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August 2, 2024

VIA EMAIL

Ms. Theresa Hamacher
Mr. Clark Santos
Pleasant Water, Inc.
261 White's Path – Suite 5
South Yarmouth, MA 02664

Re: Saltwater Intrusion Assessment – Pleasant Water, Wellfleet, MA

Dear Ms. Hamacher and Mr. Santos:

The Horsley Witten Group, Inc. (HW) is pleased to submit this letter to you summarizing our evaluation of the potential for saltwater intrusion concerns at the Pleasant Water supply wells. As we understand it, Pleasant Water is considering adding additional homes to its existing public water supply (PWS) system and, given the proximity of the PWS wells to salt water, are concerned about the potential for salt water intrusion in the wells if pumping were to be increased to accommodate the demand from the additional homes. The evaluation described herein considers the potential limitations of increasing water withdrawals related to saltwater intrusion at the PWS wellfield. Our evaluation was conducted consistent with our limited Scope of Work for this project intended as a preliminary evaluation which will help inform your options regarding water supply.

Background

Pleasant Water Inc. (Pleasant Water) is a PWS in Wellfleet, Massachusetts, which provides drinking water to the small residential community of Pleasant Point. The system consists of three active pumping wells, two abandoned wells, a small building housing electrical control and treatment systems, and a distribution system. Pleasant Point is a highly seasonal community, and water usage during the summer months can be as much as seven times higher than winter use.

Not every home in Pleasant Point is served by the water utility. Some coastal homes, currently on private domestic wells, have noticed salty taste in their water. As such, the community and water utility are considering adding these homes to the distribution system for Pleasant Water.

Pleasant Water contracted HW to assess the potential for saltwater intrusion to occur at the wells operated by the utility, and the capacity for the utility to increase pumping in order to serve those additional customers.

Saltwater Intrusion

Saltwater intrusion refers to the phenomenon where salty or brackish groundwater enters a pumping well. In coastal freshwater aquifers like that of Pleasant Point, a relatively thin lens of freshwater sits atop an underlying saltwater wedge which starts at sea level near the coastline and increases in depth further inland. Saltwater underlies the entirety of the aquifers of the Outer Cape and, since saltwater is denser than freshwater, the freshwater aquifer essentially "floats" above the saltwater beneath. Higher freshwater head (potential surface above sea level, or "water table" in an unconfined aquifer such as Pleasant Point) yields a lower interface between fresh and salt water. The thickness of this freshwater lens (the difference between the freshwater head and the elevation of the freshwater-saltwater interface) is based on the density difference between the two fluids. Ghyben and Herzberg first defined this relationship for seawater and freshwater as the ratio of head to freshwater lens thickness of 40:1 (e.g., if groundwater head is 1 foot above sea level, then fresh groundwater is expected for 40 feet below sea level at that point). Note however that this theoretical "interface" depth is the depth to full salinity oceanic water. A fairly thick "mixing zone" creates a gradation from full salt water to full fresh water above this interface.

The wedge of the saltwater interface owes its shape to the typical increase in freshwater head at distances further from the coast. Freshwater enters the aquifer through recharge from precipitation that does not run off, evaporate, or transpire from plants. Recharge raises the water table, and since gravity pulls groundwater downward, a potential gradient is created towards sea level at the coast. Groundwater does not flow freely through the aquifer material. Hydraulic conductivity is a property of aquifer material which describes the ability of groundwater to flow through the material, or conversely, the resistance to flow that the material provides relative to the potential gradient. With lower conductivity material, a higher gradient is needed to move water towards the coast than would be needed with a higher conductivity material. For an equilibrium to be established, the potential gradient provided by groundwater heads must increase to the point that the total recharge entering the system equals the amount of discharge to the coast, necessarily meaning that freshwater heads must be higher inland to drive this discharge. With the higher inland freshwater head, the saltwater interface elevation becomes deeper based on the Ghyben-Herzberg relationship.

Any pumping well will draw down the water table in the aquifer in the vicinity of the well. As the freshwater head decreases there becomes less weight of freshwater floating atop the saltwater interface, which causes the interface to rise. The rising of the interface below a pumping well is referred to as “upconing” because saltwater rise is highest below the well (where drawdown is also greatest) and decreases laterally away from the well. The lateral and vertical extent of drawdown (and thus upconing) is a function of the well pumping rate and the conductivity of the surrounding aquifer material. After some amount of upconing occurs, there exists a “critical elevation”, beyond which any additional pumping will result in destabilization of the interface and a rapid rise in interface elevation; to the point where salt water may be directly withdrawn by the pumping well. The analyses undertaken by HW included an analysis of this critical discharge rate as well as modeling of impacts at sub-critical pumping rates.

Pumping Test

Analytical methods for estimating potential saltwater intrusion rely on understanding the hydraulic conductivity of the aquifer material in the vicinity of the well. HW, with the support of Pleasant Water, conducted a pumping test in February 2024, in order to calculate the hydraulic conductivity of the material at the Pleasant Water wellsite.

Description of the Site

The PWS wells and treatment building are located between 220 and 300 feet from the nearest coastline at Pleasant Landing. Well #1 is approximately 220 feet from the coastline. Well #5 is approximately 275 feet from the coast, approximately colinear with well #1 perpendicular to the coastline. Well #5 is approximately 20 feet from the line between wells #1 and #4, and 20 feet closer to the coast than well #4. As-built plans provided by Pleasant Water indicate that well #1 is the deepest well, with a 3-foot screened interval ending 27 feet below the ground surface. Well #4 has a 4-foot screened interval with a bottom elevation of 22 feel below ground surface and Well #5 also has a 4-foot screened interval with a bottom elevation 26 feet below ground surface. Well #3, an abandoned well, was utilized as the observation well during the pump test and its elevation was surveyed. The top of well #3 is 18.36 feet above the NAVD88 datum and the ground surface 1-foot below the top was utilized as the ground surface for all three wells. The properties of the wells are summarized in table 1 below.

Well	Distance from coast	Lateral distance	Screen bottom and elevation	Use
#1	220′	0	-9.6′ bottom 3′ screen	Pumping Well (active during pump test)
#3	225′	0	Unknown	Abandoned Well (monitored during pump test)
#4	240′	10	-3.6′ bottom 4′ screen	Pumping Well (not utilized during pump test)
#5	250′	0	-7.9′ bottom 4′ screen	Pumping Well (not utilized during pump test)

Table 1: Pleasant Water wells

Pumping Test Operation

Well #1 was the active pumping well used for the pumping test because, being both the deepest and the nearest to the coast, is the most susceptible to saltwater intrusion and would therefore provide conservative data about the potential for salt water upconing. Two monitoring points were established for the pumping test:

- Well #3, approximately 5 feet away from Well #1, and
- Wellfleet Harbor at the Wellfleet Town Pier.

At each monitoring point, a water pressure and temperature data logger (TD-Diver by Van Essen Instruments) was affixed with string and placed in the water at a depth sufficient to ensure that the logger would not be exposed during the test. The logger in Well #3 recorded at a 1-minute frequency. The harbor logger at the Town Pier recorded with a 3-minute frequency. A third data logger was placed in a tree near the pump station to monitor atmospheric pressure, which is utilized during post-processing to compensate pressure readings from the other two loggers to account for changes in barometric pressure. Each monitoring point was surveyed for elevation using high-accuracy RTK GPS and manual depth to water measurements were performed to establish initial starting water level elevations for the data records.

Pre-test monitoring began on February 22nd, 2024. Well #1 was shut down starting in the afternoon of February 22nd, with primary production switched to Well #5 (furthest from the monitoring point at Well #3) for this pre-test monitoring period to facilitate stabilization prior to test start.

On February 26th, 2024 HW staff and Todd Everson gathered at the Pleasant Water pump station to begin the pumping test. An additional data logger was placed in Well #3 with a 1-second sampling frequency to record high-resolution data during the fastest drawdown period at test start. Manual depth-to-water readings were taken at the Town Pier and Well #3. Pumping was switched to Well #1, and a hydrant was opened to instigate production of approximately 20 gallons per minute. Flow was assessed using a graduated bucket at the discharging hydrant, as well by reading the master meter in the pump house building. In addition to the logger in place, Well #3 was actively monitored with manual depth to water readings at frequent intervals during the beginning of the test. Active monitoring of the master meter and Well #3 water level continued for several hours on the afternoon of the 26th.

The pump test continued until the afternoon of February 28th, 48 hours after initiation. Water levels at Well #3 were monitored intermittently by Todd Everson and HW staff during this period, and water levels were determined to have stabilized prior to ending the test. Again, HW staff were present on site to place another high-frequency data logger in Well #3, record master meter readings, and perform manual depth-to-water measurements prior to and following test shut down. To shut down the test, pumping was transferred from Well #1 to Well #5, and the discharge hydrant was closed to return the system to normal off-season operation. Following the end of the test, loggers were left in place for another week to record the full period of recovery and return to baseline conditions.

Water Quality Sampling

Three water quality laboratory analyses were provided to HW by Todd Everson from before, during, and after the pump test, as well as corresponding field measurements. Key results are summarized in Table 2 below:

	Sodium (mg/L)	Chloride (mg/L)	Spec. Conductance (umhos/cm)	Conductance (field measured) (uS/cm)
2/22/24 10:15	19	27	142	164.2
2/27/24 13:50	32	54	211	147
2/28/24 13:50	35	59	221	252

Table 2: Key water quality data before, during, and after the pump test.

