Technical Memorandum

Sacramento Valley Groundwater-Surface Water Simulation Model Technical Memorandum 1A (SVSim TM-1A)

Subject:	**Modeling Approach for C2VSIM Enhancement**
Prepared For:	Chris Bonds, DWR
Technical Work Completed by:	Mesut Cayar, Dominick Amador, and Tim Durbin
Technical Work Reviewed by:	Linda Bond, Tim Durbin, and Saquib Najmus
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1 Purpose and Background

The purpose of this Technical Memorandum (TM) is to summarize the results of the modeling investigations of the effects of horizontal and vertical discretizations of an aquifer on representing the stream depletion. The Department of Water Resources (DWR) is improving DWR's existing C2VSim model to ensure that it meets essential requirements for evaluating the impacts of groundwater substitution transfers on stream depletion, and for computing water budgets necessary for sustainable groundwater management. This requires a realistic and accurate representation of the aquifer, a sufficiently fine grid, and a transparent non-proprietary modeling code available for review and revisions. A series of modeling experiments were conducted as part of this investigation.

2 Organization

The primary content of this TM is modeling investigation results, which are best presented in graphical charts. As a result, this TM is organized into small text sections supported by annotated figures, which are presented at the end of text sections. The text sections are:

- Design of Experiments
- Results of Horizontal Discretization Cases
- Results of Vertical Discretization Cases
- Summary and Recommendations

3 Design of Experiments

In order to understand the impacts of different levels of horizontal and vertical discretization on stream depletion, several test models were established with a 7 mile by 5 mile model domain. Aquifer parameters for the model were extracted from a representative area of C2VSim within the Sacramento Valley (Figure 1). All test runs were competed with an identical 1 month pumping schedule and the set of aquifer parameters presented in Table 1.

Table 1: Model Test Parameters

	K_H (ft/day)	S_Y (/day)	S_S	K_V (ft/day)
C2VSim Layer 1	55	0.16	1E-05	0.010
C2VSim Layer 2	55	0.16	1E-05	0.010
C2VSim Layer 3	6	0.13	1E-05	0.005

Initially a baseline scenario was established, then, different cases of horizontal and vertical discretizations were tested with numerical models. All scenarios were tested under two pumping conditions to assess the stream depletion under differing stresses. The model test problem scenarios are presented in Table 2 below:

Table 2: Model Test Scenarios

Scenario	Description
Baseline	The baseline scenario consists of a 40ft horizontal grid spacing near stream and 19 vertical aquifer layers. The simulation time step the baseline scenario is daily and the model was run for 10 years. Figures 2 and 3, provided at the end of this TM, show the horizontal and vertical discretization of the Baseline scenario, including the locations and depth of the pumping wells for different pumping conditions.
Vertical Discretization	Model scenario runs were performed with 4, 9, and 19 layers (Figure 4)

Horizontal Discretization	Model scenario runs were performed with 40 feet, 100 feet, 150 feet, and 300 feet horizontal grid spacing near stream. The grid spacing increases geometrically away from the stream to reach 1-mile spacing at a distance of 2 miles from stream (Figure 5).
Pumping Scenario A	Scenario A pumping was 500 acre-feet in the first month from a shallow well 300ft from the stream with perforation screen interval at a depth of 100ft to 200ft.
Pumping Scenario B	Scenario B pumping was 3,000 acre-feet in the first month from a deep well 5,000ft from the stream with perforation screen interval at a depth of 500ft to 600ft.

3.1 Testing Model

DWR’s Integrated Water Flow Model (IWFM) was chosen as the primary model to test impacts of horizontal and vertical discretizations. IWFM is a data-driven, comprehensive hydrologic simulation model that couples a three-dimensional finite element simulation of saturated groundwater flow with one-dimensional land surface hydrologic processes. Simulations within this framework account for stream flow, lakes, vertical unsaturated zone flow, and ungauged watersheds adjacent to the model boundary. IWFM simulates water demand based on land use, soil and climatic properties, and agricultural management parameters. Furthermore, it also models supply in terms of surface water diversions and groundwater pumping to meet these demands. These features make IWFM an appropriate tool both to simulate historical conditions in a basin and to perform water resources management planning studies for future.

The mathematical representation of existing IWFM code was determined to be adequate for evaluating the stream depletion after consultation with the modeling experts of DWR’s Bay Delta Office (BDO).

3.1.1 Reference Models

For the purpose of establishing relative accuracy of IWFM, the results of IWFM was compared with the following:

- Results of another numerical model, FEMFLOW3D, published by USGS.
- An analytical solution, called WTAQ, published by USGS.

FEMFLOW3D is a computer simulation of groundwater flow in three-dimensional groundwater systems using the finite-element method. A comparison of IWFM and FEMFLOW3D simulation results (Figure 6) shows that FEMFLOW3D computes 267AF less stream depletion than that computed by IWFM in 10-years of simulation. This difference accounts for about 9% of the total pumping volume of 3,000AF and can be attributed to the differences in model formulation and computational methods.

In order to understand the differences between models better, it was decided to compare the two models with the analytical solution WTAQ. The computer program WTAQ calculates hydraulic-head drawdowns in a confined or water-table aquifer that result from pumping at a well of finite or infinitesimal diameter. Developed by the USGS, this program is based on analytical models of axial-symmetric groundwater flow in a homogeneous and anisotropic aquifer.

The WTAQ model setup is shown in Figure 7. The model simulations of IWFM and FEMFLOW3D were developed with an equivalent grid and parameters to the WTAQ analytical solution. The model simulation results are shown in Figure to 10. The figures demonstrate that simulated groundwater levels of both FEMFLOW3D and IWFM are within 0.5 feet of analytical solution (WTAQ).

4 Results of Horizontal Discretizations

To investigate the effects of horizontal discretization on stream, multiple model scenarios were developed at 40 feet, 100 feet, 150 feet, and 300 feet grid spacing near stream. This horizontal grid spacing was increased geometrically across the stream to 1-mile spacing at a distance of 2 mile from the stream. The grid spacing along the stream was kept the same (0.5 mile) as in the current C2VSIM fine grid model.

Simulation results show horizontal discretization (ΔL) of 100 feet, 150 feet and 300 feet were able to replicate the stream depletion of the Baseline scenario within 98% accuracy. Figure 11 shows the results under the shallow well pumping at 300ft from stream and Figure 12 shows the results under the deep well pumping at 5000ft from stream.

5 Results of Vertical Discretizations

To investigate the effects of vertical refinement on stream-aquifer interaction, multiple model scenarios were developed. The aquifer was vertically discretized into 4, 9, or 19 layers with geometrically increasing layer thicknesses as shown in Figure 4.

The results of vertical discretization scenarios for pumping from shallow and deep well are shown in Figure 13 and Figure 14 respectively.. From these results, it can be concluded that the 4-layer model did not have the adequate level of accuracy, but the 9-layer model was able to replicate the stream depletion of the Baseline scenario within 99% accuracy.

6 Summary and Recommendations

The results of the modeling investigation relating to the effects of horizontal and vertical discretizations of an aquifer on representing stream depletion are summarized in Appendix Table 1 and are listed as follows:

6.1 Recommendations

IWFM Code Version

- As recommended by DWR BDO staff, it is recommended to use IWFM version 3.02 within the 2015 framework. IWFM 2015 was developed to give the user the flexibility to use different versions of IWFM within the same environment.

