



FW: Dry Creek Watershed Open House - 01/18

Michael Brinton <brintonm@stancounty.com>

Fri, Jan 21, 2022 at 10:53 AM

To: "depobook@gmail.com" <depobook@gmail.com>

Cc: Frederic Clark <CLARKF@stancounty.com>, Dhyan Gilton <GILTOND@stancounty.com>

Comments received

From: Kent Naraghi <kent@snaraghifarms.com>

Sent: Monday, January 17, 2022 11:37 AM

To: Michael Brinton <brintonm@stancounty.com>

Subject: Dry Creek Watershed Open House - 01/18

*** **WARNING:** This message originated from outside of Stanislaus County. **DO NOT** click links or open attachments unless you recognize the sender and know the content is safe ***

Dear Michael,

I wanted to email you about tomorrow's open house related to the Stormwater Management and Groundwater Recharge Project in the Dry Creek Watershed.

My mother, Sharon Naraghi is the landowner for one of the eleven sites to be evaluated for the project. I am planning to attend the open house but my mother hoped to attend remotely, especially due to the increase in COVID cases. Will the meeting be conducted virtually as well?

Please let me know, thank you for your time.

Sincerely,

Kent Naraghi

(209) 608-1372



**STANISLAUS COUNTY
DRY CREEK WATERSHED**

**STORMWATER MANAGEMENT AND
GROUNDWATER RECHARGE STUDY**

Name: Rick ARNOLD

Date: 1-18-2022

Phone: (209) 479-3589

Email: Rick ARNOLD 022 @YAHOO.COM

COMMENTS:

PROPOSE TO USE DRY CREEK IN SAME MANNER AS OUR CANAL SYSTEM IS USED. HEAD WALLS WITH GATE VALVE AND RIP RAP ON EACH SIDE TO RETAIN WATER AT SEVERAL AREAS TO RETAIN THROUGH OUT THE CREEK. WILL NOT IMPACT ANY ONE PROPERTY IF WATER DAMS OR HEAD WALLS ARE ONLY 5' + OR - TALL. SHOULD NOT IMPACT PROPERTY VALUES OR CROPS.



**STANISLAUS COUNTY
DRY CREEK WATERSHED**

**STORMWATER MANAGEMENT AND
GROUNDWATER RECHARGE STUDY**

Name: Jennifer Buck

Date: 1/18/22

Phone: (209) 480-3475

Email: Unarnold22@yahoo.com

COMMENTS: Site 15 Flood

We recently bought our home within the last couple of years. We were under the impression the trees (oak) are protected. The reason we bought the property was to have land for my 2 year old to grow up on and play. Now, that will be taken and his safety is a concern.



STANISLAUS COUNTY
DRY CREEK WATERSHED

STORMWATER MANAGEMENT AND
GROUNDWATER RECHARGE STUDY

Name: Drew Lemos

Date: 1/18/22

Phone: () _____ - _____

Email: dlpilot@yahoo.com

COMMENTS:

- 1) main concern is erosion and pesticide percolation into soil.
- 2) Secondary concern is erosion runoff leaving trash and silt across private property and at base of dam
brush, trees, and vegetation

Meneses family
615 North Hopper Road
Modesto, CA 95357

January 18, 2022

Stanislaus County Department of Public Works
1010 Tenth St., Suite 4200
Modesto, CA 95354

RE: Phase II Evaluation of Stormwater Management and Groundwater Recharge
Projects in the Dry Creek Watershed of Stanislaus County

To whom it may concern:

We believe in preserving farmland and the environment. Our position is that there should be no dam anywhere on Dry Creek. It would do more harm than good. The environmental cost would be too high.

A dam on Dry Creek would immediately destroy that part of the creek on which it is built, and the loss of native habitat would result in the suffering and death of wildlife. Not only would animals die, but ancient oak trees would be destroyed.

Dry Creek is a migratory corridor for native species. A dam would effectively cut the creek in two. Besides the impact on wildlife, the creek itself would suffer for many miles in both directions. The decline might be slow, but it would be certain.

Dams store heat as well as water, which leads to algae growth and the release of greenhouse gases. Dams are one of the biggest contributors of methane. Thus, dams actually worsen climate change.

Because of sedimentation, a dam on Dry Creek would actually lose effectiveness over time.

By now the county has received a letter from California Oaks, a division of the California Wildlife Foundation. With that letter, the county received a pdf containing a document with information about the incised-valley fills (IVFs), also known as paleo valleys, that belong to Modesto, and which have great potential in the restoration of groundwater. As an introduction to that document we recommend an article in Bay Nature magazine, Winter 2022, "Capturing the Flood in California's Ancient Underground Waterways" by Erica Gies, January 4, 2022. It may be easily found online.

Using Modesto's paleo valley would help both with flooding and in restoring groundwater. Should Stanislaus County successfully begin to utilize it as a means of water management, it would be admired for its innovation. Professor Fogg, mentioned in the above Bay Nature article, is at UC Davis (gefogg@ucdavis.edu) and Professor Weissman, also mentioned in the article, is at the University of New Mexico (weissman@unm.edu).

Stanislaus County also may learn from what is being done in Fresno with "Leaky Acres". Another option would be use of existing canals in the winter to channel excess water, which would also help with both flooding and aquifer recharge. Restoration of the flood plain should also be explored.

Dry Creek is a piece of California as it once was, a piece of California that should be protected and valued. We would lose far more than we would ever gain by putting a dam across Dry Creek. Better solutions should be found now, rather than taking an easy approach which would create more problems.

Most sincerely,

Adeline, Linda, and Rose Meneses



FW: Dry Creek Dam proposals

Michael Brinton <brintonm@stancounty.com>

Fri, Jan 21, 2022 at 11:10 AM

To: "depobook@gmail.com" <depobook@gmail.com>

Cc: Frederic Clark <CLARKF@stancounty.com>, Dhyan Gilton <GILTOND@stancounty.com>

Comments received

From: Anita Young <ayyoungbooks2@gmail.com>

Sent: Wednesday, January 19, 2022 1:22 PM

To: Michael Brinton <brintonm@stancounty.com>

Subject: Dry Creek Dam proposals

*** **WARNING:** This message originated from outside of Stanislaus County. **DO NOT** click links or open attachments unless you recognize the sender and know the content is safe ***

Hello, Mr. Brinton. I attended last night's open house on the proposals for damming Dry Creek and would like to submit the following comments:

--There seemed to be little or no support for any of the proposed sites from the farming community, and a great deal of opposition because any of the sites would result in property/financial loss for farms and ranches in the area.

--We oppose any alteration of the creek channel caused by a dam. Dry Creek is the last natural-flowing stream in our area. Altering the flow of Dry Creek will change or damage riparian habitat, and will have a negative impact on native oaks (protected in Stanislaus County), other plant life and wildlife.

--We believe there are better ways to have a Managed Aquifer Recharge in Stanislaus County that does not affect Dry Creek. We doubt that the slowing of the creek by a dam after a flood event would actually help to recharge the aquifer.

--We believe that the costs of engineering a dam on Dry Creek could be better spent on relocating disadvantaged people who are living in the floodplain.

--We now live in an era of mega storms. Much of the modeling was done using the flood of 1997. With the intensity of these mega storms, even a model using a 100-year flood is likely to underestimate the volume of water such a storm could produce. Damming Dry Creek would be ineffective in the face of a mega storm.

--The release of methane by dams is a growing concern because methane contributes to greenhouse gasses and climate change. Methane is produced by underwater microbes that feast on the organic matter that accumulates in silt behind dams. (source: <https://www.science.org/content/article/hundreds-new-dams-could-mean-trouble-our-climate>)

Anita Young

Chair, Yokuts Group of the Sierra Club

| "CARbon emissions is everybody's CAR."



FW: Site 15 flood map Questions

Michael Brinton <brintonm@stancounty.com>

Fri, Jan 21, 2022 at 12:11 PM

To: "depobook@gmail.com" <depobook@gmail.com>

Cc: Frederic Clark <CLARKF@stancounty.com>, Dhyan Gilton <GILTOND@stancounty.com>

Written comments received.

From: Paul Joslin <pauljoslin4@gmail.com>

Sent: Tuesday, January 18, 2022 6:01 PM

To: Michael Brinton <brintonm@stancounty.com>

Subject: Site 15 flood map Questions

*** **WARNING:** This message originated from outside of Stanislaus County. **DO NOT** click links or open attachments unless you recognize the sender and know the content is safe ***

Questions for dry Creek meeting

1. how long will the water be stored behind the dam? Will it be released as fast and safely as possible to protect Crops from being destroyed.
2. How many homes and there value will these dams protect versus how much crop land will be destroyed and its value?
3. And which neighborhoods specifically are being protected
4. If Don Pedro and Tuolumne river is maintained at a safe and normal level during heavy storms are these dams even needed if dry creek can flow naturally without the Tuolumne river backing up into dry Creek
5. How long did the Stanislaus County take to prepare this plan and how long did you give the landowners to prepare for this meeting

Thank you,

Paul R. Joslin

Broker Associate
DRE #02013143

Joslin Real Estate
12645 Bentley St.
Waterford Ca 95386

(209) 872-0026 cell

(209) 874-1801 office

January 15, 2022

Frederic Clark
Deputy Director
Stanislaus County Department of Public Works

Copy to: Buck Condit & Terry Withrow of the Stanislaus County Board of Supervisors
Representative Josh Harder

Re: Phase II Evaluation of Stormwater Management and Groundwater Recharge Projects in the Dry Creek Watershed of Stanislaus County

Dear Mr. Clark,

We are in receipt of your letter of December 29, 2021 in which information was provided regarding the potential impact of a dam construction project near our properties which adjoin the Dry Creek channel. Our properties are located near Site 15 which has been ranked 2nd highest in the Total Matrix Score per the Evaluation of Stormwater Management and Groundwater Recharge Projects in the Dry Creek Watershed of Stanislaus County. The construction of a dam at Site 15 would have extreme negative impact on our ability to protect our primary residences from erosion due to the dam, destroy an established and historical Valley Oak grove, and destroy a unique ecosystem and wildlife habitat.

Our residences lie above Dry Creek and the Valley Oak grove and many of us have spent monies, labor, and time fortifying our land and securing our residences against erosion with retaining walls using both artificial and natural resources. If the dam is constructed at Site 15, these efforts will not withstand the amount of water and flow artificially placed on Dry Creek. Expedited erosion would be unavoidable and our primary residences face destruction and crippling economic damages.

Our properties contain a historical grove of Valley Oaks many of which are over a hundred years old with diameters between 3 and 4 feet. These are treasured trees and a unique feature of this area of Dry Creek. These beautiful Valley Oaks cannot survive in standing water of the kind anticipated and planned by a dam at Site 15.

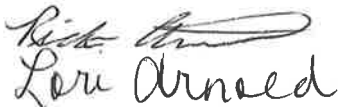
Further, the unique ecosystem and wildlife habitat that exists in this area of Dry Creek with the Valley Oak grove cannot be overstated. We have hawk pairs that have lived in the Oaks for years, blue herons that nest here, beavers that make their own dams, red and grey foxes, coyotes, and much more. Flooding their habitat will destroy their homes and the ecosystem that sustains them.

Your information indicates that impact on stakeholders is weighed more heavily than most other factors you consider when choosing a dam location. The negative impact on our properties cannot be overstated and the destruction of a historical Valley Oak grove and the ecosystem and wildlife it supports would be tragic. We respectfully request a different site for a dam be selected.

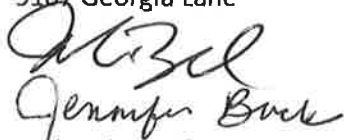
Sincerely,





John and Wendelin Warwick
9019 Georgia Lane



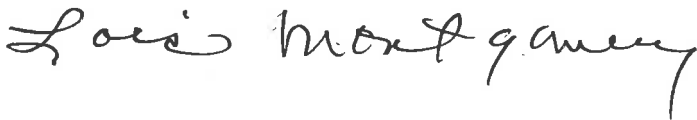
Rick and Lori Arnold
9107 Georgia Lane



Joel and Jennifer Buck
9107 Georgia Lane

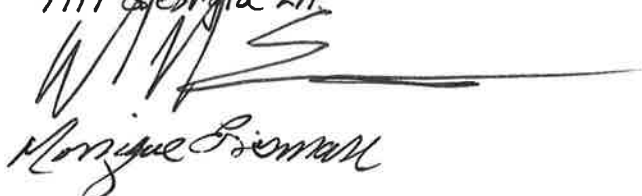
TOM & KAREN WEIMER
9161 CREEKSIDE LANE



9101 GEORGIA LN
MODESTO



Edward and Monique Erisman

9119 Georgia Ln.





Fw: Evaluation of Stormwater Management and Groundwater Recharge Projects in the Dry Creek Watershed.

Michael Brinton <brintonm@stancounty.com>

Mon, Jan 24, 2022 at 3:18 PM

To: Eric Johnson <depobook@gmail.com>

Cc: Frederic Clark <CLARKF@stancounty.com>, Dhyan Gilton <GILTOND@stancounty.com>, Mike Milczarek <mike@gsanalysis.com>, John Lambie <jlambie@e-purwater.com>

From: M. Trieweiler <cvelect@aol.com>

Sent: Sunday, January 23, 2022 5:53 PM

To: Michael Brinton <brintonm@stancounty.com>

Subject: Evaluation of Stormwater Management and Groundwater Recharge Projects in the Dry Creek Watershed.

***** WARNING:** This message originated from outside of Stanislaus County. **DO NOT** click links or open attachments unless you recognize the sender and know the content is safe *******

Hello, Mr. Brinton.

I attended the meeting of Jan 18 on the Criteria for evaluating and comparing potential stormwater management sites identified in the Phase I; Evaluation of Stormwater Management and Groundwater Recharge Projects in the Dry Creek Watershed and would like to submit the following comments:

I found it dishonest to refer to the Tuolumne River and Dry Creek flood of 1997 as a 25 year flood event, when in fact it was considered a 250 year flood event.

I discussed this issue with City of Modesto employee Mike Gilton and retired City of Modesto employee Frank Rataczak who were both in the middle of the crisis that occurred in this 1997 disaster. Mr Rataczak assured me the flooding that occurred in the low income housing district areas was the result of Tuolumne River water flows. Mr Rataczak said that after the flooding a lot of the low income housing in the Airport District's lowest areas was removed and not replaced.

My comment at the meeting was that the small amount of water that may of may not be recharged back into the aquifer depending on the site, would cost the taxpayers \$2,500 to \$4,000 per acrefoot. Today's average cost for an acrefoot of water in California is \$70, how can anyone justify \$2,500 or more for an acrefoot of water?

One thing I never found or got an explanation for was, what were the maintenance costs for and what was the period of time period these estimates were based on?

There seemed to be little or no support for any of the proposed sites from the farming community, and a great deal of opposition from most of the participants attending this meeting. This project would be bad for the taxpayers, bad for the farmers, bad for its environmental impact on the floodplain areas of the creek.

Milton Trieweiler

76 year old lifetime resident of Stanislaus County

Phone num. 209-535-1274

P.O. Box 2020

Turlock CA 95381-2020

|

JACK B. OWENS

ATTORNEY AT LAW

CA BAR #45723

JACKBOWENS@ATT.NET

OFFICE 209-602-3791
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P.O. Box 299
EMPIRE, CA 95319

Meneses family
615 North Hopper Road
Modesto, CA 95357

February 7, 2022

Stanislaus County Department of Public Works
1010 Tenth St., Suite 4200
Modesto, CA 95354

RE: Phase II Evaluation of Stormwater Management and Groundwater Recharge
Projects in the Dry Creek Watershed of Stanislaus County

Dear Mr. Brinton:

This letter is in response to the invitation extended to us at the meeting on January 18th, to submit comments regarding Phase II of the Dry Creek dam project.

At that meeting, and also in the written explanation of the project, we were told that the purpose of the proposed dam across Dry Creek is to address two major concerns:

- 1) Flooding
- 2) Groundwater recharge

Flooding: Looking at the FEMA maps, it appears that Dry Creek does not flood much even during 100-year floods. Nevertheless, it has been stated that water flows from Dry Creek can contribute to flooding if they occur at the same time that MID and TID release water from the Don Pedro Reservoir on the Tuolumne. MID and TID are currently considering plans to enlarge Don Pedro, are considering sites for secondary storage, and are also exploring the possibility of connecting with the New Melones Reservoir. These efforts will go much farther to mitigate flooding than would damming Dry Creek.

At the January 18 meeting, we heard concern expressed about the potential of flooding due to the planting of almond trees in the foothills where once grew grasses. If indeed flooding results from the removal of grasses, cover-cropping should be done beneath the trees.

The best solution for those living in areas that may be threatened by flooding is relocation to safer areas. Restoration of the flood plain would help with groundwater recharge.

Groundwater recharge: Most of the soils in the Dry Creek Watershed have low permeability. Percolation would be problematic. Also, as one individual said at the

January 18 meeting, Dry Creek now is often essentially tail water. Water quality is a serious consideration for any groundwater recharge project. Nutrient rich water would also encourage algae growth even if the water is held for only a short period. Sedimentation would be another problem for any dam on Dry Creek. All of these factors point to negligible benefit for aquifer recharge.

There were two main objections to a dam voiced at the January 18 meeting:

1). Damage to property, including productive farmland. No one wants to see good farmland damaged or taken out of production, or homes or barns damaged or destroyed.

2). Damage to the Creek itself, which is a migratory corridor for native species. If a dam is built, that migratory corridor would be broken. The creek would be destroyed at the dam site, resulting in the loss of habitat for wildlife. Wildlife would suffer and die. Ancient oak trees would be destroyed. The ecosystem would suffer and decline for many miles in each direction of the dam. Small dams are far more damaging to an ecosystem than are large dams. No one wants to see the destruction of Dry Creek.

At the January 18 meeting, county officials invited us to share ideas on how to recharge the aquifers. This is a very complex issue for which there is no easy solution. However, California Oaks, a division of California Wildlife Foundation, has pointed us to the potential of using the incised-valley fill (IVF), also known as a paleovalley, which lies beneath Modesto. This paleovalley has already been mapped (see pdf attached to letter from California Oaks) by Amy Lansdale Kephart, who in her thesis* shows that it could be useful for water storage. As stated in a recent article from Bay Nature magazine: “The Modesto paleo valley is about a half-mile to a mile wide and 100 feet deep near the mountains, shortening to 10 feet deep farther out. She [Amy Lansdale Kephart] tracked its length for 25 miles and found it could influence groundwater flow –attracting water into it or pushing water out of it—for more than 12 miles on either side of the valley and for hundreds of feet in depth.” (Bay Nature magazine, Winter 2022, “Capturing the Flood in California’s Ancient Underground Waterways” by Erica Gies, January 4, 2022)

Below is a link to the complete article, which describes the potential of using the paleovalleys, “the veins and arteries of the groundwater system”:

https://www.google.com/url?q=https%3A%2F%2Fbaynature.org%2Farticle%2Fcapturing-the-flood-in-californias-ancient-underground-waterways%2F%3Futm_source%3DBay%2BNature%26utm_campaign%3D21e9c47884-BN%2BNewsletter%2B01%252F06%252F2022%26utm_medium%3Demail%26utm_term%3D0_092a5caaa2-21e9c47884-199028791%26mc_cid%3D21e9c47884%26mc_eid%3Dddd4aab031&sa=D&sntz=1&usq=AFQjCNGnZAfMKvh0SSoEI_yHOXhgbUYWMQ

Professor Fogg, mentioned in the above article, is at UC Davis (gefogg@ucdavis.edu) and Professor Weissman, also mentioned in the article, is at the University of New Mexico (weissman@unm.edu).

Knowledge of the paleovalley may aid in the selection of land most suitable for flooding for aquifer recharge, and/or for selection of sites where injection wells (dry wells) would work best. Use might be made of the paleovalley in a project similar to Fresno's "Leaky Acres", which would both recharge the aquifers and mitigate flooding.

Dams may be a necessity in California in today's economy, but they are not a necessity —nor are they appropriate— on every creek and river. They must be located, as they generally have been, where they do the most good. Dams are not the answer to every water problem. Damming Dry Creek is not a real solution either to control flooding or for aquifer recharge, nor is it cost-effective. To dam Dry Creek is to destroy it needlessly.

While we see no benefit to be gained from damming Dry Creek, undeniably there would be terrible loss, destruction and great expense. This project should not go forward. Instead we should turn to better methods of flood control and aquifer recharge, methods that promise far more, will do far more, and will cost far less, both economically and environmentally.

Sincerely,

Rose Meneses

*Lansdale, Amy LeVan (2005) Influence of a Coarse-Grained Incised-Valley Fill on Groundwater Flow in Fluvial Fan Deposits, Stanislaus County, Modesto, California, USA. Unpublished Master of Science thesis. Department of Geological Sciences, Michigan State University.

Mr. Michael Brinton, PE Project Manager
Stanislaus County Public Works
1010 Tenth St, Suite 4200
Modesto, Ca 95354

2-12-2022

Dear Mr. Brinton:

Re: Phase II Evaluation of Stormwater Management and Groundwater Recharge Projects in the Dry Creek Watershed

I appreciate Stanislaus County ("County") conducting an open-house on the above mentioned project and submit these comments in addition to my participation at this workshop and in other venues including lengthy discussions with the project engineers and others involved in the project. While I fully support the County managing and harnessing our water resources to ensure local needs such as, farming, drinking water, environmental, flood protection and groundwater management are met, it is clear this project, as currently proposed does not achieve these objectives and will have very little true benefit as it is currently designed. As such, I urge the County to reconsider the use of the available grant funds. Grant funds will be best used on regional, coordinated GSP projects that achieve the objectives of the Sustainable Groundwater Management Act ("SGMA") in coordination with the Stanislaus and Tuolumne Rivers Groundwater Basin Association Groundwater Sustainability Agency, of which the County is a member.

At the meeting, County staff indicated the project would collect flood waters off of Dry Creek and use them for groundwater recharge. However, the presenters also acknowledged they did not know how much groundwater recharge would be achieved as those details had not been worked out yet. Further after lengthy discussions with the project engineers, they have acknowledged that groundwater recharge through percolation would be minimal in the area and that Modesto Irrigation District ("MID") and Turlock Irrigation District ("TID") already do a good job mitigating the Dry Creek flood flows with their management of the Don Pedro releases.

As such, as currently drafted, this project does not appear to be necessary at this time, and the grant funds could be better used studying and implementing a coordinated regional approach guided by the recently finalized SGMA GSP plan for our watershed.

Most recently, MID and TID have filed a junior water rights application that included the Dry Creek flows with the State Water Resources Control Board. This pending MID and TID application will render the project unnecessary or unable to be undertaken by the County.

Notably, and as acknowledged at the workshop, MID and TID already monitor the Dry Creek flows and manage water releases from Don Pedro to minimize flood flow impacts from Dry Creek. MID, TID and OID should be the lead agencies on any SGMA PSP projects that include Dry Creek. Additionally, it does not seem wise for the County to continue pursuing this project as it is presently proposed without MID and TID given their pending water rights application.

In my opinion, the County's most prudent course at this time would be to use the grant funding to enact a coordinated regional project that is guided by the recently finalized SGMA GSP plans and is designed to maximize groundwater recharge which was designed with the full input of the affected landowners and community at the earliest planning stages of the project.