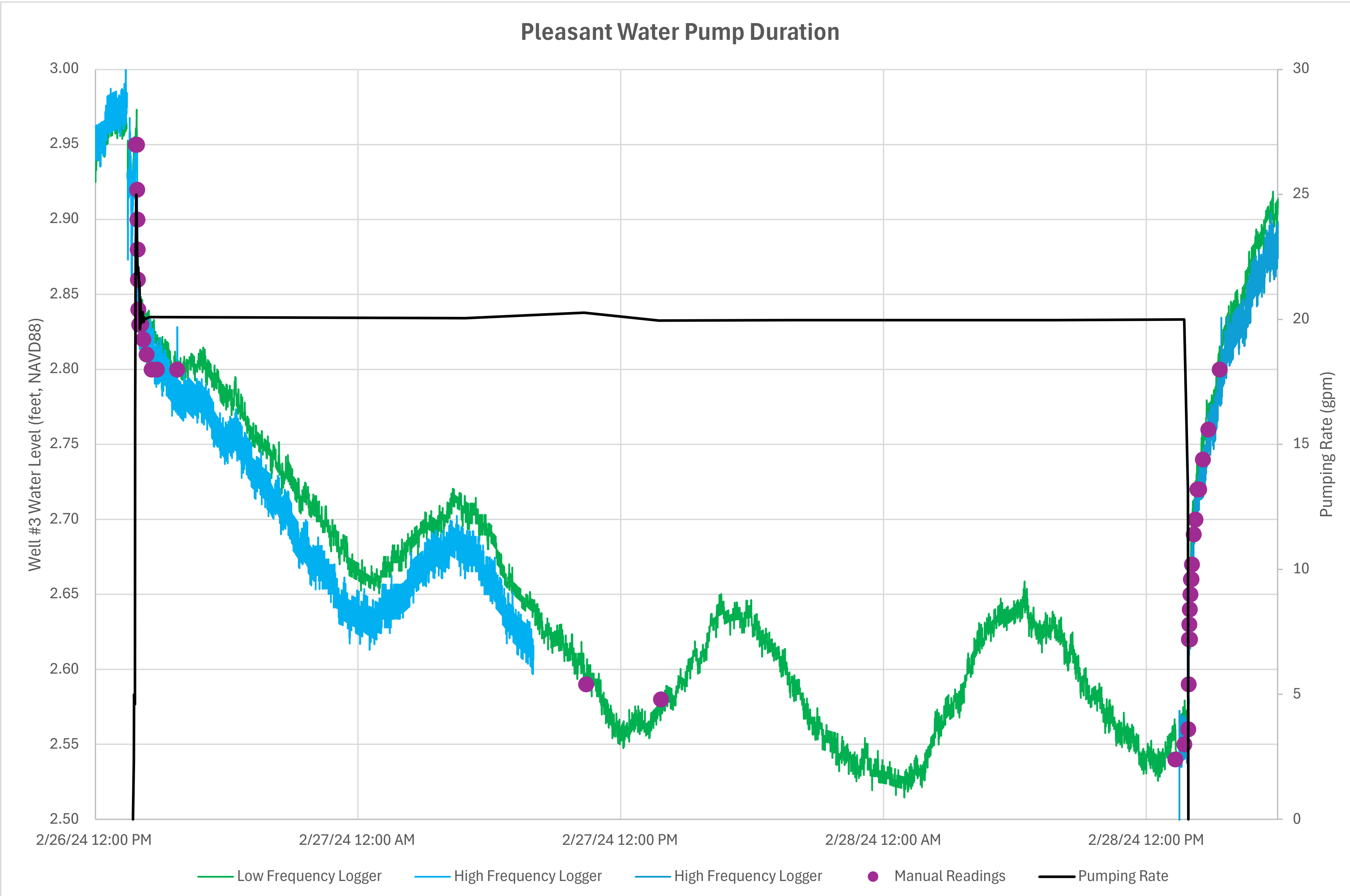
Estimating Aquifer Properties

Preliminary Findings

Water level data recorded by loggers, manual depth to water readings, and pumping rate information were analyzed following the pump test. Water level loggers record pressure, which includes the weight of any water above the logger as well as atmospheric pressure. Fluctuations in atmospheric pressure are compensated for by subtracting the changes recorded by the barometric logger, leaving only the signal of changing water levels in the well. Compensated water levels were converted to elevations based on the surveyed elevation of each monitoring point, coupled with manual depth to water readings recorded before and after the pump test. Water elevation data for the duration of the test is presented in Figures 1a, 1b, and 1c.

It is important to note that surveyed elevations are measured relative to the North American Vertical Datum of 1988 (NAVD88), which does not specifically represent “sea level”. Actual “sea level” varies from the datum over time and at different locations. The average sea level (relative to NAVD88) recorded at the Town Pier was 0.28 feet over the duration of the monitoring period, and tidal fluctuation ranged from -5.52 feet to 6.77 feet. The average groundwater elevation in Well #3 prior to the start of the test was 2.98 feet. As such, the average freshwater head at Well #3 during the pumping test was 2.7 feet above the average harbor level over that same time period.

Figure 1a



Pleasant Water Pump Duration
Well #3 Water Level (feet, NAVD88)
3.00
2.95
2.90
2.85
2.80
2.75
2.70
2.65
2.60
2.55
2.50
Pumping Rate (gpm)
30
25
20
15
10
5
0
2/26/24 12:00 PM
2/27/24 12:00 AM
2/27/24 12:00 PM
2/28/24 12:00 AM
2/28/24 12:00 PM
Low Frequency Logger
High Frequency Logger
High Frequency Logger
Manual Readings
Pumping Rate

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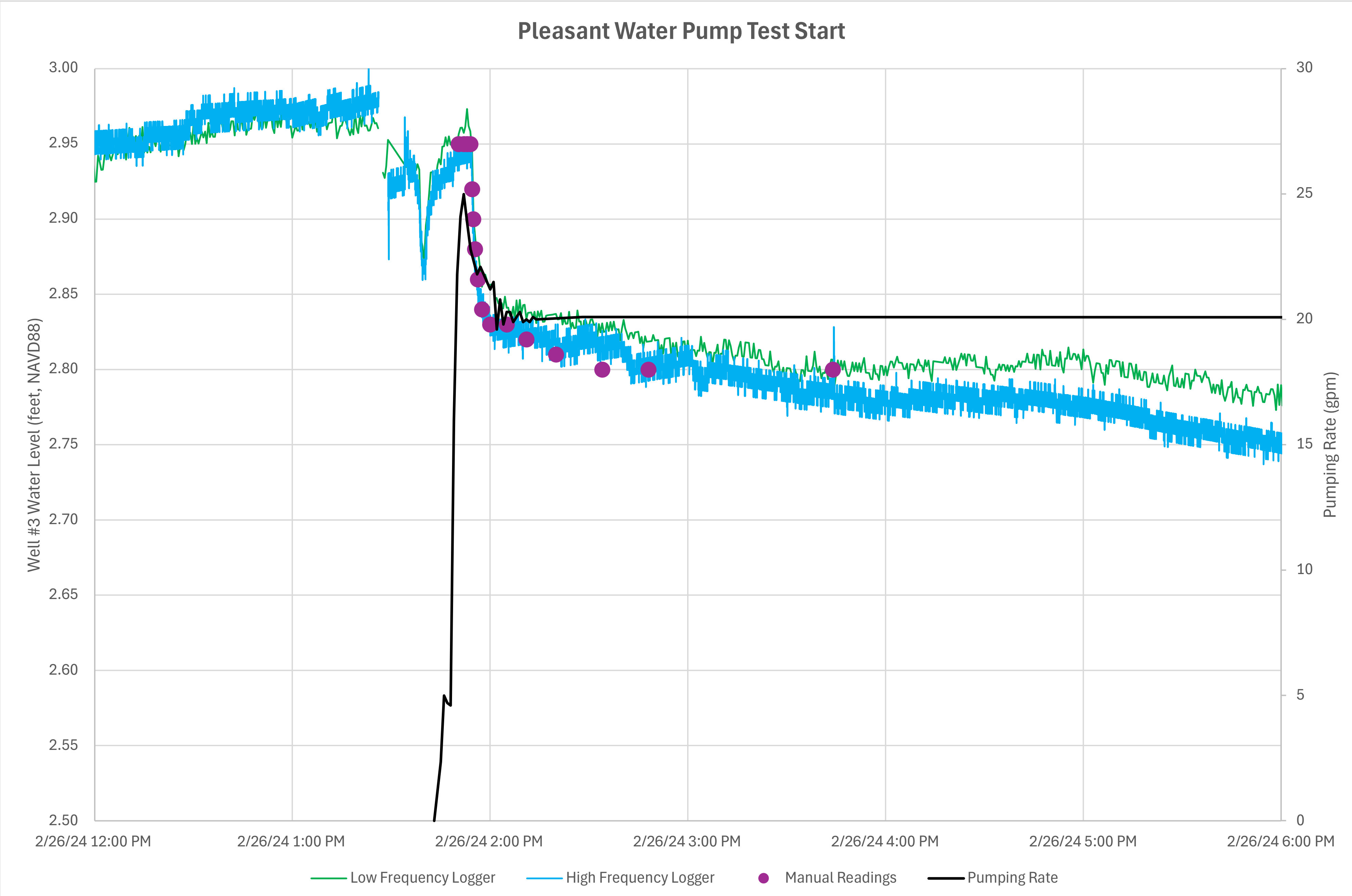
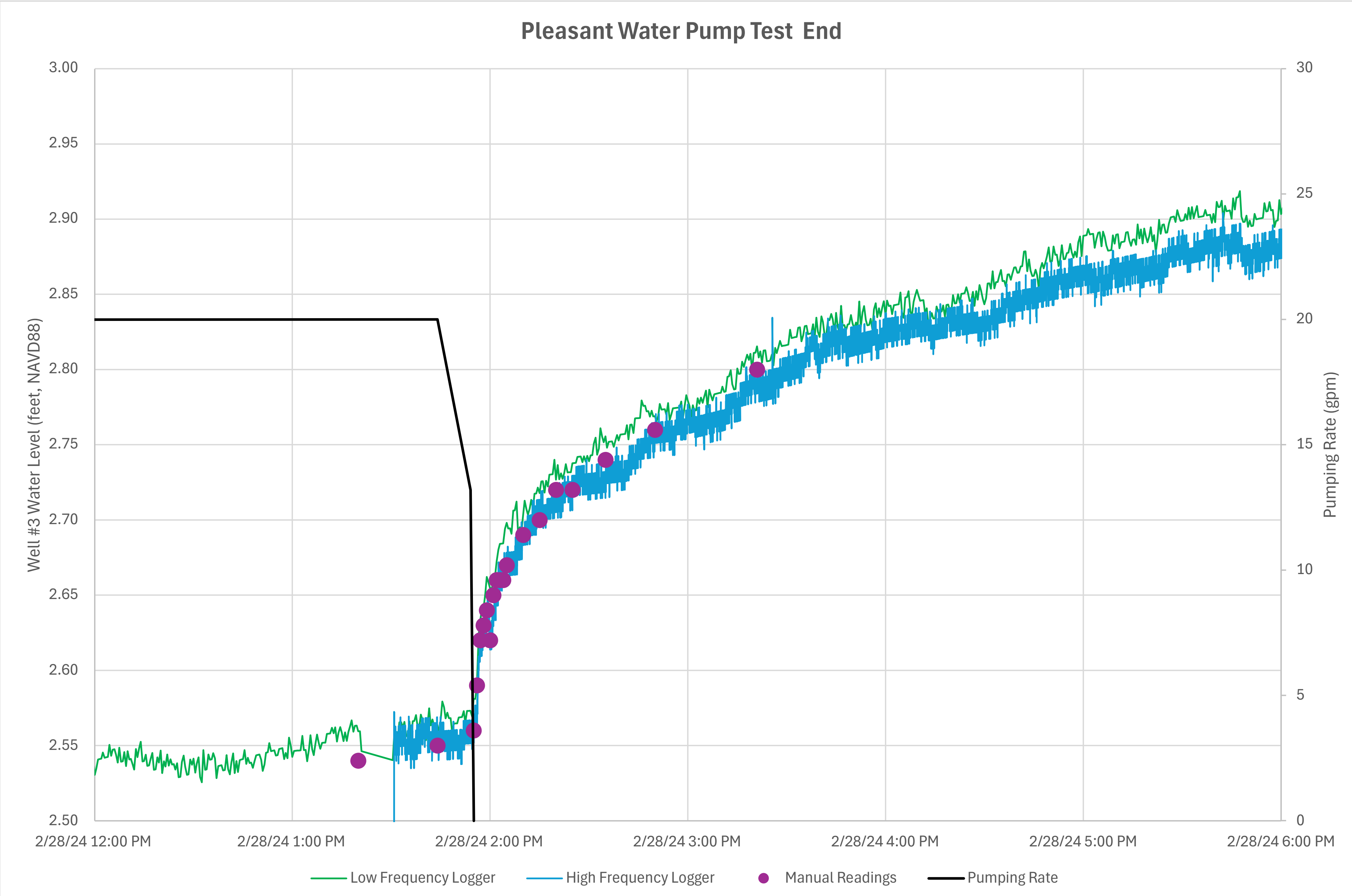


Pleasant Water Pump Test Start
Well #3 Water Level (feet, NAVD88)
Pumping Rate (gpm)
3.00
2.95
2.90
2.85
2.80
2.75
2.70
2.65
2.60
2.55
2.50
30
25
20
15
10
5
0
2/26/24 12:00 PM
2/26/24 1:00 PM
2/26/24 2:00 PM
2/26/24 3:00 PM
2/26/24 4:00 PM
2/26/24 5:00 PM
2/26/24 6:00 PM
Low Frequency Logger
High Frequency Logger
Manual Readings
Pumping Rate

Figure 1c



Pleasant Water Pump Test End
Well #3 Water Level (feet, NAVD88)
Pumping Rate (gpm)
3.00
2.95
2.90
2.85
2.80
2.75
2.70
2.65
2.60
2.55
2.50
30
25
20
15
10
5
0
2/28/24 12:00 PM
2/28/24 1:00 PM
2/28/24 2:00 PM
2/28/24 3:00 PM
2/28/24 4:00 PM
2/28/24 5:00 PM
2/28/24 6:00 PM
Low Frequency Logger
High Frequency Logger
Manual Readings
Pumping Rate

Water levels in Well #3 exhibit a signal of tidal influence before, during and after the pump test. The amplitude of this tidal signal is approximately 0.11 feet. Total drawdown from pre-test water levels in Well #3 to stabilization was approximately 0.45 feet. The primary objective of the pump test is determination of the hydraulic conductivity of the surrounding aquifer material, which relies on analysis of the amount and rate of drawdown in Well #3 in response to pumping in Well #1. Since the amplitude of tidal fluctuation in water level at Well #3 constitutes a significant portion of the total degree of drawdown in the well, an analysis was undertaken to isolate the component of water level change attributable to tidal influence in order to then isolate the component attributable to drawdown due to pumping.