Vertical Discretization

- The results of the modeling scenarios indicate that while a 4 layer model is insufficient to accurately capture the stream-aquifer interaction, there is minimal difference between 9-layer model and 19-layer model.
- A 9 layer model is recommended for evaluating the impacts of groundwater substitution on stream depletion. It is also recommended that the top 300 to 350 feet of aquifer be divided into about 5 layers, starting with a 50-feet top layer with gradual increase to

higher thicknesses; the aquifer between 300 to 700 feet depth be divided into 2 to 3 layers, while the aquifer below 700 feet depth can be divided into 1 to 2 layers.

Horizontal Discretization

- The results of the modeling scenarios indicate that a 300-feet horizontal discretizations near the stream is adequate to capture the impacts of near-stream pumping on stream depletion because the corresponding model results are almost the same with those for 100 feet and 150 feet horizontal discretizations.
- It should be noted that a 300-feet grid spacing in IWFM does not preclude one from putting a pumping well at a distance less than 300-feet for the purposes of impact evaluation.
- A horizontal grid spacing of 300 feet near stream is recommended with gradually increasing grid spacing away from stream.

6.2 Other Considerations

Model Run Time

- A Run time analysis with the existing C2VSim coarse and fine grids was performed. All runs were executed using IWFM v3.02 for an estimated monthly simulation time of 87-years (1922 - 2009). A breakdown of simulation parameters and the corresponding model run times are listed in Table 3 below:

Table 3: Estimated Model Run Times

Pre-Calibration Model Runtime (hrs)

		Horizontal Discretization		
		100 feet	150 feet	300 feet
Vertical Discretization	4 Layers	5.0	3.9	2.8
	5 Layers	6.3	4.9	3.5
	6 Layers	7.6	5.9	4.3
	7 Layers	8.8	6.9	5.0
	8 Layers	10.1	7.9	5.7
	9 Layers	11.3	8.9	**6.4**
	12 Layers	15.1	11.8	8.5

Post-Calibration Model Runtime (hrs)

		Horizontal Discretization		
		100 feet	150 feet	300 feet
Vertical Discretization	4 Layers	3.4	2.6	1.9
	5 Layers	4.2	3.3	2.4
	6 Layers	5.0	3.9	2.8
	7 Layers	5.9	4.6	3.3
	8 Layers	6.7	5.2	3.8
	9 Layers	7.6	5.9	**4.3**
	12 Layers	10.1	7.9	5.7

** Model run time estimations assume a 87-year simulation period

- It is recommended from runtime consideration that a 9-layer model with 300-feet horizontal discretization be used for the purposes of this project because a 4-hour to 6-hour runtime is reasonable for evaluating multiple model scenarios.

Hydrogeologic Considerations

- The following hydrogeological considerations were not evaluated as part of this project:
  - Representation of pumping well perforations in aquifer layers.
  - Representation of geologic features such as Tuscan Formation.
- The well perforations for pumping wells vary over a wide range; therefore, any number of aquifer layers will not be able to represent all pumping well perforations. It is anticipated that a 9-layer model will be refined enough to adequately represent the pumping well perforations both in the shallow and deep aquifer of the Sacramento Valley.
- DWR's Northern Regional Office (NRO) indicated that currently there is insufficient geologic or hydrogeologic information to characterize the areal and vertical extent of the Tuscan hydrogeologic formation and the associated confining units in the Sacramento Valley. As a result, this consideration is not included in developing the recommendations for vertical discretization. A detailed texture analysis of the well-logs in Sacramento Valley can improve the accuracy of defining the aquifer layers and parameters.

Land Use

- The current version of C2VSim-FG land use is mapped from the coarse grid. Developing the land use and crop acreages from the original data sources might take additional time but it will improve the model calibration and defensibility of the model significantly.

Water Budget Calculation

- The implementation of Sustainable Groundwater Management Act (SGMA) may require development of water budget for each of the groundwater basin identified in Bulletin 118-3 published by DWR. It is recommended that the model grid for the Sacramento Valley IWFM be generated to follow the currently known groundwater basin boundaries as published in Bulletin 118-3. However, it should be noted that DWR is embarking on a process under SGMA to allow local agencies to request modification of groundwater basin boundaries. The revised groundwater basin boundaries will not be available in time for inclusion in the grid development for the Sacramento Valley IWFM. However, it is anticipated that the model grid will be refined enough to either capture the new basin boundaries through a regrouping of model elements or through slight modification of grid configuration.

Sensitivity of C2VSIM Results

- During the project scoping phase, it was not clear whether the entire Central Valley model (C2VSIM) will be used for the groundwater substitution evaluation project with finer horizontal and vertical discretizations in only the Sacramento Valley portion of the model or a separate Sacramento Valley model will be developed. As a result, it was initially planned that limited sensitivity studies will be conducted for key results (e.g. delta outflow, stream gain and losses in impacted reaches) of C2VSIM. However, during the project execution phase, the early results of numerical experiments on horizontal and vertical discretizations indicated that a separate Sacramento Valley model is necessary to achieve reasonable run time and reduce the level of effort for input data preparation and model calibration. The modeling investigation results indicate significant changes in stream depletion and simulated water levels near stream due to changes in horizontal and vertical discretizations from the current C2VSIM fine grid model. The same results will be propagated accordingly to delta outflow, stream gain and losses; therefore, the sensitivity studies on C2VSIM key results became unnecessary.

6.3 Summary

The key decisions and recommendations of the current project are summarized in Table 4.

Table 4: Summary of Decisions and Recommendations

No.	Key Decision Item	Decisions and Recommendations
1	IWFM Code Version	IWFM version 3.02 in IWFM 2015 Framework
2	C2VSIM Grid Version to start from	C2VSim-FG (Sacramento)
3	Mesh refinement (grid refinement around and away from stream and number of aquifer layers)	9 vertical layers 300-ft horizontal grid spacing near stream with gradual increase in grid spacing away from stream. Maintain the current 0.5 mile discretization along the stream.
4	Additional streams to be included in model (hydrology, streambed)	To be determined in Phase 2
5	Full Central Valley or Sac Valley separate model	Sacramento Valley
6	Mesh generation	To be determined in during scoping for Phase 2
7	IWFM/C2VSIM overview for IRWM Modeling staff	TBD
8	Hydrologic simulation period (to establish initial conditions)	Water Years 1922-2013
9	Calibration period	Water Years 1972-2013
10	Calibration targets	To be determined in Phase 2
11	Model outputs for presentation to ensure output is generated at the needed scale (may require code modification)	To be determined in Phase 2
12	Identify post-processing tools need for presentations	To be determined in Phase 2

Figures

List of Figures:

