Analysis of Streamflow Depletion and Well Interference under Various Conditions

In the process of revising the County well ordinance and developing policies to minimize impact on streamflow and public trust values, County staff have analyzed the potential effects of individual wells under various conditions using several different analytical models. These models are used to provide a sensitivity analysis and evaluate the extent to which different factors may influence streamflow depletion. However, it's important to note that analytical models rely on various assumptions, commonly including the presumption of steady-state conditions for the stream and aquifer. In reality, the degree of stream depletion is likely to fluctuate in response to changing climate conditions over time. Modelled estimates of depletion are likely somewhat inaccurate as the environment of the Santa Cruz Mountains is inconsistent with many of the underlying assumptions upon which the models are based. The amount of total depletion that is estimated to be presently occurring based on numeric groundwater models and flow measurements (Table 4) is considerably less than the amount that would be calculated by multiplying the number of current wells by the worst-case calculations of the direct effect of individual wells provided by the analytical models.

Estimates of streamflow depletion were calculated and analyzed using a combination of models including the USGS web based calculation, STRMDEPL08 (available at https://mi.water.usgs.gov/software/groundwater/CalculateWell/index.html), the analytical depletion function (ADF) model developed by Li et al. 2022 (found at: https://github.com/FoundrySpatial/streamDepletr), and ADF model developed by Bakker in 2013 (found at: https://github.com/mbakker7/ttim). Below are the key observations based on our analysis.

Key Observations Relative to Direct Streamflow Depletion:

1. The amount of depletion is not substantially reduced by a greater setback from the creek, especially in aquifers characterized by high transmissivity and low storativity. Increasing the setback from 50 ft to 1000 ft only reduces the amount of depletion by 25-30% for formations with moderately favorable aquifer properties concerning stream depletion impacts.
2. Wells pumping 10 af/y or less have very minimal impact on direct flow depletion: less than 0.01-0.02 cfs at a setback of 50 ft from a creek. Incorporating a seal depth of 100 feet further diminishes depletion, with the depletion reduced by approximately 82% for aquifers characterized by low transmissivity and high storativity values, and depletion reduced by up to 31% for aquifers with high

transmissivity and low storativity values. Previous analysis showed that total non-municipal pumping has reduced the 10th percentile dry season flow by 2-4% in the Santa Margarita Groundwater Basin and 15-17% in the Mid-County Groundwater Basin. Cumulative impacts are not expected to increase in the future, given the low rate of new rural development and the active management of both basins to reduce the impacts of municipal pumping and raise groundwater levels.

3. Pumping from a deeper zone below an aquitard greatly reduces the impact of streamflow depletion (Hunt, 2003). The amount of depletion when pumping from below an aquitard at a 50 ft separation is 95-97% less than depletion that occurs at the same distance when pumping is from an unconfined aquifer that is more hydraulically connected to the stream. Encouraging new and replacement wells to have a deep seal below an aquitard is expected to be a very effective way to reduce streamflow depletion. These conditions are expected to occur within the Monterey Formation and certain parts of the Purisima Formation.
4. Some of the calculations were done assuming the annual volume of pumping all took place in 180 days during the dry season. However, if a 2-year drought was assumed, with the same rate of pumping assumed for the dry season for 700 days, the amount of depletion increased by 17% in the Purisima AA and 56% in the Santa Margarita. If the pumping was from below an aquitard, depletion increased by about 90% in both aquifers when compared with the 180-day scenario, although the amount of depletion was still only 1.6% of the pumping volume.
5. Incorporating a deep seal within 1000 feet of a stream is an effective method to mitigate streamflow depletions and reducing drawdown in the upper portion of the aquifer, where the stream is most likely closely interconnected to (Figure 1). This mitigiation strategy is particularly impactful for streams connected through aquifers with low permeabilities. However, the degree of reduction in depletion is notably more pronounced when the well is closer to the stream, likely due to the attenuation of the cone of depression.

   For wells with extraction rates of less than 100 AFY located beyond 1000 feet from the stream, the impact of the well seal diminishes (see "TTim_stream_depletion_100-1000ft.pdf" and "Stream depletion vs seal depths.pdf" as the curvature of the cone of depression flattens out at farther distances. At these longer distances, the overall drawdown resulting from the pumping volume of the aquifer becomes the primary factor contributing to streamflow depletion.

For instance, when assessing the effects of wells situated 50 feet from a stream, tapping into an aquifer with median values of transmissivity and storativity in the Santa Margarita Formation, a seal depth of 100 feet is projected to decrease stream depletion by approximately 54%, while a 200-foot seal depth could reduce it by around 72%.

For wells positioned 200 feet from the stream under similar geological conditions, a 100-foot seal depth is estimated to mitigate stream depletion by approximately 43%, and a 200-foot seal could reduce it by approximately 62%.