A simple sinusoidal function was developed to account for the tidal fluctuation component during the pretest phase and manually fit to the pre-pump test monitoring data at Well #3. The function was then applied to the duration of monitoring and subtracted from water levels measured in Well #3 in order to provide water levels throughout the test compensated for the tidal fluctuation. The function applied was a simple sinusoidal wave function with amplitude and temporal offset parameters manually set to fit the data to the highest degree possible. The fit of the tidal adjustment factor and adjusted water elevation at Well #3 is shown in Figure 2. The manual fitting process yielded the following function describing the tidal influence on water level data:

$$\text{Adjustment} = A * \sin(S+(T/24)*4*\pi*(1440/1480))$$ Where:

A = Amplitude of tidal signal (0.11 feet)

S = Temporal shift of tidal influence at Well #3 compared to the Town Pier tide (1.5 hours)

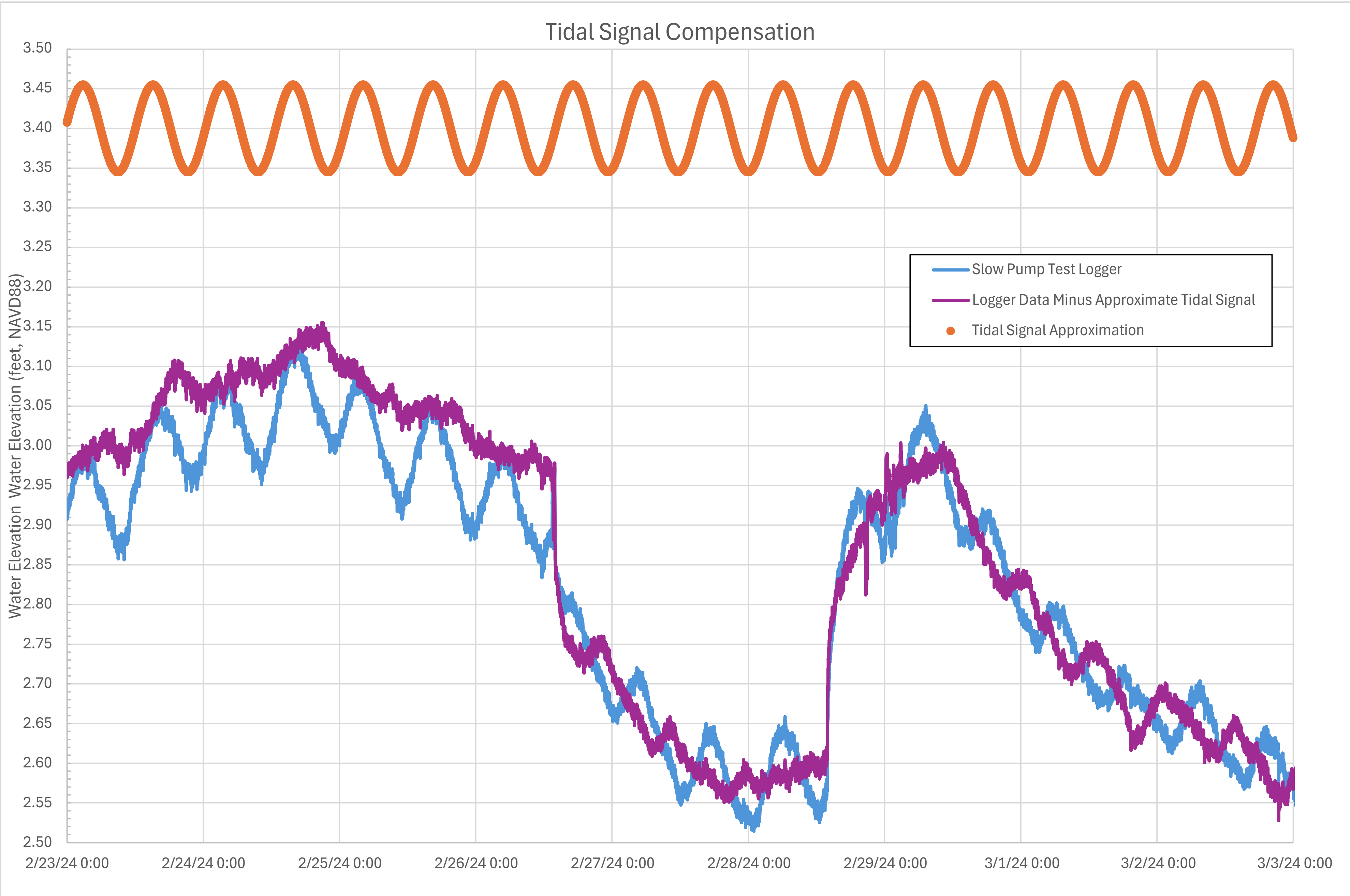
T = Time (days)

1440/1480 relates the time (in days) to a single tidal cycle(1480 minutes)

Hydraulic Conductivity Calculation

Water level data from the pumping test, compensated for tidal influence, was analyzed to estimate hydraulic conductivity of the aquifer using the Cooper-Jacob straight-line time-drawdown method. The Cooper-Jacob method incorporates pumping rate, drawdown, aquifer thickness, time, and distance from the monitoring well to the pumping well to estimate transmissivity, storativity, and hydraulic conductivity properties of aquifer materials.

Figure 2



Tidal Signal Compensation
Water Elevation (feet, NAVD88)
3.50
3.45
3.40
3.35
3.30
3.25
3.20
3.15
3.10
3.05
3.00
2.95
2.90
2.85
2.80
2.75
2.70
2.65
2.60
2.55
2.50
2/23/24 0:00
2/24/24 0:00
2/25/24 0:00
2/26/24 0:00
2/27/24 0:00
2/28/24 0:00
2/29/24 0:00
3/1/24 0:00
3/2/24 0:00
3/3/24 0:00
Slow Pump Test Logger
Logger Data Minus Approximate Tidal Signal
Tidal Signal Approximation

In order to apply the Cooper-Jacob method in an unconfined aquifer, drawdown values must first be adjusted to account for changes in aquifer transmissivity due to drawdown reducing the thickness of the aquifer. The bottom of the aquifer in this setting is inferred to be the freshwater-saltwater interface, the depth of which was estimated using the Ghyben-Herzberg relationship. Utilizing the 40:1 ratio for freshwater-seawater from Ghyben Herzberg, and a freshwater head of 2.7 feet above sea level, the interface at this point is anticipated to be 108 feet below sea level. Including the freshwater head yields a total freshwater aquifer thickness of 110.7 feet. The Jacobs modification was applied to correct for change in this thickness using the following formula:

$$[\text{Corrected DD}] = \text{Measured DD} – (\text{Measured DD}^2/2*[\text{Saturated Thickness}])$$

The saturated thickness applied in this context is the freshwater saturated thickness described above. The measured drawdown was 0.41 feet. The maximum Jacobs correction applied to the data based on this formula was 0.001 foot. Given the small amount of drawdown observed during the pump test, and the relatively high saturated thickness of the aquifer, a negligible Jacobs correction value was the reasonable result of this analysis.

The results of the Coopers-Jacob analysis is shown in Figures 3a and 3b, representing the most-conservative and least-conservative potential results of the analysis of pump test data. Considering this range of potential solutions, the hydraulic conductivity can be interpreted to be between 29 and 54 feet per day. These results align with typical near-surface hydraulic conductivity values on the lower portion of Cape Cod.

Saltwater Upconing Potential

The hydraulic conductivity values determined from the Cooper-Jacob analysis were applied to analytical and computation modeling methods to assess the potential for saltwater intrusion to impact the Pleasant Water PWS wells under anticipated increased pumping scenarios.

Analytical Solutions

An analytical solution to the critical discharge problem was performed using the formula developed by Dagan and Bear (1968). This analysis was performed to provide a reasonable maximum extent of the range of potential outcomes from a groundwater model-based solution described below.

First, the Ghyben-Herzberg equation was utilized to estimate the depth to the freshwater-saltwater interface below Well #1. With a static water table of 2.98 feet observed in Well #3 and sea level measured at 0.28 feet, the Ghyben-Herzberg equation predicts 108 feet depth to the saltwater interface and a total freshwater thickness of 110.7 feet. The elevation of the bottom of