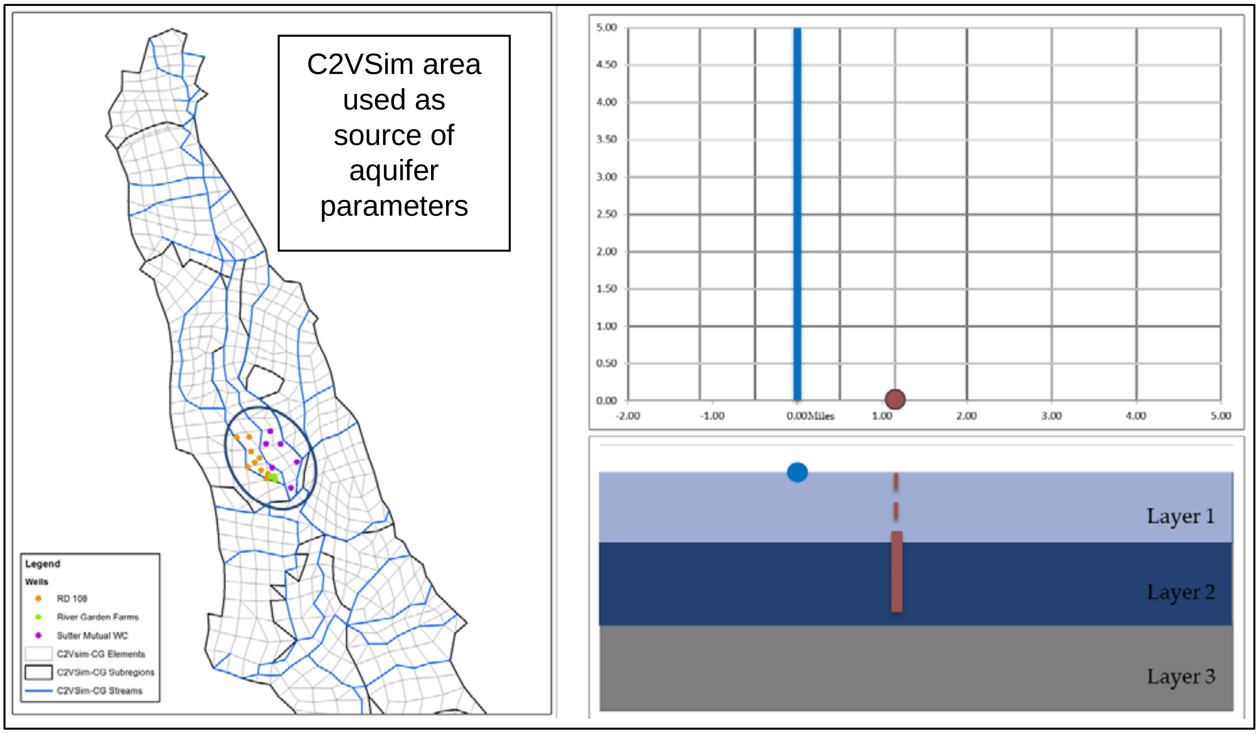

Figure 1: Model Domain (7 mile by 5 mile)