However, when evaluating the impacts of wells situated at farther distances, such as 1000 feet from the stream, the effectiveness of the seal diminishes significantly. In this scenario, with aquifers of similar properties as above, a 100-foot seal depth is anticipated to reduce stream depletion by only 3%, while a 200-foot seal might reduce it by just 5%.

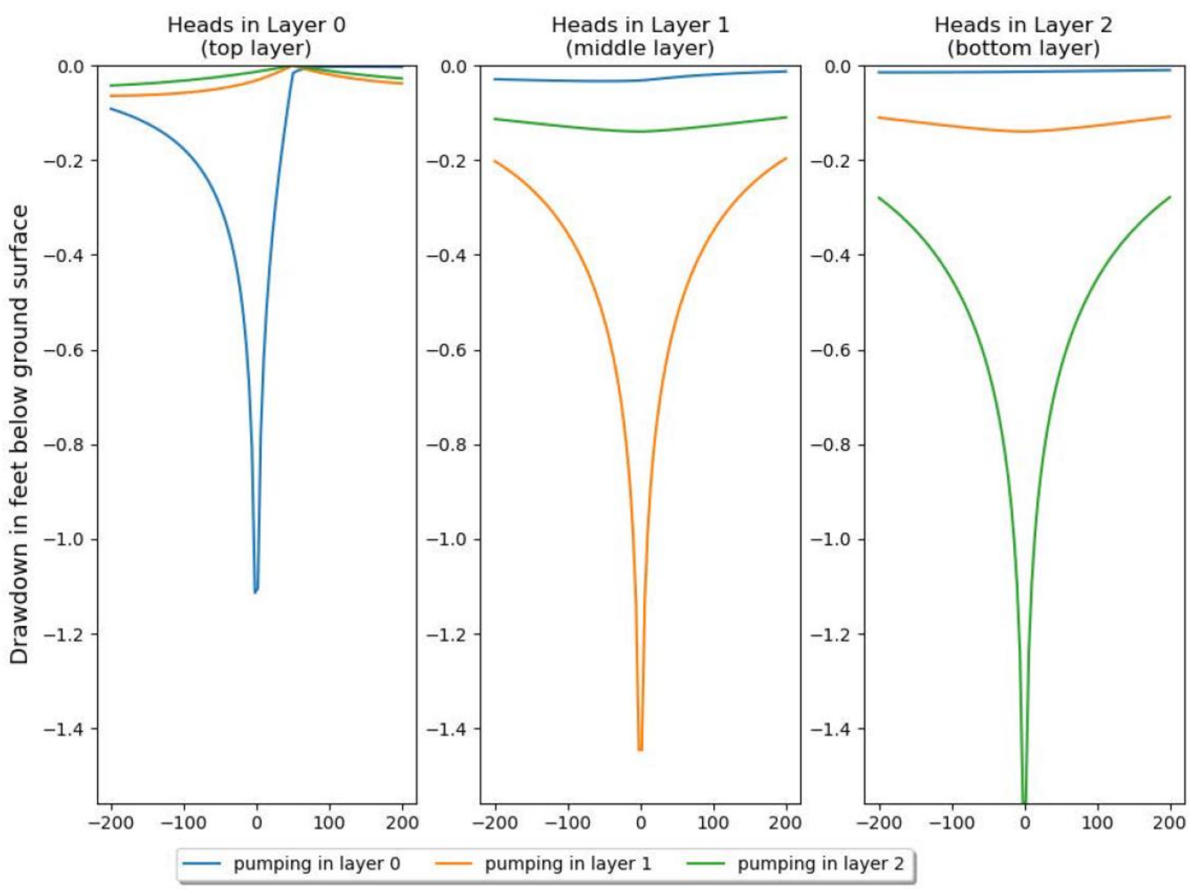


Figure 1- Drawdowns at Different Seal Depths (TTim, Bakker 2013)

6. Beyond 1000 feet, well seal depths are not expected to have a significant impact for wells using less than 100 AFY (see observation #7), and the primary driver to further reduce stream depletion depends on increasing the distance between the stream and the well. For example, considering depletion modeled for wells without seals located in aquifers with high transmissivity and low storativity values, where the zone of influence is expected to be most extensive, stream depletion impacts are reduced by approximately 50% when the well location is increased from 800 feet to 2000 feet (Figure 2). The reduction is projected to be even more significant with distance for aquifers with lower permeabilities.