I believe the highest and best use of the Dry Creek flood flows would be to build a Dry Creek Dam for Stormwater Storage and agricultural in-lieu recharge as outlined in the pending MID and TID application.

If there is to be a substantial Dry Creek Dam for long term water storage it should be on undeveloped rangeland immediately east of the Crabtree Rd Dry Creek Bridge as described in the recent MID TID water rights application. This dam should be used for stormwater storage that can be used for in-lieu recharge for irrigation purposes similar in concept to MID's in-lieu recharge program that was first utilized following the very wet 2017 water year.

The flood waters would be collected and held behind the dam, providing further mitigation for the high flows experienced during storm events, and stored. That water can then be released to farmers for in-lieu recharge for irrigation purposes instead of using deep wells. Such a project should be designed to ensure it helps achieve the goals and objectives of the recently finalized SGMA GSP plans .

Thank you for the opportunity to submit positive input on this project.

Louis F Brichetto
PO Box 548
Oakdale Ca. 95361
mbl 209-985-8543



E-Mail, BrichettoLouis@msn.com

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Michael Brinton, PE Project Manager
Stanislaus County Public Works
1010 Tenth Street, Suite 4200
Modesto, CA 95354

February 17, 2022

Re: Comments on the January 18, 2022 meeting – Phase II of Stormwater Management and Groundwater Recharge Projects in the Dry Creek Watershed of Stanislaus County

Dear Mr. Brinton,

We have done a cursory look at the materials that were sent to us as property holders along Cry Creek and can see that much work had been done on this study. It was unfortunate that you and your team were not given respect from your audience to relay your findings to the attendees. We have many questions and these are some of them; how a decision on placement site will ultimately be made, how and by what entity operation of the site would be handled, how would this be funded and is the cost justified by the benefit, what will be the consequences to the native Quercus trees and wildlife that thrive along the creek, how and when will there be collaboration with the irrigation districts.

Our personal opinion is based on these points:

1. Water is most important issue we face, so this project has merit.
2. Most of the proposed sites would destroy existing farm land when constructed or potentially inundate private property with water during a flooding event.

Consequently, we think that alternative study/plans are warranted. An actual storage dam further up Dry Creek in a less developed area and where there are more natural basins could address not only storm flooding, but also be a source for agricultural irrigation water that is presently being pumped from the groundwater that this project hopes to recharge.

Thank you for asking for input and giving us this opportunity to give it.

Sincerely,



Rod and Melanie Walker
P. O. Box 118
12019 Lone Oak Road
Waterford, CA 95386
(209) 531-6593



California Wildlife Foundation/California Oaks, 201 University Avenue, H-43 Berkeley, CA 94710, (510) 763-0282

January 18, 2022

Michael Brinton, PE
Stanislaus County Public Works
1010 Tenth St, Suite 4200
Modesto, CA 95354

RE: Technical Memorandum 1 – Phase II Dry Creek Watershed Stormwater Management and Groundwater Recharge Multiple Account Analysis Results (12/13/21)

Transmitted via email: brintonm@stancounty.com

Dear Mr. Brinton:

The California Oaks program of California Wildlife Foundation works to conserve oak ecosystems because of their critical role in sequestering carbon, maintaining healthy watersheds, providing native plant and animal habitat, and sustaining cultural values. We are writing at the request of Rose Meneses, a property owner whose home overlooks Dry Creek. She is concerned about potential impacts to riparian habitat, including oaks, posed by the proposed project.

Oaks provide vital plant and animal habitat that supports California's biodiversity, providing food and shelter for many of California's native species, including 2,000 plants, 5,000 insects and arachnids, 80 amphibians and reptiles, 160 birds, and 80 mammals.¹ Oaks also sequester carbon, which is released into the atmosphere when they are removed. The *Oaks 2040—An Inventory of Carbon and California Oaks* report, published in 2006, estimated 675 million metric tons of carbon dioxide stored in oak trees as well as the understory in woodlands and forested lands.²

The authors of “Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits” address the importance of keeping trees standing:³

Intact, old-growth forest is a major long-term carbon sink due to its complex structure, large trees, accumulating soils and relative resilience to fire and drought (Luyssaert et al., 2008; Maxwell et al., 2019). The IPCC acknowledges that ‘*most [destroyed] forest ecosystems will take longer than 100 years to return to the level of biomass, soil and litter pools [found in forest in an] undisturbed state*’ (Aalde et al., 2006). Recovery of ecosystem services and biodiversity may take centuries, especially the return of rare or endemic species, which are particularly

¹ Meadows, R. 2007. “Oaks: Research and outreach to prevent oak woodland loss.” *California Agriculture* 61(1):7–10.

² Gaman, T. *An Inventory of Carbon and California Oaks*. California Oak Foundation, 2008.
<https://californiaoaks.org/wp-content/uploads/2016/04/CarbonResourcesFinal.pdf>

³ Di Sacco A et al., “Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits.” *Glob Change Biol.* 2021;00:1–21. <https://onlinelibrary.wiley.com/doi/10.1111/gcb.15498>

vulnerable to disturbance (Gibson et al., 2011; Rey Benayas et al., 2009). Extinct species, of course, will never return...

Intact, old-growth forest is of the greatest value for carbon storage (Maxwell et al., 2019) and wildlife (Deere et al., 2020) and should be prioritized for protection.

Mitigating impacts to oaks: Oak protection is required by Stanislaus County's General Plan. Policy Four of the Conservation/Open Space Element is to *Protect and enhance oak woodlands and other native hardwood habitat.*

Implementation measure 1 is:

1. *Require all discretionary projects that will potentially impact oak woodlands and other native hardwood habitat, including but not limited to hardwood rangelands... to include a management plan for the protection and enhancement of oak woodlands and other native hardwood habitat.*

If oaks are removed to advance the project California law requires the greenhouse gas (GHG) impacts of proposed oak removals to be assessed. California Environmental Quality Act's (CEQA) sole GHG focus is "the mitigation of greenhouse gas emissions or the effects of greenhouse gas emissions." Net present value of GHG emissions forms the foundation of the state's greenhouse reduction objectives, as well as the California Forest Protocol preservation standards. Every ton of carbon dioxide (CO₂) released into the atmosphere by oak woodland or forest conversion represents a measurable potential adverse environmental effect, which is covered by CEQA. Thus, California requires the analysis and mitigation of greenhouse gas emissions associated with proposed oak woodland or forest conversions.

Further, if an oak management plan is developed as mitigation for oak removals and oak seedlings or saplings are installed then proper site assessment and careful selection of trees and plants are essential to achieve success. Maintenance until trees and plants are established is vital, including with protective caging, fencing, and monitoring. California law requires a seven-year establishment period.⁴ The availability of sufficient resources is essential to allow for professional restoration design, the selection of suitable plant material, sufficient irrigation and weeding, and ongoing monitoring of site conditions.

Many oak mitigation projects throughout California have failed, in large part due to the lack of investment in needed resources over the necessary period of time to ensure success.

Aligning with California Department of Water Resources conservation goals: Department of Water Resources' conservation strategy for the 2018 update of its *Central Valley Flood Protection Plan* is built on the principles of achieving net systemwide improvements to riverine and floodplain ecosystems; increases in flood system flexibility and ecosystem resiliency; prioritization of investments in multi-benefit flood-risk reduction projects that incorporate ecosystem improvements; and coordination and collaboration with land management agencies

⁴ Public Resources Code Section 21083.4 applies to mitigation for the removal of oaks that are not commercial species, which are five inches or more in diameter as measured at a point 4.5 feet (breast height) above natural grade level. One of the authorized mitigation measures is the replacement or restoration of former oak woodlands. The establishment period is seven years.

and existing conservation efforts.⁵

In this vein, we attach two maps and an aerial photograph from *Influence of a coarse-grained incised-valley fill on groundwater flow in fluvial fan deposits, Stanislaus County, Modesto, California, USA*. We also include a copy of the full study. The maps and photograph depict a relatively coarse-grained incised valley-fill (IVF) beneath the city of Modesto. The primary purpose of the study was to understand the impact IVFs have on regional groundwater flow, contaminant transport, and the potential for artificial aquifer recharge in the Tuolumne River fluvial fan aquifer around Modesto, California. The Winter 2022 issue of *Bay Nature* includes an article about IVFs and their potential for flood protection.⁶

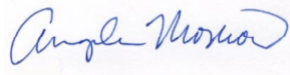
We bring this to your attention should the findings be helpful for less environmentally-impactful flood and/or groundwater planning for this or other proximate projects.

Thank you for your consideration of our comments.

Sincerely,



Janet Cobb
Executive Officer
California Wildlife Foundation
jcobb@californiawildlifefoundation.org



Angela Moskow
Manager
California Oaks Coalition
amoskow@californiaoaks.org

Encls. Two maps and an aerial photograph that depict a relatively coarse-grained incised valley-fill beneath the city of Modesto

Influence of a coarse-grained incised-valley fill on groundwater flow in fluvial fan deposits, Stanislaus County, Modesto, California, USA

⁵ Department of Water Resources, Central Valley Flood Protection Plan Conservation Strategy, November 2017, p 3-1.

⁶ See: https://baynature.org/article/capturing-the-flood-in-californias-ancient-underground-waterways/?utm_source=Bay+Nature&utm_campaign=21e9c47884-BN+Newsletter+01%2F06%2F2022&utm_medium=email&utm_term=0_092a5caaa2-21e9c47884-199028791&mc_cid=21e9c47884&mc_eid=ddd4aab031

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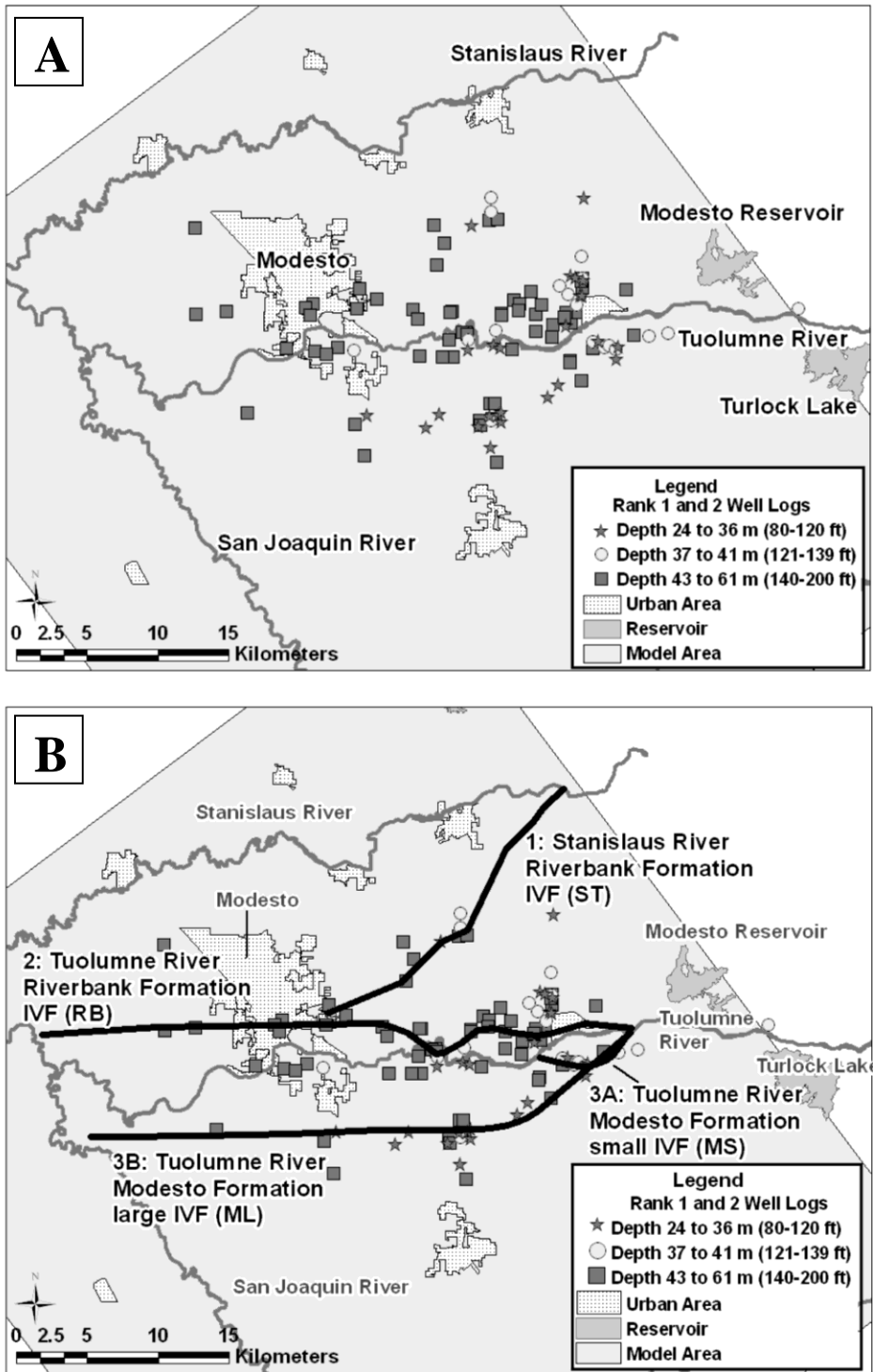
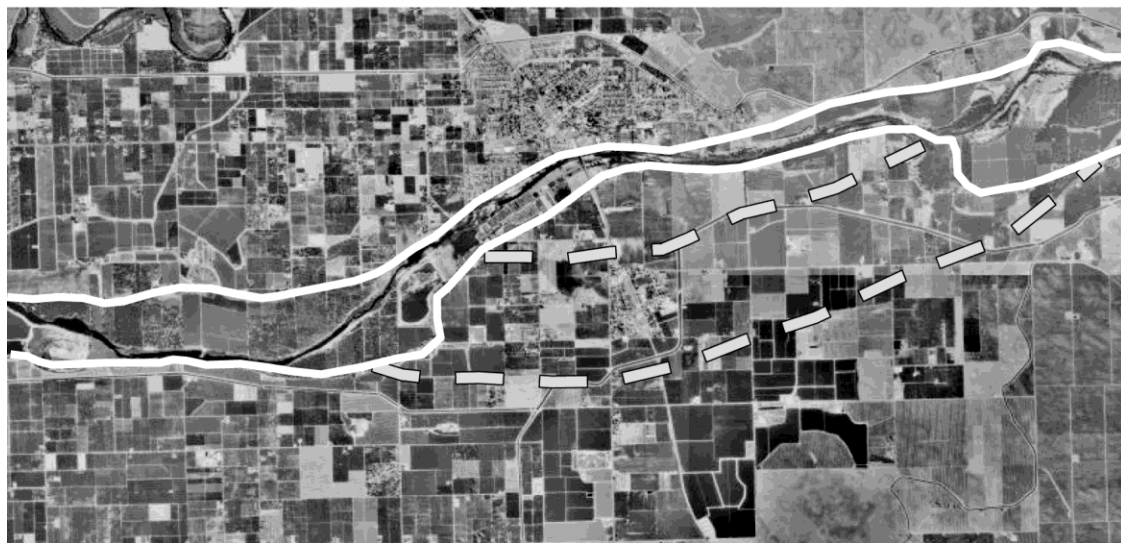


Figure 7: Aerial photograph showing the potential location of the Modesto small IVF loop (outlined by the light gray dashed line). The solid white line represents the current river valley.

USGS 4 km S of Waterford, California, United States 16 August



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INFLUENCE OF A COARSE-GRAINED INCISED-VALLEY FILL ON
GROUNDWATER FLOW IN FLUVIAL FAN DEPOSITS, STANISLAUS COUNTY,
MODESTO, CALIFORNIA, USA

By

Amy LeVan Lansdale

A THESIS

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ABSTRACT

INFLUENCE OF A COARSE-GRAINED INCISED-VALLEY FILL ON GROUNDWATER FLOW IN FLUVIAL FAN DEPOSITS, STANISLAUS COUNTY, MODESTO, CALIFORNIA, USA

By

Amy LeVan Lansdale

A relatively coarse grained incised-valley fill (IVF) was identified beneath the city of Modesto, California using geophysical logs. The Tuolumne River fluvial fan IVFs are the result of periods of degradation followed by rapid aggradation due to cycles of Quaternary climate change. These IVFs were located through the use of driller's well logs. Results indicate that the location of the relatively coarse grained IVF can be reasonably approximated by identifying the basal gravel unit of the IVF in the driller's well logs. From the well log analysis and the use of topographic maps, the wedge shaped IVFs are approximately 0.7 to 1.6 km wide and approximately 3 to 30 meters thick with a 5 to 9 meter gravel base that thins down fan. The influence of these IVFs on the regional groundwater flow was tested using a steady-state saturated groundwater model adapted from a USGS model (S. Phillips, unpublished model, 2005). Groundwater flow and contaminant transport models with and without the IVF deposits of the Tuolumne River show IVFs significantly influence groundwater flow and contaminant transport. Specifically, results indicate that the Tuolumne River IVFs provide potential for (1) increased groundwater production rates (2) rapid contaminant transport within the IVF sediments and (3) rapid contaminant movement from the IVF into the contiguous aquifer sediments. The presence of an IVF beneath the city of Modesto, in particular, may have implications for artificial aquifer recharge and regional water quality.

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Chapter 1: Introduction and Scope of the Study

INTRODUCTION

Modeling in heterogeneous fluvial aquifers can be a very difficult venture. Heterogeneities often exist at various scales within aquifer sediments and have the potential to largely impact or entirely control the direction and velocity of groundwater flow and contaminant movement.

Without detailed field investigations of the spatial distribution of hydraulic conductivity (K), aquifer heterogeneity is significantly more difficult to replicate in groundwater models. For this reason, many studies have begun to employ more qualitative information into approaches that generate K distributions in fluvial aquifer deposits, utilizing known geologic relationships to develop aquifer conductivity fields (e.g. Fogg, 1986; Schiebe and Freyberg, 1995; Webb and Anderson, 1996; Weissmann *et al*, 2004). These studies highlight the importance of preserving the influence of geologic structure in modeling groundwater flow and contaminant transport.

Maintaining the geologic structure within a fluvially deposited aquifer becomes particularly important in scenarios where the contrast between the hydraulic conductivities of the aquifer deposits is high (Webb and Anderson, 1996). Results from Webb and Anderson (1996) showed that in these types of settings, the geologic structure that coincides with the hydraulic conductivity (in their study the braided channel forms) can control regional groundwater flow and particle movement.

In this study, I will examine a similar scenario to determine the influence of a relatively coarse grained incised valley fill (IVF) on groundwater flow in the Modesto area in California. Within the study area, there is a lack of detailed field data on aquifer heterogeneity, but the geological framework is reasonably well understood (Janda, 1966;

Marchand, 1977; Huntington, 1980; Marchand and Allwardt, 1981, Lettis, 1988; Burow *et al.*, 2004; Weissmann *et al.*, 2006). Despite the deficiency in detailed aquifer data, we were successfully able to adapt a pre-existing groundwater model to incorporate the geologically-based, geometrical relationship of the relatively coarse-grained IVF. The IVF is added using techniques which preserve the valley geometry and the internal stratigraphy to assess the influence of this discrete geologic structure on the regional groundwater flow and contaminant transport.

PURPOSE OF STUDY

The main purpose of this study is to understand the impact IVF deposits in the Tuolumne River fluvial fan aquifer around Modesto, California, can have on regional groundwater flow, contaminant transport, and artificial aquifer recharge. This was accomplished by (1) assessing the stratigraphic character of the study area with well logs and core, (2) constructing model domains that capture this stratigraphic character, and (3) simulating groundwater flows and solute tracers through these models to evaluate the influence IVFs have on groundwater and contaminant transport. This work provides the foundation for future studies that will better define and model the IVF.

This study area along the Tuolumne River was chosen because geophysical well logs revealed the presence of a relatively coarse grained IVF deposit within Tuolumne River fluvial fan deposits directly beneath the city of Modesto, California (Burow *et al.*, 2004). Groundwater flow and contaminant transport models in previous studies of similar IVF deposits of the Kings River near Fresno, California, showed that IVFs significantly influence groundwater flow and contaminant transport (Weissmann *et al.*, 2004). Specifically, results indicated that the Kings River IVF provides potential for (1)

increased groundwater flow and production rates (2) rapid contaminant transport within the IVF sediments and (3) rapid contaminant movement from the IVF into the contiguous aquifer sediments. If the identified IVF beneath the Modesto area has a similar effect, then it may have implications for artificial aquifer recharge and regional water quality in that area.

Current models of the hydrogeology in the Modesto, California, area are being developed by the USGS. The main source of model inputs is previously collected data (driller's logs, geophysical logs, and a few continuous cores) which are used to characterize the hydrogeology of the Modesto area (*Burow et al., 2004*) and create a regional scale model of the geology (*Burow et al., 2004*) and groundwater flow (S. Phillips, unpublished model, 2005). While the model that has been developed is a reasonable representation of the region's geology and hydrologic regime, it does not implicitly include the IVFs. The USGS model may be largely improved with the additional application of sequence stratigraphic concepts, described by Weissmann *et al.* (2002b, 2006), to depict and include IVF geometry and character into the groundwater flow model. An understanding of sequence stratigraphy in the area can aid in more accurately modeling the geology to illustrate various hydrofacies and their influence on the groundwater flow.

The model developed for this study utilizes an understanding of the area's sequence stratigraphy to develop multiple conceptual models to test the influence of IVFs. Using the same data the USGS used to develop models of the Modesto area, four geologic realizations of various combinations of IVF locations were developed for this study. A comparison among groundwater models of these realizations and the recently

developed USGS groundwater model will improve the current understanding of regional groundwater and contaminant transport trends in the Modesto area.

THESIS OUTLINE

This thesis is divided into three main sections with subsequent appendices:

1. The first section, chapter 2, discusses the development and results of the Modesto area groundwater model and flow and transport simulations. I plan to submit this chapter for publication.
2. The final section of this thesis, chapter 3, is the conclusion where I describe major results of this work and suggest ideas for future work.
3. Subsequent appendices that support this work include:
 - a. Appendix A: Delineating the IVF and study area geology
 - b. Appendix B: Unconsolidated Sediment Core Description
 - c. Appendix C: Driller's logs
 - d. Appendix D: Sequence Boundary Surface Generation
 - e. Appendix E: Opening USGS MODFLOW Model In GMS
 - f. Appendix F: Adapted Model Generation
 - g. Appendix G: IVF Fortran Code
 - h. Appendix H: Vertical Hydraulic Conductivity and Anisotropy Ratio Fortran Code
 - i. Appendix I: General Head Boundary Fortran Code
 - j. Appendix J: Well Fortran Code

Chapter 2: Influence of a Coarse-Grained Incised-Valley Fill on Groundwater Flow in Fluvial Fan Deposits, Stanislaus County, Modesto, California, USA

INTRODUCTION

A relatively coarse grained incised-valley fill (IVF) deposit was identified in geophysical well logs beneath the city of Modesto, California (Burow *et al.*, 2004). A recent investigation by Weissmann *et al.* (2004), showed the impact of a similar IVF in the King's River area. To gain insight to the potential impact the IVF can have on regional groundwater flow and contaminant transport in the Modesto area, an investigation of the subsurface geometry, position, and hydrogeologic significance of the valley fill was conducted. Recommendations based on this research are made for further, higher resolution studies. The investigation includes : (1) development of multiple geologic realizations which test different potential locations of the IVF, (2) production of a corresponding number of flow and transport groundwater models, (3) particle pathline analyses that examine the potential for artificial recharge in the IVF, and (4) recommendations for further investigation in the area.