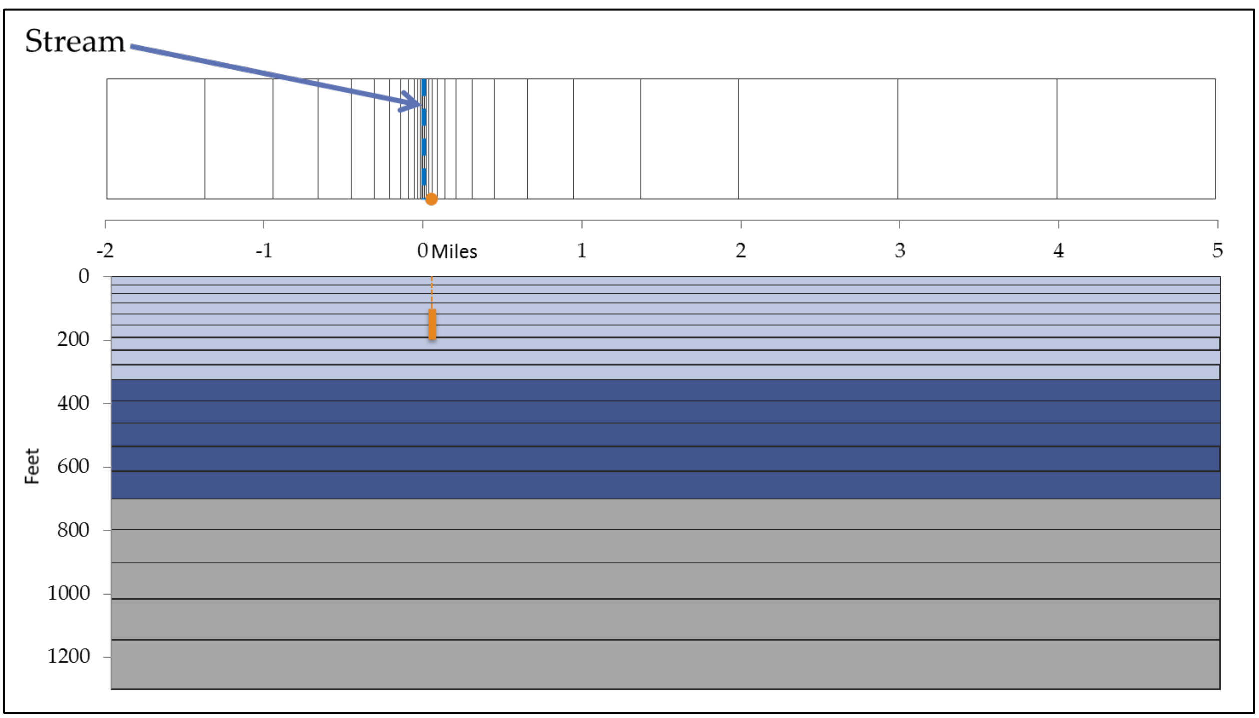

Figure 2: Baseline A Discretization and Well Configuration

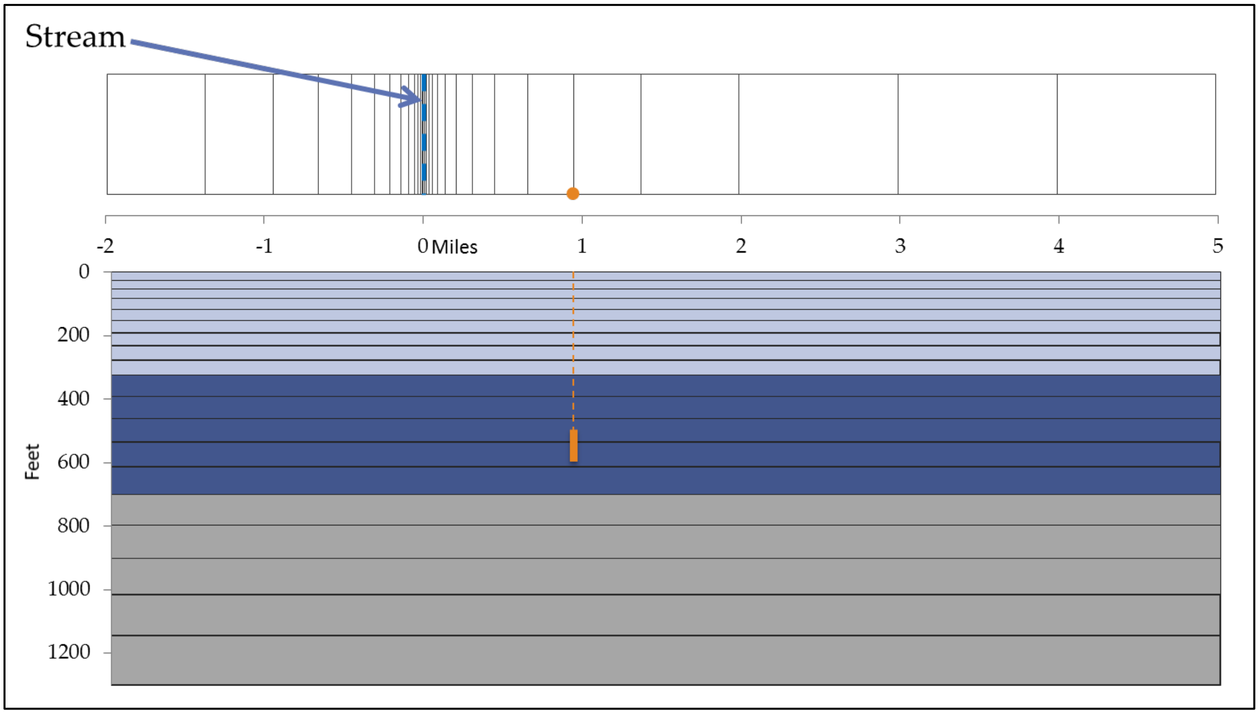

Figure 3: Baseline B Discretization and Well Configuration

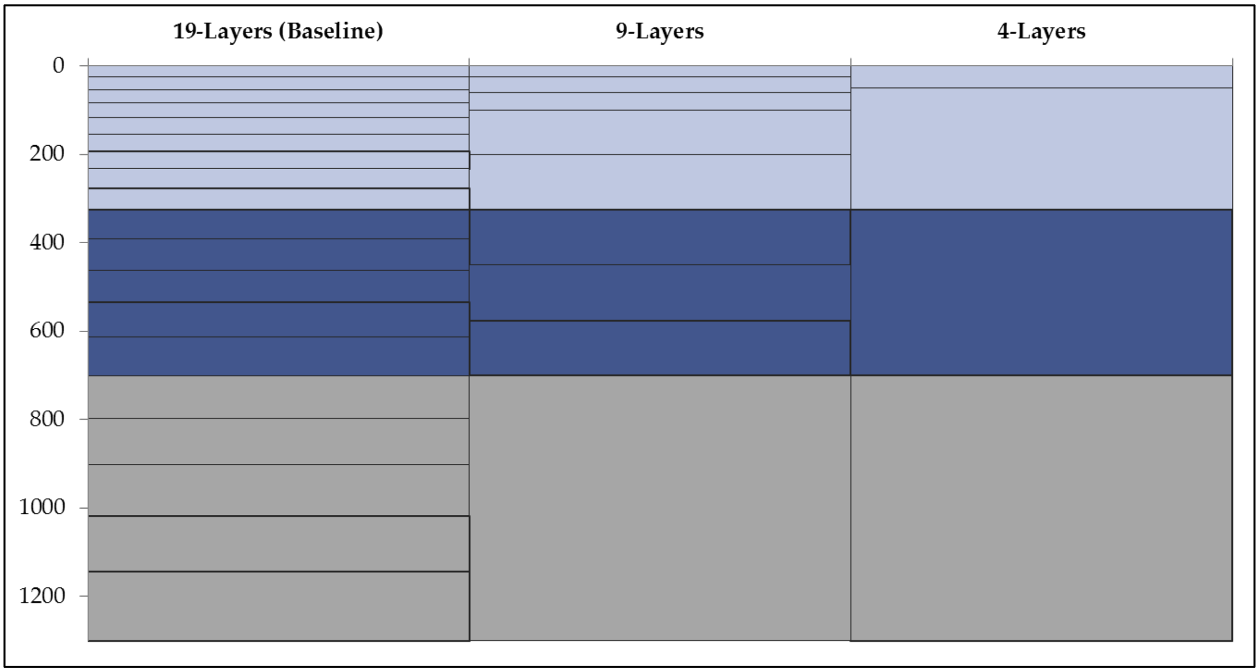

Figure 4: Vertical Discretization and Layering Scenarios