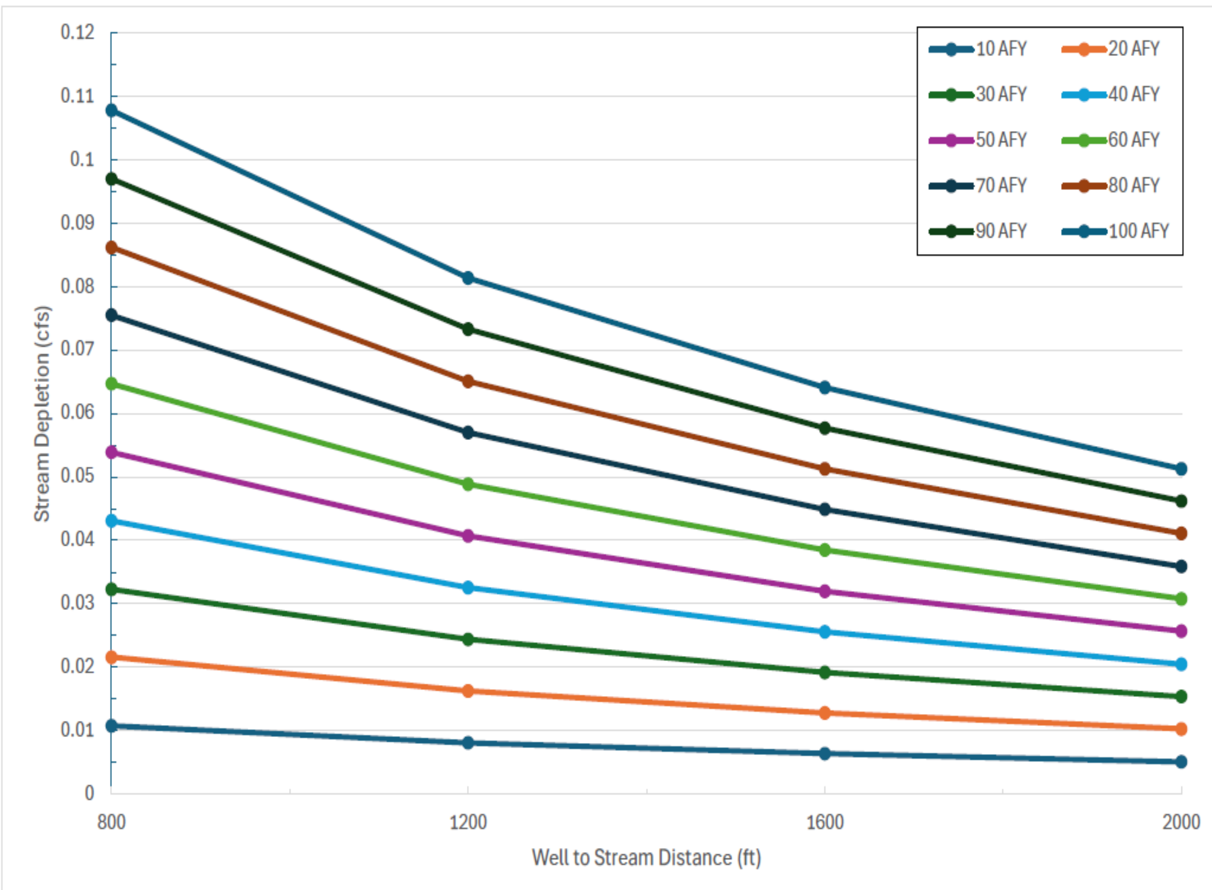


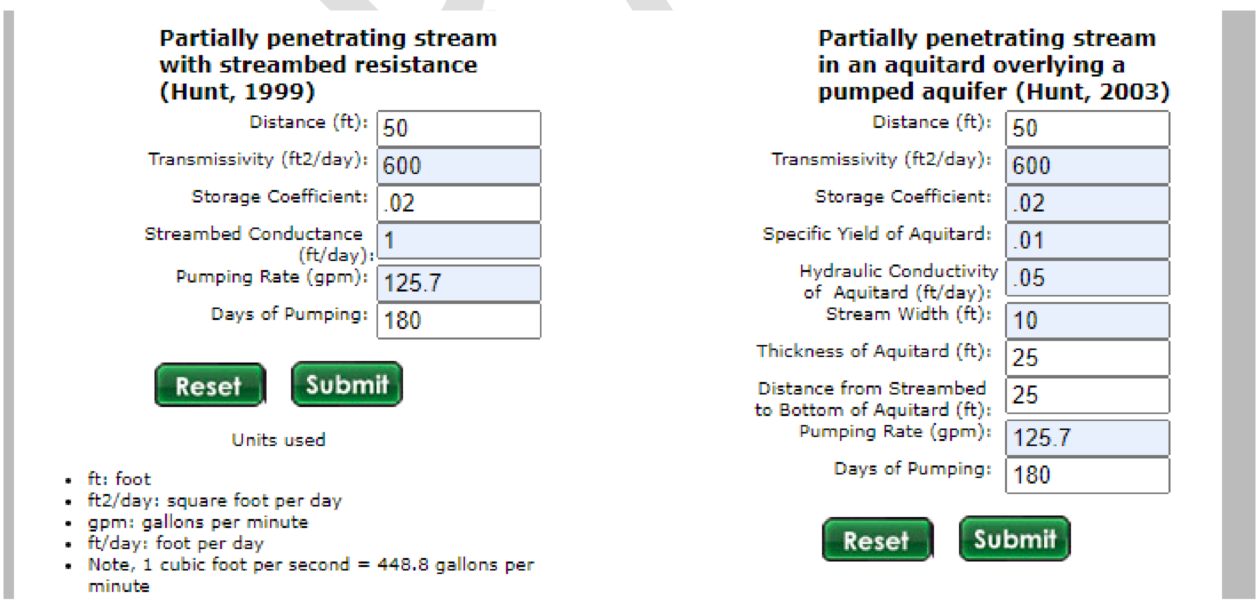
Figure 2- Stream Depletion Beyond 800 Feet without Seals (TTim, Bakker 2013)