Figure 3a

Pleasant Point, Wellfleet

(Cooper Jacob Straight Line Time - Drawdown Analysis)

$$T = \frac{2.3Q}{4\pi\Delta(h_o - h)}$$

$$S = \frac{2.25Tt_o}{r^2}$$

Q	20	gpm	Pump Rate	t_o	3	min	From Chart
Δ(ho-h)	0.22	ft	From Chart	r	4	ft	dist. From PW
T	**3,203**	**ft^2/day**	Transmissivity	**S**	**0.94**		Storatvity

$$K = \frac{T}{b}$$

b	110.00	ft	Aquifer Thickness
K	**29.12**	**ft/day**	Hydraulic Conductivity

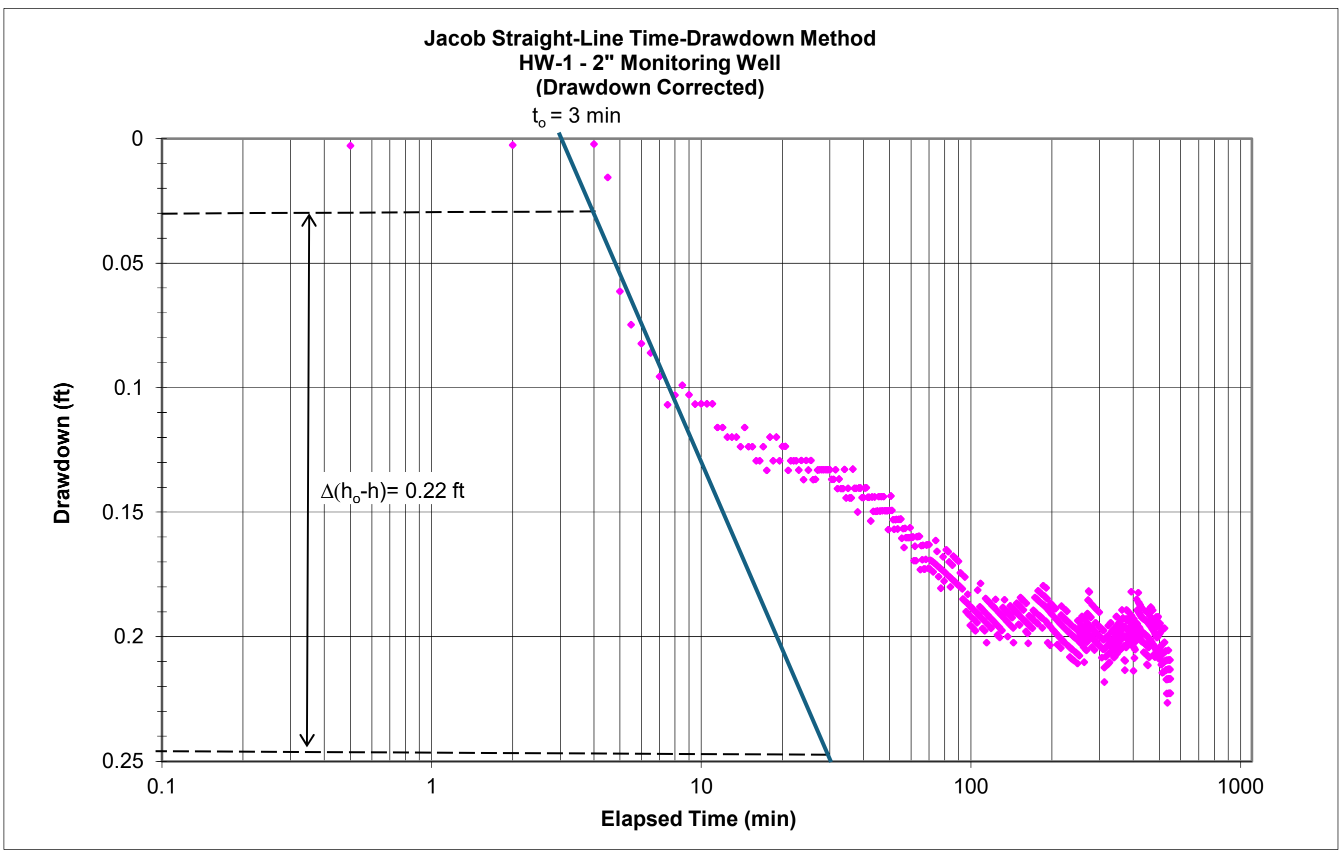


Figure 3b

Pleasant Point, Wellfleet

(Cooper Jacob Straight Line Time - Drawdown Analysis)

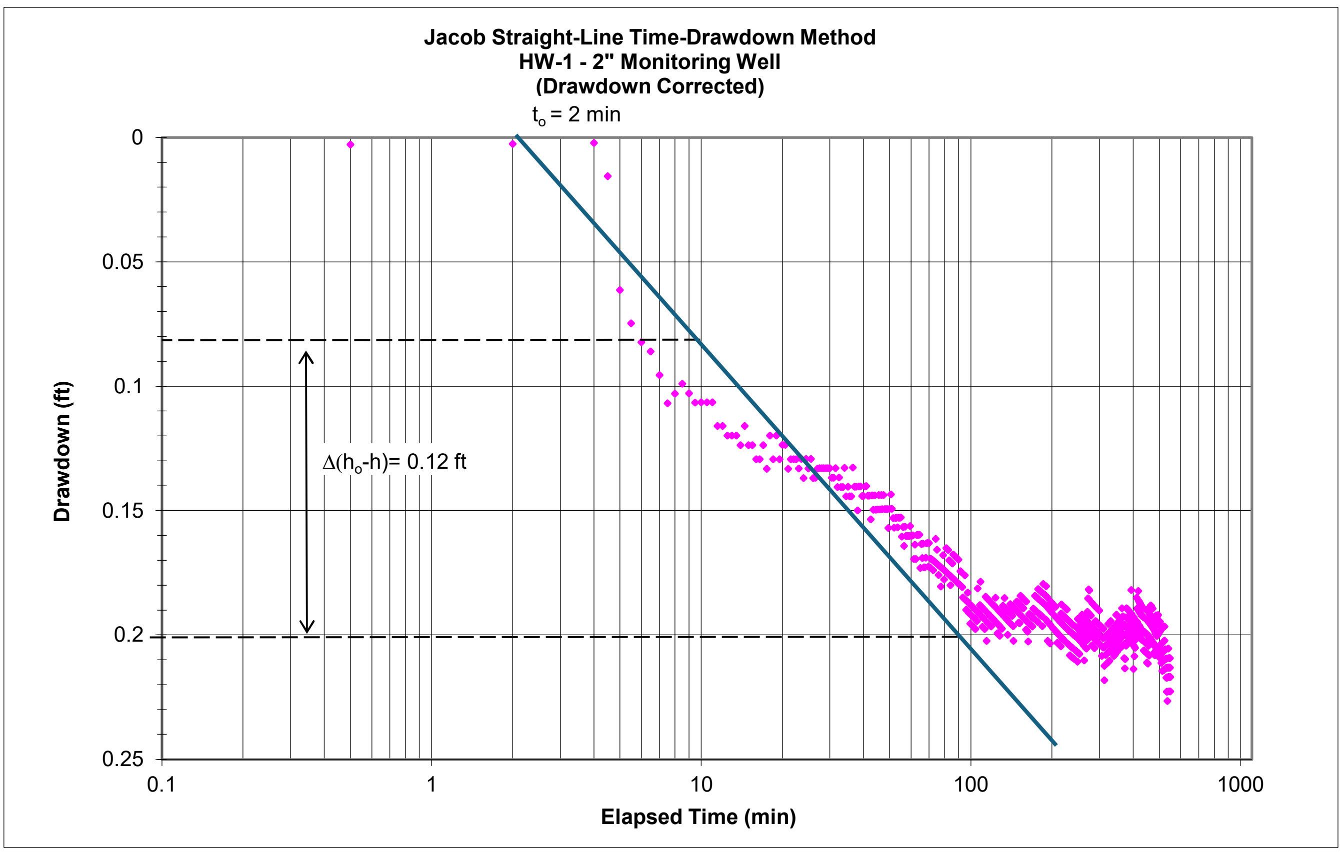
$$T = \frac{2.3Q}{4\pi\Delta(h_o - h)}$$

$$S = \frac{2.25Tt_o}{r^2}$$

Q	20	gpm	Pump Rate	t_o	2	min	From Chart
Δ(ho-h)	0.12	ft	From Chart	r	5	ft	dist. From PW
T	**5,872**	**ft^2/day**	Transmissivity	**S**	**0.73**		Storatvity

$$K = \frac{T}{b}$$

b	110.00	ft	Aquifer Thickness
K	**53.38**	**ft/day**	Hydraulic Conductivity



the screen in well #1 (-9.6 feet) is 98.4 feet above the predicted saltwater interface. This position, coupled with the estimated hydraulic conductivity value of 29 feet per day, is sufficient to calculate the critical discharge rate according to the equation developed by Dagan and Bear (1968). Dagan and Bear's formula suggests a theoretical critical pumping rate of 71 gallons per minute. Note that this value represents a hypothetical threshold for pumping that would create critical upconing of the full salt water interface and is greatly in excess of any sustainable pumping rate for continued supply of fully fresh water.

Qmax < 0.6 ∏ d^2 K ((ps-pf)/pf)		Dagan and Bear (1968)			
			Q	3850	Max pumping rate (cf/d)
			d	98	Distance from Well bottom to interface(ft)
Qmax =	13577.34 cfd		K	30	Hydraulic Conductivity (ft/day)
	101558.5 gpd		(ps-pf)/pf	0.025	fresh /salt density difference
	71 gpm	**Critical Pumping Rate**			

Figure 4: Parameters utilized in calculating critical well discharge.

Numerical Groundwater Model Solution

Analytical solutions to the saltwater interface problem (such as Dagan and Bear's critical discharge calculation) rely on a "sharp interface" assumption, where the brackish transition zone is ignored in favor of the mathematically simpler abrupt change from fresh to salty water. While this makes the analysis less-complex, the solution ignores the outcome that low-salinity water of undesirable taste may be withdrawn from the well at pumping rates below the critical pumping rate found by the analysis. Additionally, the solution found by Dagan and Bear's analysis solves only the critical pumping rate for a single well and does not incorporate the three well configuration of the Pleasant Water system.

To best reflect the interface transition zone and to incorporate the three-well configuration of the system, HW developed a three-dimensional, numerical, groundwater model of the Pleasant Point coastal aquifer system. The model was developed in the USGS's SEAWAT version 4 (Langevin et al., 2012), which couples the groundwater flow model MODFLOW-2000 (Harbaugh et al. 2000) and the solute-transport model MT3D-MS (Zheng et al., 2012) to calculate density-dependent flow solutions for problems such as the location of the freshwater-saltwater interface. The model was developed using the Groundwater Vistas version 8 graphical interface (Environmental Simulations Inc., 2020).

The groundwater model developed to assess conditions at Pleasant Point utilizes a generalized representation of the coastal aquifer system. The coastline is represented as a straight line of constant head, salt concentration, and density at one edge of the model domain. Head at this boundary is the average tidal elevation observed at the Wellfleet Pier during the monitoring period of 0.28 feet. Salt concentration is that of average seawater, or 2.185 pounds per cubic foot. The density of seawater is expressed as a relative increase compared to freshwater, 2.5%.

The model domain extends 1,000 feet in each horizontal dimension with rows and columns equally spaced 20 feet apart. The vertical domain ranges from 20 feet to -200 feet. The model is separated into 12 flat vertical layers in order to provide appropriate vertical resolution, with elevations described in Table 3 below.

Layer	Layer bottom	Layer	Layer Bottom
12	-200	6	-25
11	-100	5	-20
10	-50	4	-15
9	-40	3	-10
8	-35	2	-5
7	-30	1	0 (top = 20)

Table 3: Layers elevations in the numerical model.