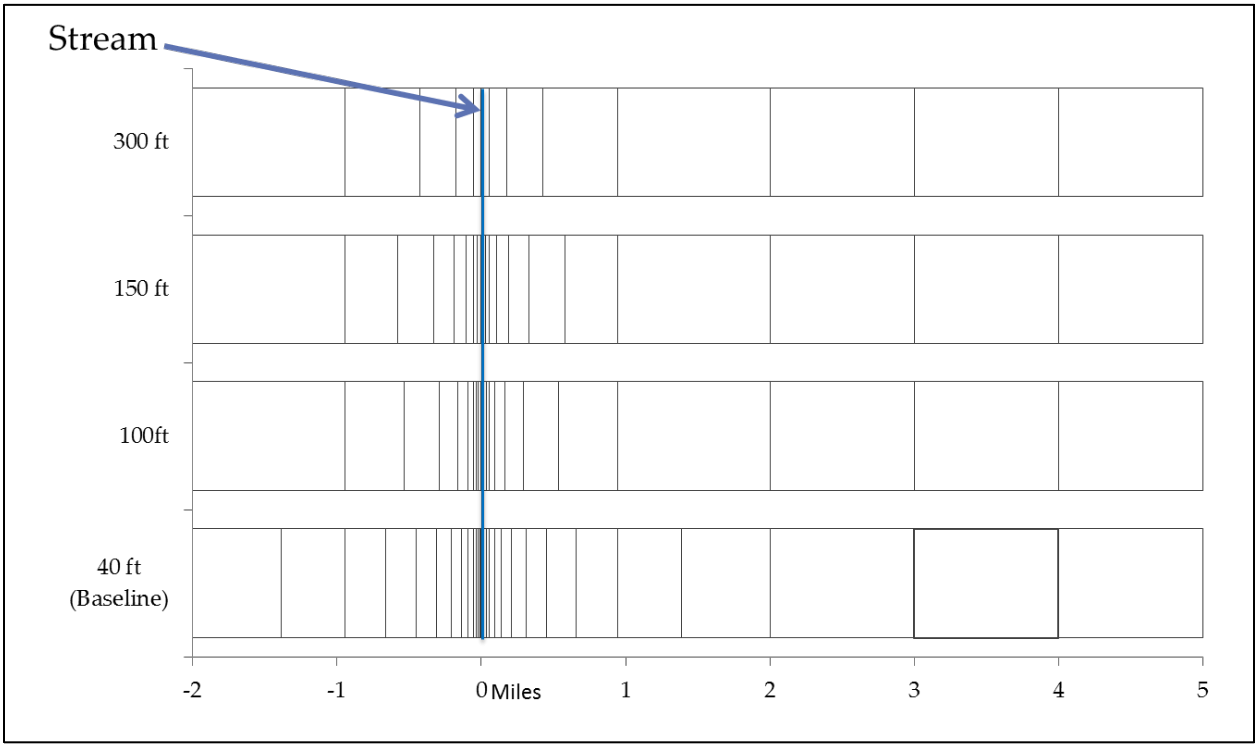

Figure 5: Horizontal Discretization and Grid Scenarios

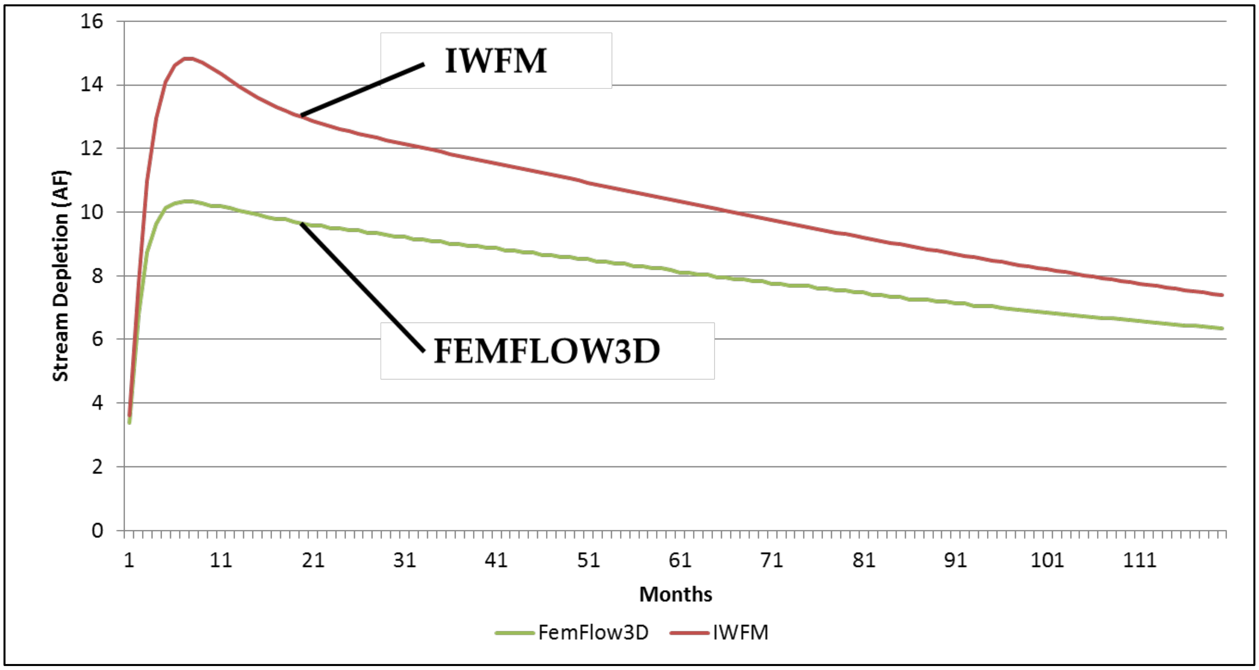

Figure 6: IWFM vs FEMFLOW3D Model Results

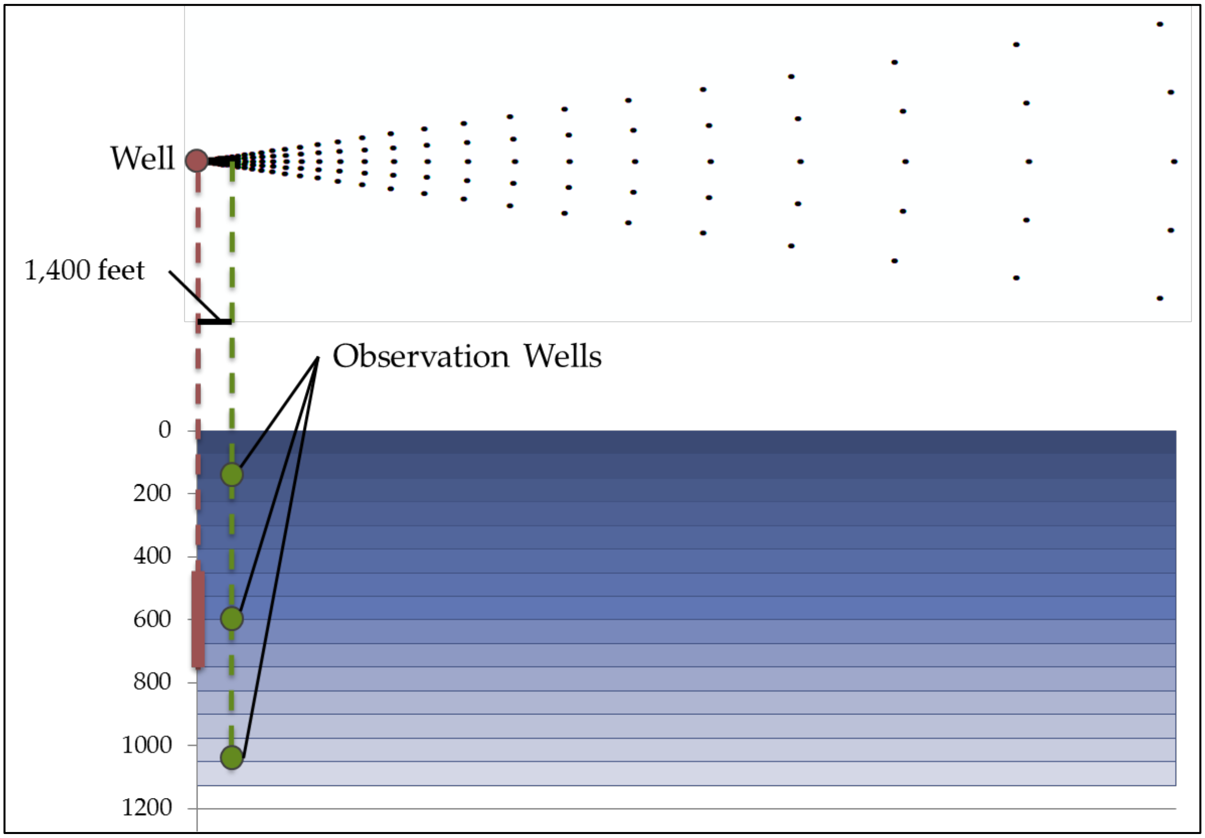

Figure 7: WTAQ Model Setup

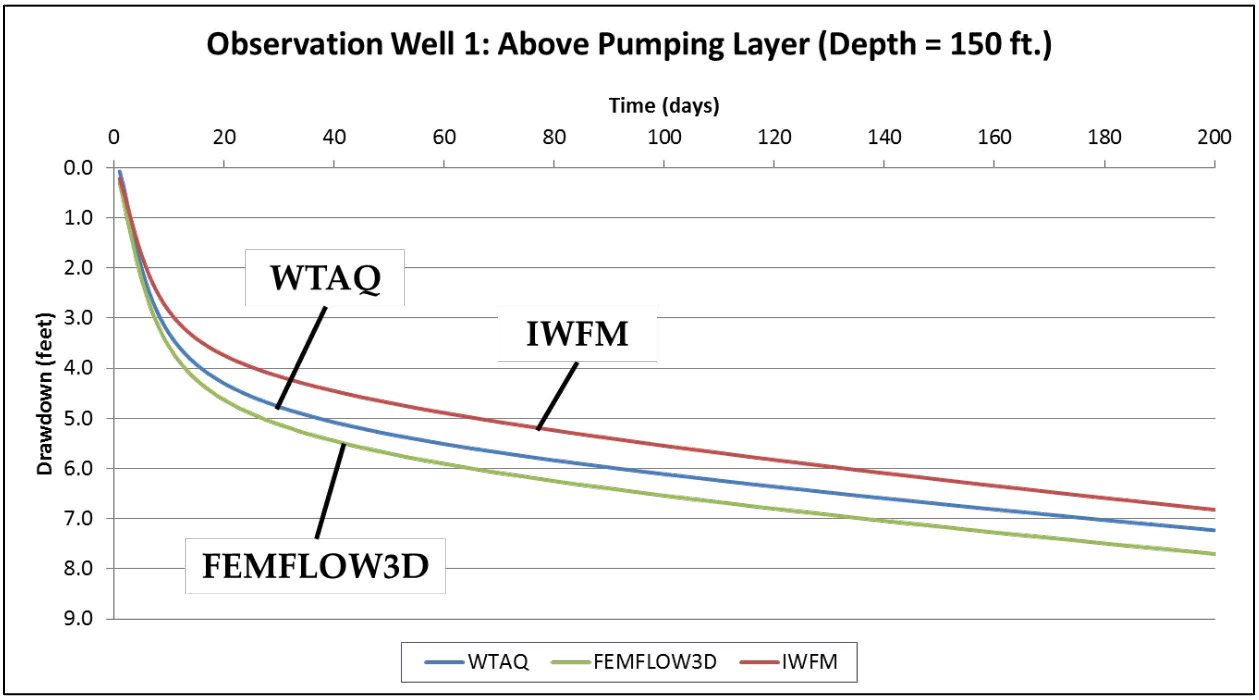

Figure 8: Results of WTAQ Analytical Solution

