 13. Economic analysis of plugging and acid rehabilitation treatment using an average flow rate of 100 gallons per minute and historical kW/gal usage for Well 3 before treatment as annualized energy costs for plugging (blue geometric gradient line), and kW/gal values after treatment with the added fixed cost of the acid treatment as annually amortized treatment costs (orange curved line). The point of convergence of the two lines indicates the breakeven point for rehabilitation versus no rehabilitation in years of operation. For the June 2019 acid treatment in Well 3 the point of convergence is approximately 9-years from the time of the treatment.

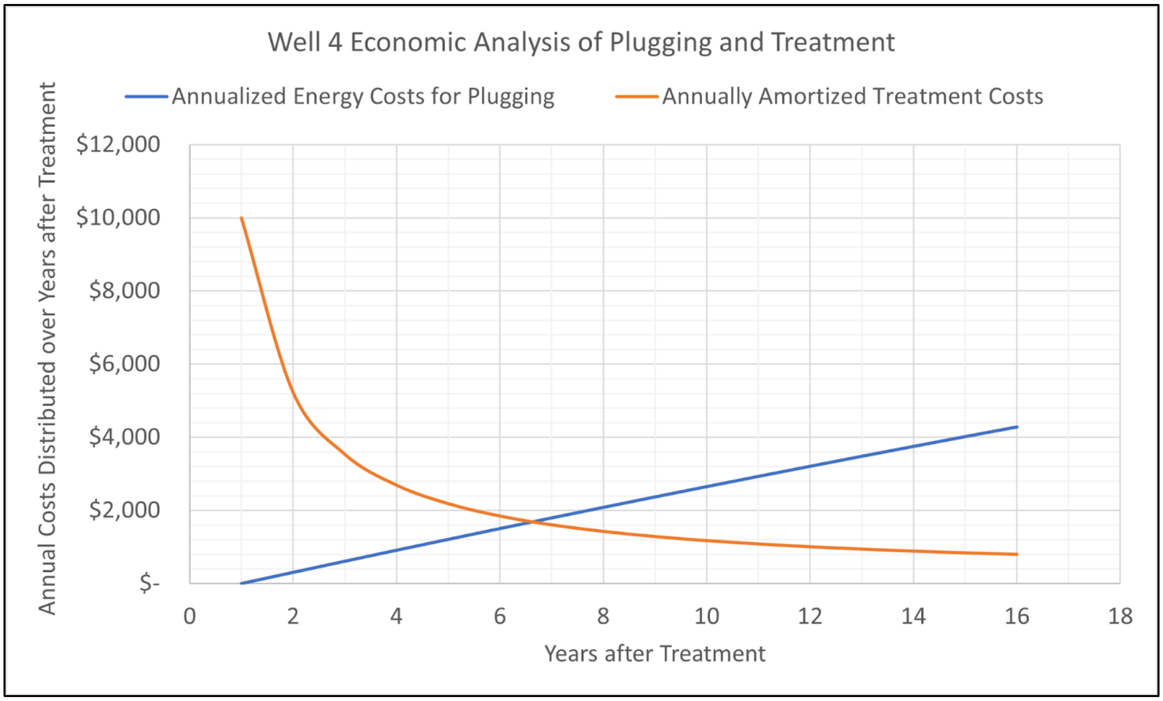

Figure 14.: Economic analysis of plugging and mechanical scrubbing rehabilitation treatment using an average flow rate of 100 gallons per minute and historical kW/gal values for Well 4 before treatment as annualized energy costs for plugging (blue geometric gradient line), and kW/gal values after treatment with the added fixed cost of the mechanical scrubbing treatment as annually amortized treatment costs (orange curved line). The point of convergence of the two lines indicates the breakeven point for rehabilitation versus no rehabilitation in years of operation. For the October 2017 mechanical scrubbing treatment in Well 4 the point of convergence is approximately 6.5-years from the time of the treatment.

4.1 **Well 3**

When Well 3 was installed in 1997, a specific capacity of 3.85 gallons per minute (gpm) of flow per foot (ft) of drawdown (3.85 gpm/ft) was measured in a step-drawdown test. Using the SCADA data from December 2016, the performance of Well 3 was then observed to have deteriorated tenfold to approximately 0.36 gpm/ft. Because of the lack of information between the testing in 1997 and the SCADA installation in December 2016, no performance trends can be determined prior to December 2016 since 1997 (almost 20 years).

Mechanical scrubbing was performed in Well 3 in February 2017 in conjunction with downhole video logging to examine the extent of plugging of the well screen. The video logs showed instances of mineral precipitation inside the well screen but not pervasively. The scrubbing caused a modest improvement in the specific capacity of Well 3 from approximately less than 0.5 gpm/ft to almost 1 gpm/ft. This modest improvement suggests there is mineral precipitation occurring but probably more so in the formation outside the well screen where scrubbing is not effective and video is not possible.

The specific capacity trend calculated from the SCADA data (2017 through 2021) shows that the performance was relatively maintained over the course of the following year of 2018 at approximately 1.0 gpm/ft (see Figure 15). The acid treatment in June 2019 significantly improved the specific capacity when compared to the specific capacity prior to the acid treatment (from less than 1 gpm/ft to approximately 1.5 gpm/ft). The performance improvement from the acid treatment further supports the belief that mineral precipitation is occurring in the formation outside the well screen.

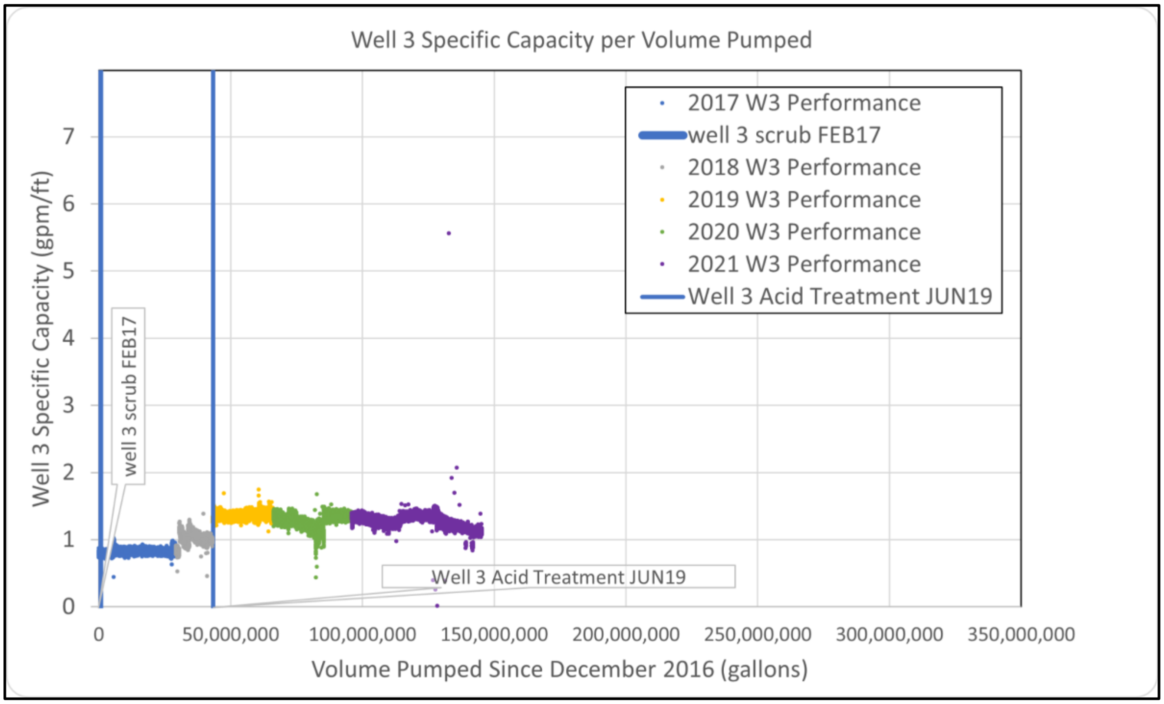

Figure 15. Performance history for Well 3 from 2017 through 2021. For ease of visual interpretation, each year of data is color-coded. Solid vertical lines depict the times when well rehabilitation efforts were implemented. Short-term peaks in performance are due to decreases in total flow as mentioned previously in Figure 8.