7. Tier 1 wells are expected to have a minimal impact on stream depletion, given their expected requirements, which include a minimum 50-foot stream setback and a

100-foot seal depth when situated in close proximity to the stream. At 50 feet, the maximum estimated depletion ranges from nearly negligible (0.00002 cfs) to 0.0032 cfs (refer to "TTim_Tier1_modelled_stream_depletion.pdf"), with the former corresponding to very low permeable conditions, and the latter corresponding to very permeable conditions. These ranges are projected to be even lower for streams with streambed resistance or scenarios where an aquitard is situated between the stream and the well screen.

Streamflow Depletion Analysis Using USGS Analytical Models:

For the USGS application, three models were primarily used: a partially penetrating stream with nearby pumping from an unconfined aquifer (Hunt, 1999) a partially penetrating stream in an aquitard overlying a pumped aquifer (Hunt, 2003), and a fully penetrating stream with no streambed resistance (Jenkins, 1968). Hunt, 2003 was used to evaluate the effects of requiring a deep seal to the first impermeable layer. Below is a figure showing the set-up for running STRMDEPL08 for pumping from an aquifer associated with the Purisima AA formation with a stream that partially penetrates the aquifer and has streambed resistance (left), and with a stream partially penetrating an impermeable layer with properties similar to the Monterey Formation overlying a pumped aquifer (right). Aquifer parameters are taken from the Groundwater Sustainability Plans, with generally the median figures used (see Table 3).


Partially penetrating stream with streambed resistance (Hunt, 1999)

Distance (ft):	50
Transmissivity (ft2/day):	600
Storage Coefficient:	.02
Streambed Conductance (ft/day):	1
Pumping Rate (gpm):	125.7
Days of Pumping:	180

Reset Submit

Units used

- ft: foot
- ft2/day: square foot per day
- gpm: gallons per minute
- ft/day: foot per day
- Note, 1 cubic foot per second = 448.8 gallons per minute

Partially penetrating stream in an aquitard overlying a pumped aquifer (Hunt, 2003)

Distance (ft):	50
Transmissivity (ft2/day):	600
Storage Coefficient:	.02
Specific Yield of Aquitard:	.01
Hydraulic Conductivity of Aquitard (ft/day):	.05
Stream Width (ft):	10
Thickness of Aquitard (ft):	25
Distance from Streambed to Bottom of Aquitard (ft):	25
Pumping Rate (gpm):	125.7
Days of Pumping:	180

Reset Submit

The USGS analytical models were run for two different aquifer types, the Purisima AA, which has the potential for low to moderate permeability, and the Santa Margarita formation, which has the potential for high permeability. The models were run for various pumping rates and stream setbacks (Table 1). The pumping rates were derived from the annual production (af/y), with a worst case assumption that the total annual amount is drawn during the typical 6-month dry period (180 days), and maintained at a consistent average amount of continuous pumping to achieve that volume. The volume of pumping for 100 af/y at a 50 ft setback was also considered for situations where pumping occurred below an aquitard, over a 700 day period (2-year drought) and a 10-year period, to understand potential long term effects. However, very long-term effects would normally be mitigated by recharge during normal wet winters.

Purisima AA (T=600, S=.02)180 days			Depletion (cfs) with indicated setback from creek (ft) 180 days of pumping, unless noted otherwise			
Af/y	summer gpm	pumping cfs	50 ft	100 ft	200 ft	1000 ft
0.5	0.6	0.0014	0.001*	0.001	0.0009	0.0007
2	2.5	0.0056	0.004*	0.004	0.0039	0.003
10	12.6	0.0280	0.0204*	0.0201		0.0149
100	125.7	0.2801	0.2035*			0.1486
100	125.7	0.2801	0.2383*	No aquitard, 700 days		
100	125.7	0.2801	0.2613*	No aquitard, 3650 days		
100	125.7	0.2801	0.0095**	Pumping from below aquitard		
100	125.7	0.2801	0.0181**	Below aquitard, 700 days		
100	125.7	0.2801	0.0388**	Below aquitard, 3650 days		
250	314.3	0.7002	0.5765*			0.4288
	1000	2.2282	1.619*		1.547	1.1845