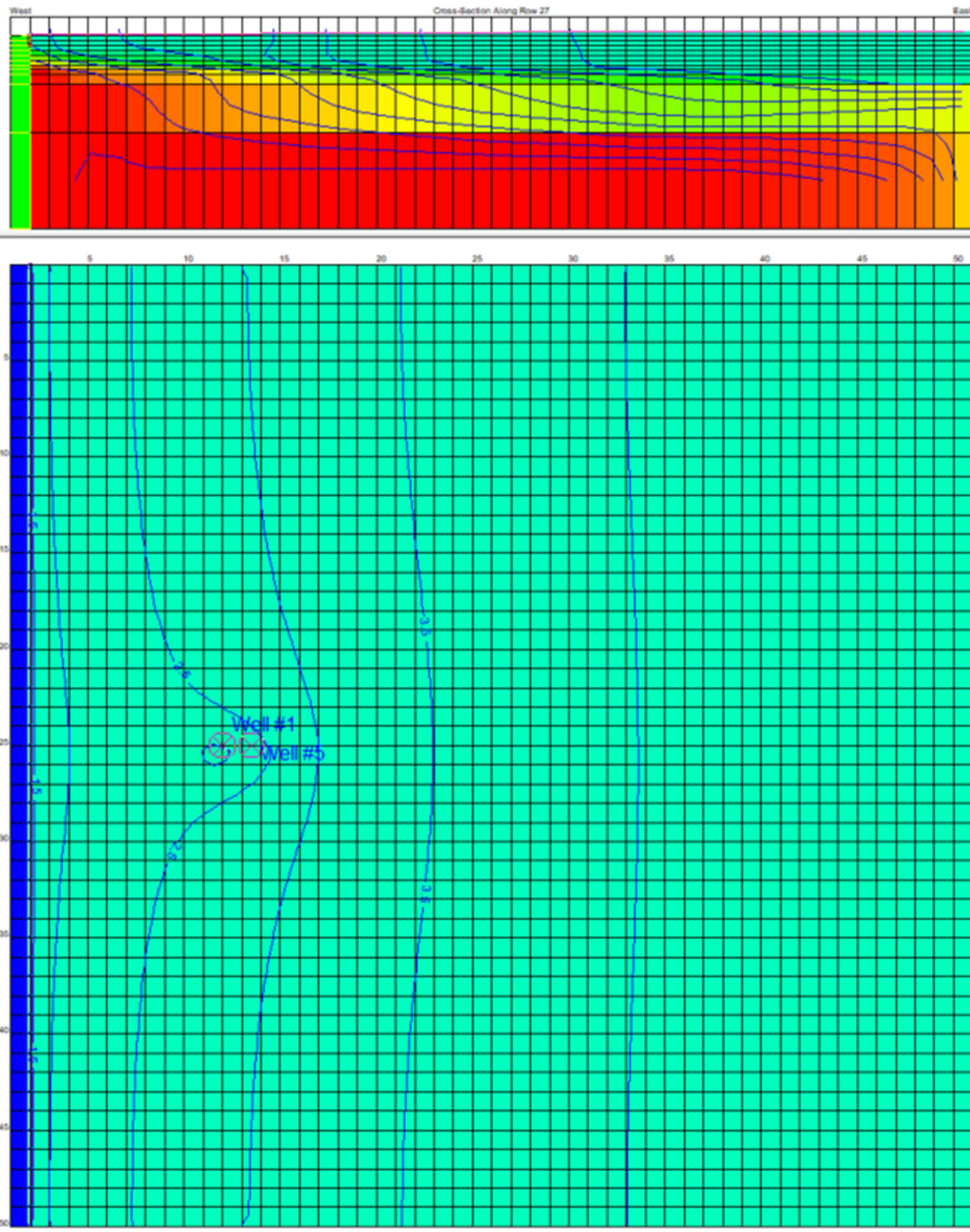


Figure 5: Model cross section (top) showing vertical layering of the model (vertical exaggeration of 1). Model horizontal domain (bottom) and the location of Wells #4 and #5. The coastline is represented by blue constant head boundary cells to left.

Aquifer properties applied in the model were determined based on parameters described in the USGS model of the lower Cape Cod Aquifer system (Masterson, 2004), as well as hydraulic conductivity determined from the pumping test. Key properties taken from Masterson are summarized in Table 4 below:

Property	Value
Recharge	35 inches per year
Specific storage	0.0001
Specific yield	0.25
Porosity	0.3

Table 4: Model parameters taken from Masterson, 2004.

Lateral hydraulic conductivity in the model layers 1-8 was assigned as 29 feet per day, equal to the more conservative result of the Pleasant Water pumping test Cooper-Jacob analysis, and vertical conductivity was assigned as three feet per day. Vertical conductivity is typically lower than horizontal conductivity, and a typical anisotropy ratio of 10:1 is utilized in the USGS groundwater model for the area (Masterson, 2004). Lower layers in the model necessitated a lower conductivity value to calibrate freshwater heads at Well #3. Layers nine through twelve have a horizontal conductivity of ten feet per day and a vertical conductivity of one foot per day.

The use of lower conductivity values for deeper sediments in the lower Cape Cod aquifer system aligns with the practice utilized by Masterson, 2004 and is based on the glacial processes which formed Cape Cod. The sediments which formed the outer Cape were deposited following the Last Glacial Maximum approximately 20,000 years ago. As the glaciers receded to the north, and sea levels remained approximately 300 feet lower than current conditions, a glacial lake occupied what is now Cape Cod Bay. Glaciolacustrine material deposited in the former lake is finer (including fine sands and silts) than the coarse materials in the outwash plains deposited by moving meltwater streams, yielding a lower conductivity aquifer material. Over time as the glaciers continued to melt and retreat northward, coarser outwash deposits gradually overrode the finer underlying lake deposits creating the “coarsening upwards” stratigraphy of the Outer Cape. The hydraulic conductivity and extent of this material can only be assumed for the specific domain of the Pleasant Point model due to a lack of deep borehole and stratigraphy information in the immediate vicinity of Pleasant Point. The value of 10 feet per day utilized in this model is within the range utilized by Masterson, 2004.

Model Scenarios Assessed

Baseline

Baseline conditions in the model were assessed to represent non-pumping and typical pumping conditions for Pleasant Water. First, no pumping is applied in the model for a period of 50 years to allow the freshwater-saltwater interface to established undisturbed. Following this initialization period, stress periods representing summer and winter pumping conditions were applied. Winter pumping rates were determined based on 2023 pumping data provided to HW by Todd Everson. Pumping rates from November through May averaged 1,300 gallons per day. For the summer season, pumping rates averaged 4,600 gallons per day. The summer season was defined as 120 days and the winter defined as 245 days. This annual cycle was applied to the model for 15 years following the initial 50-year stabilization period. Withdrawal was evenly distributed between the three pumping wells throughout each stress period.

Application of the Baseline pumping rates to the model yielded low, but non-zero, salinity concentrations at all three pumping wells. Well #1 was modeled to have the highest concentration at 0.38 parts per thousand (ppt). Well #5 was modeled to withdraw a peak salinity of 0.10 ppt and Well #4 was modeled to withdraw 0.05 ppt.

A second, more conservative representation of baseline conditions was also performed. In this case, the year-round average pumping rate of 2,685 gallons per day was applied as the wintertime average. For the summer season, the peak pumping rate of 6,734 gallons per day was applied throughout the entire season. Both of these values are higher than the actual data suggests, providing a conservative degree of stress.

Non-zero salinity values were predicted by the model in all three wells throughout the pumping period. The highest salinity values are in Well #1 where salinity concentrations peak at 0.51 ppt. Peak concentration in Well #5 is 0.14 ppt and 0.06 ppt in Well #4.

Six New Service Connections

The conservative assumptions included in the baseline scenario already reflect a condition with significantly higher pumping rates than actual historical data suggests. In order to reflect six additional service connections, an additional 1,800 gallons per day were added to both the winter (4,485 gpd) and summer (8,534 gpd) pumping rates. This scenario is conservative in two ways. First, it assumes year-round water use for new connections, despite the highly seasonal water use demonstrated by existing connections. Second, 300 gallons of water use per household per day is among the highest estimates of national average domestic water use, with other estimates being approximately half of this value. Withdrawal in this scenario was equally distributed between all 3 pumping wells. As such, this scenario reflects pumping at each well of 1,495 gpd in the winter and 2,845 gpd in the summer.

Peak salinity values increase marginally compared to the baseline scenario under the increased pumping condition. The highest concentration modeled in Well #1 is 0.95 ppt, in Well #5 a peak of 0.29 ppt, and in Well #4 a peak of 0.12 ppt.

Twelve New Service Connections

Twelve new service connections were modeled in the same manner as the previous six new service connection model. Another 1,800 gallons per day were added to the total withdrawal for both the winter (6,285 gpd) and summer periods (10,323 gpd), distributed equally between the three pumping wells. Each well was modeled to represent 2,095 gpd withdrawal in the winter and 3,445 gpd in the summer.

Peak salinity values increased marginally compared to the baseline and six additional connections scenarios. The highest concentration is again modeled in Well #1, where values peak at 1.47 ppt. Well #5 is modeled to receive 0.47 ppt and Well #4 sees 0.20 ppt.

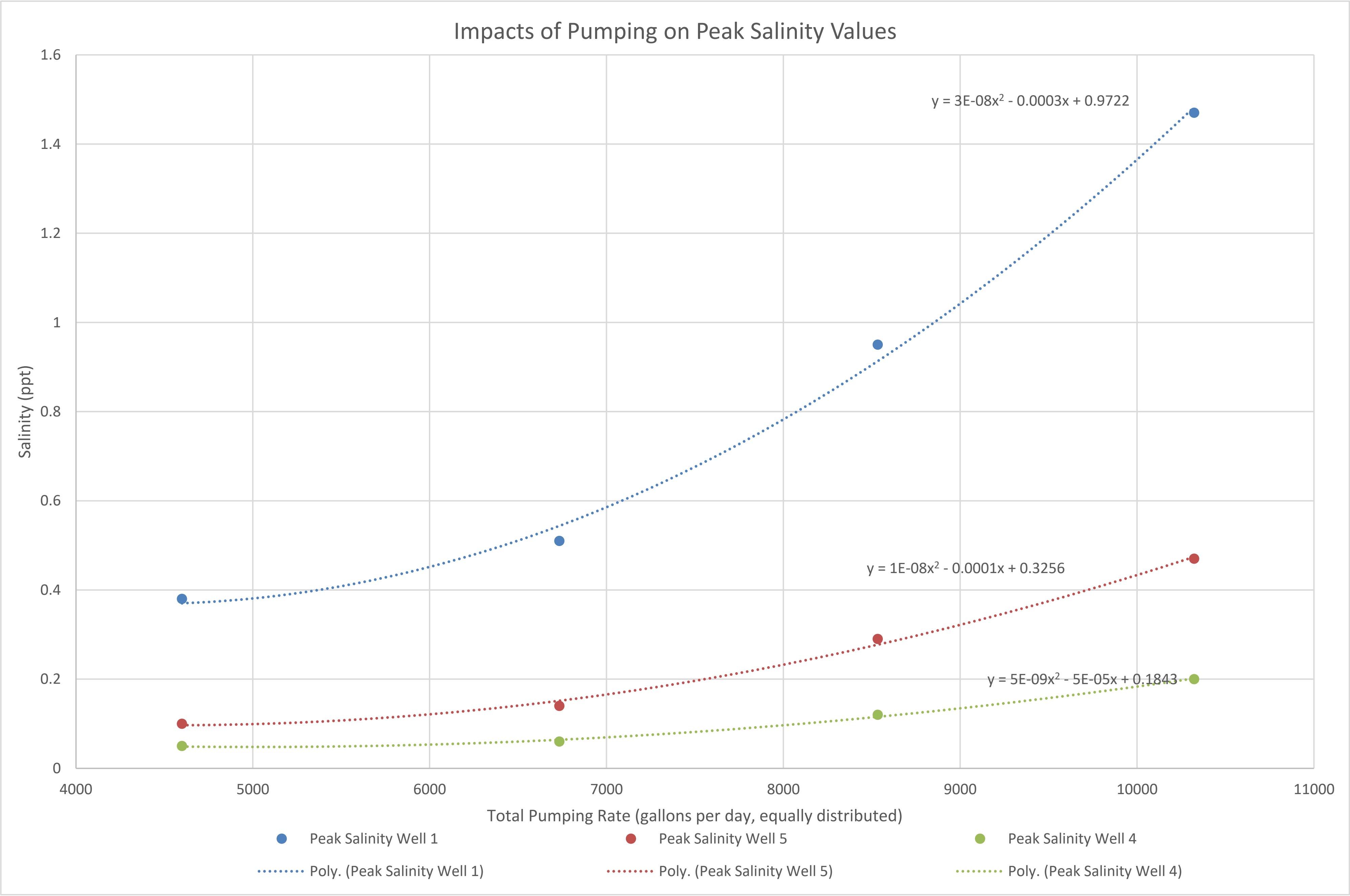
A second representation of the twelve-connection scenario was modeled to explore unequal application of well pumping rates. For this scenario, Well #1 was disused entirely and all pumping was applied to Wells #4 and #5. Modeled salinity concentrations increased in all wells under this scenario (despite not pumping, the model still calculates salinity at Well #1). Well #1 showed a peak concentration of 2.20 ppt, Well #5 showed 0.73 ppt, and Well #4 showed 0.41 ppt.