4.2 **Well 4**

Well 4 was installed in 2008 and its original specific capacity was 9.1 gpm/ft based on the analysis of the 2008 step-drawdown test. Analysis of the initial SCADA data, in December 2016, showed that its performance deteriorated almost tenfold to approximately 1 gpm/ft (see Figure 16).

Well 4 was scrubbed mechanically in October 2017 and this made substantial improvements in the specific capacity from less than 1 gpm/ft to approximately 3 gpm/ft. If the acid treatment recommended for Well 4 has similar success as seen in Well 3, which resulted in more than a 100% increase in specific capacity, then we would anticipate that Well 4 would also experience a significant increase in performance. We recommend that acid treatment of Well 4 might be performed longer than the conventional treatment period used for rehabilitating Well 3 so that more improvement might be realized.

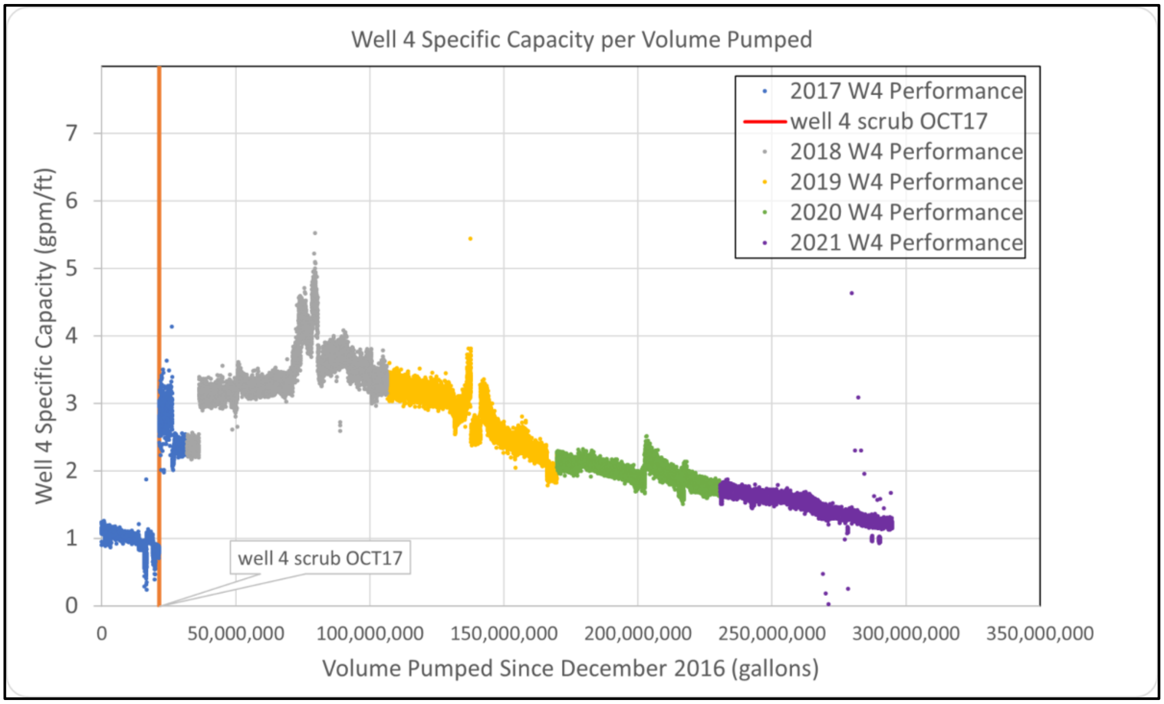

Figure 16. Performance history for Well 4 from 2017 through 2021. For ease of visual interpretation, each year of data is color-coded. Solid vertical lines depict the times when well rehabilitation efforts were implemented. Short-term peaks in performance are due to decreases in total flow as mentioned previously in Figure 8.

4.3 **Well 5**

When Well 5 was installed in 2011, it had a specific capacity greater than 5 gpm/ft as determined from a multiday constant-rate test. Based on analysis of the SCADA data (see Figure 17), its performance has since diminished to about 1 gpm/ft.

No rehabilitation efforts have been performed on Well 5 to date, and, as a result, the performance of Well 5 is suffering. Scrubbing and/or acid treatment of Well 5 would likely improve its performance. Given the obvious improvements observed in both wells 3 and 4, we would anticipate Well 5 would respond similarly.

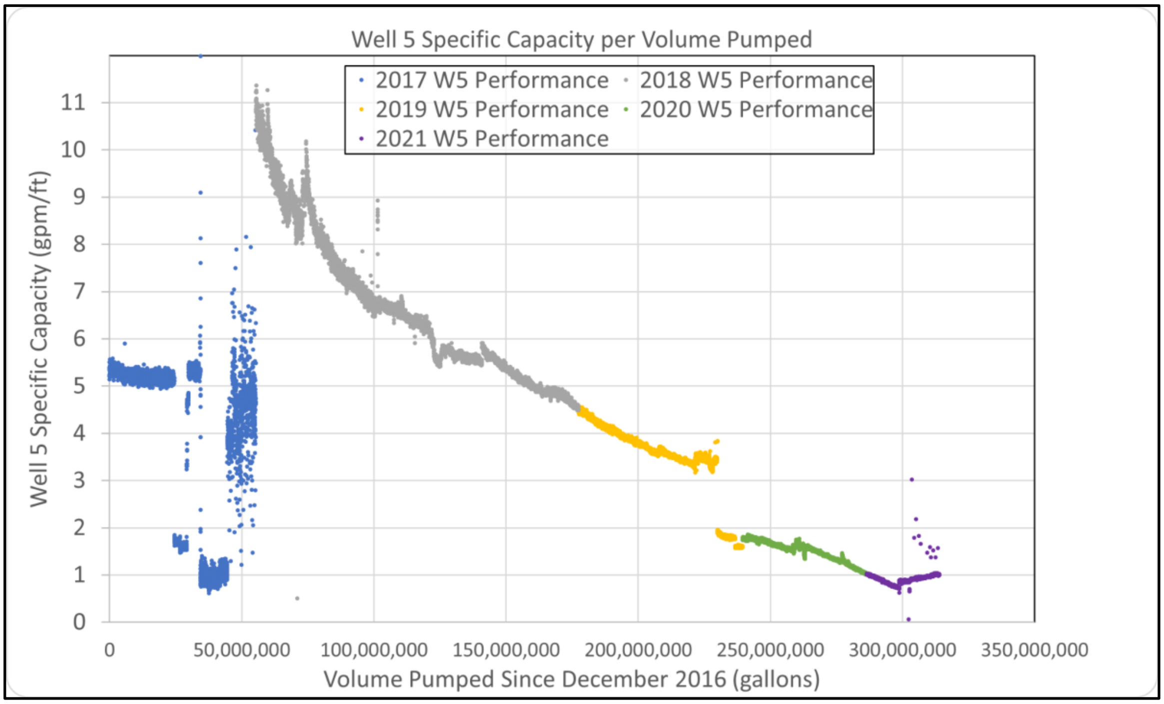

Figure 17. Performance history for Well 5 from 2017 through 2021. For ease of visual interpretation, each year of data is color-coded. Short-term peaks in performance are due to decreases in total flow as mentioned previously in Figure 8.