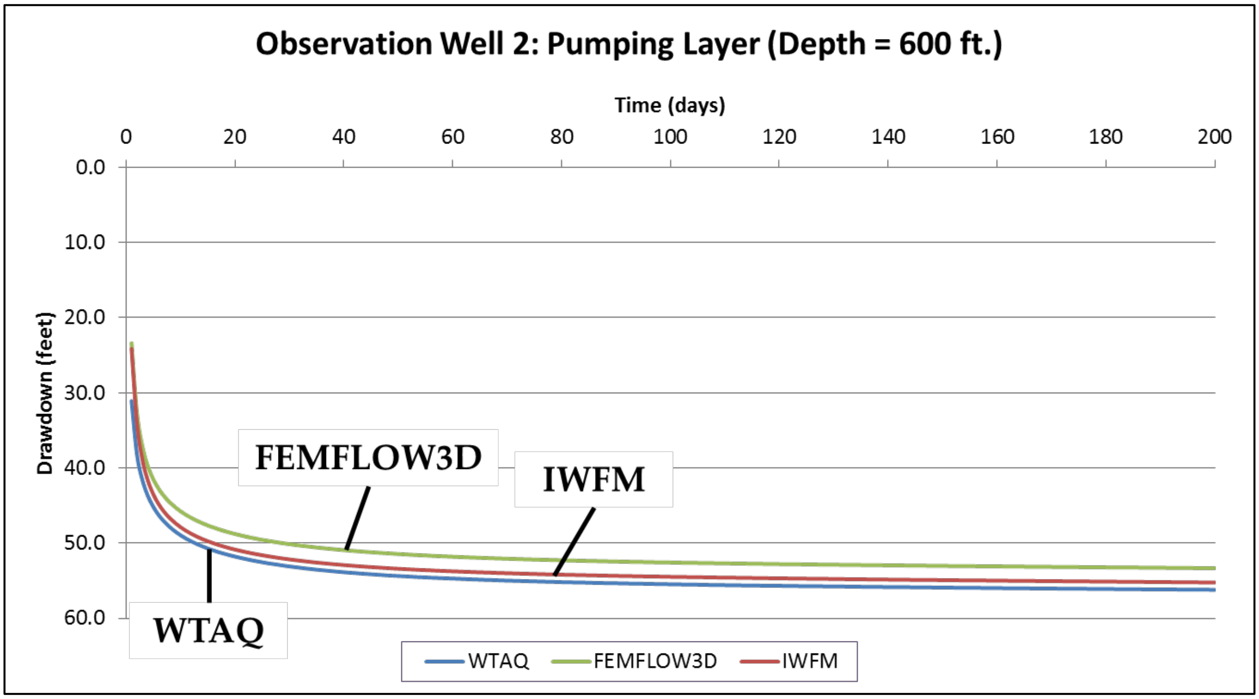

Figure 9: Results of WTAQ Analytical Solution

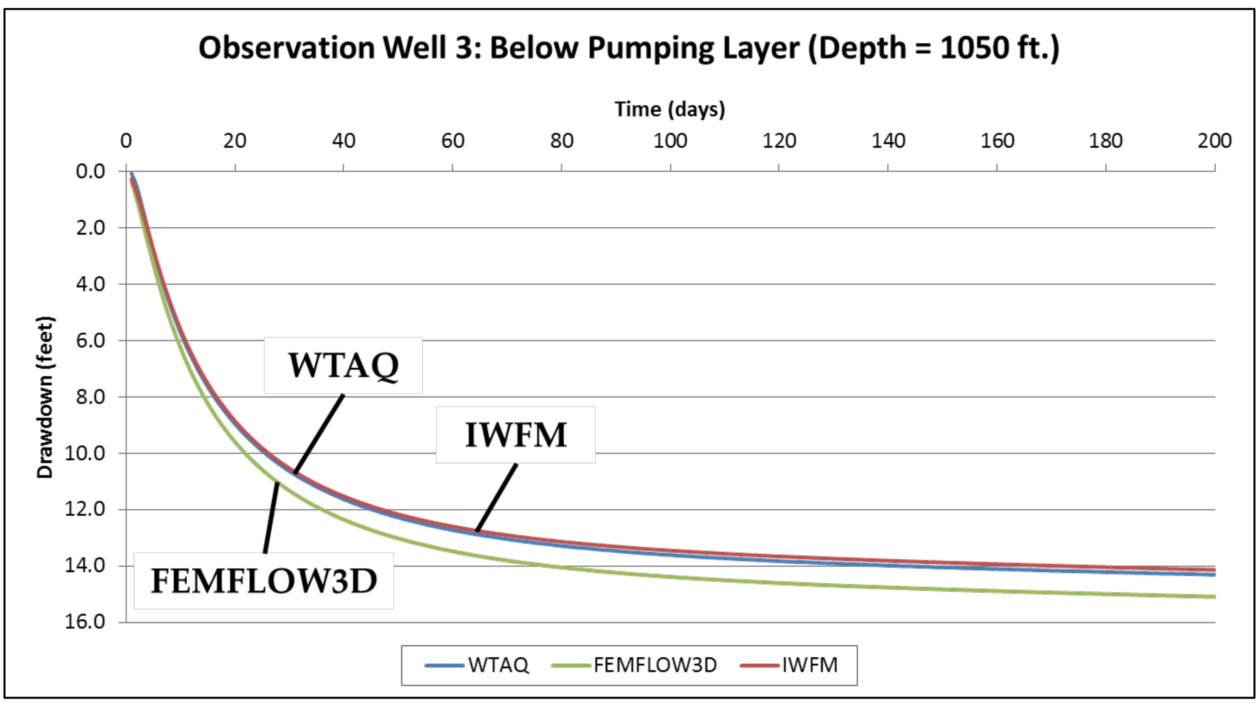

Figure 10: Results of WTAQ Analytical Solution

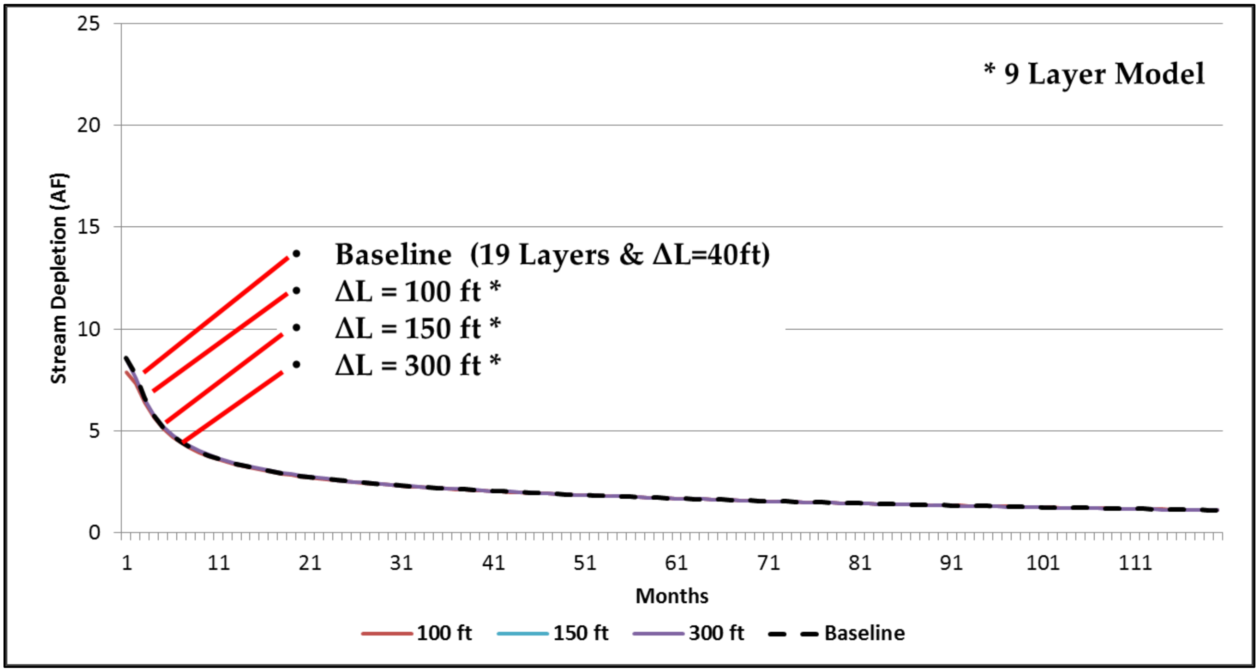

Figure 11: Horizontal Discretization - Results of IWFM Scenario A Model Runs (Shallow Well at 300ft from Stream)