To test the impact of the IVFs on the regional groundwater flow and illustrate the importance of understanding and using sequence stratigraphic concepts at this site, this chapter reports on comparisons of realizations that include various scenarios of IVF locations, as described in Appendix A, with an adaptation of a model generated by the USGS that does not implicitly include the IVF deposits (Burow *et al.*, 2004; S. Phillips, pers. comm., 2005). In this chapter, the development of the USGS groundwater flow model, the modifications made to the model (inclusive of the addition of the IVFs), and various simulations of solute transport are described.

STUDY AREA

Regional and Local Geology

The San Joaquin Basin is located within the California's Great Valley, an approximately 700 km long (north to south) by 100 km wide (east to west) valley that is bound on the east by the Sierra Nevada and on the west by the Coast Ranges. The valley is divided into two sub-basins by the Stockton Arch, a buried transverse arch, with the Sacramento Basin in the north and San Joaquin Basin in the south. The basin is underlain by crystalline basement rock and approximately 9 km of Mesozoic and Cenozoic sedimentary rocks and sediments (Bartow, 1988). Structurally, the basin is asymmetric with a gently sloping eastern margin that abuts the Sierra Nevada, and the more steeply sloping western edge adjacent to the Coast Ranges. This study focuses on the Tuolumne River fan located in the northeast portion of the San Joaquin Basin (Figure 1 *NOTE: Some of the figures included in this thesis are presented in color.*). The fan was formed where the Tuolumne River flows west out of the Sierra Nevada into the San Joaquin Basin.

Quaternary fluvial fan deposits from numerous rivers along the eastern San Joaquin Valley, including the Tuolumne River fan, preserve evidence of past phases of aggradation and degradation from varying amounts of sediment supply and discharge in response to recurring glacial periods in the Sierra Nevada (Janda, 1966; Marchand, 1977; Huntington, 1980; Marchand and Allwardt, 1981, Lettis, 1988; Weissmann *et al.* 2002b, 2006). Fluvial fans are differentiated from alluvial fans in this study to emphasize that fluvial fans are characterized by perennial fluvial processes, while alluvial fans are characterized more by ephemeral debris flows or sheetfloods.

To understand the climatically induced cycles of deposition in the fluvial fans, Weissmann *et al.* (2002b) investigated the fluvial fan deposits on the Kings River fan and applied a sequence stratigraphic model. This sequence stratigraphic model describes changes in *accumulation space* and *preservation space* (after Blum and Törnqvist, 2000) that resulted in the cyclic deposits in the area. Accumulation space is defined as one component of accommodation space and refers to the volume of space available to be filled with sediment on a process-scale. It is dependent on the balance of sediment supply and stream discharge as well as channel geometry. Preservation space is also a component of accommodation space, and, in this case, is a more long-term, net accommodation and is controlled by the subsidence rate. It is the space below the lowest level of sediment removal.

On the Kings River fan, packages of relatively rapidly deposited fluvial fan deposits, or open fan deposits, separated by paleosols indicate periods of aggradation across the fan, or increased accumulation space, punctuated by periods of degradation and fan incision, or restricted accumulation space and quiescence on the upper parts of the fan. Preservation space was created by constant subsidence in the area, which lowered the deposits below the lowest level of erosion. Sequence boundaries in this model are identified as the paleosol surface and respective IVF base that divide the fluvial fan deposits into five stratigraphic units.

The five sequences mark distinct periods of regional aggradation and degradation. Specifically, fluvial fan aggradation or degradation on the Kings River fan occurred as sediment supply to discharge ratios increased or decreased with changes from glacial to interglacial climate. Interglacial periods are marked by limited aggradation, a low accumulation space, and an intersection point located distally on the fan (Figure 2)

(Weissmann *et al.*, 2002b). This portion of the cycle is when deposition occurred only at the distal end of the fan allowing paleosols to form in the exposed upper fan outside the incised valleys. Glacial periods are characterized by a large amount of laterally extensive aggradation on the fan, a high accumulation space, and an intersection point proximally located to the apex of the fan. Weissmann *et al.* (2002b) suggested that this sequence stratigraphic model can assist in the prediction of facies distributions and stratigraphic relationships in areas exposed to similar conditions.

Due to the similar cyclic depositional character among the fans in the eastern San Joaquin Basin, the sequence stratigraphic model described in the Kings River fan study can be applied to other fans in the basin (Weissmann *et al.*, 2006). However climate and sediment supply to stream discharge ratios are only two of the controls on the deposition of the fluvial fans in the valley (Weissmann *et al.*, 2006). Factors that control the overall amount of accumulation space available during periods of climate fluctuation and hence sequence geometry development are: (1) the sediment supply to stream discharge ratio, (2) the rate of basin subsidence, (3) the amount of local base level change, and (4) the basin width (Weissmann, *et al.*, 2006). These controls vary within the San Joaquin Basin and influence the sequence geometry on individual fans.

Controls on the Tuolumne River sequence geometry in particular are (1) glacial influence in the drainage basin (2) relatively low subsidence rates (approximately 30cm/1000 yrs, Lettis, 1988) due to the river's location in the northern portion of the San Joaquin Valley, and (3) the San Joaquin River local base level control on Tuolumne River elevation (Weissmann *et al.*, 2006). The Tuolumne River drainage basin in the Sierra Nevada was glaciated during the Quaternary, which resulted in cycles of significant fluctuations in the sediment supply and stream discharge. Because the

Tuolumne River is in the north, where the valley is narrower and subsidence rate is relatively low, sequence thickness and lateral extent were thinner and smaller than observed in southern portions of the valley. This resulted in an overall reduction in accumulation and preservation space, which caused the lateral progression of apexes and the thinner fluvial fan units deposited along the Tuolumne River than were seen along the Kings River (Weissmann *et al.* 2006; Bennett *et al. in press*) (Figure 2). The local base level is connected to the San Joaquin River and ultimately sea level. This resulted in deeper incision and sediment bypass in the distal portions the fan during interglacial periods, also reducing the overall amount of accommodation space available to be filled.

The area within the scope of this study is delineated by the Sierra Nevada and the San Joaquin River to the east and west, respectively, and by the Stanislaus and Merced Rivers to the north and south (Figure 3). The study area is approximately 48 km (30 miles) long (west to east) and 19 km (12 miles) wide (north to south). Dissecting the site is the Tuolumne River, which flows east to west through the middle of the study area (Figure 3). Deposits at the site are composed mainly of Cenozoic sedimentary deposits (Marchand and Allwardt, 1981). These thick, slightly westward dipping fluvial fan deposits along the Tuolumne River decrease in age to the west, toward the San Joaquin Basin center (Figure 1). Uplift and erosion have exposed older fan units in the eastern portion of the basin. This study of the Modesto area will focus on the Quaternary Pleistocene fluvial deposits: the Turlock Lake Formation, the Riverbank Formation and the Modesto Formation. A more comprehensive description of the older units in the area can be found in Marchand and Allwardt (1981).

GENERATING GEOLOGIC REALIZATIONS TO BE MODELED

Each stratigraphic unit of open-fan deposits is bound at the top and bottom by a paleosol and is composed of silty, sandy, and clayey sediments with discrete coarser-grained channel deposits (Figure 4). Nestled among the relatively fine-grained open-fan sediments are the relatively coarse-grained IVFs, characterized by a thick basal gravel lag (5 to 9 meters) that gradually fines up to the surface (Figure 5).

Characterization of hydrofacies within the fluvial fan deposits was done by using methods similar to those described in Weissmann *et al.* (2002b) where we utilized several sources of geologic data, including driller's well logs, geophysical logs, and lithology from continuous core samples. Cooperation with the U.S. Geological Survey (USGS) in Sacramento, California afforded access to several thousand paper copies of the Department of Water Resources (DWR) driller's logs within the study area, geophysical well logs from city wells, and recently obtained, relatively-continuous, soft sediment core. Also available from the USGS were digitized spatial data of the area hydrology, geology, soils, topography, and approximate pumping rates of the city of Modesto municipal wells (S. Phillips, unpublished data, 2005).

Multiple geologic scenarios were created using two soft sediment cores (a total of 155 meters (509 ft) of core—Appendix B) and lithologic descriptions from approximately 10,000 driller's well logs. The lithology from the soft sediment core samples was used to better understand the overall character of the fluvial fan deposits, and the driller's well logs were used to identify the IVF in the area.

Open Fan Deposit Character

Continuous core samples collected by the USGS from two well locations were assessed: one located in a proximal fan position and the other on a distal portion of the

fan (Figure 3). The proximal well, MREA, was drilled to a depth of 96 m (315 ft) and the distal well, MRWA, was drilled to a depth of 59 m (195 ft).

Hydrofacies observed in these cores include: (1) gravel channel deposits (not recovered in these cores but observed in drillers' logs and described by Weissmann *et al.*, 2002b) (2) sand channel deposits (3) silty sands, silty clays, and clay overbank deposits, and (4) pedogenically altered deposits. The core descriptions show that the western extent of the study area contained more fine-grained sediments of the distal fluvial fan deposits, while the eastern extent of the study area contained the more coarse-grained proximal fluvial fan sediments. More detailed descriptions of these hydrofacies are in Appendix A.

Incised-Valley Fill Geometry

Through the interpretation of approximately 10,000 drillers' well logs and geophysical well logs, we were able to locate the originally identified IVF along with several other plausible additional valley fills. Further analysis of the location and depth of the IVFs was completed by mapping selected well logs in ArcMap.

The well logs that note gravels of sufficient thickness (> 3 meters) were assigned a rank of 1 to 4 in 0.5 increments based on how accurately the log's description of the stratigraphy resembled the fining-upward prototype characterization of the IVF, as observed in the geophysical well logs by Burow *et al.* (2004) and described for the Kings River fluvial fan by Weissmann *et al.* (2002b) (See Appendix C). A well assigned a rank of 1 denotes the best representation of the IVF, with a thick gravel base fining upward to sand then silt and clay, while a well ranked 4 contains thick gravel but does not resemble the ideal fining-upward succession contained within the IVF deposits. The drilling

method and the consistent quality of individual drillers were also used to determine the rank of the well.

The geometry of the IVF was approximated through the analysis of well logs and assessment of the modern Tuolumne River valley geomorphic configuration in topographic maps, which is assumed analogous to the interglacial character of the paleovalleys to be modeled. The IVF is estimated to (1) be 0.7 to 1.6 kilometers wide, (2) range from approximately 30 meters thick at the apex of the fan to approximately 3 meters thick at the toe of the fan, giving it a wedge-shaped appearance, and (3) have a 5 to 9-meter-thick gravel base near the fan apex that thins down fan (Figure 5).

Using the database of well logs, a map of the various ranked wells was created within ArcGIS. Because each plotted well does not represent the IVF, a subsequent map exclusively of the highest ranked wells, 1 through 2, was generated to emphasize any elongate channel patterns (Figure 6A). General trends indicate presence of (1) a paleovalley trending northwest from beneath the city of Modesto in the west side of the site, (2) a paleovalley trending just north of and paralleling the current Tuolumne River, (3a) a shallow paleovalley as a short meander loop in the eastern portion of the site, and (3b) a shallow paleovalley trending to the southwest, also in the eastern extent of the study area.

Further analysis to determine which geologic formation these valleys correlate to was conducted by looking at the basal gravel depths (Figure 6B). The gravel depths were mapped in intervals of the expected depths of the IVF base. A 6 m (~20 ft) resolution was allotted for possible error or variation in accuracy among drillers. A depth of 24 to 38 m (80 to 125 ft) was expected for the Modesto Formation IVF basal gravel, and a depth of 43 to 61 m (~140 to 200 ft) was expected for the Riverbank Formation IVF basal gravel

depth. From this map, the previously identified four IVF trends are still prevalent; however four valleys can be segregated. The possible valleys interpreted to exist from this map are: (1) a Riverbank Formation IVF from the Stanislaus River to the north that may trend beneath the city of Modesto, (2) a Riverbank Formation IVF from the Tuolumne River that appears to be clearly marked adjacent to the current river valley and may potentially cross the modern river valley in the eastern reach of the river, and (3) the two potential positions for the Modesto Formation IVF—(A) a small loop adjacent to the modern Tuolumne River in the eastern reach of the river (identified in an aerial photo of the current surface—See Figure 7) and (B) a southwestern trending IVF projecting from the same location as position A. These trends are reemphasized when slightly lower ranked wells (rank 2.5) were added to the map.

Because significant uncertainty exists as to whether these trends are real, this study focuses on addressing multiple conceptual scenarios of valley fill orientation and geometries. Initial interpretations of the various locations for the Modesto IVF (positions A and B) and the potential Stanislaus River IVF influence from the north provide a foundation for the following four geologic scenarios that test the combinations of these channel positions. The resulting four realizations are summarized in Table 1, and include: (a) Riverbank IVF from Tuolumne River and the Modesto IVF A, or the small loop adjacent to the modern Tuolumne River(RB/MS), (b) Riverbank IVF from Tuolumne River and the Modesto IVF B the large IVF that projects southwest from the apex (RB/ML) (c) Riverbank IVF from the Stanislaus River and the Tuolumne River and the Modesto IVF A the small loop (RB/ST/MS) and (d) Riverbank IVF from the Stanislaus River and the Tuolumne River and the Modesto IVF B (RB/ST/ML).

GROUNDWATER MODEL DEVELOPMENT

Steady-state groundwater and transport models were produced using Groundwater Modeling System 5.1 (GMS 5.1) and were modified from a MODFLOW 2000 model developed by the US Geological Survey (S. Phillips, unpublished model, 2005, Burow *et al*, 2004). The Stanislaus, Merced, and San Joaquin Rivers provide relatively natural hydrologic boundaries on the north, south and west sides of the model domain, respectively. The Sierra Nevada is approximated as a no-flow boundary to the east. The steady-state model includes the influence of pumping in the city of Modesto and is calibrated to match measured water levels in the region. Along with the groundwater flow and contaminant transport models of the multiple geologic realizations, simulations testing the artificial recharge potential of the IVF scenarios were also assessed. Based on the results of the flow and transport models and the artificial recharge model, recommendations are made on where future more comprehensive investigations should be conducted. Methods for generating numerical models of these realizations are described below.

USGS Model

The framework for the model used in this study of the influence of the IVF was generated by the USGS (S. Phillips, unpublished model, 2005). The finite difference steady-state model (produced in MODFLOW) was constructed based on the hydrogeologic characterization of the Modesto area described in Burow *et al*. (2004). Included in the report by Burow *et al*. (2004) is a description of how the model area geology was characterized using existing data and how the area water budget was

calculated using information about water deliveries, pumping, and recharge within several subwatersheds.

A coarse-fine geologic model was produced by Burow *et al.* (2004) using geophysical logs and lithologic descriptions from driller’s well logs to develop representative percent coarse sediment fractions (F_{coarse}) for the model area (F_{fine} was subsequently calculated as the remaining percent). To determine F_{coarse} , a binary texture classification of “coarse grained” or “fine grained” was used to assign either 100 or 0 percent coarse grained: gravels and sands were assigned 100 percent and silts and clays as well as more consolidate sediments were assigned 0 percent. The percent coarse fractions were then determined using a weighted average for 1-meter (3.3 feet) depth intervals. Horizontal and vertical hydraulic conductivities (K_h and K_v) across the study area were calculated with these percent coarse fractions and various combinations of end-member conductivities (a K_{coarse} and a K_{fine}). Equivalent conductivities were calculated using the arithmetic mean for K_h and the harmonic mean for K_v shown below in equations 1 and 2.

Arithmetic Mean for K_h

$$K_{equiv} = (F_{coarse} \times K_{coarse}) + (F_{fine} \times K_{fine}) \quad (1)$$

Harmonic Mean for K_v

$$K_{equiv} = \frac{1}{\frac{F_{coarse}}{K_{coarse}} + \frac{F_{fine}}{K_{fine}}} \quad (2)$$

The groundwater model was run systematically with equivalent conductivities for several combinations of end-member K values and calibrated to wells in various locations of the model (wells below the Corcoran Clay, above the Corcoran Clay but below the water

table, and east of the Corcoran Clay as well as some shallow wells in the western portion of the model) (S. Phillips, pers. comm., 10/4/05). The root-mean squared error (RMSE) was determined and plotted for each end-member combination to determine the combination with the least amount of error. The final end-members used to assign K values are 80 m/day (262 ft/day) for K_{coarse} and 0.008 m/day (0.02624 ft/day) for K_{fine} .

The 1 meter interval data set of equivalent K values was smoothed within a 10 meter (32.8 feet) vertical window (+ or -5 meters (16.4 feet) from the point being sampled) and then resampled every 5 meters (16.4 feet). The 10 meter smoothed data set was kriged using two nested structures: (1) Gaussian variogram model and (2) exponential variogram model. This kriged grain size-to-K model implicitly includes the IVFs, which is evident by regions of coarse grained deposits in various locations, especially south of the Tuolumne River.

From the data included in the report by Burow *et al.* (2004), a 16-layer model was created. The model area is approximately 62 km long and 55 km wide and has a maximum thickness of ~420 meters. The model uses the Block Centered Flow (BCF) package and the PCG2 (preconditioned conjugate gradient 2) solver. The vertical discretization of the USGS model was developed as various percentages of the total thickness between two halves of the model. The top half was discretized between the top of layer 8 (the Corcoran Clay) and the top of the model (the land surface). The bottom half was discretized as percentages of thickness from the bottom of layer 8 to the bottom of the model (an artificially generated surface). Layer 8 top and bottom in the western portion of the model were assigned based on thickness estimates of the Corcoran Clay from Page (1986).

Boundary Conditions

The boundary conditions in the USGS model are defined by general head boundary (GHB) cells. The boundaries along the perimeter of the northern, southern, and western portion of the model represent the expected vertical gradient in the aquifer. In the top model layer, the rivers are GHBs. The San Joaquin River is denoted completely by GHB cells. The other three westward flowing rivers (Stanislaus, Tuolumne, and Merced Rivers) in the area are represented as a combination of GHB cells and specified flux cells. In the western portion of the model area, these westward flowing rivers are GHBs because they are connected to the water table, where the depth to the water table is relatively low. However, in the east, the rivers are no longer connected to the water table and are denoted with a specified flux cell (described below in recharge). Each general head boundary cell requires two inputs: (1) a head value and (2) a conductance value.

Initial head values for the GHB representing rivers were determined from stream gage data and the area topography. The lateral boundary GHB heads that represent the expected vertical gradient were estimated from water-level data (S. Phillips, pers. comm. 8/1/05 and 12/5/05). A vertical gradient of 0.05 meters of head per meter of depth (thickness) was applied to the initial head values to produce the head elevations for the GHB (ghbhead). The gradient applied was based on vertical gradients observed in nested wells northeast of Modesto and generalized flow directions based on the approximate average elevation of the perforated interval of deep production wells in the area (S. Phillips, unpublished data, 9/26/05 and 9/20/05).

The average elevation of the perforated interval of deep production wells is estimated to be within layer 9 of the model. This heavy pumping generates a complex vertical gradient with downward flow from layer 1 to layer 9 and upward flow from layer 16 to layer 9. To recreate the influence of deep production wells on the flow regime, a

gradient of 0.05 meters of head per meter of depth was multiplied by the depth to the cell center. This value was then *subtracted* from head levels in layer 1 for layers 2 through 9 (the layer below the Corcoran Clay), reducing the head elevations with depth and creating a downward flow. Conversely, the gradient was multiplied by the depth of the center of the cell and *added* to the head assigned to layer 9 for layers 10 through 16, increasing the head elevations with depth creating upward flow toward layer 9. Additionally, to prevent the head value calculated for layers 10 through 16 from exceeding the head value in layer 1, mathematically possible but physically implausible, head levels that were calculated to be greater than the head elevation in layer 1 were set equal to the head elevation in layer 1.

The conductance (ghbcond) through the GHB cells was determined depending on the location of the cell in the model: the top layer river cells had different conductance calculations than the rest of the GHB cells. In general, conductance is calculated using two variables: (1) the horizontal hydraulic conductivity assigned to the cell and (2) the cell thickness. Constants also included in the calculation are: (1) cell size (400m) and (2) general head boundary distance (400m).

$$\mathbf{ghbcond = KH*thick*cellsize/ ghbdist} \quad (3)$$

For the GHB cells that delineate rivers in layer 1, this boundary allows a small amount of vertical flow, while below layer 1 along the western model edge and for all layers along the north and south extent of the model, the boundary reflects the overall lateral flow from the east. To implement this condition, the conductance through layer 1 GHB cells at the location of the rivers was calculated using the vertical hydraulic conductivity, riverbed thickness (1m), river width (25m), and a vertical conductivity multiplier of 10.

$$\mathbf{ghbcond} = \mathbf{KV} * ((\mathbf{cellsize} * \mathbf{rivwidth}) / \mathbf{bedthick}) * \mathbf{vkrivmult} \quad (4)$$

Recharge

Recharge to the aquifer was assigned from the 2000 water budget reported by Burow *et al.* (2004), and was determined with a land use approach. Burow *et al.* (2004) divide the study area (same as the model area) into the 47 sub-regions (the smallest possible) where the amount of surface water deliveries could be evaluated. Separate water budgets were evaluated for each of the 47 sub-areas containing non-urban (crop and vegetation) and urban settings. Recharge in non-urban settings was estimated with crop demand (calculated from National Oceanic and Atmospheric Administration (NOAA) and the California Department of Water Resources data), surface water deliveries (from local irrigation district data), and precipitation (from NOAA data) in combination with land use surveys for Stanislaus and San Joaquin counties. Urban area recharge was approximated using estimates of applied water, leakage from distribution lines, and precipitation. Recharge from rivers is assumed to be 0.005 m/d in locations where the river was not connected to the water table. Although this recharge value is the best current approximation, recharge rates over the rivers could not accurately be estimated with the available data, and calibration of this parameter was poorly constrained (S. Phillips, pers. comm., 08/01/05).

Base-soil Evaporation

Transpiration for this model was accounted for separately in the water budget from Burow *et al.* (2004). Thus, the evapotranspiration package (ET) was used in this groundwater model to account for base-soil evaporation with a maximum evaporation rate of 1.6 m/yr at land surface. This rate was determined from pan evaporation

estimates; however significant uncertainty exists around this value. The maximum extinction depth is 2.1 meters below the land surface.

Wells

Pumping from three types of wells (urban-supply, agricultural, and water-table-control, or have known "drainage") is accounted for in the model. (Water table control wells are shallow pumping wells located mostly in the western portion of the model that prevent the water table from rising to a point where it can interfere with crop roots.) Although domestic wells are numerous in the area, pumpage from wells in this category is extremely small compared to pumpage from urban supply, agriculture and water-table-control wells, so it was ignored.