Plots of modeled salinity concentrations at each well for the duration of each scenario are included in appendix A.

Discussion

Each model scenario considered a total summer pumping rate divided equally between all three pumping wells. The total summer pumping rates considered included 4,600, 6,734, 8,534, and 10,323 gallons per day. With each increase in pumping rate, the peak salinity observed at each well at the end of the summer season increased. The change in peak salinity at each pumping rate is shown in Figure 6. The assumptions made in this analysis to represent higher-pumping scenarios were deliberately chosen to be conservative, overrepresenting actual anticipated pumping rates at every step. As such, Figure 6 may be used to estimate the expected peak summer salinity at pumping rates between the modeled scenarios.

Figure 6



Impacts of Pumping on Peak Salinity Values
y = 3E-08x² - 0.0003x + 0.9722
y = 1E-08x² - 0.0001x + 0.3256
y = 5E-09x² - 5E-05x + 0.1843
Salinity (ppt)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
4000
5000
6000
7000
8000
9000
10000
11000
Total Pumping Rate (gallons per day, equally distributed)
Peak Salinity Well 1
Peak Salinity Well 5
Peak Salinity Well 4
Poly. (Peak Salinity Well 1)
Poly. (Peak Salinity Well 5)
Poly. (Peak Salinity Well 4)

Seasonally cyclic pumping strongly influences the salinity of water at each well. Each year, reduced pumping in the offseason leads to a minimum salinity less than 50% of the peak value from the summer prior. This result indicates that routine monitoring of raw water salinity and corrective reductions in pumping rate should be an effective strategy in managing salinity levels. If conductivity continues to increase with time, or if the freshening recovery typical of off-season conditions lessens with time, consideration should be given to reducing pumping rates before further saline intrusion into the aquifer occurs. The model assumes consistent aquifer recharge and initial freshwater heads reflecting conditions observed during the pump test. Periods of drought and variation in local freshwater heads may increase of reduce the impact of pumping on salinity.

Saltwater intrusion so close to the coastline involves both a vertical and horizontal component. Dagan and Bear's estimation of critical pumping rates involves the vertical component of upconing. Other assessments of saltwater intrusion focus on the lateral movement of saltwater inland. Analytical solutions for the lateral movement of the interface typically focus on fully-penetrating wells (such as Strack, 1976), and as such were not applicable to this assessment. Lateral movement of the interface is computed by the numerical model, however, and is likely responsible for a significant component of the increase in salinity modeled at the pumping wells. In order to qualitatively assess the degree of lateral versus vertical movement of saltwater, concentration results from the model were imported into a three-dimensional visualization software (Voxler, Golden Software). The results, shown in Figure 7, indicate that the departure from the baseline position of the saltwater interface is primarily horizontal. Drawdown around the pumping wells is relatively symmetrical laterally around the well field. The shape of the bulge in the saltwater interface however is oblong perpendicular to the coast, supporting the conclusion of lateral movement. This lateral component of saltwater flow demonstrates the vulnerability of Well #1 compared to the other pumping wells.

Wells #4 and #5 are generally better protected from detrimental impacts of saltwater intrusion due to their increased distance from the coast and from their shallower depths. Modeled drawdown within the wellfield shows that the lateral extent of drawdown from each individual well spills over into the area of influence of the well next to it. As such, the cumulative impact of the wellfield is more significant than the impact of any one specific well. In the final model run, considering twelve additional connections and only Wells #4 and #5 pumping, salinity concentrations in all wells increased, despite no pumping occurring at Well #1. The interface, pulled laterally from the coastline towards Well #1 by the drawdown of the other two wells, leads to a significant increase in salinity at this well.

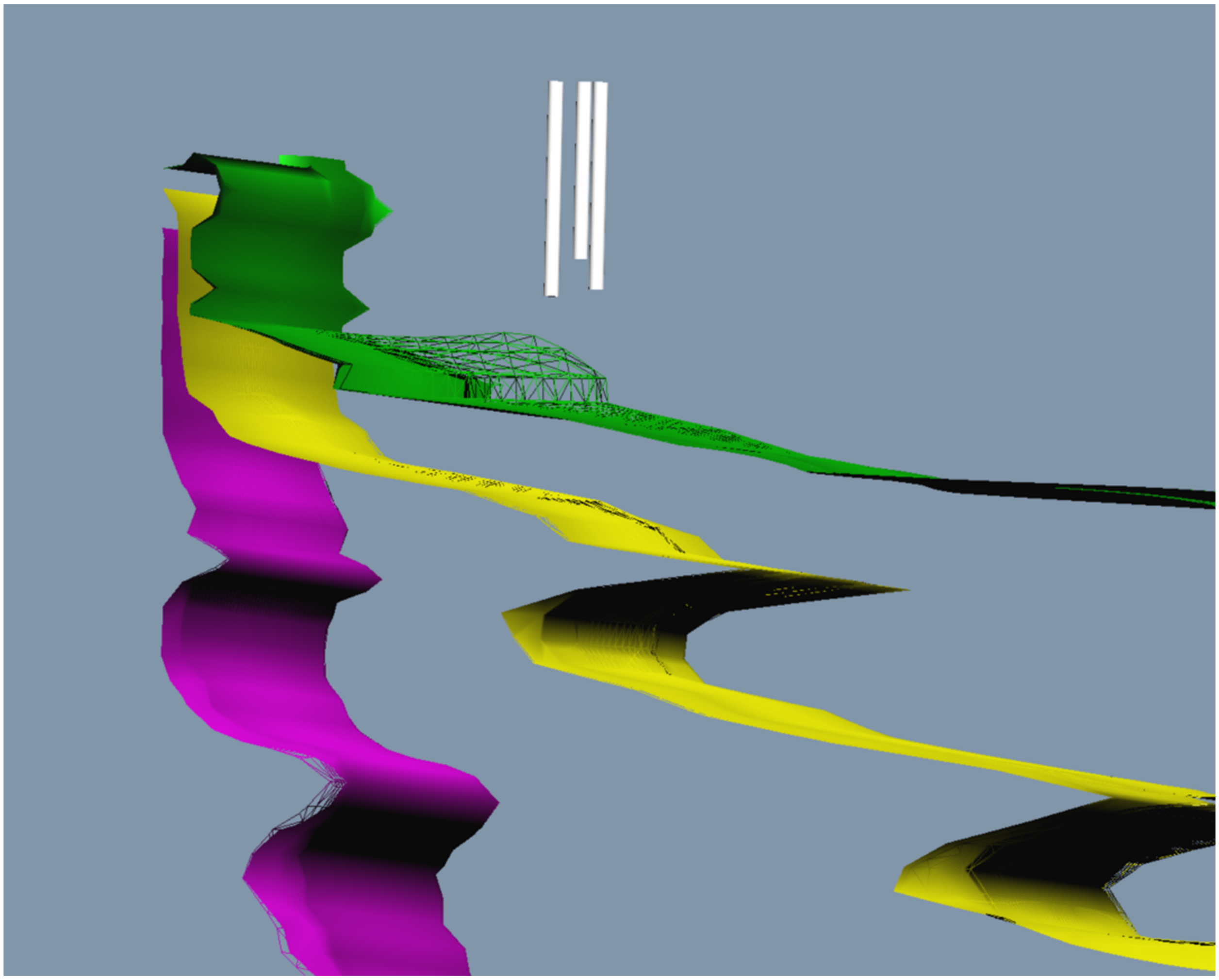


Figure 7: Three dimensional isocontour surfaces of salinity concentrations of 1.6 ppt (green), 16 ppt (yellow) and 32 ppt (purple). Solid surfaces represent pre-pumping conditions, and the wireframe bulge in the green surface represents the position of 1.6 ppt surface under pumping conditions. The Pleasant Water wells are represented by vertical white columns. Vertical exaggeration is 5:1.

Conclusions

Traditional analytical approaches for understanding saltwater intrusion concerns such as the critical discharge calculation performed in this analysis support the conclusion that Pleasant Water could increase pumping without the risk of introducing significantly saltier water into the PWS wells. A number of factors contribute to this conclusion:

- The wells at Pleasant Water are relatively shallow, which increases the critical elevation of upconing before interface stability collapses.
- The hydraulic gradient near the coastline is relatively steep, providing a relatively thick freshwater aquifer for a position so close to the coastline.

- The pumping rates at which Pleasant Water operates and seeks to expand to are relatively low, limiting the amount of drawdown and upconing anticipated under proposed conditions.

In addition to the sharp interface analytical approach, HW undertook a three-dimensional, numerical, solute-transport modeling approach to understand the transition zone between fresh and salt water. Development, implementation, and interpretation of this model warrants further consideration of the impacts of pumping on the raw water quality produced by Pleasant Water. Low, but not insignificant, concentrations of salt are modeled to be introduced to the well under the proposed increase pumping scenarios.

No clear threshold for acceptable salinity levels in drinking water is established. EPA has established a secondary standard for chloride of 250 mg/L (0.25 ppt) based on taste. This standard is equal to that of the World Health Organization, which is also based on taste. Chloride comprises approximately 60% of the mass of salt, and as such the concentration of salt at this standard would be 0.41 ppt. Several of the modeled scenarios considered above exceed this threshold, and negative impacts to taste of water produced at Well #1 would be anticipated under those scenarios, should the modeling results prove accurate. Increased reliance on Wells #4 and #5 would maintain lower salinity production of water even at higher pumping rates.

Recommendations

Based on the assessments described herein, it appears that Pleasant PWS could increase pumping moderately without inducing the intrusion of significantly more saline water into its PWS wells. The 6 and 12 additional home scenarios described herein are based on information provided by Todd Everson to HW and the water use per home applied by HW for the modeling is conservatively based on the highest estimates of national-average water use. Actual and permittable water use per home connection should be evaluated by Todd Everson and Pleasant Water relative to permit requirements and local PWS system knowledge.

The Pleasant PWS wells are located quite close to the coast and some salinity is already detectable in the PWS wells under current conditions. In addition, conductivity was observed to increase slightly in the pumping well during the 48-hour pumping test indicating that the well screens are already in the top of the brackish mixing zone above the true saltwater interface. Modeling indicates that reduced offseason pumping should allow salinity levels to decrease each winter before the subsequent summer higher pumping rates and thereby preventing the salinity levels to increase continually over time. However, salinity should continue to be monitored regularly to ensure that such a trend of long-term increasing salinity does not occur as a result of increased pumping.

In addition, we recommend that additional home connections be added slowly and incrementally rather than all at once in order to allow for continued monitoring of potential negative impacts before those impacts become significant. We understand that permitting for the desired additional connections will need to occur in totality but recommend that actual connections occur gradually.