Santa Margarita (T=3000, S=.1)			Depletion (cfs) with indicated setback from creek (ft), 180 days of pumping, unless noted otherwise			
Af/y	summer gpm	pumping cfs	50 ft	100 ft	200 ft	1000 ft
0.5	0.6	0.0014	0.0004*			
2	2.5	0.0056	0.0018*	0.0017		0.0012
10	12.6	0.0280	0.0089*			
20	25.1	0.0280	0.0089*			
50	62.9	0.0560	0.0177*			
100	125.7	0.2801	0.0885*	0.0869	0.0839	0.0616
100	125.7	0.2801	0.1383*	No aquitard, 700 days		
100	125.7	0.2801	0.1994*	No aquitard, 3650 days		
100	125.7	0.2801	0.0023**	Pumping from below aquitard		
100	125.7	0.2801	0.0044**	Below aquitard, 700 days		
100	125.7	0.2801	0.0100**	Below aquitard, 3650 days		
	1000	2.2282	1.1000*		1.0456	0.7798

*Uses Hunt, 1999 model with a streambed conductance of 1 (ft/day)

**Uses Hunt, 2003 model using aquitard properties similar to the Monterey Formation

Table 1- Key Results Using USGS Models (STRMDEPL08, Reeves 2008)

Analyzing Upper Range of Streamflow Depletion and Seal Depth Impacts:

In our analysis of streamflow depletion, we focused on evaluating the extreme case impacts by analyzing various models. Specifically, we examined models that assume a fully penetrating stream without streambed resistance, such as those by Glover, Jenkins, and Bakker (with streamed resistance as an optional parameter). These models predict more significant streamflow depletion compared to models that incorporate streambed resistance or consider partially penetrating streams, such as Hunt's models.

Our simulations utilized the aquifer properties of the Santa Margarita Formation under unconfined conditions. This formation was selected because it represents one of the primary water-bearing units in the county, which is also commonly interconnected with surface water. With its potential for high transmissivity/high hydraulic conductivity values and low specific yield values, streams and aquifers associated with the Santa Margarita Formation are particularly susceptible to significant stream depletion (refer to Table 2 for aquifer properties).

We conducted the models for various pumping rates and stream setbacks over a 700-day period, corresponding to a 2-year drought cycle. During this timeframe, stream discharge reaches near-equilibrium with the aquifer under steady-state conditions (see Figure 3). To simulate drought conditions and the worst-case effects of intermittent pumping, we derived pumping rates from annual production, assuming that the total amount is drawn during the typical 6-month dry period and maintained over a 2-year drought period. This effectively doubles the amount of typical usage during normal years over the modelled period and serves as a very conservative approach (e.g., 2 AFY wells are modeled as 4 AFY wells).

To analyze the influence of seal depths on stream depletion, we employed the TTim model developed by Bakker in 2013, known for its effectiveness in simulating transient flow in multi-layer systems. The TTim model also served as our primary tool for assessing the worst-case and most extreme impacts on streamflow depletion.

Our simulation environment emulates a homogeneous aquifer divided into three layers, each 100 feet thick. Despite this division, all layers share identical aquifer properties, effectively representing one homogenous aquifer. The top layer is designated as phreatic to mimic unconfined conditions. The simulation includes a well screen positioned sequentially in each layer to assess the impacts of different seal depths for each respective layer. For example, during the third iteration, the well screen is placed in layer 2, effectively simulating sealing of layers 0 and 1. When the iteration has the well screen in Layer 0, the simulation effectively represents no seal for the well. Layer 0 represents the topmost layer (0 - 100 feet below ground surface), while Layer 2 represents the bottommost layer (200 - 300 feet below ground surface). The extraction of the well is averaged over the entire screen interval. An example of this simulation is provided in Figure 4, used to assess the worst-case impacts of a 50 AFY well located 200 feet away from the stream.

Table 2-14. Principal Hydrogeologic Units Hydraulic Properties

Principal Hydrogeologic Unit	Hydraulic Conductivity (feet/day)	Transmissivity (feet²/day)	Storativity[1]	Specific Yield[2]
Santa Margarita Aquifer Entire Basin	2 – 130	430-7,700	0.008 – 0.02	0.02 – 0.25
Santa Margarita Aquifer Quail Hollow/ Olympia	2 – 50	430 – 6,200	0.008 – 0.02	0.12 – 0.25
Santa Margarita Aquifer Central Portion of Basin	3 – 130	2,000 – 7,700	NA	0.02 – 0.13
Santa Margarita Aquifer Scotts Valley Area	12 – 35	1,000 – 1,700	NA	0.02 – 0.13
Monterey Aquifer [3]	0.05 – 6	170 – 1,000	0.00001 – 0.001	0.01 – 0.03
Lompico Aquifer	0.5 – 7	500 – 3,200	0.000001 – 0.001	0.02 – 0.07
Butano Aquifer	0.1 – 6	100 – 1,070	0.000001 – 0.0007	

Adapted from Kennedy/Jenks Consultants (2015); NA = non-applicable given unconfined conditions

[1] Storativity is the volume of water released from confined aquifer storage per unit decline in hydraulic head in the aquifer per unit area of the aquifer.