Pumpage was distributed by dividing the three types of wells in the model to one of two categories: (1) actual wells with measured pumpage values and (2) imaginary wells that account for unmeasured private agricultural pumpage. The measured wells were assigned an annual pumping rate for the water year 2000 (i.e. from October 1, 1999 to September 30, 2000). The imaginary wells representing the private agriculture wells were assigned annual pumping rates estimated from the water budget described in *Burow et al.* (2004), where this rate is generally estimated as the residual between sources and demand for crop water assumed to be met by private pumpage. The amount of pumpage was distributed among imaginary wells within each sub-area defined in the water budget calculation (*Burow et al.*, 2004).

Reservoirs

This model also incorporates the recharge from local reservoirs through use of the reservoir package. This package is similar to the river package. The reservoirs included in this model are the Wood Reservoir (to the northeast), the Modesto Reservoir (to the east),

and Turlock Lake (to the southeast) (Figure 8). Turlock Lake is only partially within the model boundaries, but still contributes leakage to the region and was included.

Leakage from the reservoirs is calculated by the reservoir package as the product of the hydraulic conductance of the reservoir bed sediments and the difference between the stage of the reservoir and the head in the groundwater system. However, once the reservoir and groundwater are no longer connected, the recharge rate from the reservoir is constant, not head-dependent. Reservoir bed conductance is calculated from estimates of vertical hydraulic conductivity of the reservoir bed (m/day), thickness of the reservoir bed (m), and the model cell's row and column dimensions. The modeled total inflow volume of 192,701 m³ (6,805,171 ft³) from all three reservoirs was based on an estimate made by the Modesto Irrigation District (MID) for the Modesto Reservoir, and the assumption that the other reservoirs had similar leakage rates (S. Phillips, pers. comm., 8/31/05).

Modifications to the USGS Model

The USGS model of the Modesto area was generated to obtain a better understanding of the regional flow and water budget. The model for our study aims to specifically show the influence of the IVF within this regional approximation of groundwater flow. Alterations made to the original USGS model, described in more detail below, include: (1) the addition of the IVFs, (2) altered slope of the uppermost layers in the model, (3) increased vertical discretization, (4) use of the Layer Property Flow (LPF) package, (5) addition of GHB conditions along the upper reaches of the river, (6) removal of GHB cells from the northeastern portion of the model, (7) slight alteration of the vertical head gradient calculation in the GHB, and (8) reduced vertical conductance of the reservoirs.

Addition of the IVF

Each of the four IVF scenarios (RB/ML, RB/MS, RB/ST/ML, and RB/ST/MS) was modeled in an adaptation of the USGS model (Figure 9). To add these IVFs to the model, a code was developed to assign IVF hydraulic conductivity values to the cells within the IVF (Appendix G). The code uses the elevation at the center of the cell and the lateral location of the cell to assign either the original USGS hydraulic conductivity or an IVF hydraulic conductivity. The code also accounts for the fining upward character of the valley by assigning K values that differentiate between cells that represent basal gravel, sand, or the uppermost fines (see Appendix F and G). This internal IVF stratigraphy was modeled as an elevation percentage between the top and bottom of the valley (total valley thickness). Gravel represented the basal 40% of the IVF, sand the middle 45% of the IVF, and fines the top 15% of the total valley thickness. The Kh values for the gravel and the fines sections of the IVF with values used in Weissmann *et al.* (2004), with gravel = 864 m/d and fines = 0.0864 m/d. The sand in the IVF was assigned a K of 220 m/d, instead of the 86.4 m/d used by Weissmann *et al.* (2004). We deviated from the values in Weissmann *et al.* (2004) and chose a K of 220 m/d to maintain consistency with our conceptual model which asserts that the IVF is more coarse-grained than the surrounding sediments. The reasons for increasing the K of the sand in the IVF are discussed in more detail in the results.

Slope of Upper Model Layers and Vertical Discretization

To best preserve the continuous nature and fining upward character of the IVF deposits to test their impact on the groundwater flow, the vertical discretization and slope of the layers in the upper portions of the model were changed from the original USGS model. The original 16 layer model was converted to a 27 layer model, described in

detail in Appendix F. The top of USGS layer 1 and layers 12 through 16 (23 to 27 in the new model) were not changed in the modified version of the model. Layers 2 through 16 in the modified model (USGS layers 2 through 7) have slight to drastic variations in cell thickness and/or slope of the layer elevations. The slope of these upper layers matches the gradient of the base of the IVF (Figure 10). In this modified model, the slope of the layers 2 through 5 match the Modesto small IVF base and 6 through 16 match the slope of the Riverbank IVF base.

Adaptations to the vertical discretization and the slope of the USGS model for use in this study serve to improve the model's ability to simulate the influence of the IVF while preserving as much of the original model as possible. The finer vertical discretization in the modified model best preserves the IVF stratigraphic character and geometry in the model (See Appendix F). The initial coarser vertical discretization of the model would not allow for accurate representation of the IVF fining upward stratigraphy, which is an important geologic attribute to maintain because it is vital to assessing the influence of the IVFs on groundwater flow. Additionally, because the layers that contain the IVF have the same gradient as the IVF in this model version, the Kh data imported from the IVF code preserves the continuous nature of the IVF.

Layer Property Flow (LPF) versus Block Centered Flow (BCF)

Another difference between the model generated for this study and the USGS model of the Modesto area is the flow process package used. The model generated for this study uses "Layer Property Flow" package (LPF). The LPF simplifies parameter input because it utilizes the cell elevations, as specified in the discretization file, to calculate cell thickness and ultimately the flow through each cell. The Block Centered

Flow package (BCF) does not use the cell elevation values to calculate the cell thickness and flow through each cell.

For example, the LPF package only requires model inputs of hydraulic conductivity for each cell and will use cell top and bottom elevations to calculate thickness and then transmissivity values for confined model layers prior to running the model. Using the BCF package, cell thickness are not be calculated prior to the model run; therefore, model inputs for use with the BCF package require the thickness component already be incorporated in parameter values. In practice, this means that the BCF requires a combination of hydraulic conductivities and transmissivities be assigned to the model cells. While both methods of flow calculation offer comparable results, the LPF allows more flexibility for adaptations to the model discretization and parameters (such as changing confined/unconfined layers and vertical conductivities).

Another example of the benefits of using the LPF in this case is illustrated in the use of an anisotropy factor instead of a leakance value. The leakance term is required as an input in the BCF package, and is the product of vertical hydraulic conductivity and the thickness of the cell. In the LPF, an anisotropy factor (K_h/K_v) is used instead of leakance and does not include the cell thickness, which means that these values can remain the same, despite any subsequent changes in cell thickness. For the modified model, K_h/K_v was calculated using a FORTRAN code (See Appendix H).

Addition of GHB Conditions along the Upper Reaches of the River

The northern, southern, and western general head boundary cells in the modified model are the same as those in the USGS. However, the specified flux cells that represent the Stanislaus, Tuolumne, and Merced Rivers in layer 1 of the USGS model were changed to GHB cells in the modified model (Figure 8). Despite the USGS

justification that the rivers are disconnected from the aquifer in the area, the lack of a boundary in this portion of the model causes unrealistic volumes of water to collect within the river valleys. Water filled the valley up to 10 meters above the valley base. Addition of the GHB conditions in the river valley was implemented to rectify this problem. Head elevations at these new GHB cells were assigned based on the ground surface elevation, using National Geographic TOPO! California.

To preserve the condition that the rivers are disconnected from the aquifer in the eastern portion of the model even with the addition of the GHB cells, flow between the river and the aquifer was reduced by assigning lower conductance values to the new GHB cells. The lower conductances were calculated with the same equation as the original river cells (explained above), but the vertical-K river multiplier (vkrivmult) of 10 was not included. Additionally, the uppermost reaches of the river near the reservoir were assigned even lower cell conductance values to reflect the lower conductivities of the more consolidated geologic deposits in that area. These cells were also calculated without the vertical K river multiplier and then divided by 2 as well. Reducing the conductance still allows unrealistic volumes of water to fill the river valley, 5 to 8 meters (16 to 26 ft) at most; the river still maintains losing and gaining reaches, which is the most parsimonious condition that could be achieved for the model in this study.

Removal of GHB Cells from the Northeastern Portion of the Model

Along the northeastern-most edge of the USGS model, GHB cells are dry down to an elevation of 10 to 17 meters (33 to 56 feet). While a solution can still be calculated despite the presence of dry boundary cells, it is not practical to set a boundary condition artificially high and allow the cell to dry. To avoid the drying of the peripheral GHB

cells, GHB conditions were removed from layer 1 through layer 4 (Figure 8). The exact cells where the GHB condition was removed include:

- **Layer 1: I 1; J 76 to 153**
- **Layer 2: I 1; J 81 to 153**
- **Layer 3: I 1; J 96 to 153**
- **Layer 4: I 1; J 111 to 153**

Alteration of Vertical Head Gradient in GHB

General head boundaries in the modified model were also assigned around the perimeter of the model to represent the vertical gradient in the area that is caused by deep production wells. The head and conductance values required as input for the GHBs were calculated in a manner similar to the method used for the USGS model. The vertical head gradient applied to the GHB cells, however, was calculated using slightly different methods. This modified approach produced a comparable vertical gradient.

Similar to the USGS vertical head gradient, downward flow was produced by reducing the set head elevations in layer 1 by a gradient of 0.05 meters per meter of depth (thickness) for layers 2 through layer 17 (the Corcoran Clay). Initial set head values for layer 1 GHB were determined from gage data and the area topography (S. Phillips, pers. comm., 8/1/05). One variation between the USGS GHB gradient and mine is that layer 18 heads were set equal to the heads in layer 17. This was changed to prevent an unrealistic (at this model scale) head change between the low conductivity Corcoran Clay (layer 17) and the layer below it (18). The upward flow gradient was applied to the head assigned to layers 19 through 27. To generate upward flow in these layers, the gradient of 0.05 meters of head per meter of depth (thickness) multiplied by the depth of the cell center from was added to the head values from layer 18. In a manner similar to the USGS approach, this increasing head value was constrained with the condition that the

calculated head value could not exceed the assigned head value in layer 1. If this condition occurred, the calculated head value for that layer would be ignored and the cell would be assigned the layer 1 head value instead.

Conductance calculations were made with the same methods used in the USGS model. Variations in the actual conductance values between the USGS model and the model used in this study are a result of thinner layers in areas with finer discretization or the presence of the IVF that intersects the western-most boundary.

Reduced Vertical Conductance of the Reservoirs

Another method used to reduce the volume of water that collects within the river valleys in the model, the vertical conductivities of the reservoir bed sediments were lowered in the reservoir package. Manual trials of various vertical conductivities were used to constrain the value that not only best matched the USGS estimate of the volume of inflow from the reservoirs, but also reduced the volume of water within the river valleys. The values of 0.003 (for the Wood and Modesto Reservoirs) and 0.006 m/day (for Turlock Lake) assigned to the reservoir bed sediments in the original USGS model were divided by 1.2. The resulting vertical conductances used in the adapted model are 0.0025 (for the Wood and Modesto Reservoirs) and 0.005 m/day (for Turlock Lake).

Flow Model Simulations, Particle Tracking, Solute Transport Simulation

Six steady-state flow models were run in MODFLOW 2000 for this study. They include the USGS model, the modified model without the IVFs, and a model for each of the four geologic realizations. Comparison of the head solutions, particle pathways, and transport simulations for each of these realizations gives insight into the influence the addition the IVFs have on the groundwater flow in the Modesto area.

RESULTS AND DISCUSSION

Results of the flow model simulations for this study first examine the impact that changes made to the original USGS model have in the flow solution by comparing the USGS model and the modified model without the IVFs. Once the impact of changes made to the original model is evaluated, the influence of the IVFs will be assessed with particle tracking and solute transport simulations. Although models and results were generated for each geologic realization, model results are similar for the four different IVF realizations; therefore we illustrate the influence of IVF deposits using results from the RB/ST/ML, and briefly describe variability between IVF realizations at the end of this section. The RB/ST/ML realization was chosen to illustrate the influence of the IVF, because it incorporates the influence of three potential locations of the IVFs and most clearly shows the degree of influence of the IVFs may have on the groundwater flow.

Groundwater Modeling – Comparison of models without the IVF deposits

Changes made to the USGS model (altered slope of the uppermost layers in the model, increased vertical discretization, use of the Layer Property Flow (LPF) package, addition of GHB conditions along the upper reaches of the river, removal of GHB cells from the northeastern portion of the model, and slight alteration of the vertical head gradient calculation in the GHB) appear to have little impact on the model solution.

Both models show the general trend of groundwater flow is to the west-southwest with the highest hydraulic head elevations in the east (Figure 11A and B). For the modified model without the IVF, the head solution has slightly lower heads in the reservoir area, and the head gradient appears slightly more gradual in the central portion of the model near the Tuolumne River. The large depression in the water table in the southeast corner is observed in both models. This depression is caused by a heavy

dependency on local groundwater and limited recharge through application of non-local irrigation water in this area (a significant source of recharge in other areas of the model) (Burow *et al.*, 2004; S. Phillips pers. comm., 11/9/05).

Though the USGS and the modified flow model solutions are similar, some minor variation in the flow statistics was observed. The volumetric budgets are comparable with a total volume in and out of the USGS model at approximately 5.40 million meters³ (190.7 million feet³) and the modified model at 5.42 million meters³ (191.4 million feet³). The discrepancy between the inflow and outflow of the model is smaller in the modified model relative to the USGS model, but both discrepancy values are less than a tenth of a percent (<<0.01%) of the total budget. The USGS model has a difference of 14 m³ (494 ft³) while the modified model has a difference of 0.34 m³ (12 ft³).

More specific comparison shows the USGS model has a maximum head value of 70.9 meters (232.6 feet) at the Modesto Reservoir and a minimum of -2.4 meters (-7.9 feet). The modified model has a slightly lower maximum and a similar minimum head value: a maximum of 60.2 meters (197.5 feet) at the Modesto Reservoir and a minimum of -2.2 meters (-7.2 feet). The maximum head values have a 15% difference and the minimum values ~8.9%. The mean simulated head in the USGS model is slightly lower at 19.7 meters (64.6 feet) relative to the modified model's mean head of 21.5 meters (70.5 feet) (Table 2).

Although the volumetric budget and regional flow appear similar, local variation between the two models does exist. The addition of the GHB to the upper reaches of the Tuolumne River in the modified model did not eliminate flooding within the river valley. In the USGS model, because the river was not denoted as a boundary, less water accumulated within the channel specifically in the uppermost (eastern) reaches. Along

the entire length of the river valley, however, comparable flooding is observed within both models. While the Tuolumne River is thought to be losing water to groundwater in the upper reaches, as are the Stanislaus and Merced Rivers, (based on water-level contour maps developed by the CA Dept. of Water Resources, S. Phillips, pers. Comm., 11/1/05), model results indicate that the Tuolumne River may have both gaining and losing reaches (see Advective Pathline Analysis section below). However, further refinement of our groundwater model may also be necessary in order to more accurately capture the surface water – groundwater interaction. Aside from the changes within the river, the results from both of these models indicate that the changes made to the modified model without the IVFs did not impact the overall flow model significantly as the flow budgets only varied by 0.4% and the regional head solution is approximately the same.

Influence of the IVF Deposits on Groundwater Model Results

The results from the Modesto area model that includes the wedge-shaped, coarse-grained IVFs indicate that the IVFs have a hydrogeologic significance and are capable of acting like a regional “pipeline” for groundwater flow and contaminant transport in the area. The influence of the IVF on the groundwater flow is illustrated by comparing the modified model without the IVFs (i.e. the model without the IVFs) to the model with the IVFs (specifically, the RB/ST/ML model, which is representative of results seen in the other geologic scenarios) using three methods: (1) a calculation of the head difference between the model with and without the IVF, (2) advective pathline analysis, and (3) solute transport simulation.

Head Difference

The head difference between the model with and without the IVF highlights the influence the IVF may have on the regional head distribution. The head difference was

obtained by subtracting the head solution of the model with the IVFs from the head solution of the model without the IVFs (Figure 12), and allows us to visualize the extent as well as the magnitude of the influence of the IVF. It also highlights the nature of the head difference: positive or negative.

As expected, the magnitude of the head difference decreases with distance from the IVF and is illustrated in figure 12. The areas significantly influenced by the presence of the IVFs, a head difference > 10 cm, are adjacent to the IVFs. In areas farther away from the IVFs, the head difference, and therefore the influence of the IVFs on the head elevation, decreases.

The location of positive and negative head difference values also provides significant insight into the influence of the IVFs. Areas with a positive head difference mark locations where the model without the IVF has higher head elevations than the model with the IVFs. A negative head difference indicates areas where the model without the IVFs has lower head elevations than the model with the IVFs.

In the eastern portion of the model domain, the head difference is positive. Farther west, from the location where the RB and ST IVFs (Tuolumne River and Stanislaus River Riverbank Formation IVFs) intersect to the western extent of the model, the head difference is negative. Positive head differences in the eastern portion of the model are high, approximately 1 to 4 meters, where the RB and ST IVFs are located (Figure 12). The head difference is positive all along the eastern portion of the model, but the magnitude of the head difference decreases radially with distance from the IVFs.

In the western portion of the model domain, negative head differences radiate out from the intersection of the RB and ST IVFs. The most negative head differences (approximately -2 meters) are located in the area where the IVFs intersect (Figure 12).

Farther west, the influence of the IVF remains, but the extent and magnitude of the negative head difference surrounding the RB IVF decreases.

This pattern of head differences, positive in the east transitioning to negative toward the west along the IVF, indicate that the RB and ST IVFs create areas of convergent and divergent flow. Thus, at the head of the valley, hydraulic head elevations are lower (where head difference is positive) due to the addition of the thick, coarse-grained IVFs that allow a significant amount of flow through the area. Farther down the IVFs to the west, head elevations are higher (where head difference is negative) than were observed in the model without the IVF, indicating flow is being diverted from the IVFs. In the steady-state conditions specified in this model, water flows into the IVFs at the head, but once the maximum volume of water capable of flowing through the IVF fills the valley, the water “backs-up” within this coarse “pipeline”, and raises the hydraulic heads in the western portion of the model. This in turn causes flow that is initially following the IVF to divert into the contiguous aquifer sediments.

The convergent and divergent flow regions can be inferred to represent an equilibrium plane. The transition from convergent to divergent flow along this plane shows the location in the IVF where the hydraulic conductance has reached a balance with the volume of water that can pass through. Above this point, the hydraulic conductance of the IVFs is sufficiently high to allow the volume of water entering the IVFs to pass through. Below the transition point, the hydraulic conductance of the IVFs is not large enough to allow the entire volume of water entering the IVF to pass through and the water “backs-up” and is pushed out of the IVF deposits into the surrounding aquifer sediments.

One limitation on testing the influence of the IVFs on groundwater flow in the model is the presence of artificially generated coarse areas in the USGS grain size to K model, which are a result of the implicit inclusion of the IVFs. The impact of the shallower Modesto Formation IVF (ML), in particular, on groundwater flow is dampened by surrounding coarse grained regions across the area south of the Tuolumne River. Here, the Kh of the gravels in the IVF are almost an order of magnitude greater than the surrounding deposits, while the sand is approximately the same Kh as the deposits around it. The result of this is a more localized impact on the hydraulic heads. Head elevations do not show a distinct area dividing convergent and divergent flow along the valley as can be seen with both of the Riverbank Formation IVFs (RB and ST). Instead, this valley appears to highlight local areas where the connectivity of coarse sediments is improved (Figure 12).

In some areas along the ML IVF, there is only a small positive head difference. These areas highlight where there was little improvement in the connectivity of the aquifer with the addition of the IVF and head difference varies only slightly. Areas that show little improvement in aquifer connectivity were already well connected due to the presence of coarse sediments prior to the addition of the IVF.

In other areas along the ML IVF, the head difference is negative. These areas highlight where the connectivity of the aquifer is improved locally by the addition of the IVF. Replacement of relatively finer sediments with the addition of the coarser ML IVF creates a local area of preferential flow, which displays the “back-up” of water.

The presence of the IVF within both relatively coarser and finer sediments is contrary to our conceptual model, where the IVF is thought to be relatively coarse compared to the surrounding sediments. The USGS grain size-to-K model data indirectly

preserve the coarse grained nature of the IVF. Because this data set is kriged across the model, the coarse grained nature of the IVF was probably interpolated across a large area, artificially increasing K values. Thus, the USGS method of generating K values from grain size does not exclude the IVFs and may not provide the best representation of the deposits around the IVFs to illustrate the influence of IVFs on groundwater flow.

Along the deeper Riverbank Formation IVFs to the north of the Tuolumne River (the RB and ST IVFs), the IVF is surrounded by significantly finer sediments (low K values) relative to the coarse grained sediments of the IVF (high K values). This allows for a more regional increase in aquifer connectivity with emplacement of an IVF and shows a single point of transition from convergent flow into the IVF to divergent flow out of the IVF. Implications of the varying influence on groundwater flow are described below with the results of advective pathline analysis in the model.

Advective Pathline Analysis

Simple pathline tracking in the flow models with and without the IVFs were used to show the impact the IVFs have on the groundwater flow in the Tuolumne River area. Pathline tracking allows an analysis of the advective flow pathways within the groundwater model.

Using MODPATH within GMS 5.1, 1000 particles were assigned and released from the same 4 cells in layer 1 of each model (the model without the IVF and the model with the IVF) (Figures 13, 14, 15). The 4 cells were chosen because they are located in each of the IVFs: 1 cell in the RB, 1 cell in the ST, and 2 cells in the ML (proximal and distal). The particles were tracked in both models to their ultimate fate within the steady state flow conditions.

In the model without the IVF, pathlines from particles released in the central and southern portion of the model tend to be located in the upper unconfined portions of the aquifer, while other pathlines from particles released farther north, follow the vertical gradient and trend down into the confined portions of the aquifer (Figures 13A, 14A, and 15A). The addition of the IVF shows that pathlines extend farther westward into the basin as well as deeper into the aquifer (Figures 13B, 14B, and 15B). As illustrated by the pathlines that follow the IVF trend, the IVF provides a conduit for water to flow through. The addition of the IVF also allows pathlines to spread into aquifer sediments that they previously would not reach. The vertical flow gradient from heavy pumping in the area contributes to the spread of pathlines, or water, throughout the area.

The implications of changes in head gradients through the addition of the IVF are discernible from the results of the pathline analysis. The addition of the IVF sufficiently changes the head gradients to generate areas of convergent and divergent flow. This flow pattern redirects pathlines or groundwater flow into the IVF and then diverts flow out of the IVF, thus causing the pathlines (or groundwater) to spread into contiguous aquifer sediments.

Advective pathline analysis was also used to illustrate the impact of the IVF on recharge to the aquifer from the rivers. Figures 16A and B shows a map view of pathlines from particles released within the general head boundary cells that delineate the Tuolumne River. Losing and gaining reaches of the stream can be identified by the trends of the pathlines. The Tuolumne River shows intermittent losing and gaining reaches along the stream in this model. A cross-section through the area (Figure 17A and B) shows pathlines from the losing part of the stream, at the head of the stream in the model with and without the IVF. In the model with the IVFs, the pathlines illustrate the

flow into the IVF and westward (Figure 16 and 17B). In the model without the IVFs, the pathlines have very little lateral movement and extend downward into the aquifer with the vertical gradient (Figure 16 and 17A). Particle pathlines released from along the losing portion of the stream near the Modesto area, in the model with the IVFs, show flow into the IVF and under the city (Figure 17B). Pathlines in the same area in the model without the IVF show some lateral movement beneath the city, but not to the extent shown in the model with the IVFs (Figure 17A). Comparison of pathlines in the models with and without the IVFs illustrates that the presence of the IVF near the river allows the IVF to gain recharge from the river. This is important, especially at the head of the valley where artificial recharge to the aquifer could provide a water supply for wells pumping in the Modesto area.