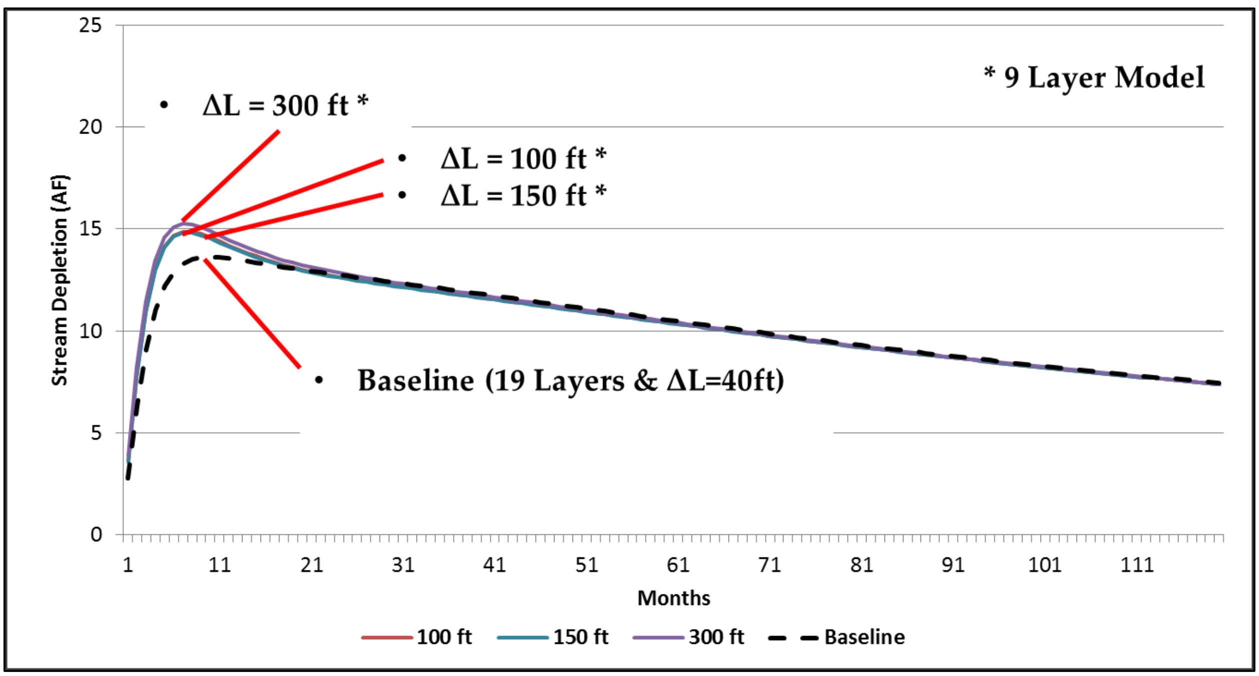

Figure 12: Horizontal Discretization - Results of IWFM Scenario B Model Runs (Deep Well at 5,000ft from Stream)

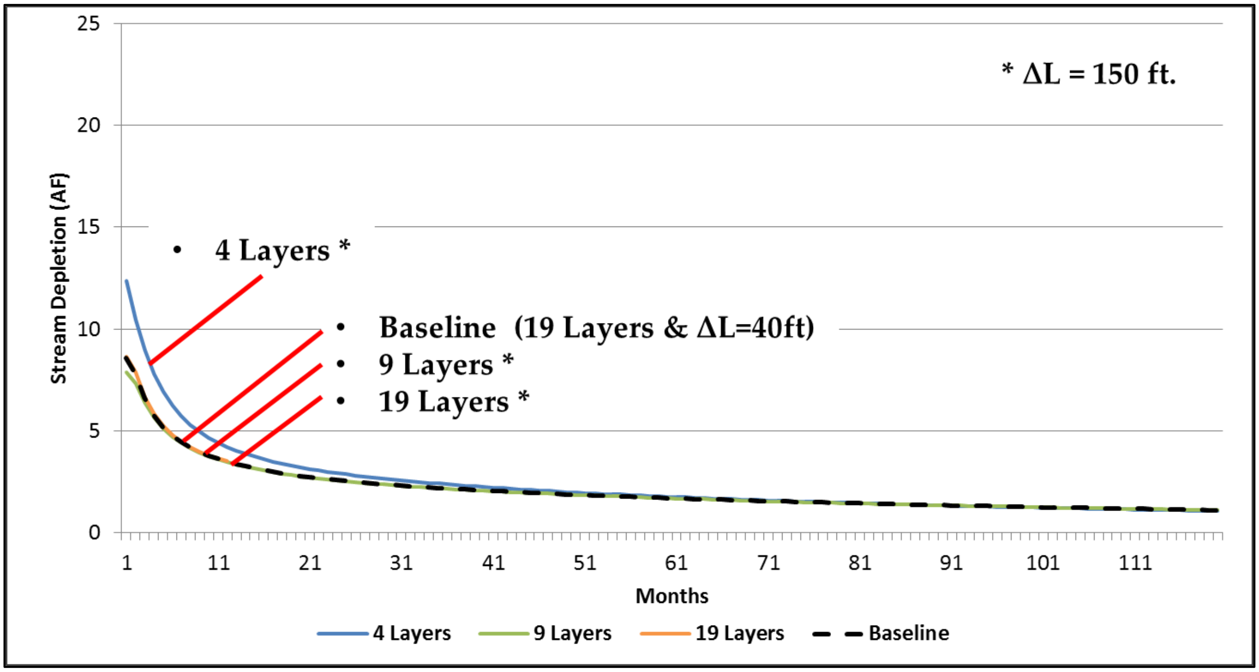

Figure 13: Vertical Discretization - Results of IWFM Scenario A Model Runs (Shallow Well at 300ft from Stream)