5 Recommendations

The salt tracer tests in Wells 3 and 4 and the acid (descaler) treatment of Well 3, suggest that Well 4 could undergo acid treatment while pumping Wells 3 and 5. It is apparent that Well 4 should undergo acid treatment to improve performance. After treating Well 4, then the observed improvements could be used to determine if Well 5 is also due for acid treatment. We suggest acid treating Well 4 longer to observe if more improvement can be achieved with a longer acidification period. If acid treatment of Well 5 is considered for the near future, a salt tracer test could be performed to confirm that it is also safe to use descaler in it.

Higher production capacities and more efficient well performance is achieved by minimizing mineral precipitation, which will be less for lower amounts of drawdown. Therefore, a strategy of minimizing well drawdowns by pumping all the wells at lower rates rather than fewer wells at higher rates to achieve the desired total flow might result in less drawdown and slower rates of precipitation. The SCADA data provides information that can be used to adjust pumping configurations to minimize drawdowns.

The SCADA system is invaluable for monitoring, understanding, and managing the well field. Improvements in making the data more readily available, such as posting to a secure website, would make it possible to monitor performance and enhance operations to minimize drawdowns and energy needs. The creation of a journal ledger documenting changes to the well field operations and SCADA monitoring is recommended, so when evaluating and analyzing the well field performance data these changes will be accounted for. Additionally, we recommend automating the data acquisition from the monitoring well (Well 2) to be included in the SCADA system, therefore, all the well data can be accessed remotely via TeamViewer.

A sophisticated computational tool for managing flows to minimize drawdown also requires independent information on static water levels in the pumped aquifer over time, especially seasonally and annually. An unpumped monitoring well, or a series of monitoring wells in the pumped aquifer, outside the influence of the pumping wells, could provide this kind of information if the well(s) were equipped with a pressure transducer and integrated into the SCADA system enabling that data to be included in the specific capacity analyses of the production wells. Without knowing how SWLs change over time, it is not possible yet to separate the well-to-well interferences due to variations in total flow and completely isolate a single production well to calculate the dynamic SWL for individual production wells. However, the addition of Well 2 has aided in a better understanding, technically and holistically, of the aquifer responses to the active pumping well-field, but it is still a single monitoring well (unpumped point) and to increase the precision and accuracy of the SWLs over time, additional monitoring wells are warranted. Furthermore, if the SCADA data is continually updated to include the broadest range of data, coupled with new monitoring well data on static water levels and performance changes from well rehabilitation efforts, the result will be financially beneficial as more informed flow-management decisions can be made.

6 Conclusions

Temporally, the Hatchery wells have manifested general trends of decreased production and higher energy consumption due to mineral precipitation in and around the wells. Monitoring data, laboratory water analyses, and downhole video logging have confirmed that naturally occurring minerals are precipitating and clogging the screens and, likely, the surrounding formations. The clogging from mineral precipitation causes more drawdown, which, in turn, makes the pumps work harder, increasing energy consumption, and reducing production rates due to declining specific capacity.

The SCADA system now provides the ability to monitor flows and drawdowns which reflect important information regarding well field performance. To be more economically strategic in managing the well field operations it is apparent that the performance data from the SCADA system must be utilized to conserve well field-related costs. The analysis of the SCADA data clearly shows that the production well's performance diminishes with use over time due to well-screen plugging as a result of mineral precipitation in and around the well-screen. The observed regained performance from well rehabilitation efforts (mechanical scrubbing and/ or acid treatment) demonstrates their effectiveness, and with the use of the spreadsheet tool the frequency of rehabilitation efforts can be assessed on a more financially sound basis by forecasting a relative breakeven cost-benefit analysis for a particular well and associated rehabilitation. The economic analysis of power consumption and treatment costs suggests that well treatment costs can be recovered in approximately 6-9 years based on the treatment's effectiveness in offsetting the performance declination due to mineral precipitation from pumping and relative drawdown. In other words, the magnitude of the regained well performance will be proportional to the rehabilitation method's effectiveness in removing the mineral precipitation buildup and unclogging the well screen.

Even though the tracer tests showed that Wells 3 and 4 can be treated using descaler solutions while pumping other wells without capturing descaler solution by the other wells; a tracer test should be conducted prior to an acid treatment to ensure the health and safety of the fish at the hatchery.

It is clear that the addition of Well 2 aided in a better understanding, technically and holistically, of the aquifer responses to the active pumping well-field, but to increase its usefulness additional monitoring wells must be utilized. The SCADA system is invaluable for monitoring, understanding, and managing the well field. The continued use of the SCADA system and implementation of the other recommendations in this report will be financially beneficial as more informed flow-management decisions can be made with confidence.

7 References

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A Appendix: History synopses on Wells 3, 4, and 5

Well-3 Installed 1997

a. 8-inch well- no well log- 1997 completed. 278 depth, screen 240-278 ft bgs, 4" drop pipe to 160 ft depth

b. Step Drawdown Test performed July 1997, specific capacity 4.3 gpm/ft (Bittner Eng. report to Mike Donofrio, 25 July 1997

c. This is the pump that is only producing 50 gpm now and that may need a new screen with redevelopment. The pump is 15 hp Grundfos submersible, same as the one in Well-4.

d. Curt and Buck Larson (Larson Well Drilling) recommend acid treatment for screen encrustation. They haven't used other methods and with all of these wells being in the same aquifer, it was inadvisable to use acid.