[2] Specific yield is the amount of water released from an unconfined aquifer if allowed to drain completely under force of gravity.

[3] The Monterey Formation is not a principal aquifer but is included here as there are aquifer test data available for it, and because its occurrence between 2 principal aquifers plays an important role in the hydrogeology of the Basin.

Table 2 “Principal Hydrogeologic Units Hydraulic Properties”, (Kennedy/Jenks Consultants, 2015)

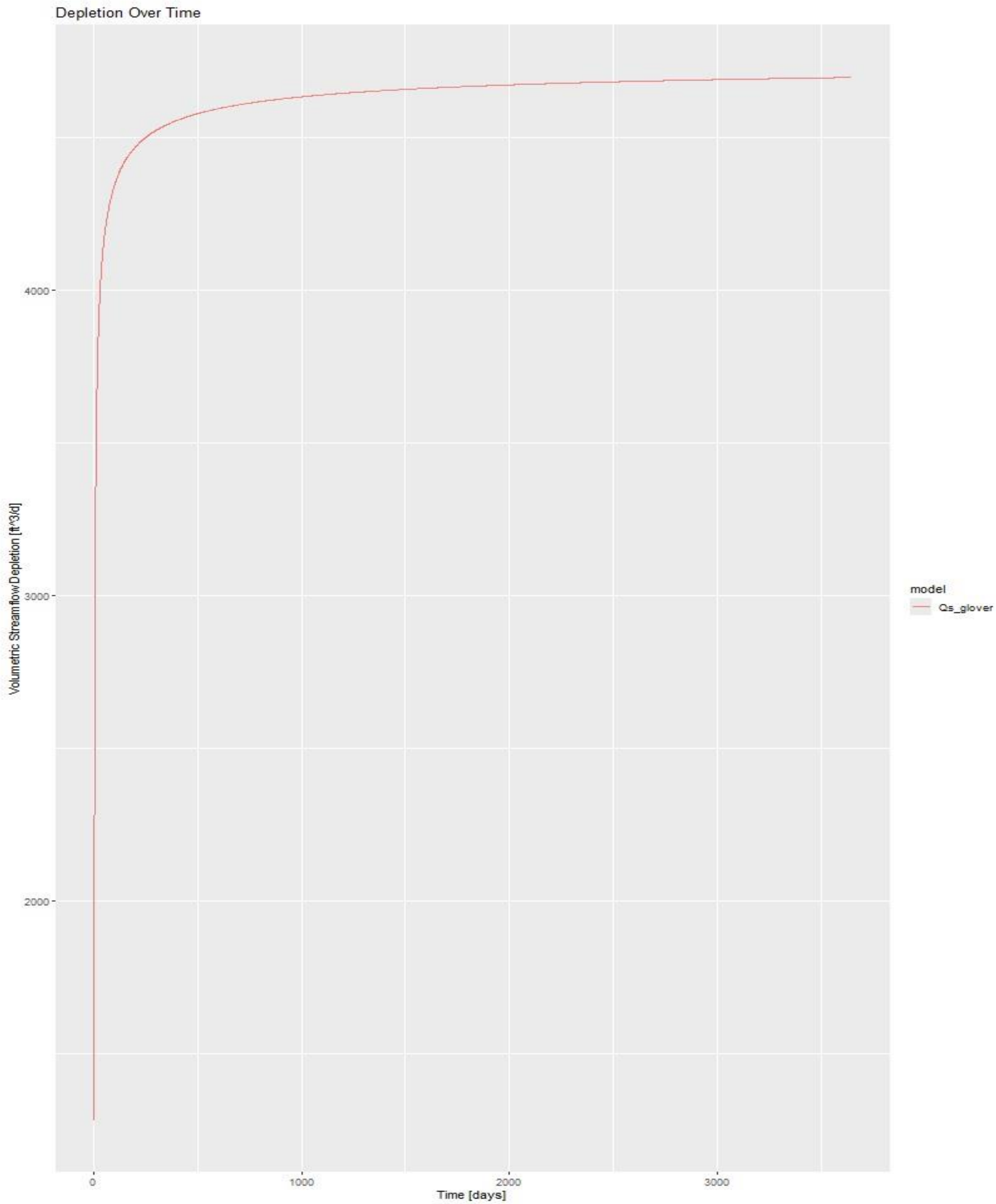


Figure 3- Stream Depletion Over 10 Years (streamDepletr, Li et. al)