Solute Transport Simulation

Transport simulations were conducted using MT3DMS to run a potential transport scenario in the modified model without the IVFs and the model with the IVFs. A constant concentration of 100 mg/L of an unspecified conservative solute was released from the same location in layer 1 in simulations for both of the models (Figure 18A and B). Data requirements for the transport simulation include groundwater flow solution from the MODFLOW simulation, longitudinal dispersivity (α_L), ratio of transverse to longitudinal dispersivity, ratio of vertical to longitudinal dispersivity, effective molecular diffusion (D^*), and effective porosity. The longitudinal dispersivity was assigned a value of 1 meter, which is based on work by Gelhar *et al.* (1992) who indicate that 1 meter is a reasonable value for a 400 meter cell size. The ratios of transverse and vertical diffusivity to longitudinal were both set equal to 1. Effective molecular diffusion was assigned a value of 5.9616×10^{-5} m²/day (Weissmann *et al.*, 2002a). The effective

porosity assigned to these transport simulations was 33% (0.33). This porosity was chosen because it provides a good average estimate for the porosity in the unconsolidated fluvial fan sediments (Weissmann *et al.*, 2002a, c). To maintain simplicity, the consolidated deeper, confined aquifer cells were assigned the same porosity. Transport simulations were run in the model with the IVF and without the IVF for 100 years.

The variation in plume morphology in these transport simulations clearly depicts the influence the IVF can have on solute transport. The model without the IVF shows a more uniform plume front that spreads laterally and vertically over a smaller area, while the model with the IVF, displays preferential lateral and vertical movement through the IVF. An interesting observation in Figure 18A is the southern most plume front shows some preferential spreading in the coarse grained areas south of the Tuolumne River. This is the area that likely has artificially high conductivity values due to the implicit inclusion of the IVF in the USGS grain size-to-K model.

Because of the vertical gradient, both models show a significant amount of vertical movement of the plume. However, in the model with the IVF, a distinct elongate lobe of the plume develops in the location of the IVF which spreads areas of the plume farther westward than they do in the model without the IVF (Figure 18B). The results show the contaminant plume front follows the IVF and moves farther to the west in the model with the IVF.

This relatively rapid plume movement within the IVF indicates that the IVF will have a large role in water quality and remediation schemes. The presence of these valleys will significantly increase contaminant residence times, which could drastically affect efforts to develop effective remediation schemes in the area. These results also indicate the aquifer is more susceptible to widespread contamination due to the presence of the IVFs.

These results are similar to those observed by Weissmann *et al.* (2004) on the Kings River.

Comparison among Geologic Realizations

Head differences among the IVF realizations show that that addition of IVFs in different spatial locations can alter the head solution. Table 3 shows that while the overall statistics of the head solution appear similar, very different local head variations are apparent when the difference between heads solutions is calculated.

Comparing head differences of the various geologic scenario head solutions allows for analysis of the impact each additional IVF has on the groundwater flow. The resulting head difference plots show the same pattern observed by adding the IVFs to the model without the IVF: lower hydraulic heads at the head of the fan and higher heads where the flow has “backed-up” in the IVF. The location of the positive and negative head differences varies depending on the IVF location. The addition of the ST valley reduces the head elevations more over a larger area in the eastern portion of the model than in models without the ST IVF. Figure 19A and B show a smaller positive head difference in the northeastern portion of the model without the ST valley. The addition of the MS valley instead of the ML valley results in a similar pattern of patchy areas of positive and negative head differences highlighting where the IVF lowers or raises the local head elevation instead of continuous regions of convergent and divergent flow along the IVF (Figure 19A and B).

While the results are similar for each of the IVF scenarios, the various locations of the IVF do highlight the potential for drastic local variation in groundwater flow. The location of the IVF will have implications for how the IVF can best be utilized for artificial recharge (i.e. where to drill wells to obtain the maximum groundwater

production rates). The areas of the aquifer most susceptible to rapid and widespread contaminant transport through the IVF will be controlled by its location. As an essential component of the groundwater system, the exact location of the IVF should be integrated into remediation schemes.

CONCLUSION

From this investigation into the influence of the IVF, we can make several conclusions about this work, including the methods used to delineate the IVF and the impact the addition of the IVF has on the groundwater flow in the Modesto area.

Our results indicate that the IVF has a significant influence on the groundwater flow in the Modesto area. We found that the IVF significantly influences regional hydrogeology by:

- acting as a regional “pipeline” of coarse sediment for groundwater flow,
- providing a preferential pathway that has the potential to provide artificial recharge to the Modesto area as well as create a conduit for contaminants to follow,
- increasing the dispersion of particle pathlines into the aquifer sediments surrounding the IVF, and
- enabling solute plumes to move farther distances more rapidly through the IVF making the aquifer susceptible to widespread contamination.

These results are consistent with those observed by Weissmann et al. (2004). They found that the IVF geometry allows it to significantly impact the groundwater flow and solute transport due to the continuous and relatively thick basal cobble unit. The continuous,

course-grained nature of the valley fill creates a highly conductive conduit for groundwater flow, cutting across any laterally bounding confining units.

The four geologic scenarios developed in our study from the drillers' well logs allowed the influence of the IVF to be assessed along with the impact of uncertainty in geologic model. Comparisons among these four scenarios give insight to the impact of incorrectly developing a conceptual model and substantiate the need to better constrain the location of these IVFs.

Future Recommendations

While these models provide a good preliminary understanding of the influence of the IVF, they should be used as a basis for further investigation into the area stratigraphy and hydrologic regime. The geologic model could use some improvement by (1) using more reliable methods for identifying the location of the IVF (2) obtaining core through several locations of the IVF to better understand IVF lithologic character, (3) collecting additional continuous core in the open fan deposit areas, and (4) more studies of the Tuolumne River's flow differential down-stream during stable flow conditions.

Further investigation into the location of the IVF should be conducted. Although the driller's logs were successfully applied, this method of locating and defining the IVFs could be significantly improved. Although multiple potential IVFs within the same stratigraphic range (i.e. two potential Modesto Formation IVFs) were identified, it is unlikely that they both exist. While driller's well logs provide a good approximate location of the IVF, to more effectively model the IVF, more reliable geophysical data should be acquired. Seismic data across the area will help better constrain the location and geometry of these features, providing more dependable estimates of the width, depth, and length of the IVF.

In this study, no core was collected within the IVF. This made modeling of the lithologic character more challenging. The character of the proximal and distal portions of the IVF need to be investigated as these are the principle areas of recharge and discharge for groundwater and will impact the location of the divergent flow from the valley. Investigation into the toe of the fan may provide insight into the influence of local base level (sea level) and the basin width on the preservation (or lack of) of the distal fan deposits. Currently, the IVF code does not account for the fact that gravels are not likely present in the distal portion of the model. With further constraints on the distal character in the IVF, this portion of the model could be improved. Additional studies near the apex of the fan will provide further insight into the geometry of the stacked IVF deposits believed to exist. This may have a significant influence on the ability to artificially recharge the aquifer.

Additional continuous core data across the fan will also help to better capture the aquifer heterogeneity outside of the IVF. One significant improvement in this area would be to add the sequence bounding paleosols. While this model does not include the paleosols, they may have an impact on the regional or local groundwater flow, acting as no or low flow barriers which could potentially increase the influence of the IVF and their ability to influence the aquifer connectivity (Weissmann *et al.*, 2004).

Studies to better constrain the differential flow during stable flow conditions along the Tuolumne River will give insight into the true potential for artificial recharge into the aquifer through the IVF. Detailed characterization of reaches along the Tuolumne River where recharge occurs is needed in order to understand the nature of groundwater-surface water interaction and conductance between the river and groundwater system. While our model highlights flow from the river as a potential

pathway for recharge to access the IVF, further studies would be needed to confirm this potential.

The groundwater and contaminant transport models produced enhance understanding of the groundwater flow and the potential for contaminant movement through the Modesto area. The models also provide a preliminary understanding of the potential influence these incised-valley fills may have on artificial recharge in the incised-valley fill.

Tables

Table 1: Summary of the geologic scenarios developed from the locations of thick gravels in the drillers' well logs delineating potential IVF locations. These scenarios will be incorporated into multiple, steady-state, saturated groundwater flow models.

IVF Age		Riverbank Incised-Valley Fill (IVF)	
		<i>Tuolumne River (RB) and Stanislaus River (ST)</i>	<i>Tuolumne River (RB)</i>
Modesto Incised-Valley Fill (IVF)	<i>Large IVF (ML)</i>	RB/ST/ML	RB/ML
	<i>Small IVF (MS)</i>	RB/ST/MS	RB/MS

Table 2: Summary of the hydraulic head maximum, minimum and mean elevations for the USGS model and the modified model without the IVF. Percent differences between the USGS model and the adapted model and between the adapted model and the model with IVFs are also included.

Head Elevation Statistics

<i>Hydraulic Head Elevations</i>	USGS	No IVF	% difference from USGS	IVF (RB/ST/ML)	% difference from the model without the IVF
Minimum Value (m)	-2.37	-2.08	12.2	-2.06	1.0
Maximum Value (m)	70.94	60.37	14.9	60.06	0.5
Mean Value (m)	19.68	22.15	12.6	22.03	0.5

Table 3: Summary of the hydraulic head maximum, minimum and mean elevations for the four geologic scenario models. Percent differences between the USGS model and the adapted model and between the adapted model and the model with IVFs are also included.

Hydraulic Head Elevations	RB/ML	RB/MS	RB/ST/ML	RB/ST/MS	Average IVF Scenarios	Modified Model without the IVF	% difference from Modified Model without the IVF
Minimum Value (m)	-2.07	-2.07	-2.06	-2.07	-2.07	-2.08	0.60
Maximum Value (m)	60.10	60.12	60.06	60.07	60.09	60.37	0.47
Mean Value (m)	22.07	22.07	22.03	22.03	22.05	22.15	0.60

Figures

Figure 1: Generalized stratigraphy of the Great Valley of California, with the white and black dashed boxes showing the approximate study area of the Tuolumne River area near Modesto, California in the Eastern San Joaquin Valley. The geologic map, based on soil surveys, shows the fluvial fan deposits in the eastern portion of the San Joaquin Valley (adapted from Weissmann *et al.*, 2006). Thick, slightly westward dipping fluvial fan deposits along the Tuolumne River decrease in age to the west, toward the San Joaquin Basin center. Uplift and erosion have exposed older fan units in the eastern portion of the basin. This study focuses on the Turlock Lake, Riverbank, and the Modesto deposits. Geologic map shown in color.

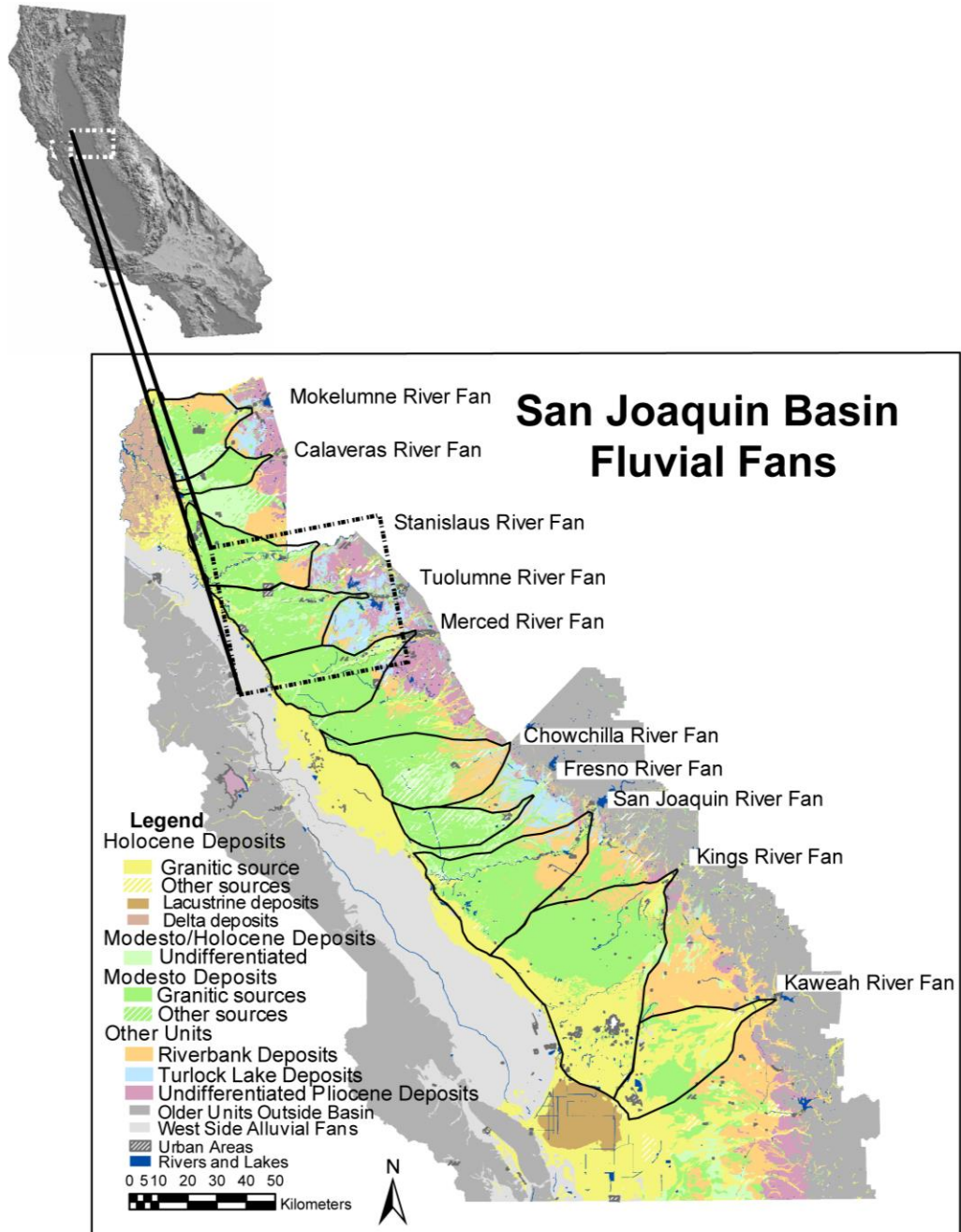


Figure 2: Schematic profile of the Tuolumne River fan stratigraphy showing the westward stepping, thin, stacked, fluvial fan units (Weissmann *et al.* 2006).

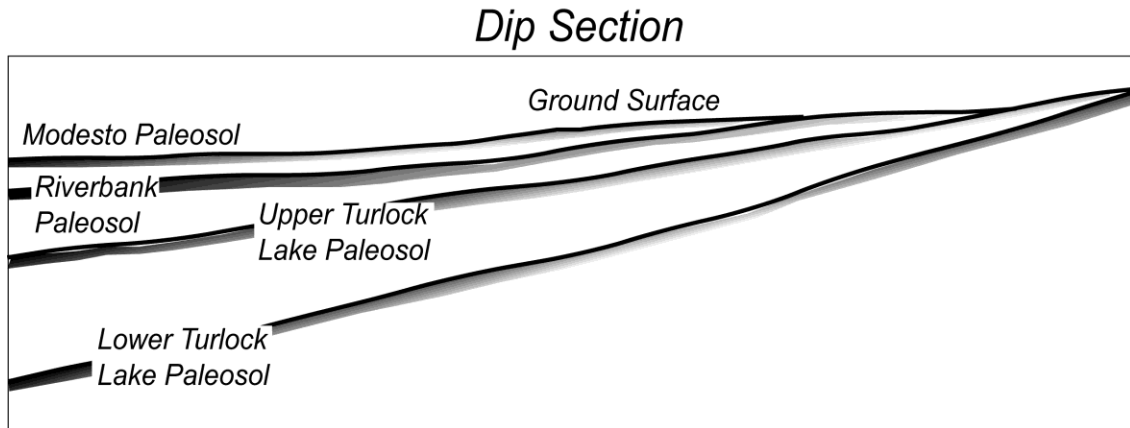


Figure 3: The Tuolumne River area near Modesto, California in the Eastern San Joaquin Valley. The black solid box denotes the entire study area. The dashed line outlines the area shown in Figure 13.

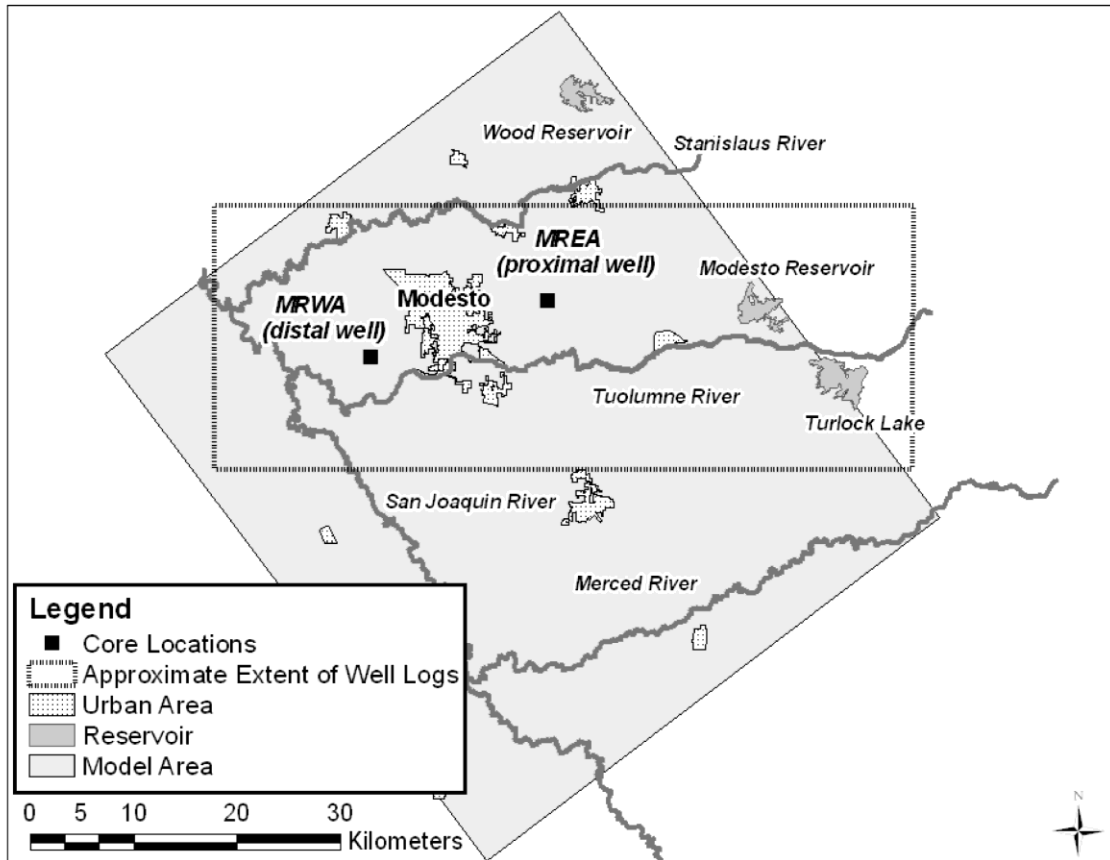
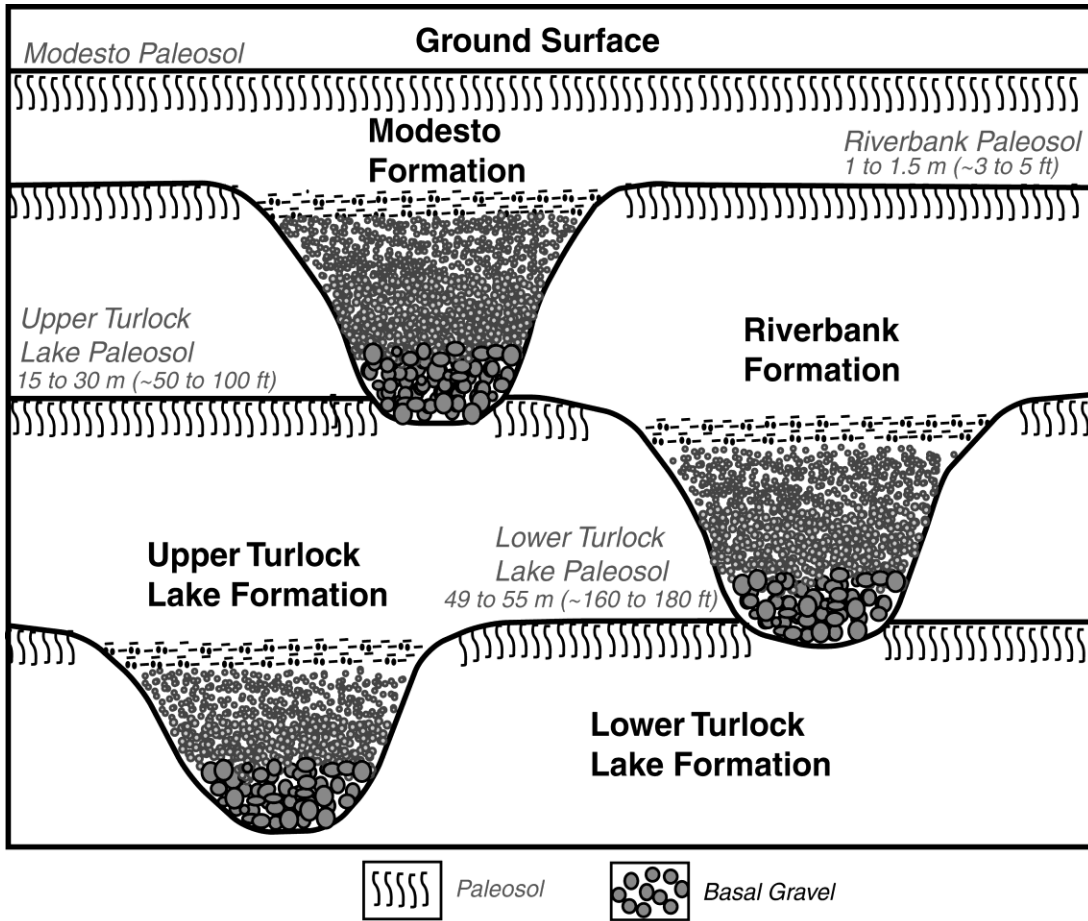


Figure 4: Each cyclic Quaternary deposit contains a relatively coarse-grained IVF nestled within finer open fan deposits of silt, clay and some sand. The IVF has a thick gravel base that fines upward to sand then fines.



NOT DRAWN TO SCALE.

Figure 5: Conceptual model of the Riverbank IVF. The valley fill is 0.7 to 1.6 km wide and ranges from approximately 30 meters thick at the apex to 0.3 meters at the toe. It has a 5 to 9 m thick gravel base that fines down fan.