e. Well screen video log 2017

f. Well screen mechanically scrubbed February 2017

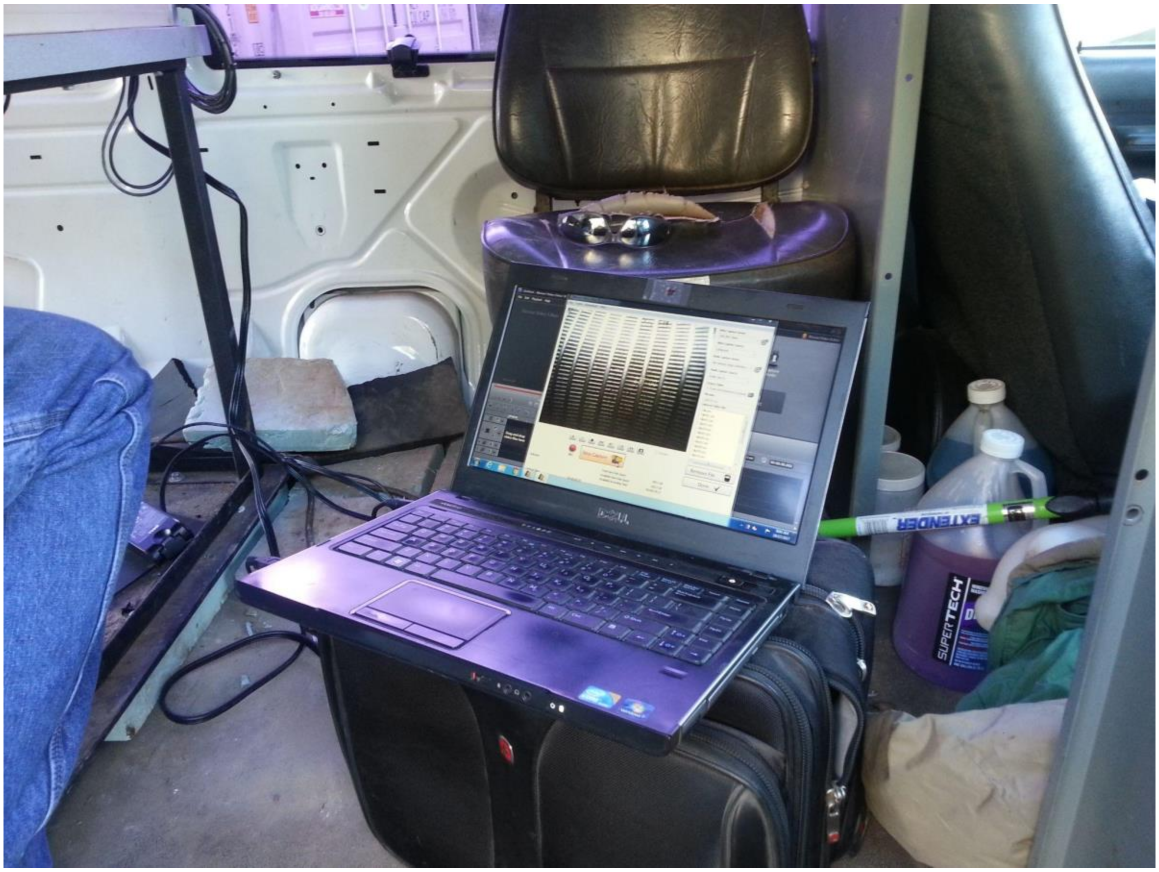
Well-4 Installed 2008

a. 8-inch well- well log- 2008 completed-, 248 ft depth, screen 210-248 ft bgs, 4" drop pipe 168 ft depth

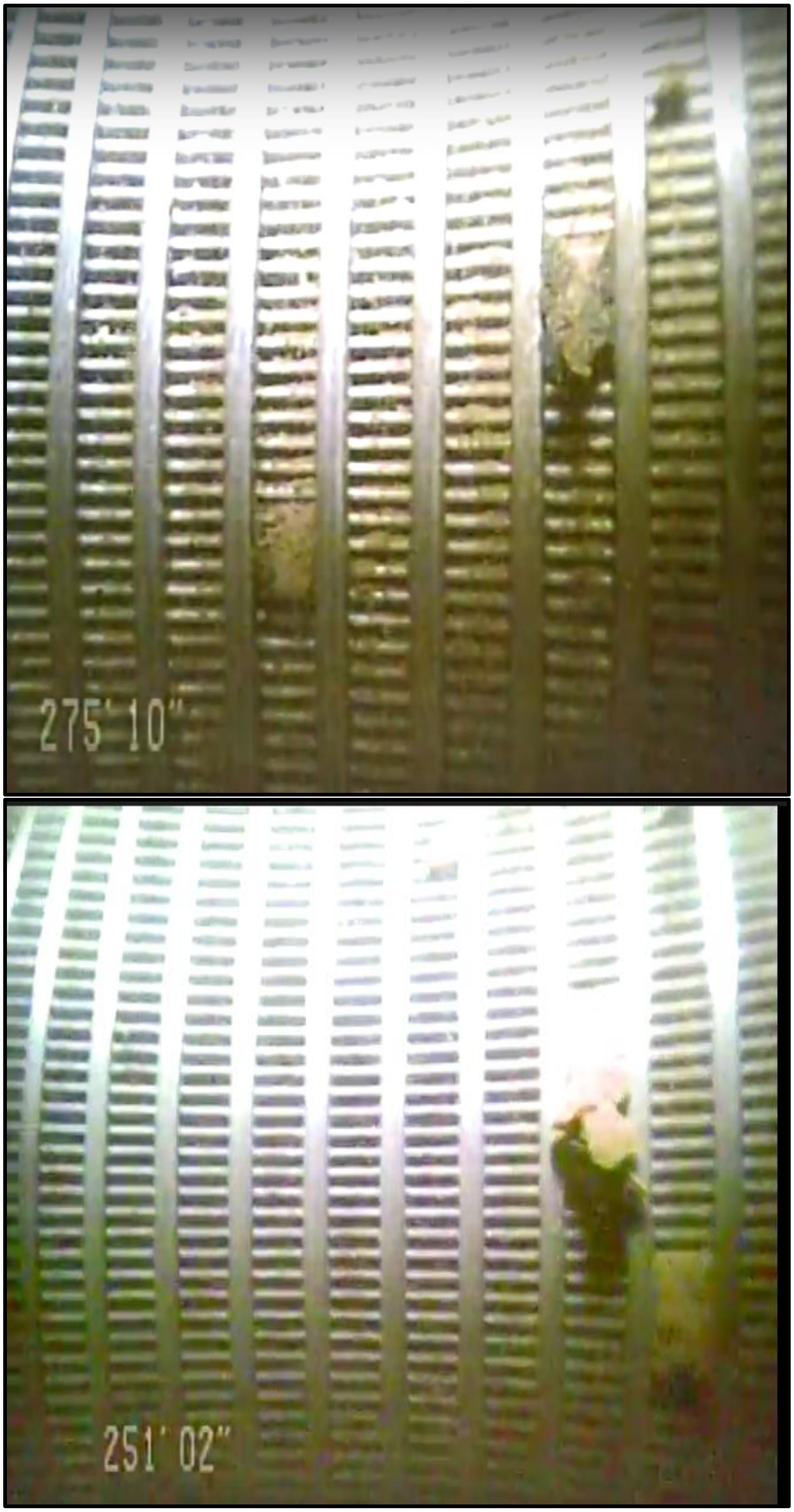
b. Step Drawdown Test Performed Specific Capacity 10.4 gpm/ft (Bittner Eng. Report to Todd Warner 11 Sept. 2008)

c. Production has decreased over time, and I'd like an estimate on doing maintenance work air surging, high pressure jetting, freezing, chemical. lt has been running since 2008. The pump is a 15 hp.

d. Well screen video log October 2017, evidence of precipitation, no evidence of screen sliding up the casing. Screen position from original installation confirmed by the video log, see field photos below.