Pumping operations should be tailored in a manner that minimizes the potential for significant saltwater intrusion. Well #1 is both the deepest and the closest to the coast making it the most susceptible to increases salinity levels. However, this does not mean simply abandoning use of the well is the best option. Distributing production between all three wells avoids generating a steep, narrow cone of depression (and thus the potential for upconing), and reduced lateral velocities pulling in horizontal saltwater flow. As an operational starting point we recommend that Wells # 4 and #5 be pumped equally, and each at a rate of approximately double that of Well #1 to best proportion any given withdrawal volume throughout the PWS system.

Most importantly, continued monitoring of conductivity and chloride is recommended to occur at as often a frequency as possible in order to ensure that the actual water withdrawn stays within the modeled parameters and that any unanticipated increases in salinity can be addressed before they worsen significantly. The Pleasant Water wells exist on the fringe of the saltwater interface, and salinity concentrations are modeled to increase in an almost linear fashion with increased pumping rates. This gradual increase in salinity expected affords the ability to monitor and adapt to actual observed salinity concentrations over time. Well #1 should be utilized as the sentinel well due its vulnerable position relative to the saltwater interface. Should salinity at Well #1 exceed the threshold determined by the operator, then Wells #4 and #5 should continue to produce water below this threshold.

Sincerely,

Horsley Witten Group, Inc.

Neal Price | Michael Demanche

References

Langevin, C.D., Thorne, D.T., Jr., Dausman, A.M., Sukop, M.C., and Guo, Weixing, 2008, *SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport:* U.S. Geological Survey Techniques and Methods Book 6, Chapter A22, 39 p.

Harbaugh, A. W., Banta, E. R., Hill, M. C., & McDonald, M. G. (2000). *MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process* (Open-File Report 00-92). U.S. Geological Survey.

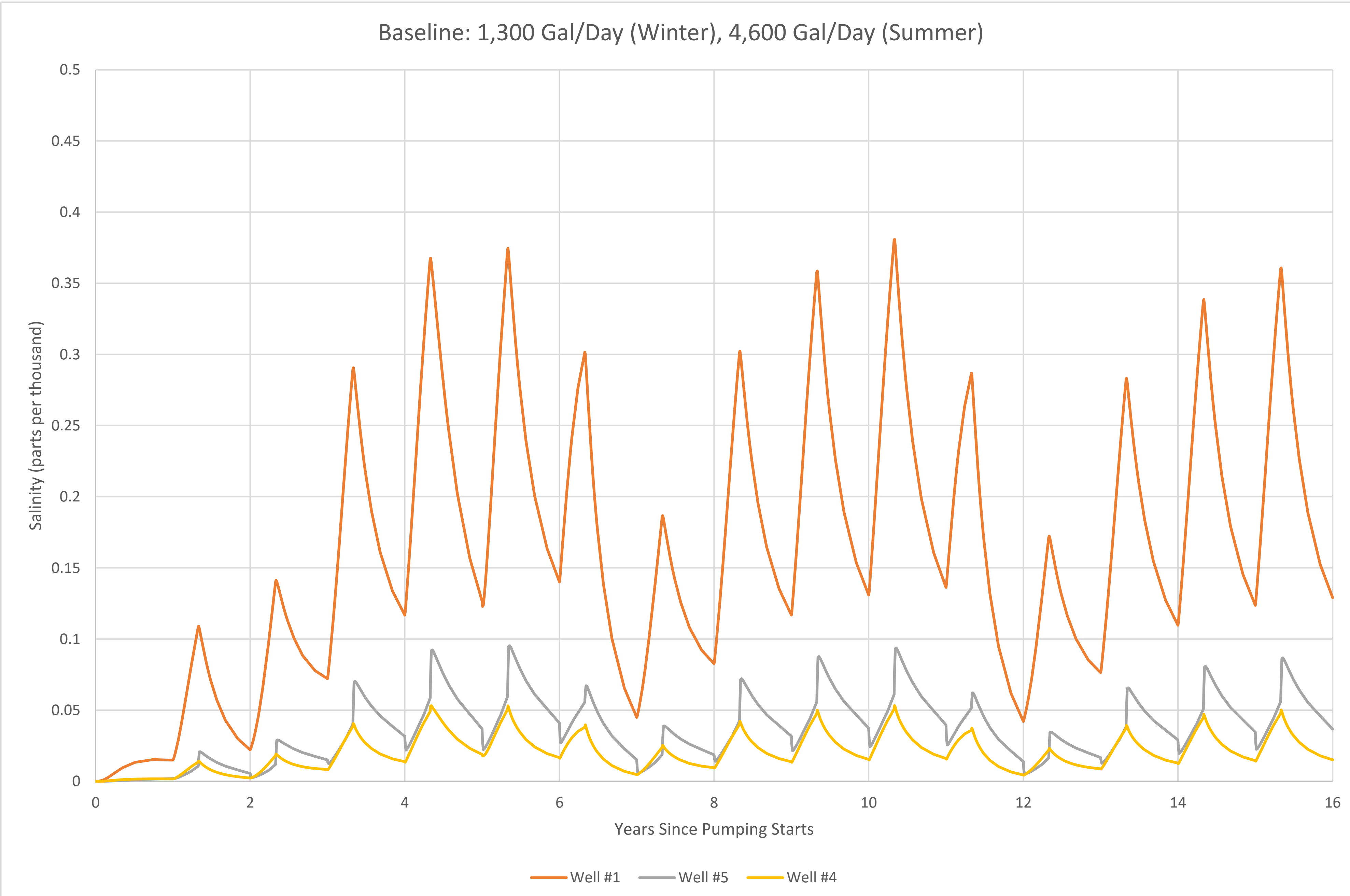
Masterson, J. P. (2004). *Simulated interaction between freshwater and saltwater and effects of ground-water pumping and sea-level change, Lower Cape Cod aquifer system, Massachusetts*. U.S. Geological Survey.

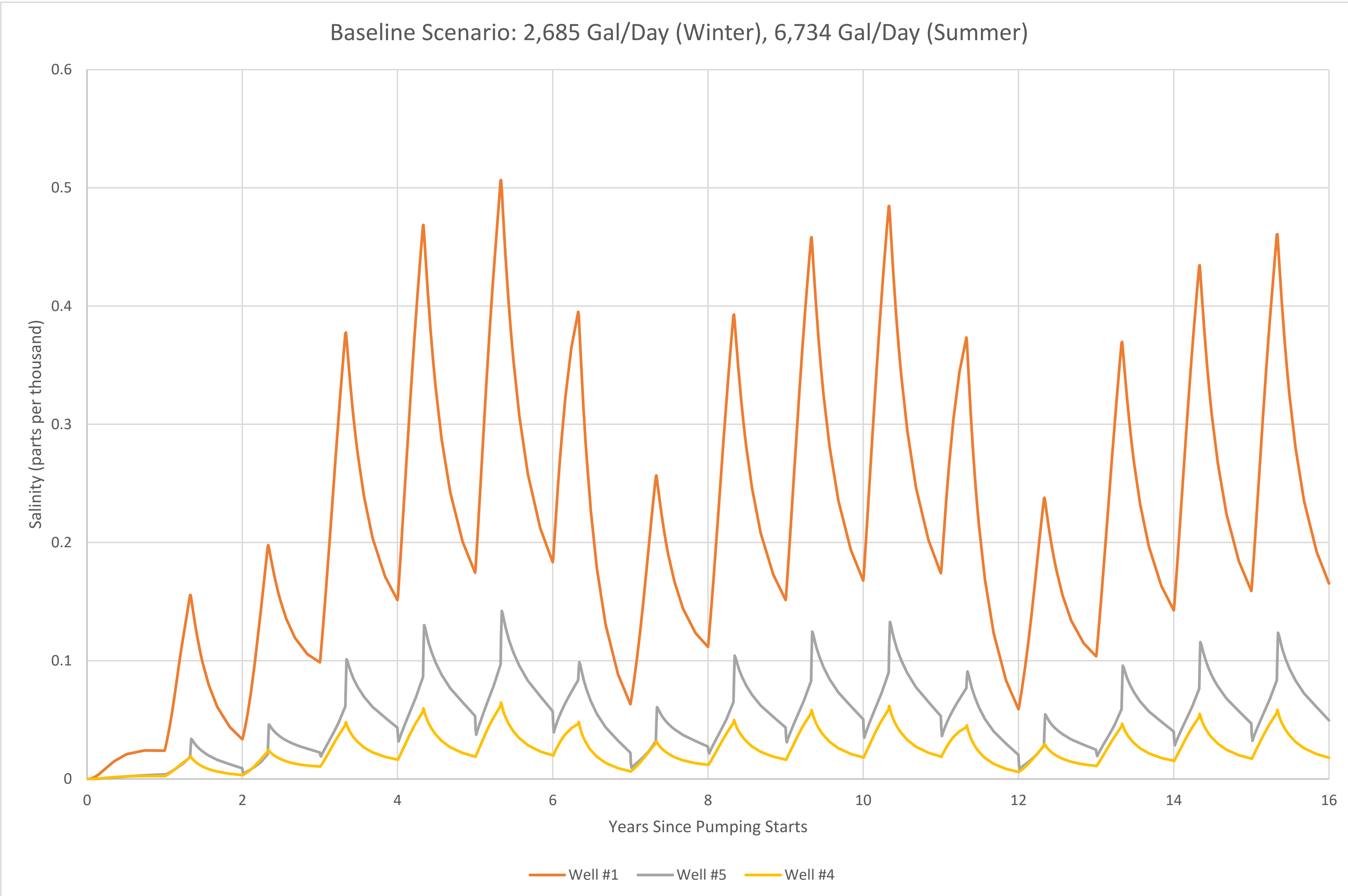
Strack, O.D.L (1976). *A Single-Potential Solution for Regional Interface Problems in Coastal Aquifers.* Water Resources Research, 12(6).