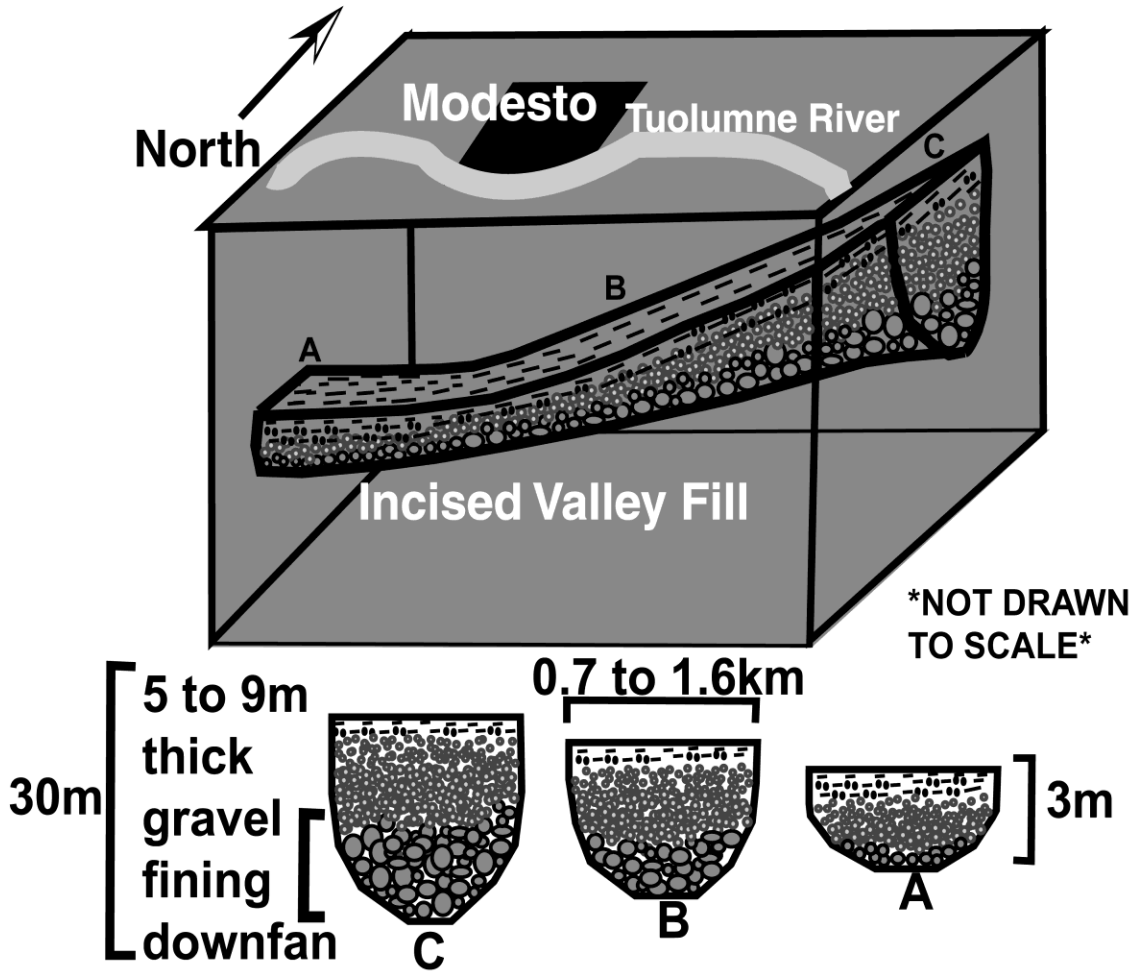


Figure 6: Wells assigned a rank of 1 and 2, plotted spatially, roughly show a few east-west elongate trends. The areas of particular interest are (1) the northwest trending line of wells that runs beneath Modesto, (2) the line of wells that trends along just north of the modern Tuolumne River, (3) a short string of wells that create a small loop to the south in the eastern portion of the river, and (4) the line of wells that begins on the southeastern part of the river and trends to the southwest.

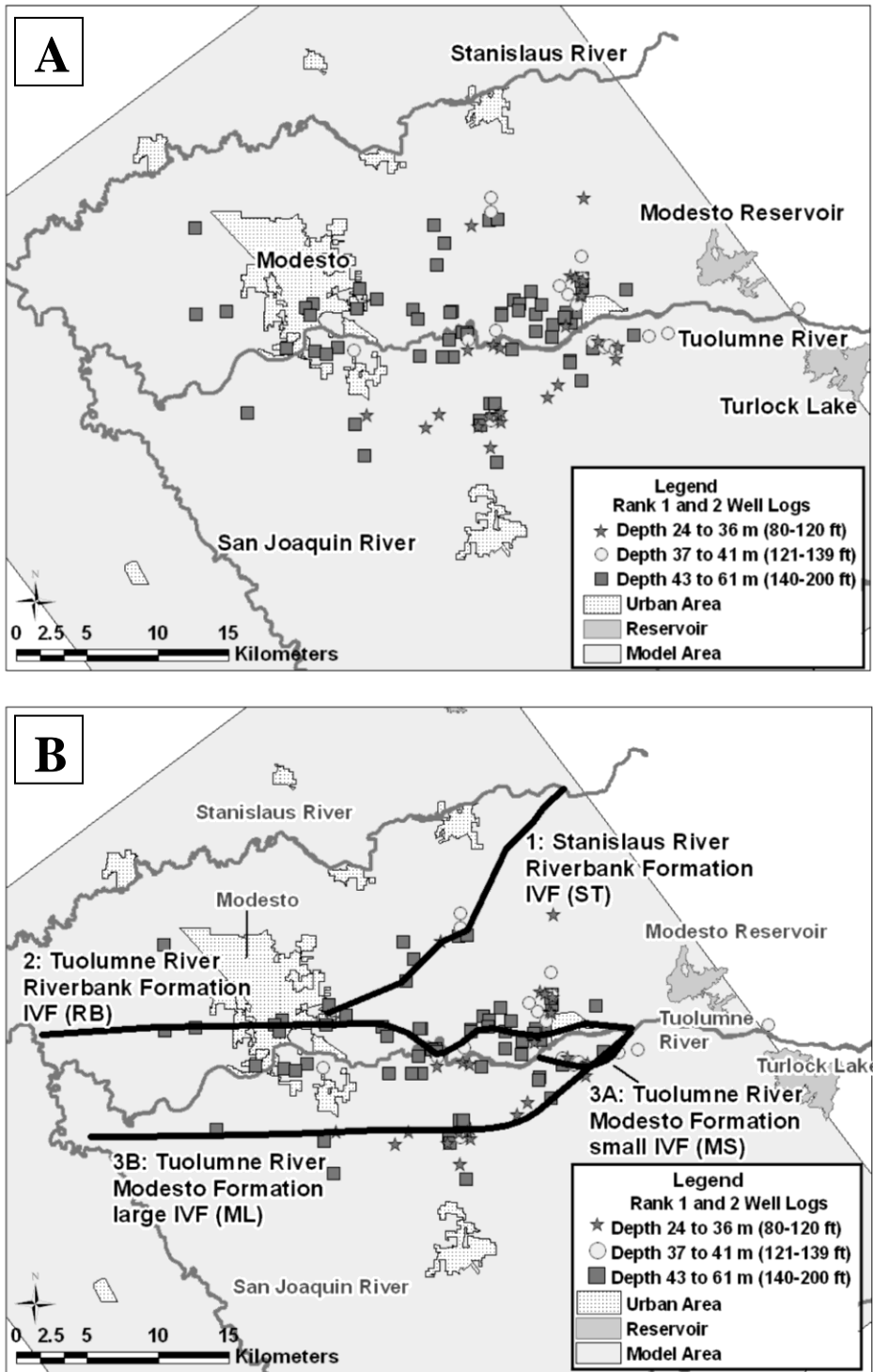
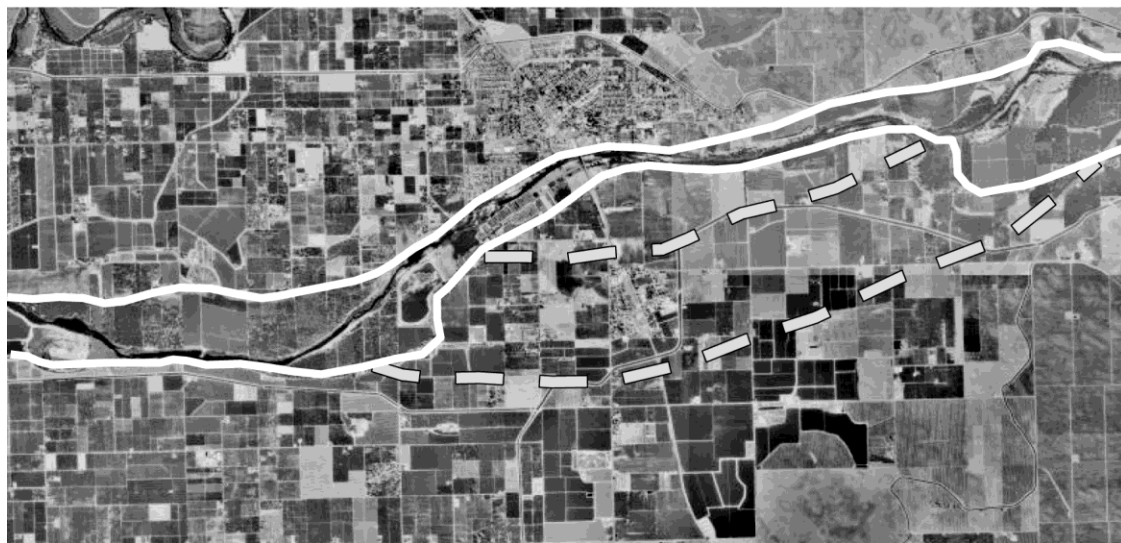


Figure 7: Aerial photograph showing the potential location of the Modesto small IVF loop (outlined by the light gray dashed line). The solid white line represents the current river valley.

USGS 4 km S of Waterford, California, United States 16 August



0 2 Km

0 1 Mi

<http://terraserver-usa.com/>

Figure 8: The specified flux cells that represent the Stanislaus, Tuolumne, and Merced Rivers in layer 1 of the USGS model were changed to GHB cells in the adapted model. The locations of the reservoirs are outlined with a thin black line. The GHB cells are represented by the dark gray dots around the perimeter of the model and over the locations of the rivers. The light gray squares represent wells.

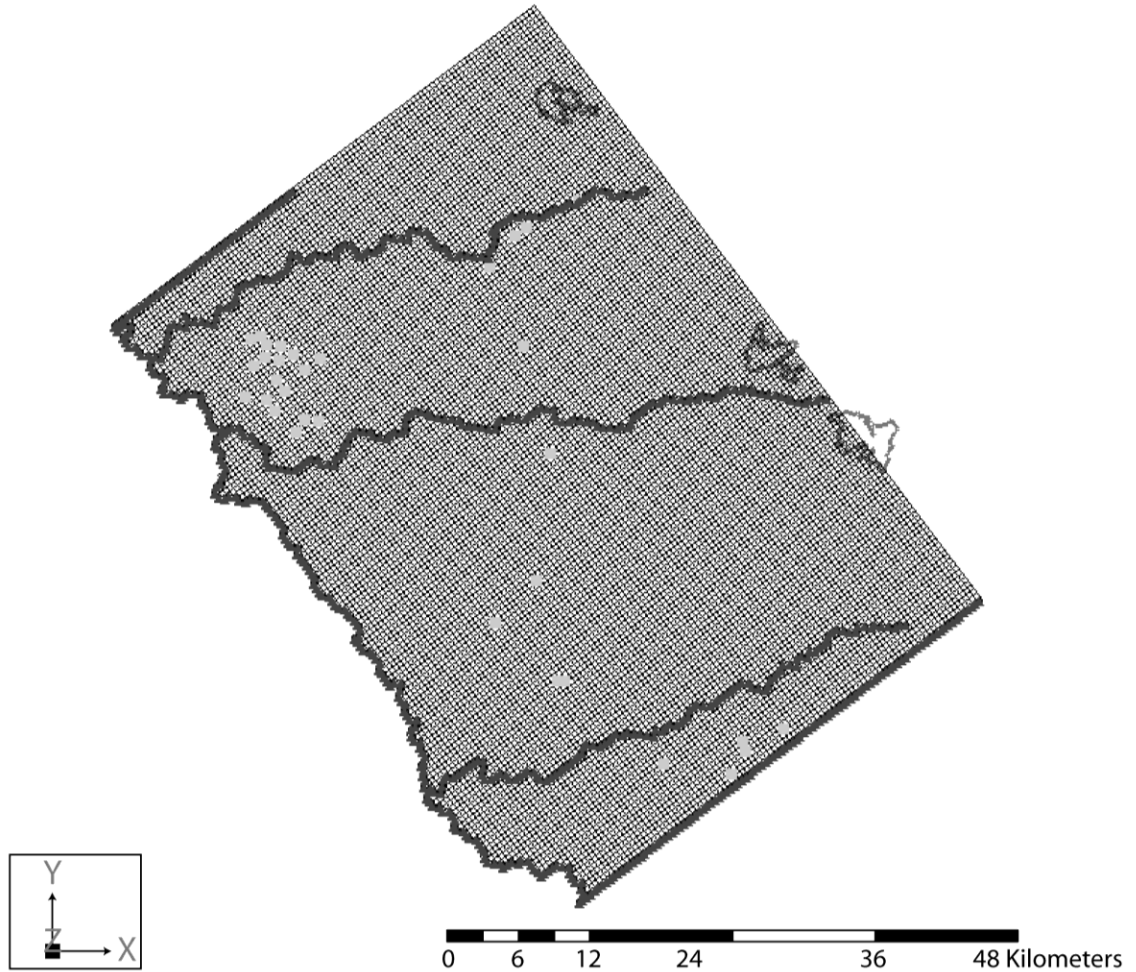


Figure 9: Four geologic scenarios were created to test the influence of the IVF: (from top left to bottom right) RB/ST/ML, RB/ML, RB/ST/MS, and RB/MS. Vertical exaggeration of 100.

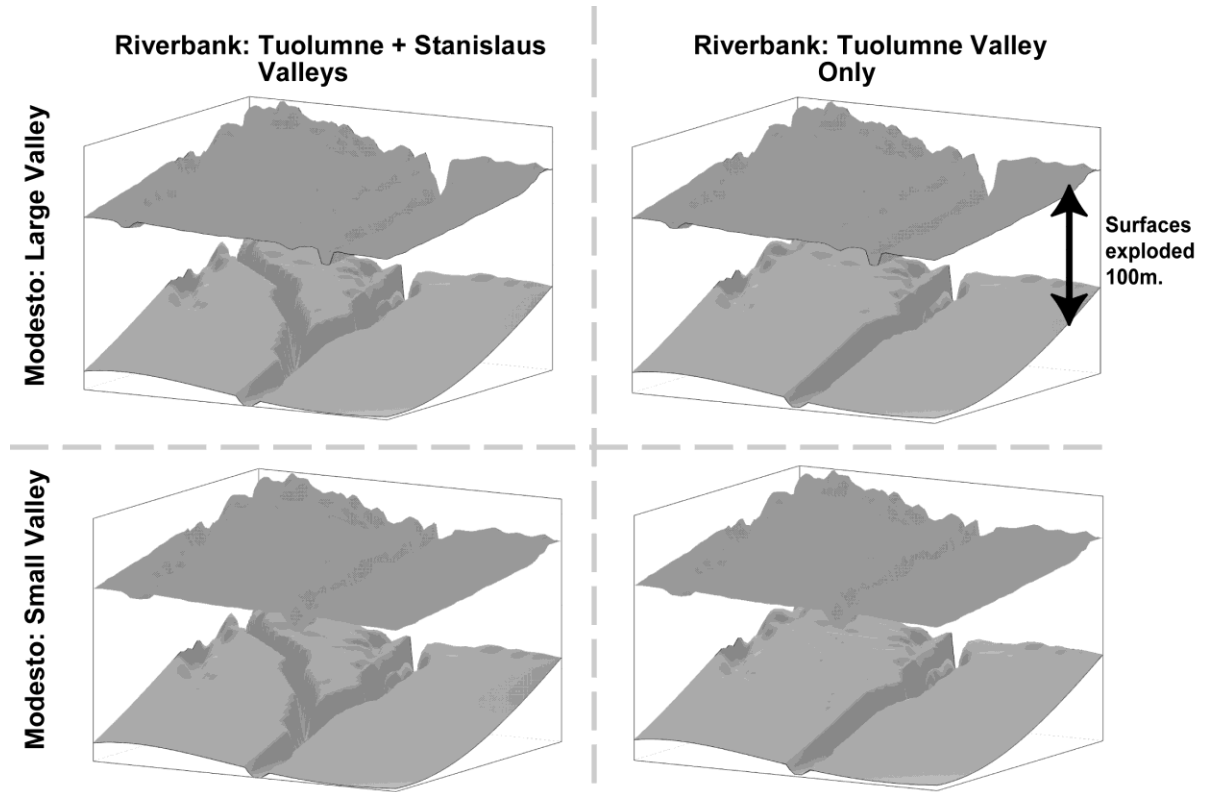


Figure 10: Row 60 (I60) in **A:** the USGS model and **B:** the newly discretized model. Vertical exaggeration is 50. Each cell is 400 meters wide.

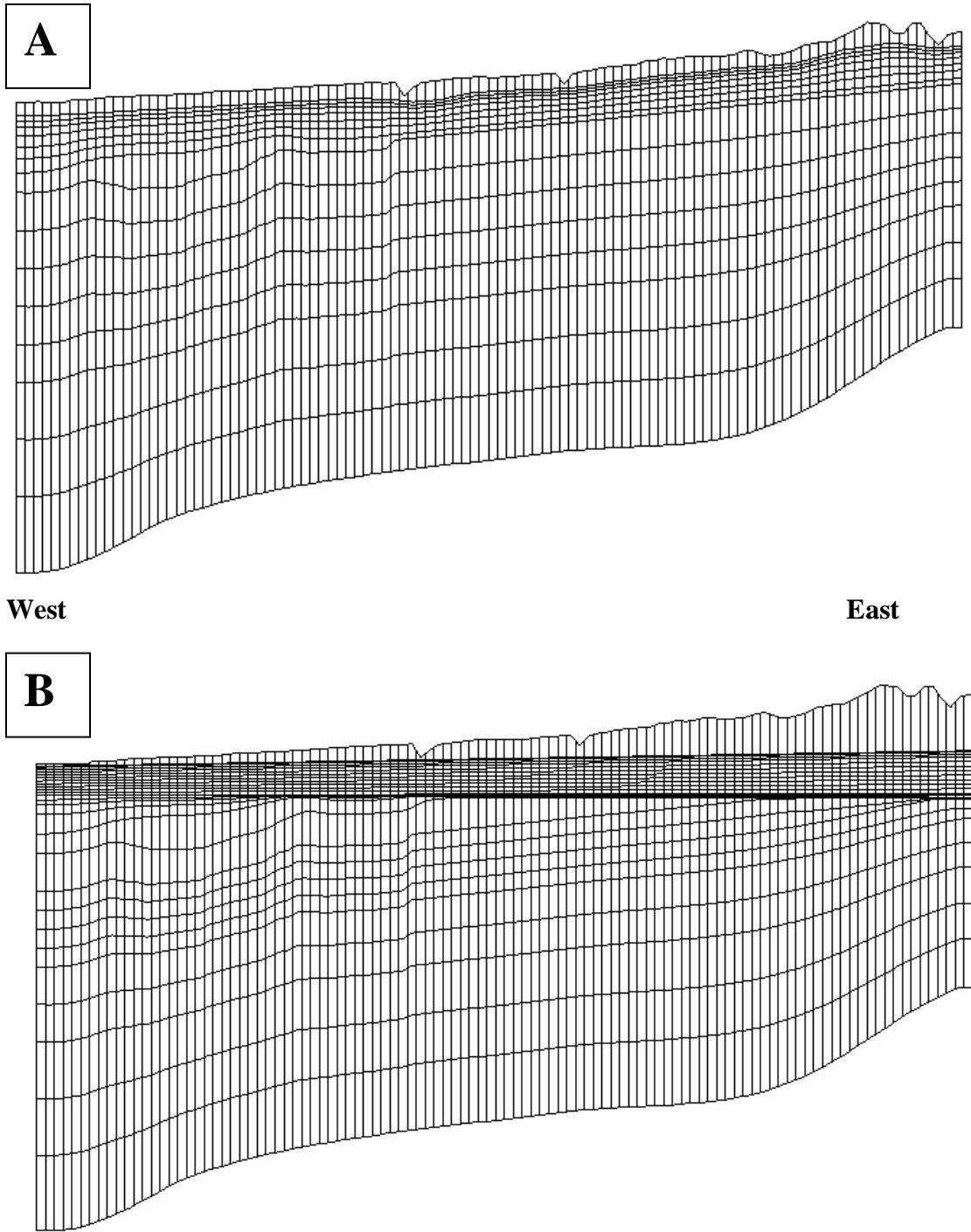


Figure 11: Comparison of (A) the USGS model and (B) the adapted model without the IVF MODFLOW hydraulic head solutions. **A:** USGS head solution. The regional groundwater flow is to the west-southwest. The large depression in the water table in the southeast corner of the model is due to a heavy dependency on local groundwater with little recharge from application of irrigation water. **B:** Adapted model without the IVF head solution. The general flow direction is the same. The heads in the area of the reservoir are slightly lower and the head gradient is slightly more gradual. The large depression in the southeast corner is maintained in this adapted model. (Elevations are in meters and the vertical exaggeration is 50). Shown in color.