EXTENDER
SUPERTECH


250' 03"



e. Well screen mechanically scrubbed October 2017

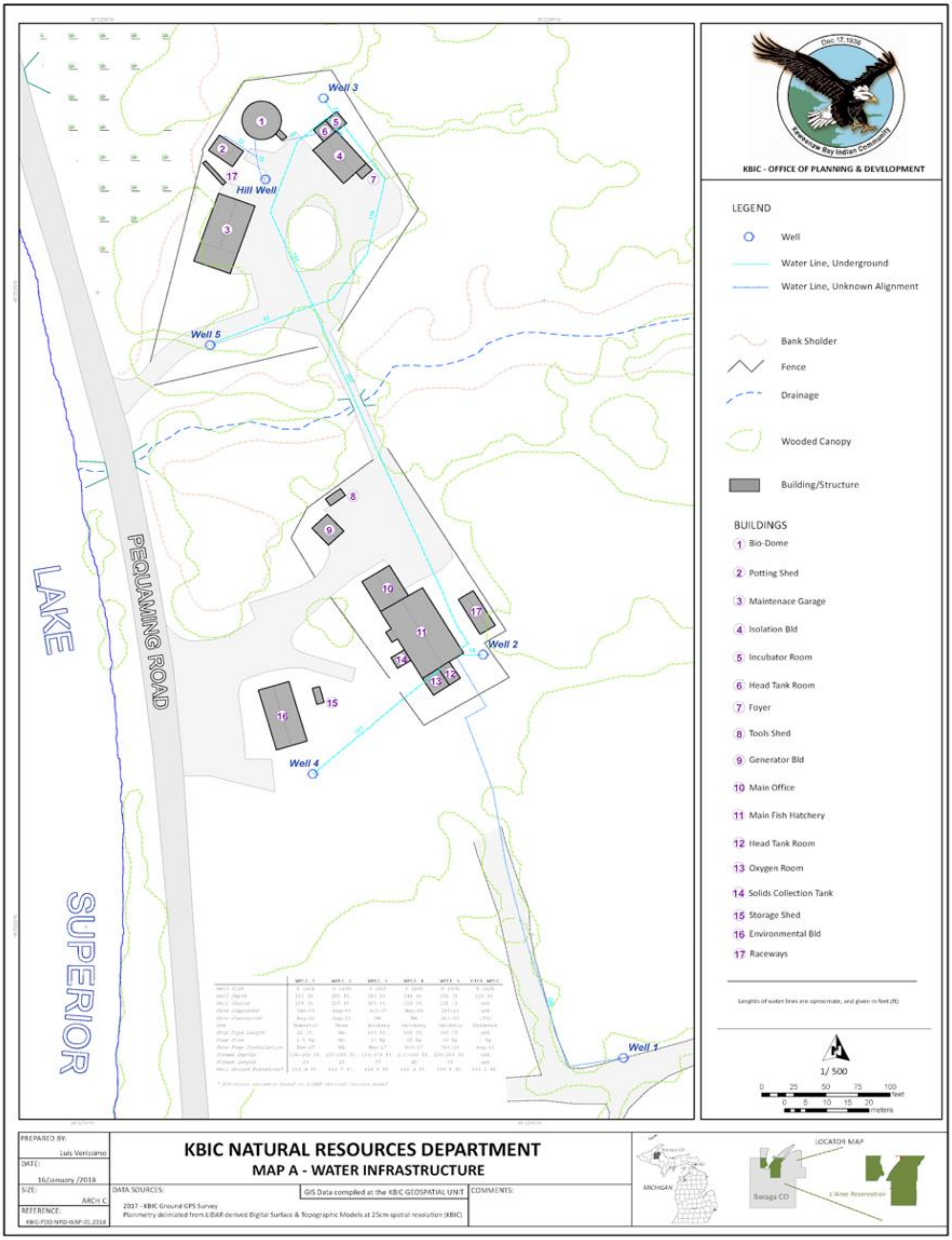
Well-5 Installed November 2011

a. 6-inch well-well log- 2011 completed- 258 ft deep, screen 228-258 ft bgs, 3" drop pipe 160 ft depth

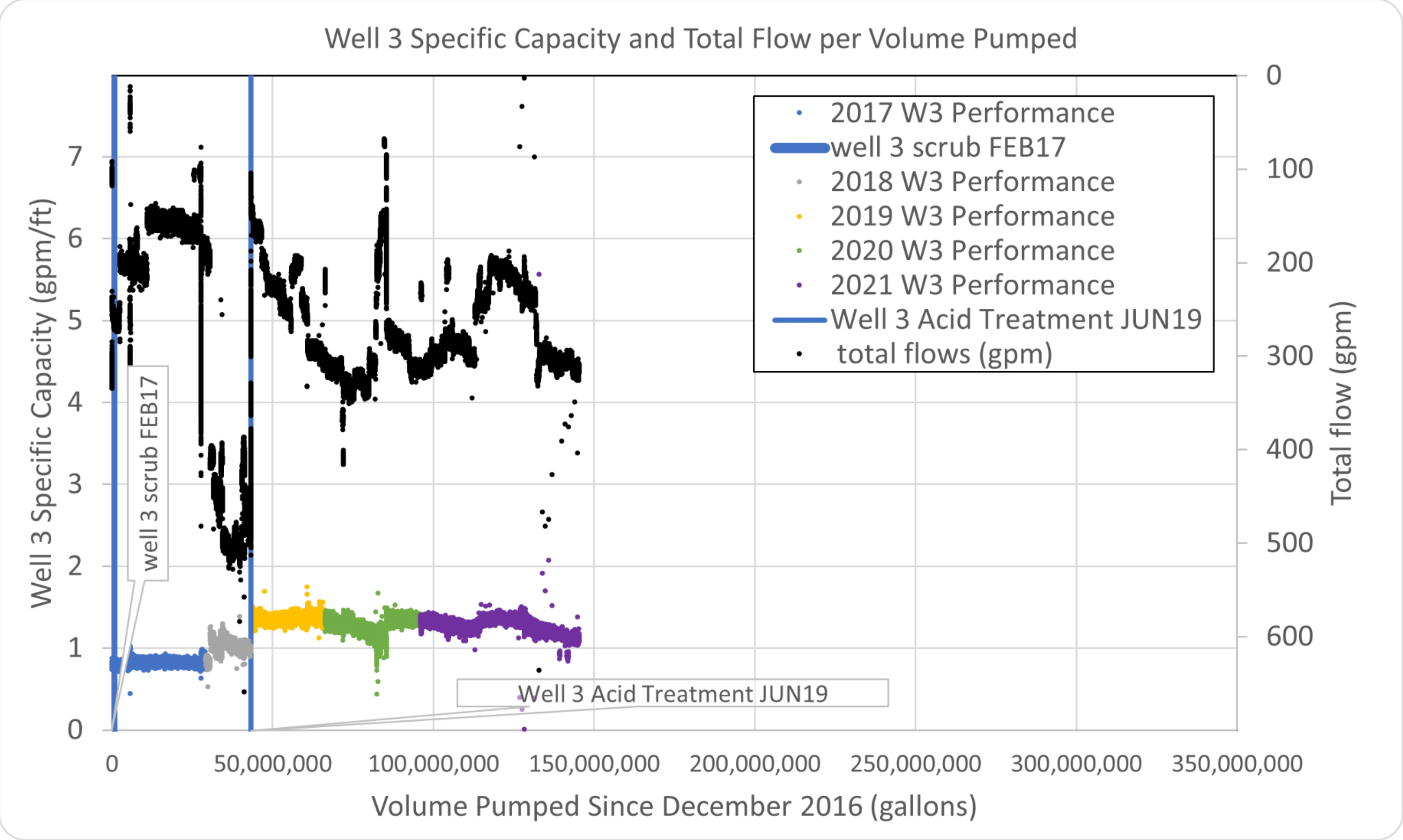
b. Constant Rate Interference Test Conducted in December 2011, specific capacity 4.8 | gpm/ft