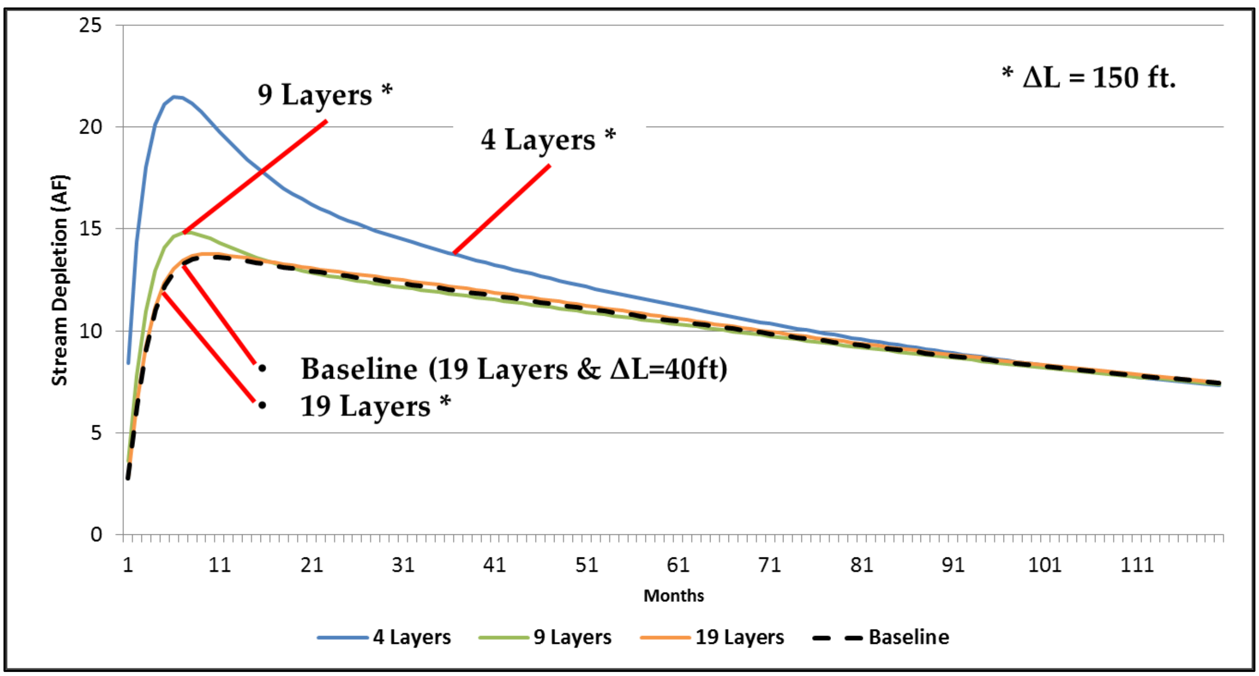

Figure 14: Vertical Discretization - Results of IWFM Scenario B Model Runs (Deep Well at 5,000ft from Stream)

Appendix

C2VSim Enhancement for the Sacramento Valley
Summary Results of Modeling Experiments

Consideration	Criteria	Numerical Experiments	Findings	Comments
Replication of Analytical Solution				
1.	Comparison of IWFM and FEMFLOW3D simulation results to the analytical solution of WTAQ model.	Performed simulations with IWFM, & FEMFLOW3D and compared the results with WTAQ.	Both models displayed reasonable accuracy in replicating analytical solution.	Simulated groundwater levels for IWFM are within 0.5 feet of analytical results (WTAQ).
Vertical Discretization				
2.	Sensitivity of stream depletion to layering (vertical discretization).	Multiple IWFM model runs were performed comparing 4, 9, and 19 layers	A 4-layer model did not have the adequate level of accuracy. A 9-layer model was able to replicate the stream depletion of the baseline within 99% accuracy.	9-Layer model is recommended - 5 layers in the top 300-350 feet to accurately simulate the near-surface hydraulic gradient and the rate of stream depletion. - 2 to 3 layers from depth 300 feet to 700 feet - 1 or 2 layers from 700 feet to the bottom of the aquifer
Horizontal Discretization				
3.	Sensitivity of stream depletion to grid spacing (horizontal discretization).	Multiple IWFM model runs were performed comparing 40, 100, 150, and 300 feet horizontal discretization (ΔL)	ΔL = 100 feet, 150 feet and 300 feet were able to replicate the stream depletion of the baseline within 98% accuracy.	ΔL = 300ft is recommended. - ΔL does not facilitate significant difference between 100 and 300 feet - Existing C2VSim-FG grid will only be refined within a band along the streams that extends 0.5 miles each direction - There will not be any longitudinal change in spacing of stream nodes
Well Distance From Stream				
4.	Proximity of the wells to the streams.	Multiple IWFM model runs were performed with pumping well locations at 300 and 5,000ft away from stream.	With recommended parameters, stream depletion was found to be accurate under both well distance scenarios, and both displayed long term differences of under 1% when compared to the baseline model run.	
Model Accuracy				
5.	Comparison of IWFM and FEMFLOW3D simulation results for a selected discretization test.	Models are run with 9-layers and 150ft discretization.	FEMFLOW3D shows 267AF less stream depletion compared to IWFM out of 3,000AF of pumping in the first 10 years.	FEMFLOW3D is fully-3-dimensional and IWFM is a quasi-3-dimensional model. -Distribution of pumping across layers are computed differently
Other Criteria				
6.	For other criteria not evaluated through modeling experiments, see comments section.			Representation of geology potentially desired by DWR / Stakeholders - representation of well perforations - representation of geologic features such as Tuscan Formation.
Runtime Considerations				
7.	Length of model runtime in both calibration and post calibration period	Performed run time analysis with the existing C2VSim-CG & C2VSim-FG runs. All runs were performed using IWFM v3.02 for an estimated monthly simulation time of 87-years (1922 - 2009).	ΔL = 100ft --> 42,000 nodes which will require a 12-14 hour run time during the calibration process and an 8 hour simulation run time post-calibration (6 minutes per year). ΔL = 150ft --> 33,000 nodes which will require a 9-10 hour run time during the calibration process and a 6 hour simulation run time post-calibration (4 minutes per year). ΔL = 300ft --> 24,000 nodes which will require a 6-7 hour run time during the calibration process and a 4 hour simulation run time post-calibration (3 minutes per year).	ΔL = 300ft produces the shortest runtime - Assumes an 87-year simulation - Applications of the model for calculating stream depletion for substitute pumping will start with one-year run and will increase by one year annually . - It is reasonable to assume that runtimes will decrease as computers are improved

ΔL = Horizontal discretization
C2VSim-CG = C2VSim Coarse Grid
C2VSim-FG = C2VSim Fine Grid
Accuracy - We developed a baseline simulation for comparison; stream depletion simulated with a 19 layer, 40-foot grid, and a daily time step. (Test simulations use a monthly time step.) Our assumption is that this level of discretization was more than enough to accurately calculate stream depletion, so we established this as our de facto "true solution."

Table A1: Summary of Model Runs and Results