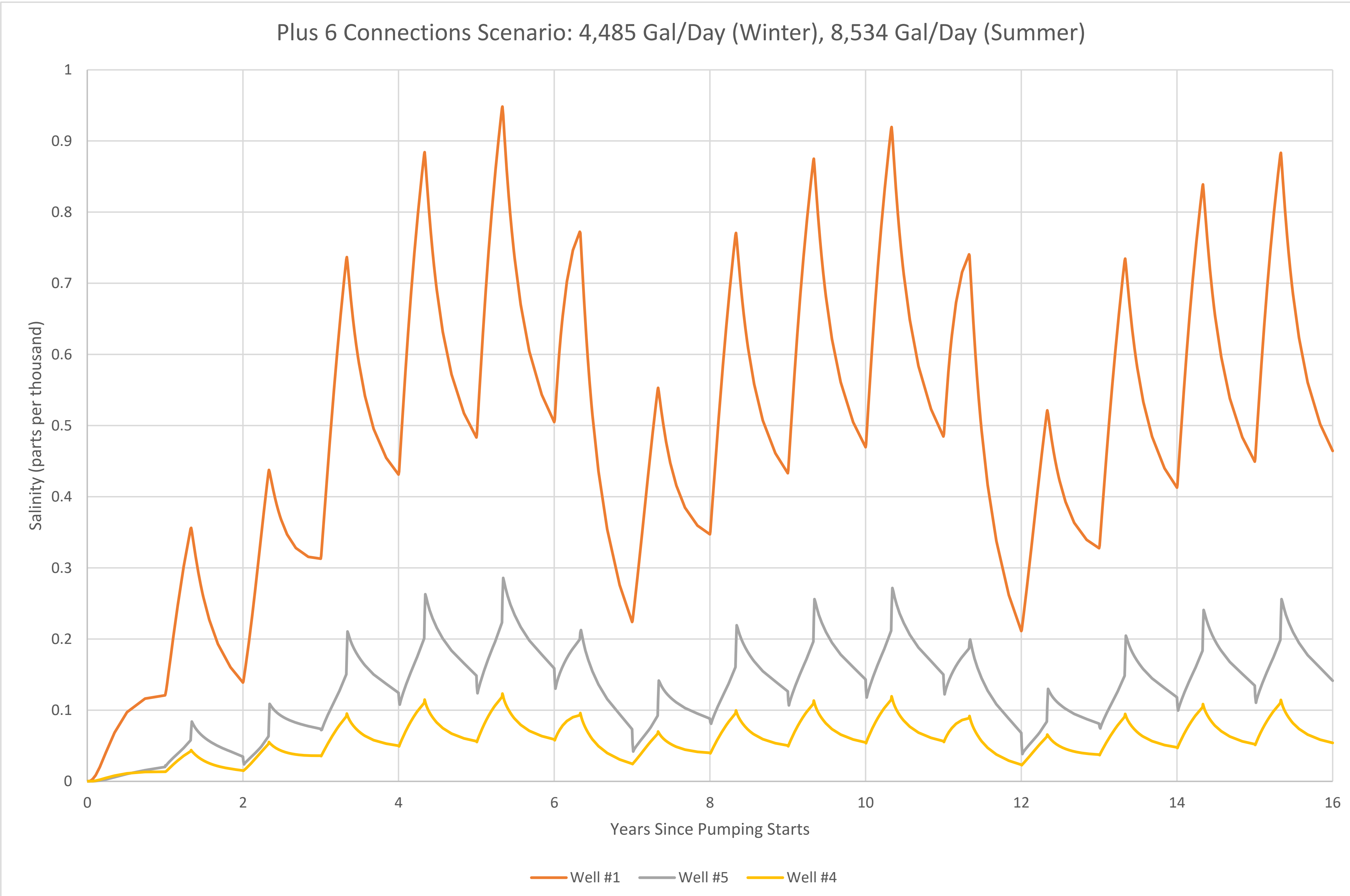
Strack, O.D.L (1972). *Some Cases of Interface Flow Towards Drains.* Journal of Engineering Mathematics Vol. 6, No. 2.

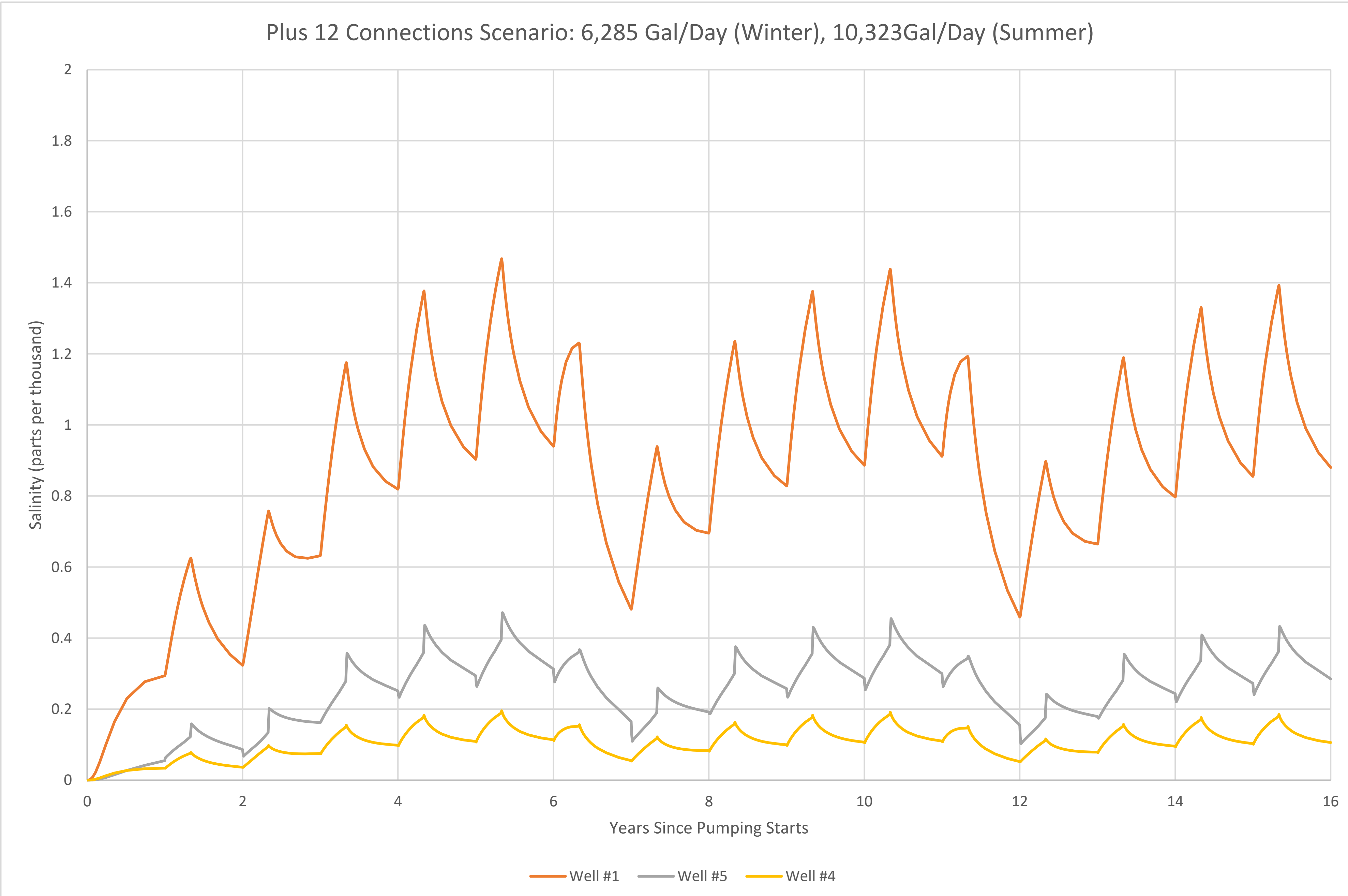
Zheng, C., & Wang, P. P. (2012). *MT3DMS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; Documentation and user's guide*. University of Alabama.

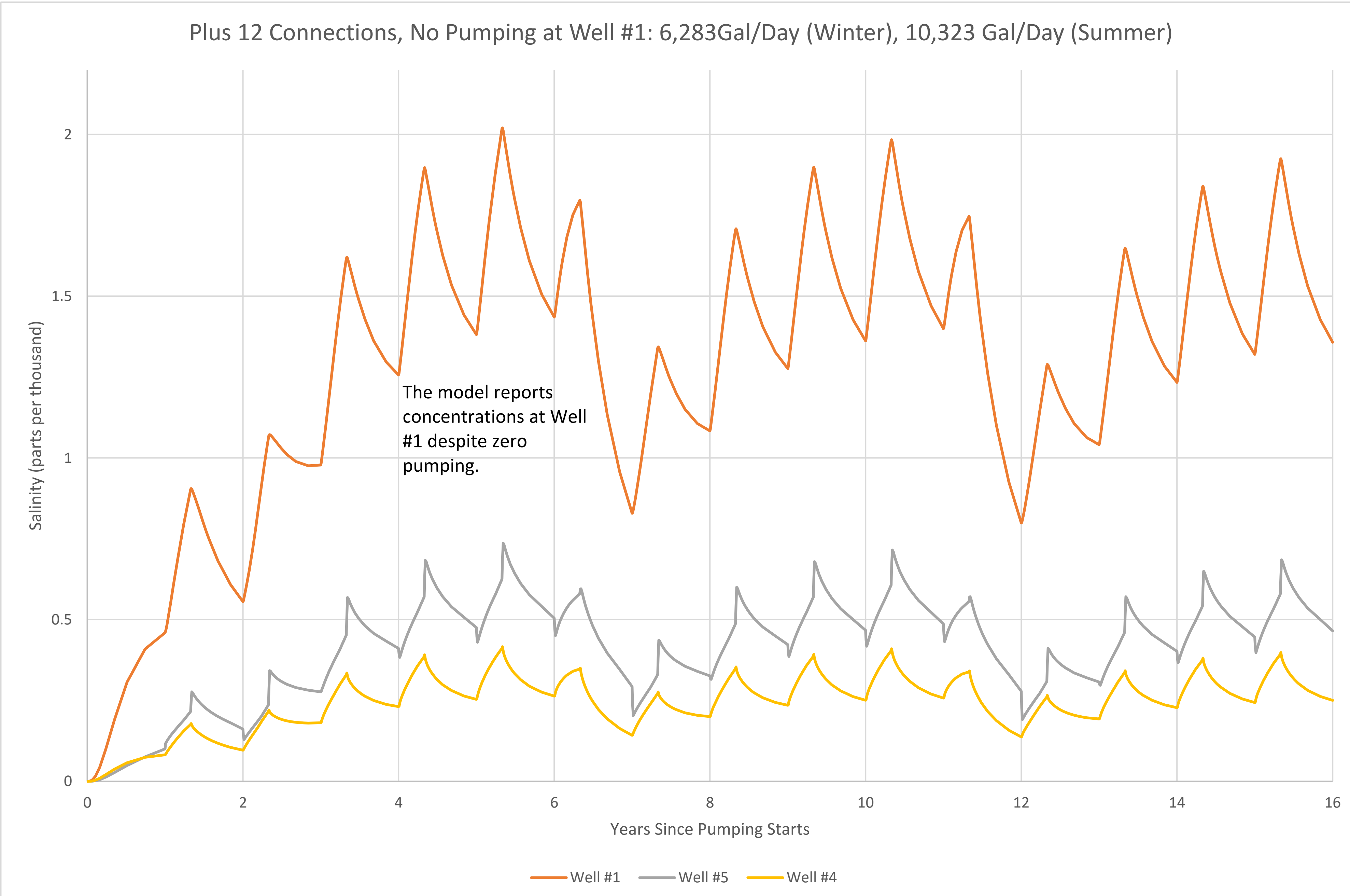
Appendix: Model Results


Baseline: 1,300 Gal/Day (Winter), 4,600 Gal/Day (Summer)
Salinity (parts per thousand)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
2
4
6
8
10
12
14
16
Years Since Pumping Starts
Well #1
Well #5
Well #4


Baseline Scenario: 2,685 Gal/Day (Winter), 6,734 Gal/Day (Summer)
Salinity (parts per thousand)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
Years Since Pumping Starts
Well #1
Well #5
Well #4


Plus 6 Connections Scenario: 4,485 Gal/Day (Winter), 8,534 Gal/Day (Summer)
Salinity (parts per thousand)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
12
14
16
Years Since Pumping Starts
Well #1
Well #5
Well #4


Plus 12 Connections Scenario: 6,285 Gal/Day (Winter), 10,323Gal/Day (Summer)
Salinity (parts per thousand)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
Years Since Pumping Starts
Well #1
Well #5
Well #4


Plus 12 Connections, No Pumping at Well #1: 6,283Gal/Day (Winter), 10,323 Gal/Day (Summer)
Salinity (parts per thousand)
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
Years Since Pumping Starts
The model reports concentrations at Well #1 despite zero pumping.
Well #1
Well #5
Well #4