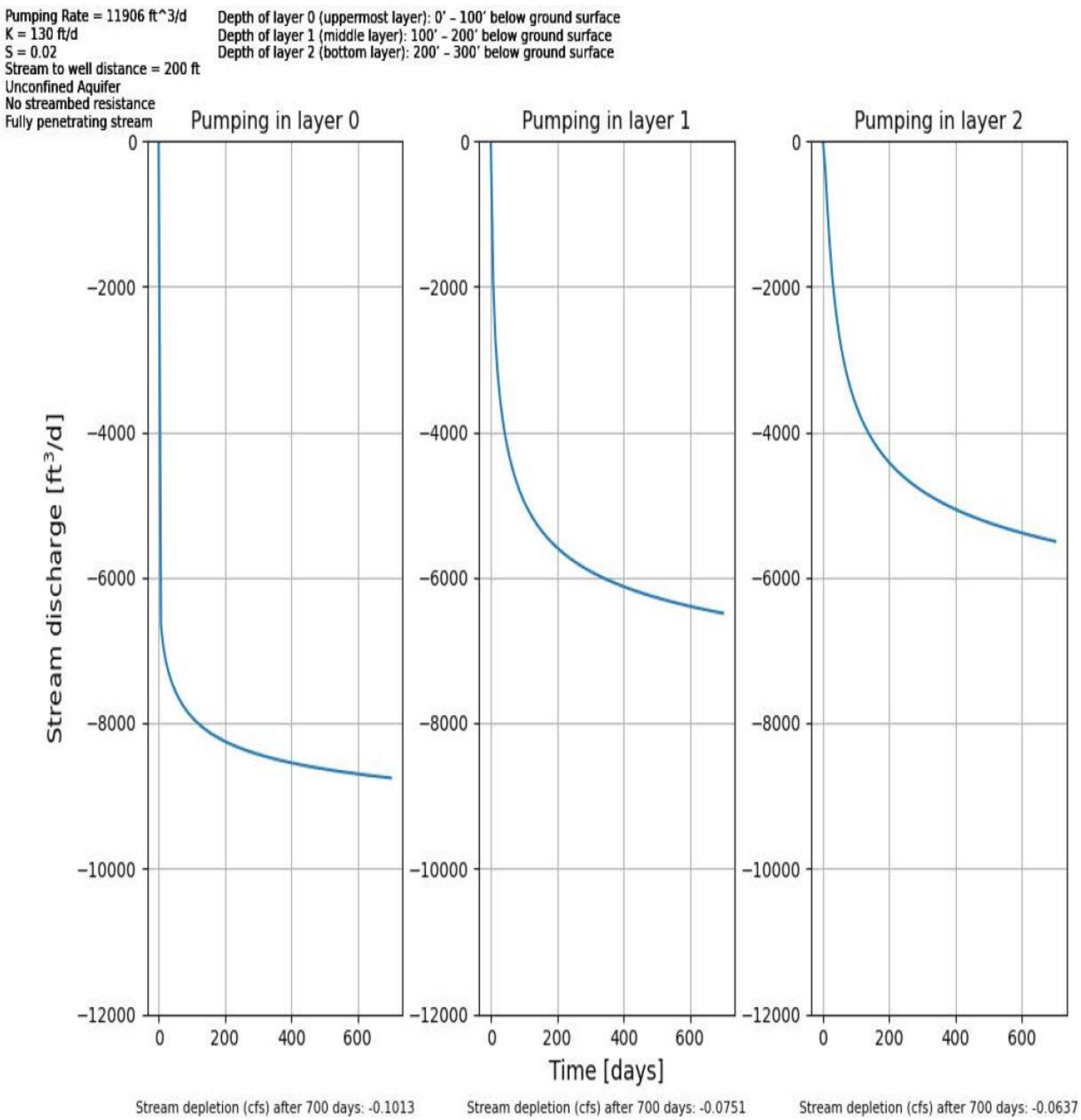


Figure 4-Simulation of Well Seal Depth Impacts on Groundwater Extraction at Different Depths (TTim, Bakker 2013)

Tool Selection for Applicants:

In evaluating streamflow depletion due to groundwater pumping, county staff have used numeric groundwater models where they have been developed for the Mid County and Santa Margarita groundwater basins. Staff have also applied the analytical models developed by Hunt, Jenkins, Li, and Bakker. Staff have assessed more complex models cited by Li, et.al. and Bakker, recognizing their significance and usefulness in establishing thresholds for policy development and testing. These models are particularly valuable for evaluating impacts over extended timeframes, intermittent pumping, seal depths, setbacks, and areas requiring more thorough analysis.

While the County staff found these programming models (Li. et al, Bakker)useful, they did not observe significant differences in the fundamental calculation for stream depletion (without incorporating well seals) when assuming fully penetrating streams with no streambed resistance compared to the simpler USGS web-based application, especially when analyzing single-point scenarios that focus on streams closest to the well. Because of this, we believe the user-friendly USGS web-based application tool is more suitable for Tier 3 applicants or consultants who may lack the programming experience to use the more advanced tools for evaluating stream depletion impacts. The web-based tool could also be appropriate for Tier 4 applicants, however since this tier requires a report prepared by a professional geologist, engineering geologist, or professional engineer who is expected to evaluate the cumulative effects on streamflow in the overall basin, we encourage these consultants to consider using more advanced tools, particularly Li et al. for evaluating cumulative impacts on a network of streams and Bakker for evaluating the influence of deeper seals in minimizing stream depletion impacts. .