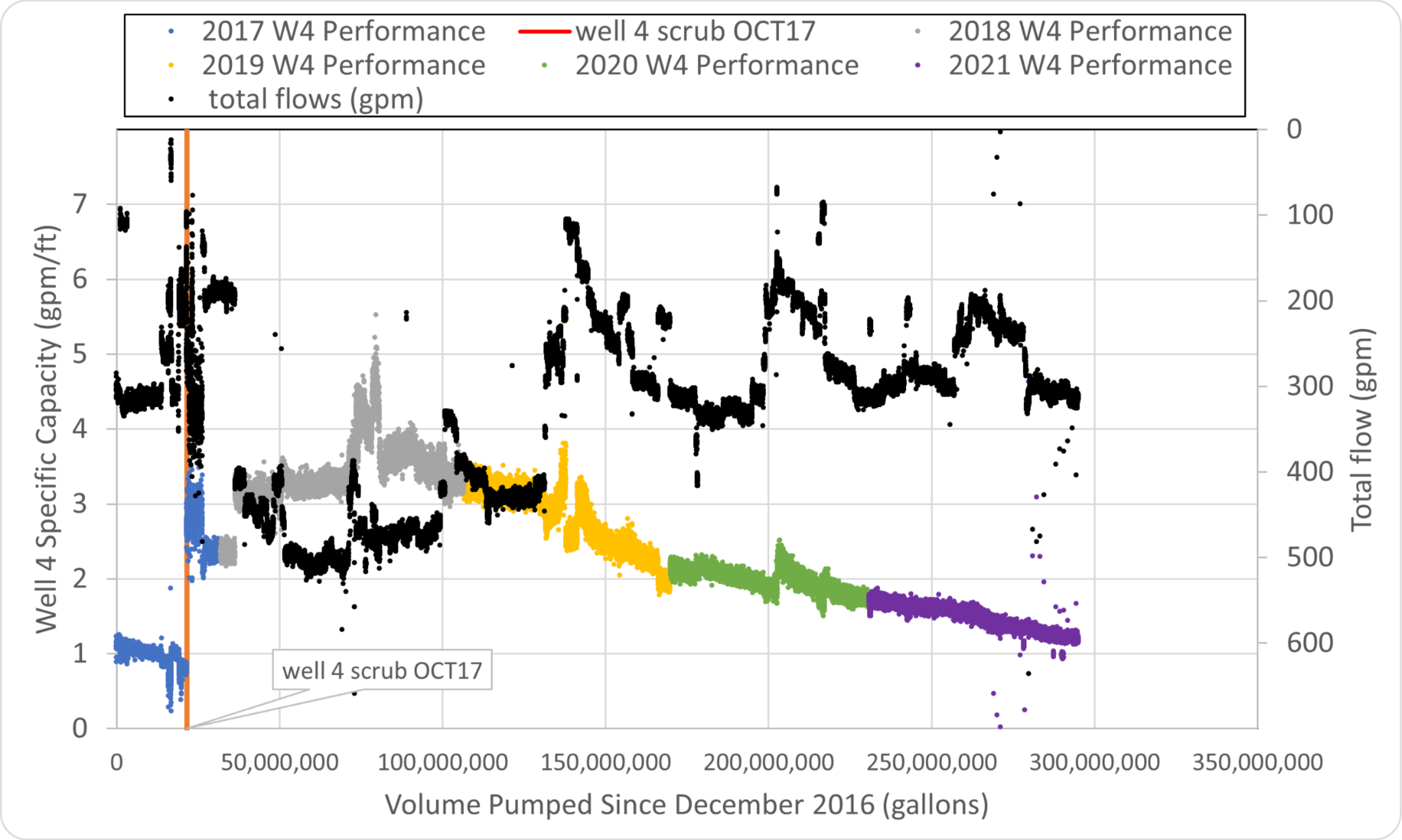
c. Former monitoring well, which was changed to a production well last month. It has a 10 hp- 6-inch Franklin motor, 460 volt, 3 phase.