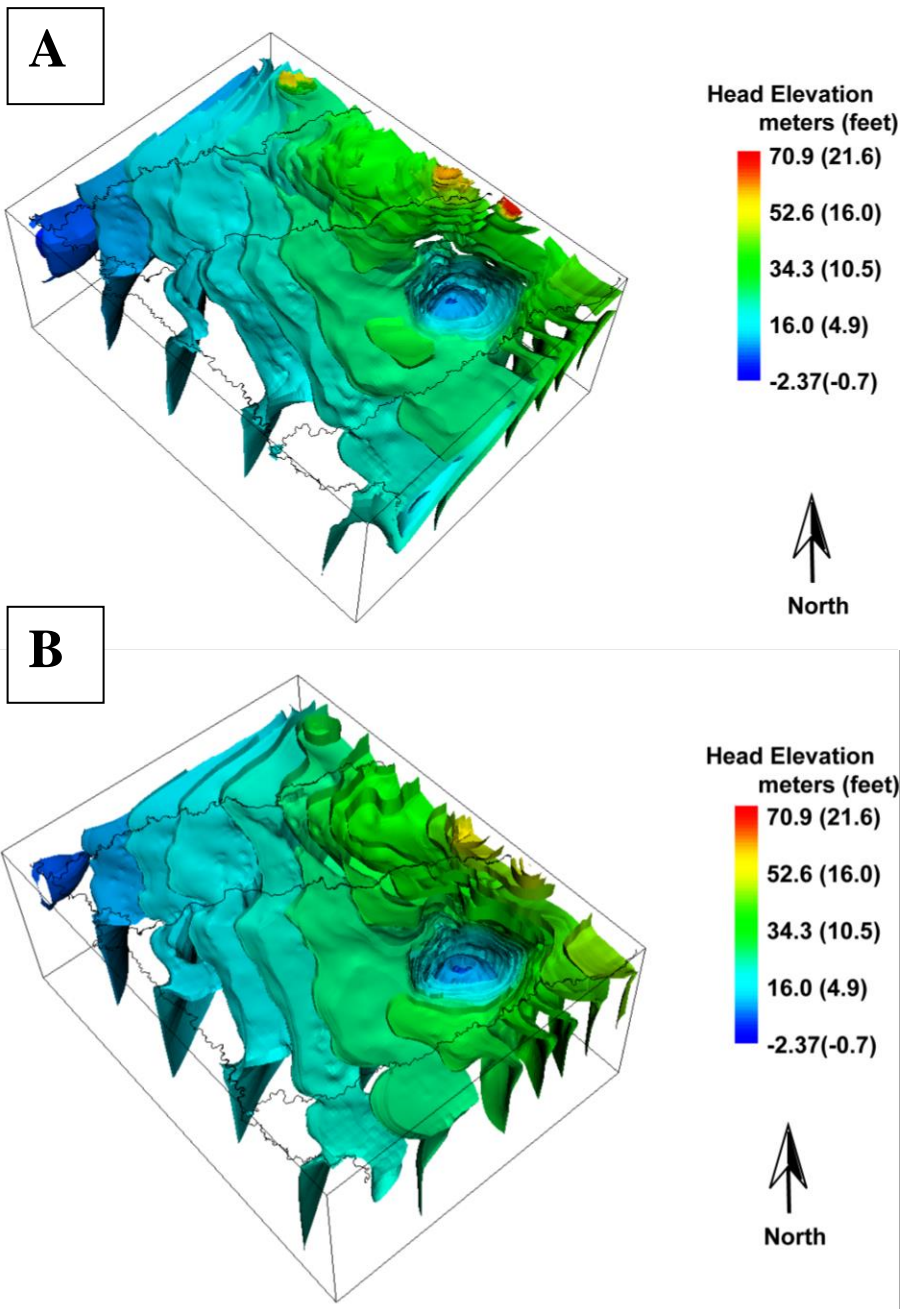


Figure 12: Head differences between the model without IVFs and the IVF model (RB/ST/ML). Positive residuals (yellow to red) indicate areas of the model where the head elevations are lower in the IVF model than in the model without the IVF. Negative residuals (green to blue) indicate areas where the head elevation is higher in the IVF model than in the model without the IVF. (Elevations are in meters and the vertical exaggeration is 50). **A:** 63 isosurfaces. **B:** 20 isosurfaces (rotated for improved view). Shown in color.

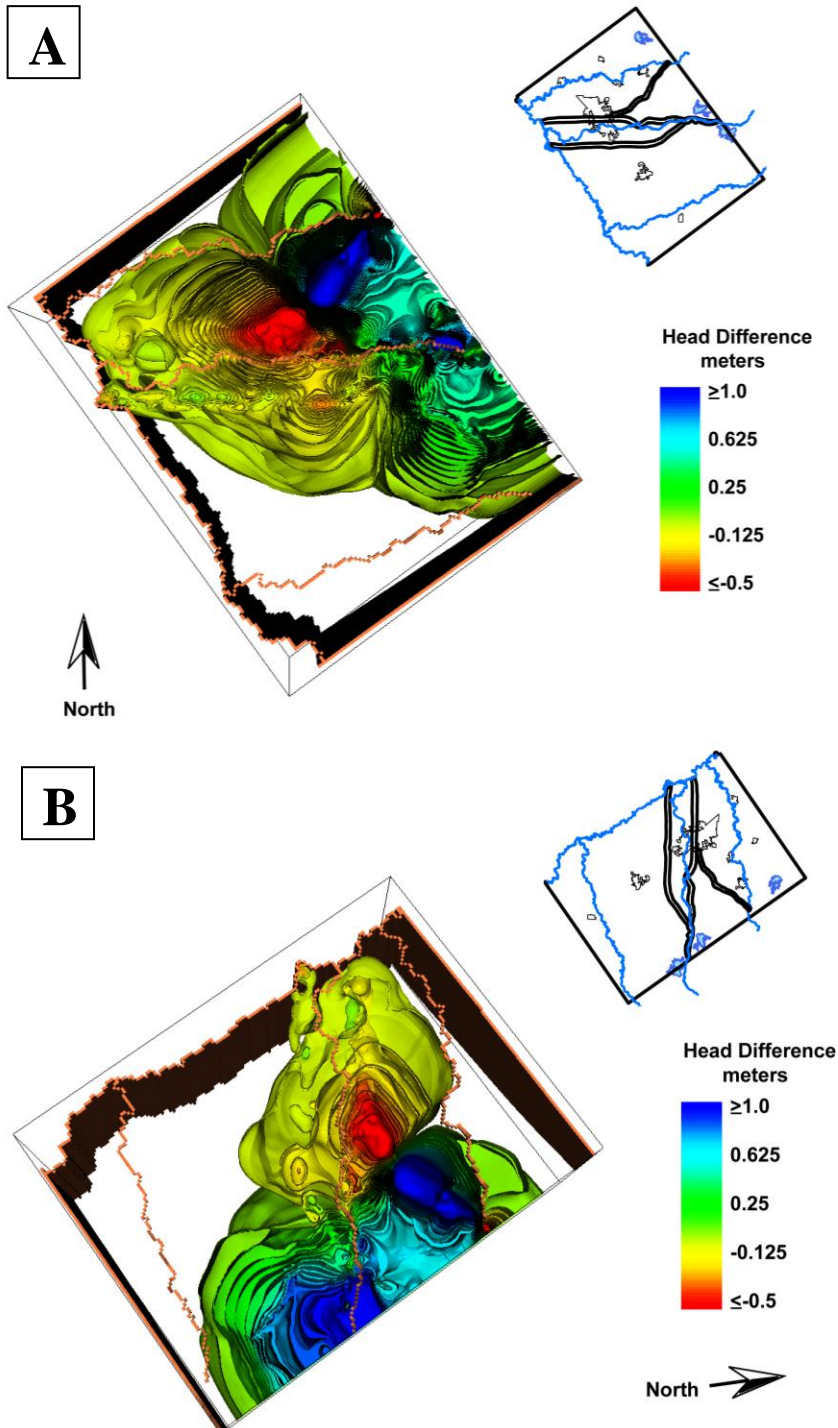


Figure 13: Pathline analysis was done using MODPATH. The light gray triangles indicate where the particle started and the black circles indicate where the particle ultimately ends up. **A:** Map view of the model without the IVF. Pathlines have the same trend along the hydraulic gradient across the model. **B:** Map view of the model with the IVF (RB/ST/ML). Pathline analysis in the model with the IVFs (RB/ST/ML) shows that pathlines extend farther to the west and spread laterally to the north and south.

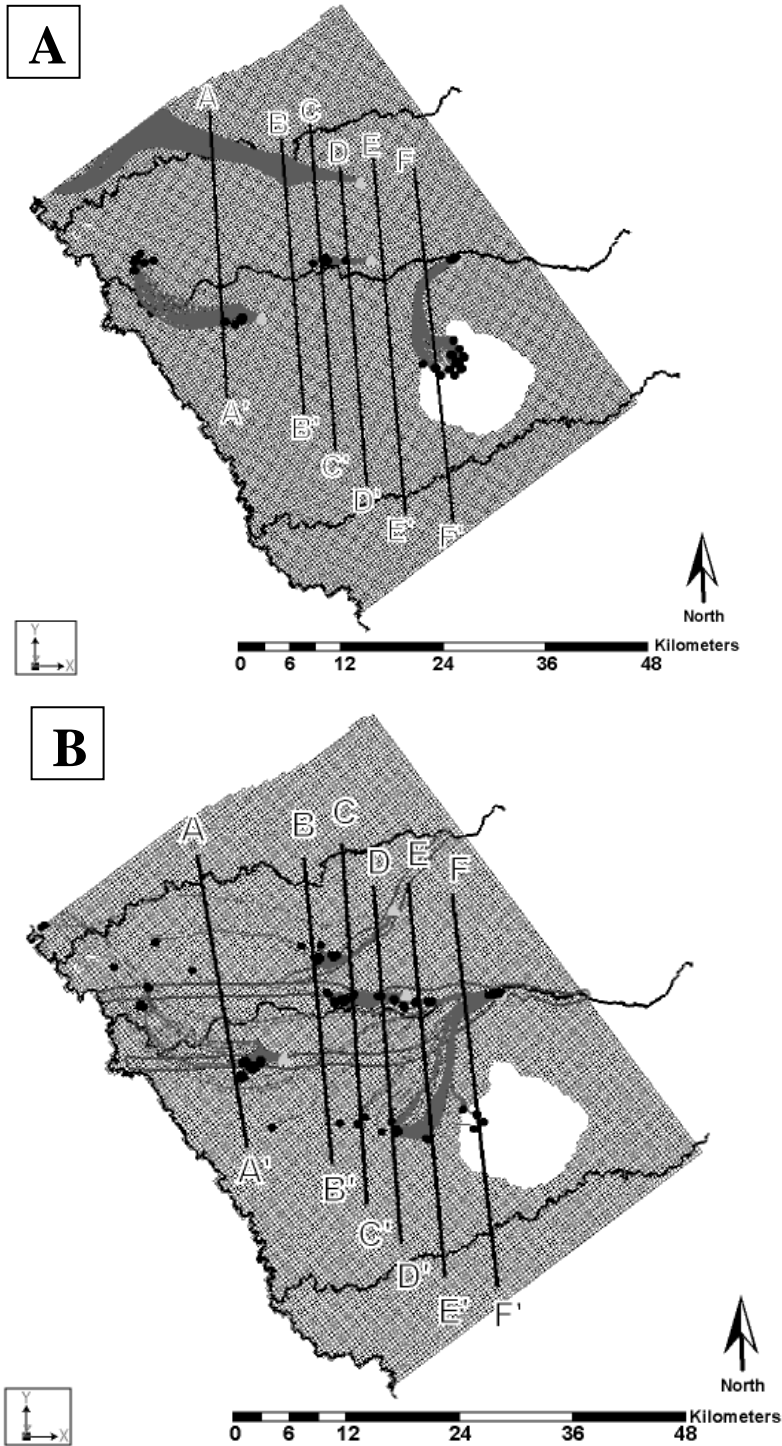


Figure 14: A cross-section of the particle pathlines displayed in the previous figure. The yellow triangles indicate where the particle path started and the black circles indicate where the particle pathline ultimately ends. Vertical exaggeration is 50. **A:** No IVF cross-section showing a view of the pathlines looking north. Particles released in the northern portion of the model have pathlines that trend downward near the bottom extent of the model. The other pathlines remain relatively shallow, but do move from the unconfined to the confined portion of the aquifer. **B:** IVF (RB/ST/ML) cross-section showing a view of the pathlines looking north. The pathlines from particles released in the north are redirected into the IVF and do not flow as deep into the aquifer as they do in the model without the IVF. The other particle pathlines also follow the path of the IVF then disperse into the aquifer. Shown in color.

WEST

EAST

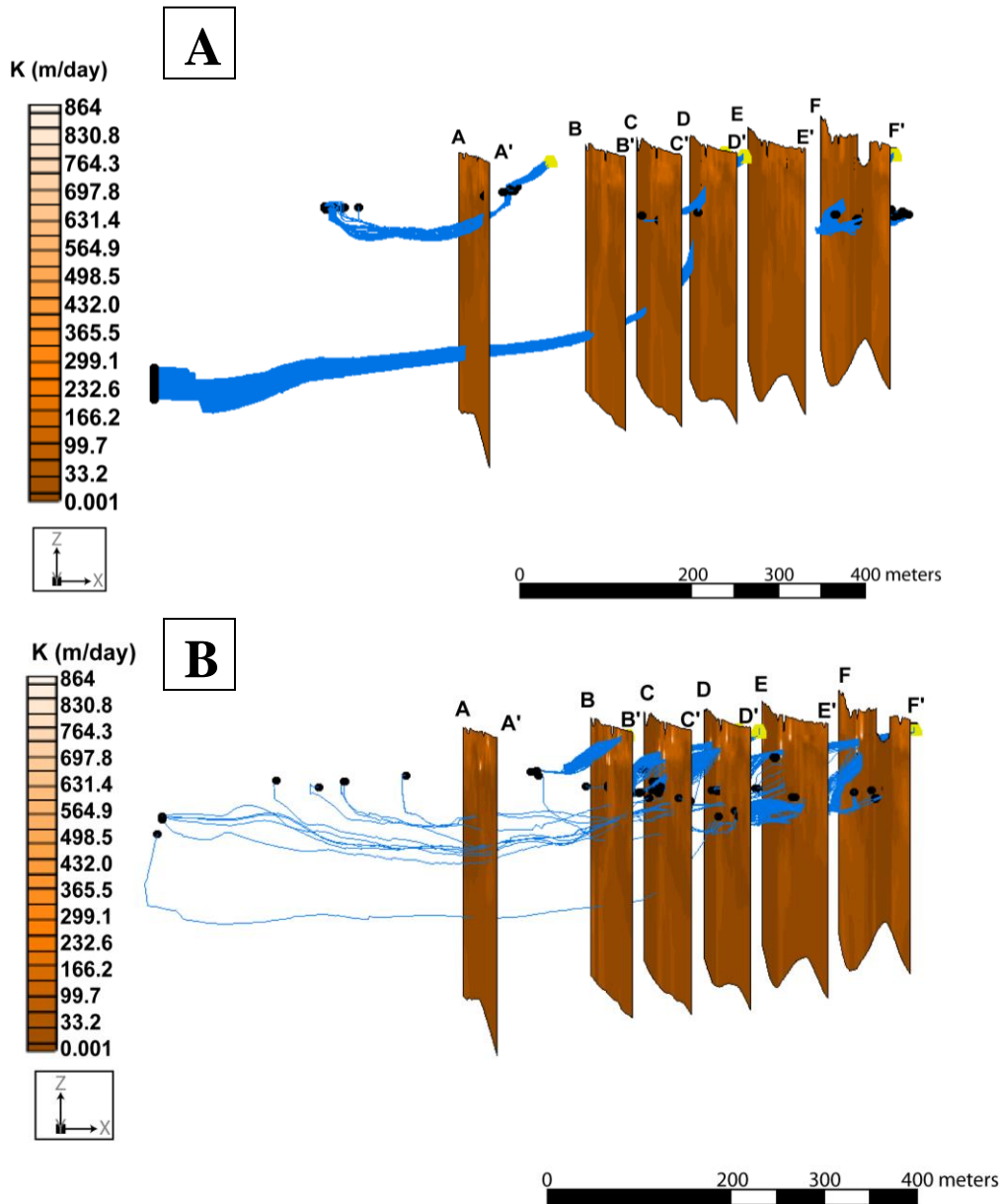


Figure 15: Cross-section of the particle pathlines shown in the previous two figures viewed obliquely from above the south edge. The yellow triangles indicate where the particle path started and the black circles indicate where the particle path ultimately ends. Vertical exaggeration is 50. **A:** In the model without the IVF, the particle pathlines follow a similar trend through the aquifer and move deep into the confined portion of the aquifer. **B:** In the model with the IVF (RB/ST/ML) the particle pathlines follow the IVF then spread out displaying the various flow paths into the deeper portions of the aquifer. Shown in color.

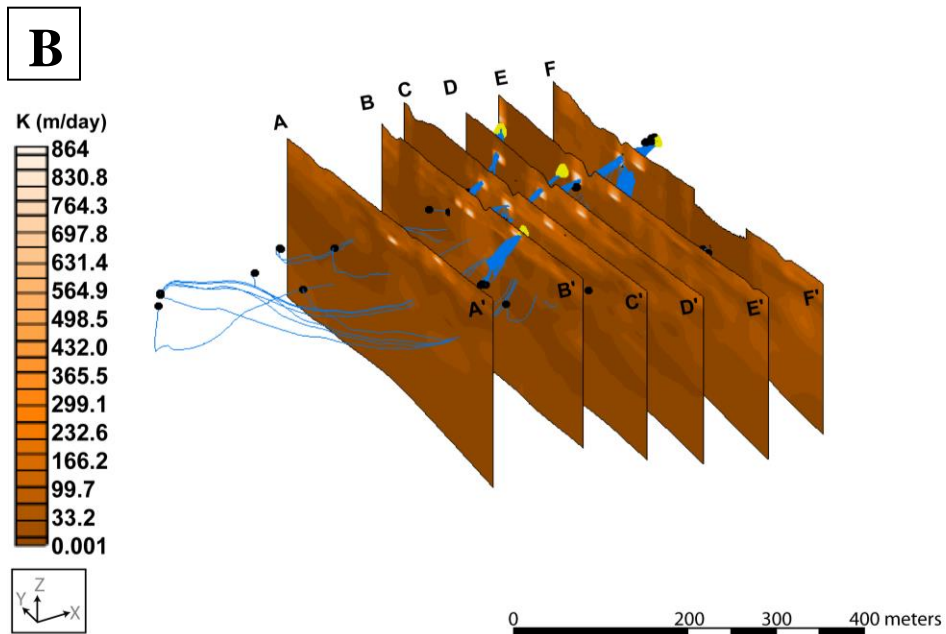
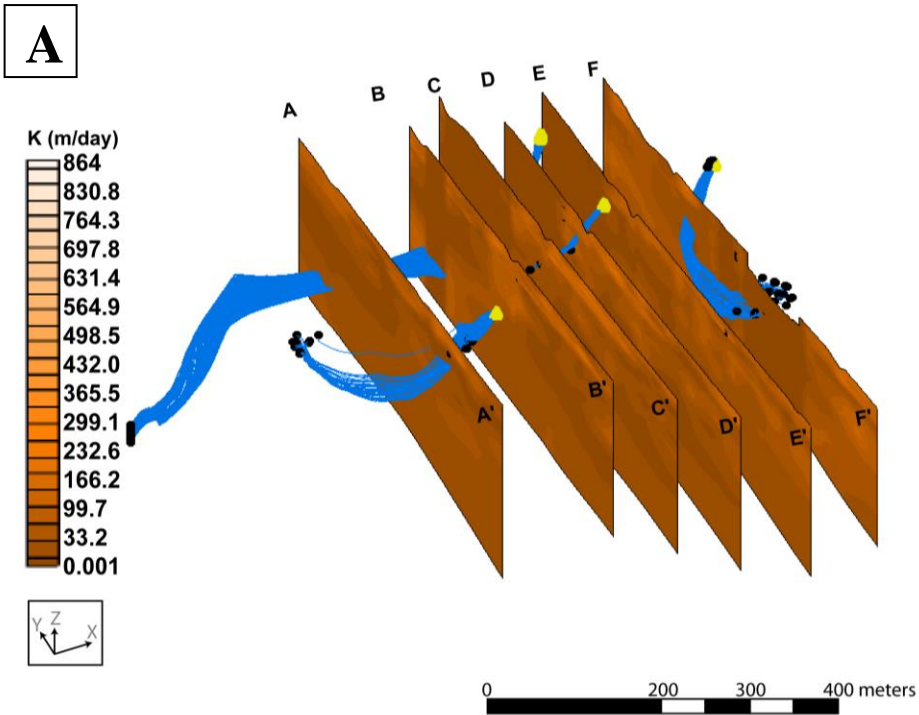


Figure 16: Map view of particles released within the general head boundary cells that delineate the Tuolumne River: **A:** In the model without the IVF the advective pathlines are short and follow the hydraulic gradient and **B:** In the model with the IVF, the advective pathlines are longer and follow the IVF. Vertical exaggeration is 50. Shown in color.

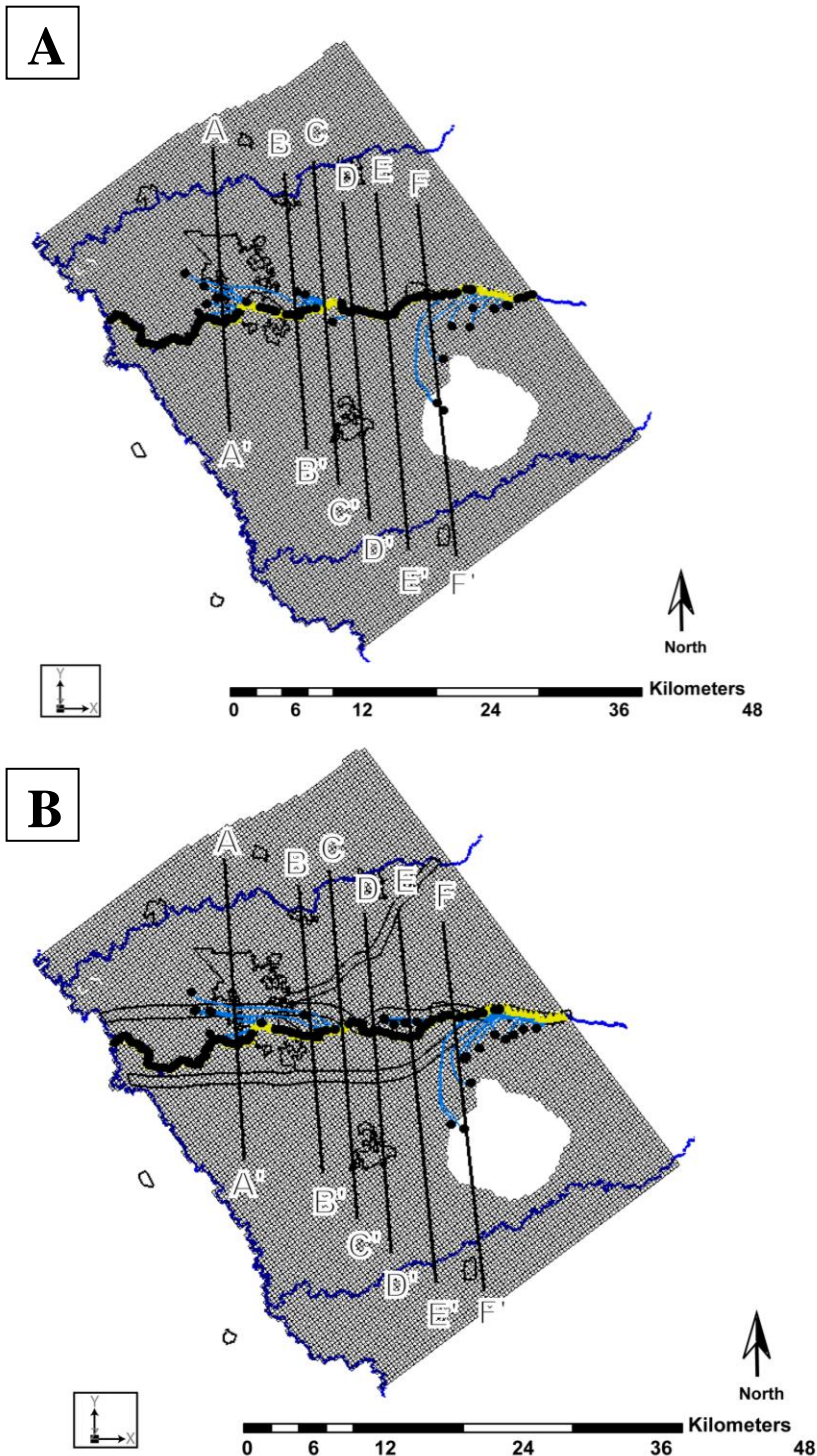


Figure 17: Cross-section of particles released within the general head boundary cells that delineate the Tuolumne Rivers. Vertical exaggeration is 50. **A:** In the model without the IVF the advective pathlines are short and follow the hydraulic gradient and **B:** The model with the IVF shows, in losing portions of the stream, the advective pathlines move from the river into the IVF. Advective pathlines from particles released within the river also migrate beneath the city of Modesto. Shown in color.