Local Aquifer Properties: Range (typical value used)	**Transmissivity (ft^2/day) {gpd/ft}**	**Storage/ Storativity**	**Specific Yield**	**Hydraulic Conductivity**
TP-a - Purissima A	(2000) {15,000}	0.00055	0.02-0.07 (0.05)	5.2
TP-aa- Purissima AA	(600) {4500}	0.03100	(0.02)	1.7
TSM - Santa Margarita	430-7700 (3000) {22,500}	0.01	0.02-0.25 (0.2)	2-130
TLO - Lompico	500-3200 (2000) {15,000}	0.0000020	.02-.07 (.05)	0.5-7
Aromas/Purisima F	(4000) {30,000}	0.004		
Tm-Monterey	170-1000	0.00001-0.001	.01-.03	.05-.6

Table 3- Aquifer parameters from Groundwater Sustainability Plans

Estimated Surface Water Depletion from Groundwater Pumping in Selected Santa Cruz County Streams					
		Dry Season Flows, cfs (All Years)			
Creek		10th Percentile	Median	90th Percentile	Source
Bean Cr. @ Mt Hermon Rd (USGS)	Estimated Natural Flow*	0.509	1.08	1.89	FF model*
	Observed *	1.9	2.25	2.82	FF Database*
	Est.depletion by total gw pumping	0.5	0.5	0.5	GSP model
	% depletion**	21%	18%	15%	
	Est depletion by Non-Mun pumping	0.08	0.08	0.08	Apply Basin-wide proportion from GSP Model
	% Non-muni depletion	4%	3%	3%	
San Lorenzo River @ Big Trees (USGS)	Estimated Natural Flow*	15.2	20.2	23.7	FF model*
	Observed*	12	19	32	FF Database*
	Est.depletion by total gw pumping	1.5	1.5	1.5	GSP model
	% depletion**	10%	7%	4%	
	Est depletion by Non-Mun gw pumping	0.23	0.23	0.23	Apply Basin-wide proportion from GSP Model
	% Non-muni depletion	2%	1%	1%	
Moore Cr	Estimated Natural Flow*	0.0542	0.153	0.452	FF model*
	Observed	0.15	0.3	0.5	Estimated based on Occasional Measurements
	Est.depletion by Non-Mun gw pumping	0.03	0.03	0.03	Water Budget
	% depletion	17%	9%	6%	
Soquel Cr. @ Soquel (USGS) ***	Estimated Natural Flow*	2.44	3.05	5.28	FF model*
	Observed *	0.84	2.86	8.05	FF Database*
	Est.depletion by total gw pumping***	1.4	1.4	1.4	GSP model
	% depletion	57%	33%	15%	
	Est depletion by Non-Mun pumping	0.15	0.15	0.15	GSP Model
	% Non-muni depletion	15%	5%	2%	

Notes
* Estimated Natural Flow and Observed Flow is provided by the California Unimpaired Flow Database, v2.1.2 (Zimmerman, et.al., 2023)
** % depletion is the estimated depletion divided by the greater of the estimated natural flow, or the observed flow plus the estimated depletion
*** Soquel Creek experiences signficant riparian surface diversions, potentially 0.5-0.7 cfs (RCDSCC,2019).
The potential effect of surface diversions has not been factored into this table, other than where the estimated natural flow is used.

Table 4- Estimated Natural Flows and Depletion Based on Natural Flows Database, Streamflow Measurements, Local Groundwater Modelling, and Water Budgets

Well Interference

Staff have used the Modified Theis Non-Equilibrium Equation to estimate the amount of drawdown at various distances from a proposed pumping well in order to evaluate the potential for well interference and potential impacts on nearby wells. Values for local aquifer properties, pumping rates and potential setbacks were entered in the formula to produce an estimated drawdown. The following table shows the setbacks required for particular pumping rates in order to keep the drawdown less than 5 ft after 180 days of pumping.

Pumping Rate (GPM)	**2**	**8**	**20**	**50**	**100**
Aquifer					
TP-a/TLO	10	10	10	10	150
TP-aa	10	10	25	500	1400
TSM	10	10	10	10	25

Equation	**s=(264Q/T)*log(.3Tt/((r^2)S)**		**Input Values**	**Result**
Q	Discharge	gpm	50	
T	Transmissivity	gpd/ft;(7.48*ft^2/d)	4500	
S	Storage Coefficient	dimensionless	0.020	
t	Pumping time	days	180	
r	Distance	ft	100	
s=	drawdown-calculated	ft		**9.0**

Staff is proposing to use a standard of 50 ft separation for de minimis wells and replacement non-de minimis wells, although a greater setback could be required for new non-de minimis wells after applying the Modified Theis Non Equilibrium Equation to the specific well and aquifer properties.