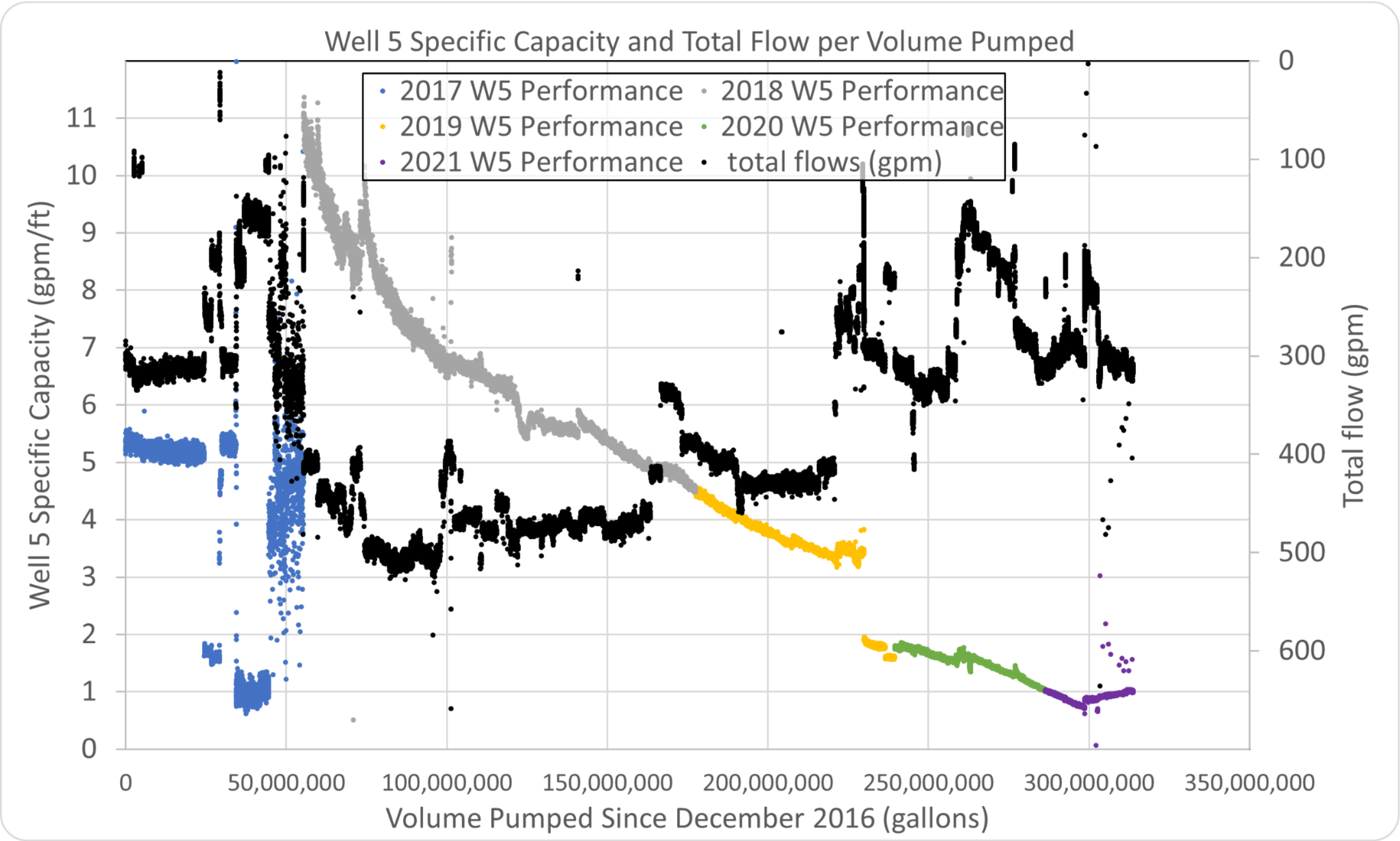
B Appendix: Site Map

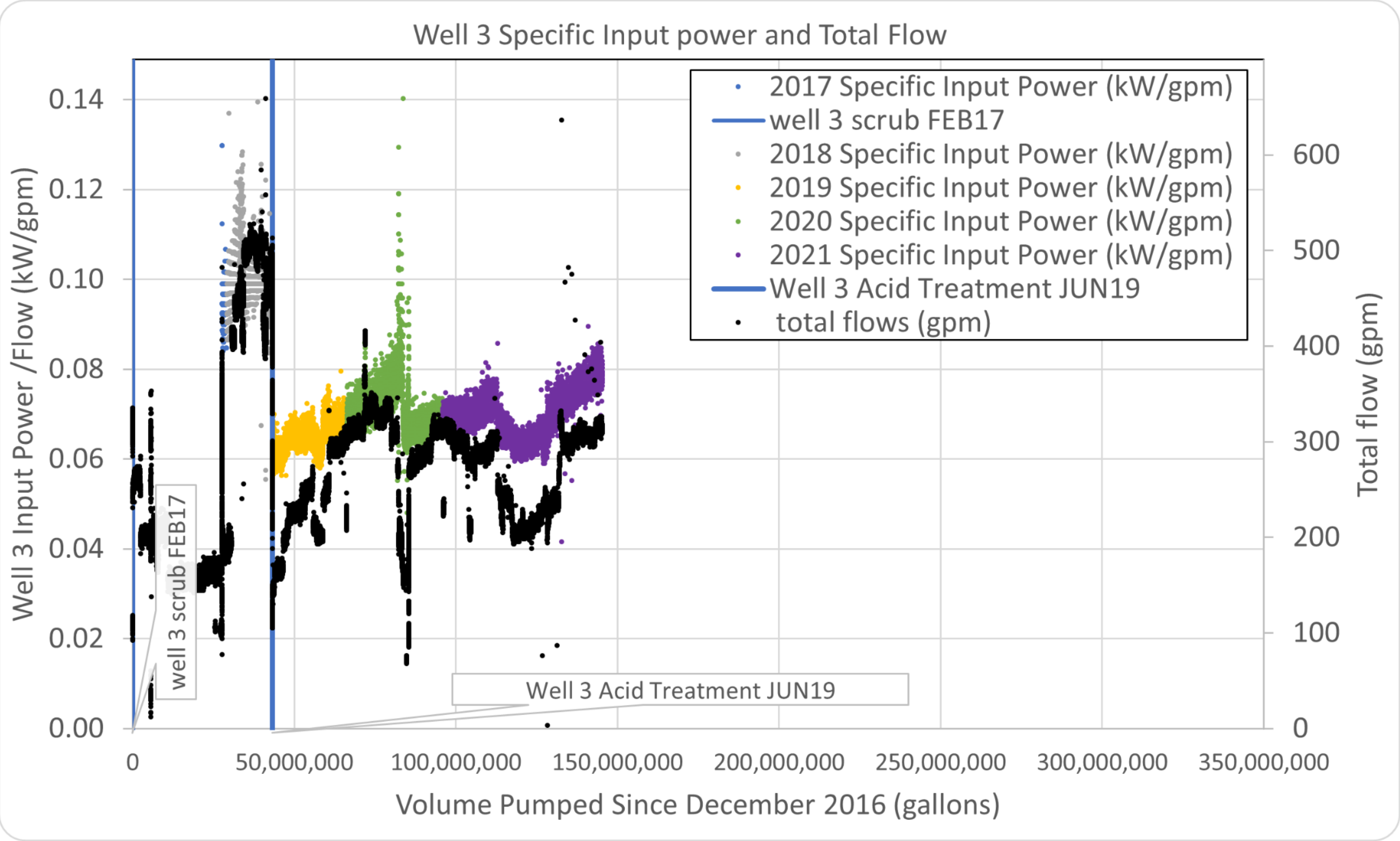


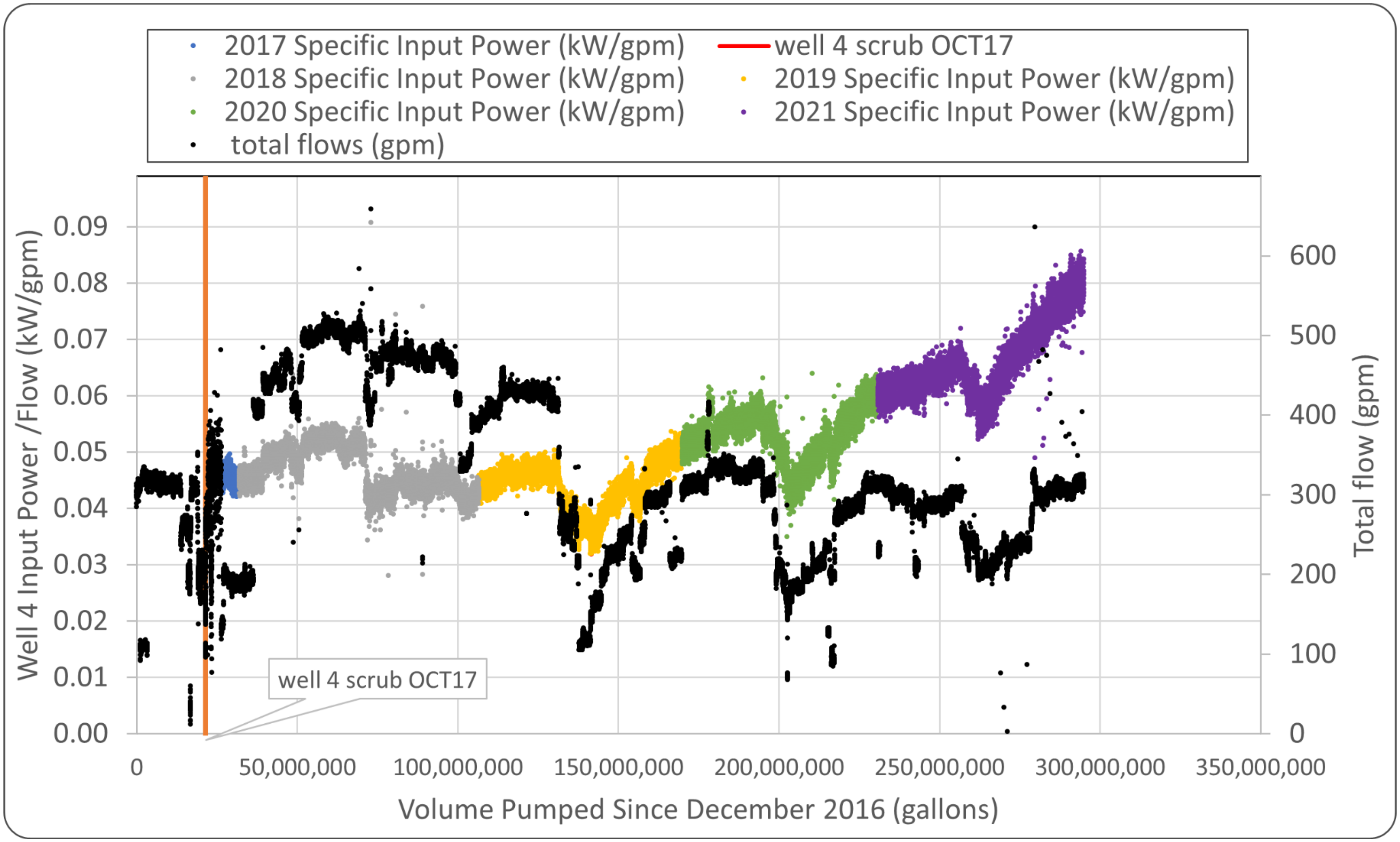
C Appendix: Additional Figures

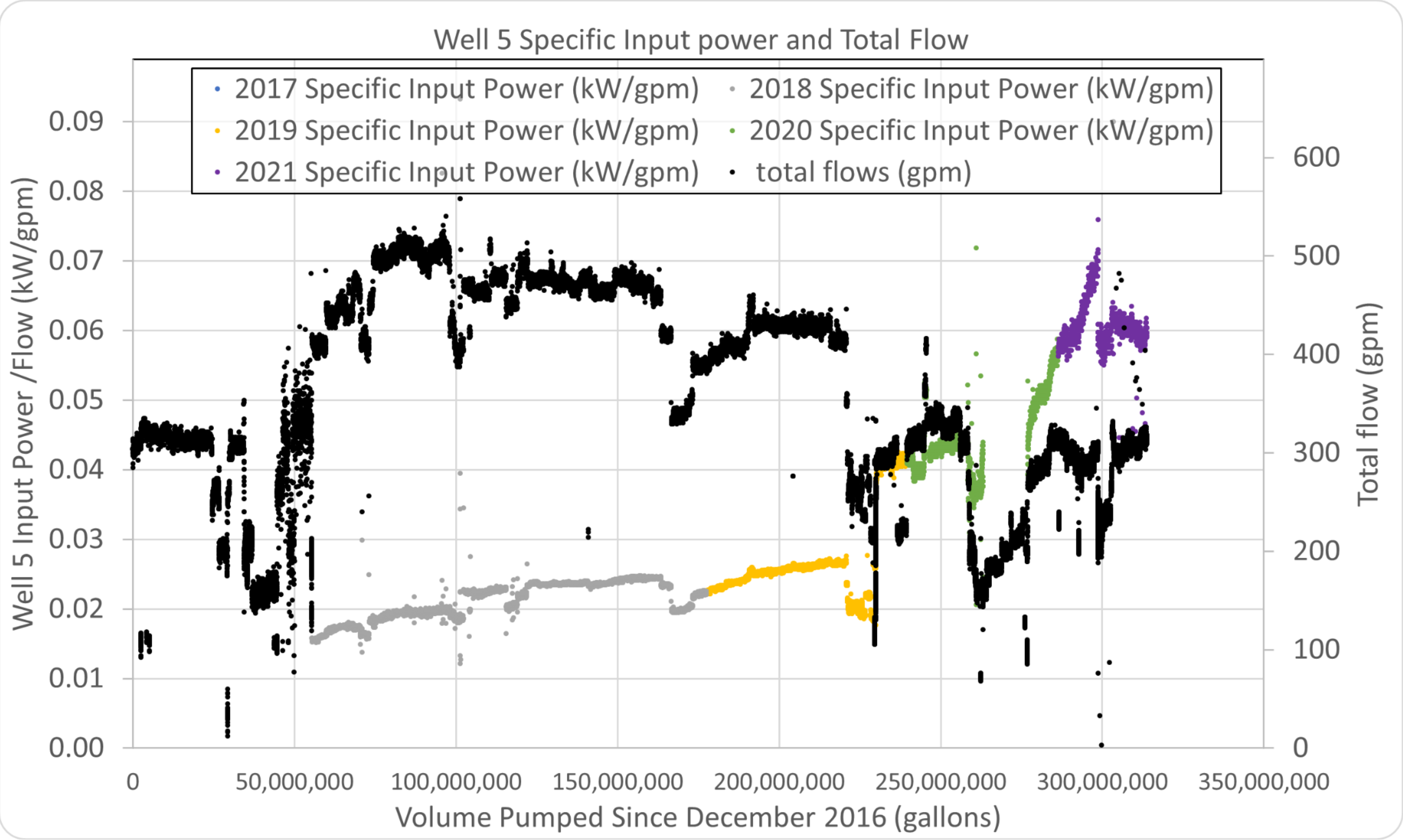



2017 W4 Performance
well 4 scrub OCT17
2018 W4 Performance
2019 W4 Performance
2020 W4 Performance
2021 W4 Performance
total flows (gpm)
Well 4 Specific Capacity (gpm/ft)
0
1
2
3
4
5
6
7
Total flow (gpm)
0
100
200
300
400
500
600
0
50,000,000
100,000,000
150,000,000
200,000,000
250,000,000
300,000,000
350,000,000
Volume Pumped Since December 2016 (gallons)
well 4 scrub OCT17


Well 5 Specific Capacity and Total Flow per Volume Pumped
● 2017 W5 Performance
● 2018 W5 Performance
● 2019 W5 Performance
● 2020 W5 Performance
● 2021 W5 Performance
● total flows (gpm)
Well 5 Specific Capacity (gpm/ft)
0
1
2
3
4
5
6
7
8
9
10
11
Total flow (gpm)
0
100
200
300
400
500
600
0
50,000,000
100,000,000
150,000,000
200,000,000
250,000,000
300,000,000
350,000,000
Volume Pumped Since December 2016 (gallons)


Well 3 Specific Input power and Total Flow
Well 3 Input Power /Flow (kW/gpm)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Total flow (gpm)
600
500
400
300
200
100
0
0
50,000,000
100,000,000
150,000,000
200,000,000
250,000,000
300,000,000
350,000,000
Volume Pumped Since December 2016 (gallons)
2017 Specific Input Power (kW/gpm)
well 3 scrub FEB17
2018 Specific Input Power (kW/gpm)
2019 Specific Input Power (kW/gpm)
2020 Specific Input Power (kW/gpm)
2021 Specific Input Power (kW/gpm)
Well 3 Acid Treatment JUN19
total flows (gpm)
well 3 scrub FEB17
Well 3 Acid Treatment JUN19


2017 Specific Input Power (kW/gpm)
well 4 scrub OCT17
2018 Specific Input Power (kW/gpm)
2019 Specific Input Power (kW/gpm)
2020 Specific Input Power (kW/gpm)
2021 Specific Input Power (kW/gpm)
total flows (gpm)
Well 4 Input Power /Flow (kW/gpm)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
Total flow (gpm)
0
100
200
300
400
500
600
0
50,000,000
100,000,000
150,000,000
200,000,000
250,000,000
300,000,000
350,000,000
Volume Pumped Since December 2016 (gallons)
well 4 scrub OCT17


Well 5 Specific Input power and Total Flow
2017 Specific Input Power (kW/gpm)
2018 Specific Input Power (kW/gpm)
2019 Specific Input Power (kW/gpm)
2020 Specific Input Power (kW/gpm)
2021 Specific Input Power (kW/gpm)
total flows (gpm)
Well 5 Input Power /Flow (kW/gpm)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Total flow (gpm)
600
500
400
300
200
100
0
0
50,000,000
100,000,000
150,000,000
200,000,000
250,000,000
300,000,000
350,000,000
Volume Pumped Since December 2016 (gallons)