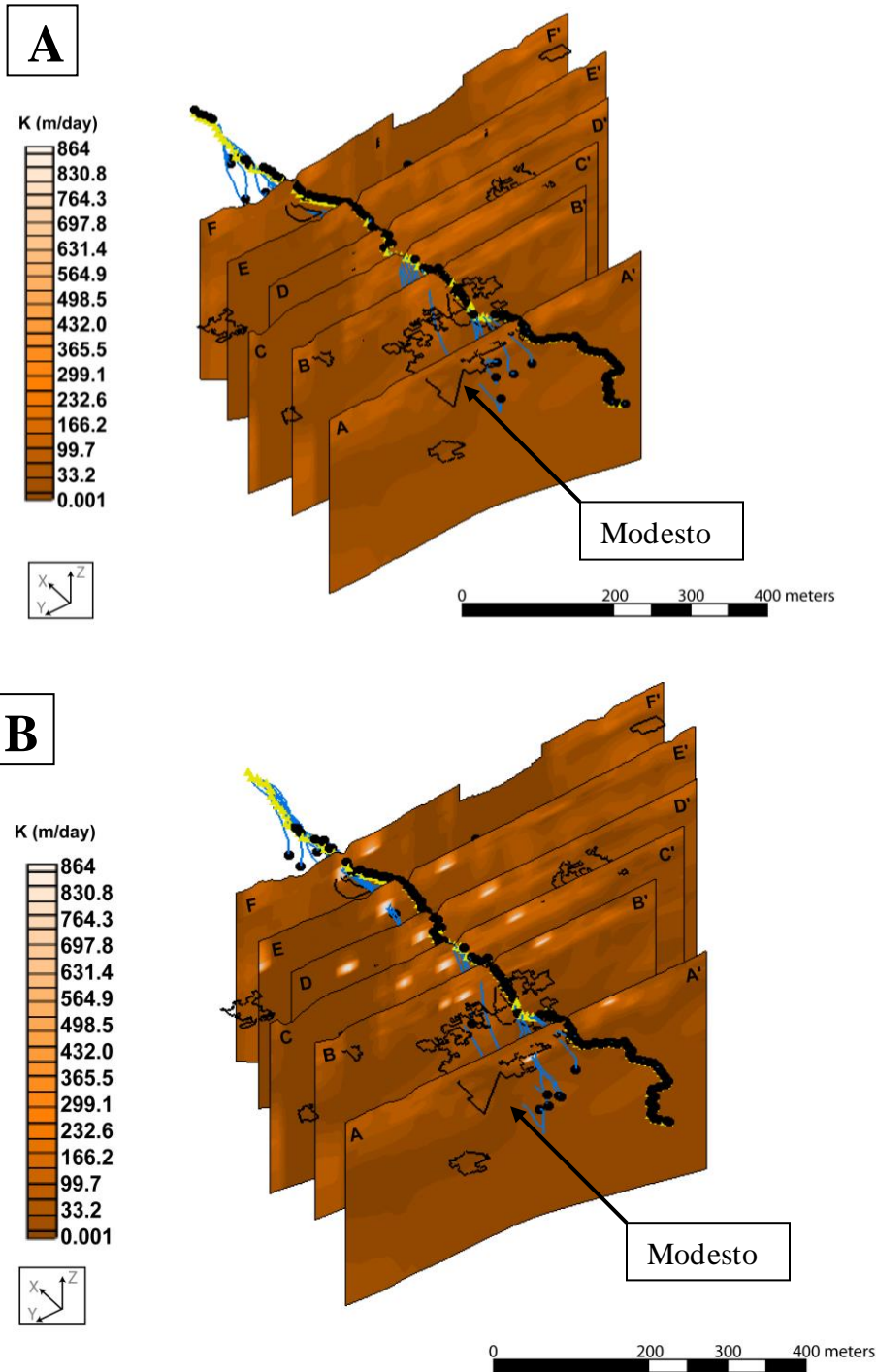
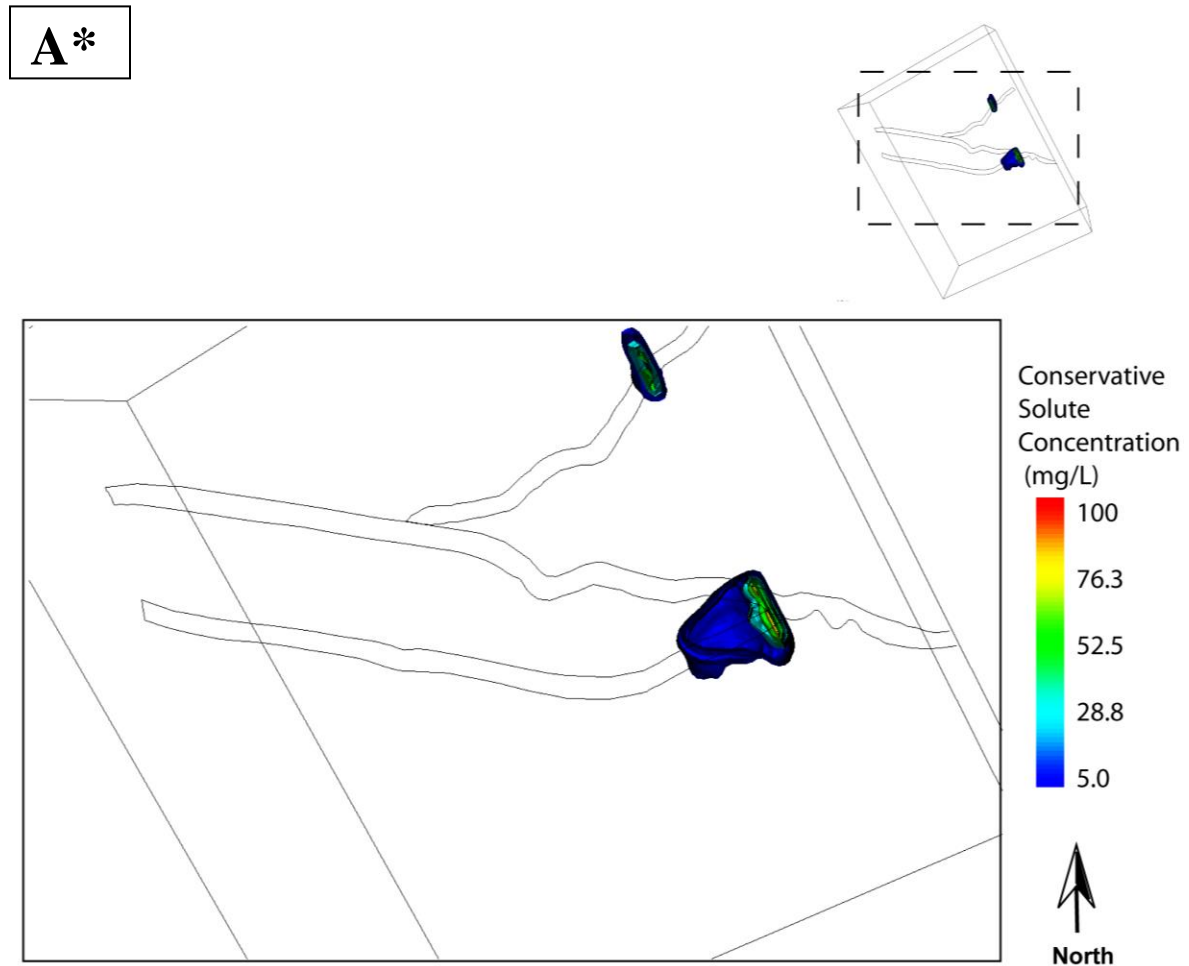


Figure 18A: Solute transport simulations were run for 150 years. **A:** Shows the uniform plume morphology in the modified model without the IVF. **NOTE:** The IVFs are NOT in this model. The IVF outline is shown only to facilitate reference between figures. **B:** Shows the plume morphology in the model with the IVFs. The plume preferentially follows the IVF and allows higher concentrations of the contaminant to move farther distances and more deeply into the aquifer in the same amount of time as the modified model without the IVFs. Shown in color.



*NOTE: In figure A, the IVF outline is only shown for reference.

Figure 18B: Solute transport simulations were run for 150 years. **B:** Shows the plume morphology in the model with the IVFs. The plume preferentially follows the IVF and allows higher concentrations of the contaminant to move farther distances and more deeply into the aquifer in the same amount of time as the modified model without the IVFs. Shown in color.

B

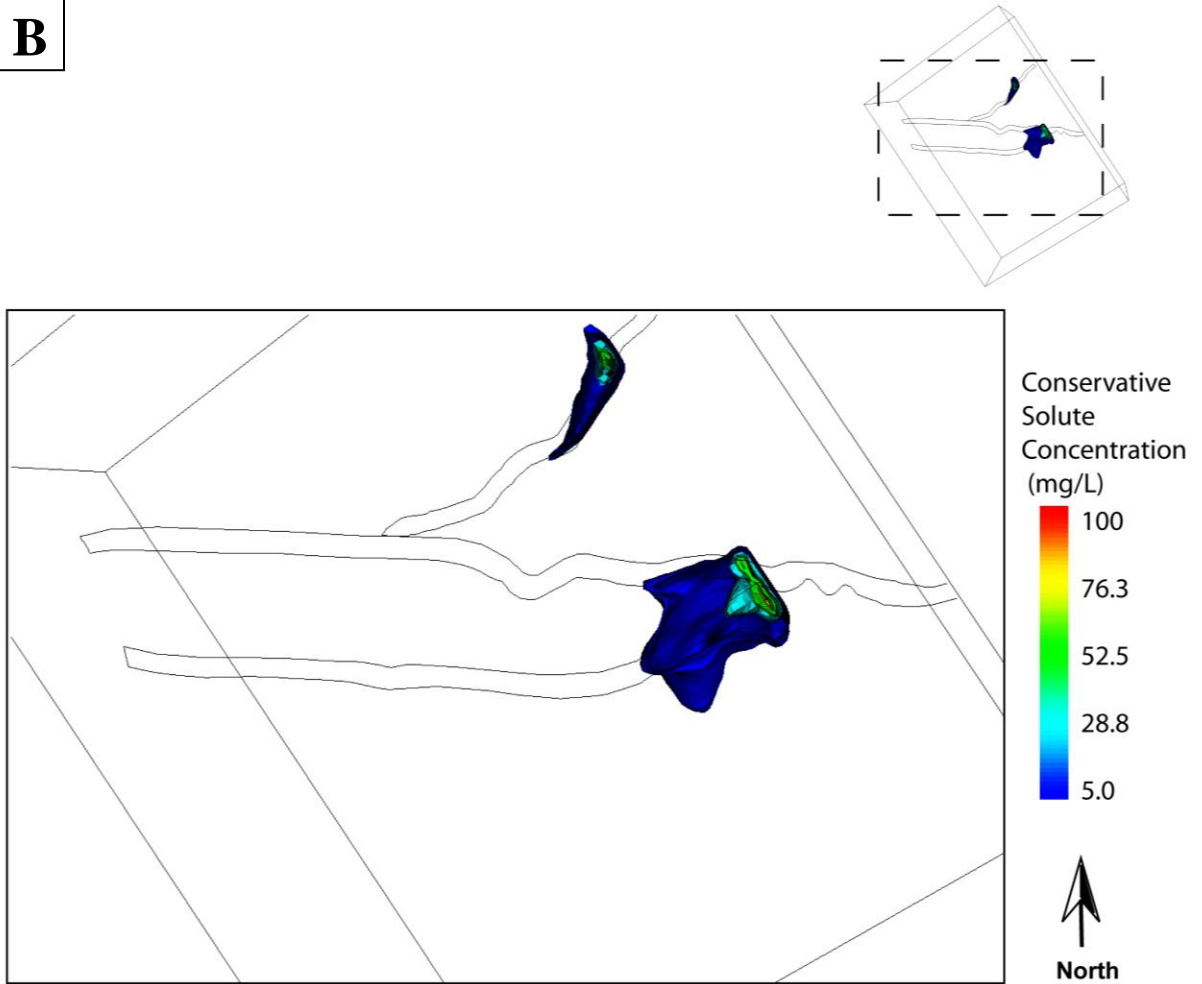
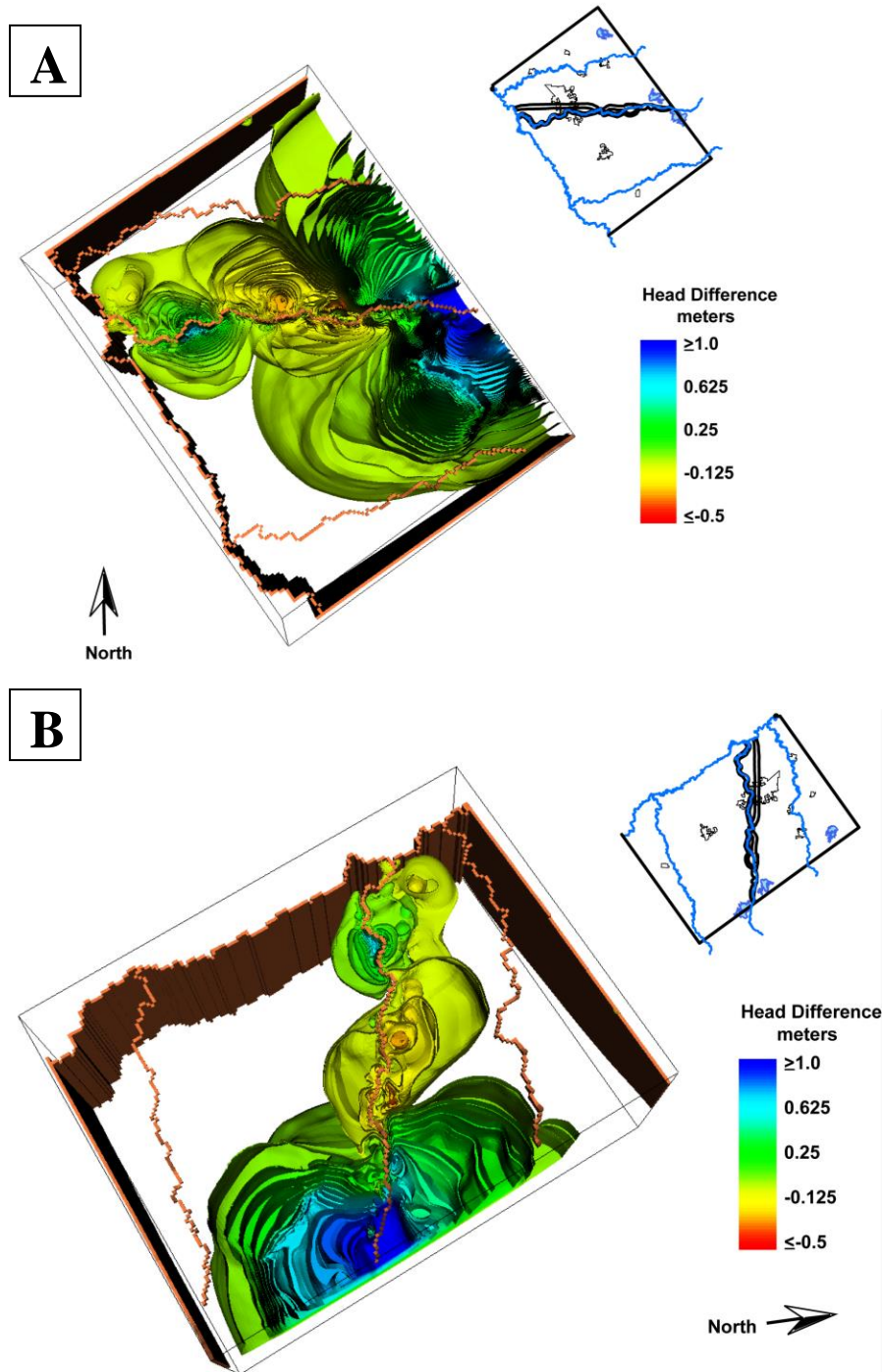


Figure 19: Head differences between the model without IVFs and the IVF model (RB/MS). Positive residuals (yellow to red) indicate areas of the model where the head elevations are lower in the IVF model than in the model without the IVF. Negative residuals (green to blue) indicate areas where the head elevation is higher in the IVF model than in the model without the IVF. (Elevations are in meters and the vertical exaggeration is 50). **A:** 63 isosurfaces. **B:** 20 isosurfaces. Shown in color.



Chapter 3: Conclusions and Future Work

CONCLUSIONS

The primary purpose of this study was to understand the impact incised-valley fills (IVFs) have on regional groundwater flow, contaminant transport, and the potential for artificial aquifer recharge in the Tuolumne River fluvial fan aquifer around Modesto, California. This task was accomplished by (1) assessing the stratigraphic character of the study area with well logs and core in order to construct model domains that capture this character and then (2) simulating groundwater flows and solute tracers through these models.

The most current regional scale groundwater model in the Modesto, California area, developed by the USGS (S. Phillips, unpublished model, 2005), used previously collected data (driller's logs, geophysical logs, and a few continuous cores) to characterize the area's hydrogeology (Burow *et al.*, 2004). While this model is a reasonable representation of the area geology and hydrologic regime, it does not implicitly include the IVFs.

By adapting the existing USGS model to incorporate the IVFs, this thesis shows that the IVFs are critical to understanding the regional hydraulic regime. To include the IVFs in the model, sequence stratigraphic concepts, by Weissmann *et al.* (2002b), were applied to characterize IVF geometry and character for integration into the USGS groundwater flow model. With a sequence stratigraphic model, a more accurate model of the regional geology could be generated, even in areas where little subsurface data were available. Addition of the IVF improves the geologic model of the Modesto area and in turn the understanding of regional groundwater flow and solute transport.

Assessment of Stratigraphic Character

Stratigraphic character assessment was completed through the analysis of two soft sediment continuous cores and many (>10,000) driller's well logs. The continuous cores were used to develop a better understanding of the fan deposits surrounding the IVF. The use of a ranking scheme for driller's well logs and subsequent analysis in this study helped to find several potential locations for the IVF. The thick gravel base of the IVF provided a means to identify the location of the IVF.

While it would have been ideal to incorporate more core data into this model, the two cores that were described in the study area did not provide a sufficient amount of data to generate statistical realizations of the area. The two cores were used to supplement the understanding of the surrounding IVF deposits.

Two conclusions come from the investigation of driller's logs: (1) such driller's logs can be used with reasonable success to generally identify the position of IVFs by focusing on presence or absence of thick gravel units and (2) multiple (four) geologic scenarios were developed to help assess the influence of the IVF on regional groundwater flow and assess the impact of model uncertainty.

While the quality of driller's logs is often unreliable, there are certain instances where these logs can be used with relative confidence. The use of the driller's logs as an initial attempt to delineate the IVF and identify the thick, gravel base of the IVF provides a good example of the appropriate application of driller's logs. Because of the coarse grained nature and significant thickness of these deposits, the driller's reliability to properly identify the interval increases.

Although the driller's logs were used in this study with some success, they should be employed for subsurface analysis with caution. For example, I was able to identify several IVF locations, which may or may not actually exist. The geometry of the IVF

was inferred from the current topography. These trends need to be validated with further geophysical survey (e.g. seismic reflection) studies to better locate and describe the IVF geometry and stratigraphy.

Simulation of Groundwater Flow and Solute Tracers

The groundwater models developed to test the influence of the IVF resulted in four main conclusions. The addition of the IVF (1) changes regional hydraulic heads regimes (2) allows pathlines (water) to move more rapidly to a greater lateral extent and deeper into the aquifer (3) allows flow (illustrated by particle pathlines) to spread into the aquifer sediments adjacent to the IVF and (4) creates a preferential pathway for contaminant plumes, decreasing solute transport times in areas where the IVF is located.

The creation of a preferential pathway from the addition of the IVF is not easily identified simply through the measurement of head elevations. As was shown by the slight variation in head elevations in the model with and without the IVF, measurements of groundwater levels alone would not indicate the presence of these preferential pathways. Examining the model head solutions alone also provided very little insight into the influence of the IVF on groundwater flow. To better illustrate the influence of the IVF, the head difference between the model with and without the IVF was used to show the areas of convergent and divergent flow. Areas where the head levels are lower in the model with the IVF indicate that the flow in that area converges on the IVF. In steady-state conditions represented by this model, the IVF is “funneling” the maximum amount of water through the available effective pore space, which causes the water to “back-up” and diverge from the IVF.

Pathline analysis experiments were used to assess the advective flow in the model and illustrate the impact of flow changes along the IVF. Pathlines in the model without the

IVF have little lateral movement and vertically tend to follow with the local gradient. Pathlines in this model do not disperse in various directions in the aquifer; rather, they all have similar trends that reflect the regional head gradients. In the model with the IVF, however, pathlines follow the IVF and are dispersed into the contiguous aquifer sediments.

Transport experiments reaffirm the pathline analysis results. In the model without the IVF, transport simulations reveal that the plume expands in a uniform radial pattern from the constant contaminant source. In the model with the IVFs, the solute transport simulations clearly illustrate the changes in the plume morphology with the addition of the IVF. The contaminant plume preferentially follows the path of the IVF. The IVF increases the distance the plume can travel in the same amount of time, thus resulting in a transport time that would be shorter than predicted using the model without the IVF.

These results show that the IVF provides a pathway of preferential flow for groundwater as well as contaminants. In the terms of managing the regional water quality, this is both beneficial and detrimental. The IVF provides the benefit of potentially providing a conduit to artificially recharge the aquifer. Recharge will be important to provide sustainable water supply to the city of Modesto. While the IVF provides a good source for artificial recharge, unfortunately, it also creates a pathway for contamination to enter and disperse into the aquifer, exposing the entire aquifer to potential contamination.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

While the realizations generated in this study provide a good preliminary understanding of the influence of the IVF, these realizations should be used as a basis for

further investigation into the area stratigraphy and hydrologic regime. The geologic realizations could be improved by (1) using more reliable methods for identifying the location of the IVF (2) obtaining core through several locations of the IVF to better understand IVF lithologic character and (3) collecting additional continuous core in the open fan deposit areas.

Further investigation into the location of the IVF should be conducted. While analysis from driller's well logs provides a good approximate location of the IVF more reliable geophysical data should be accrued, to effectively model the IVF. Seismic data across the area will help better constrain the location and geometry of these features, providing more dependable estimations of the width, depth, and length of the IVF.

In this study, no core was collected within the IVF. This made modeling of the lithologic character more challenging. The character of the apex and toe of the IVF need to be investigated as these are the principle areas of recharge and discharge for groundwater and will impact the location of the divergent flow from the valley. Investigation into the toe of the fan may provide insight into the influence of local base level (sea level) and the basin width on the preservation (or removal) of the distal fan deposits. Currently, the IVF code does not account for the fact that gravels are not likely present in the distal portion of the model. With further constraints on the distal character in the IVF, this portion of the model could be improved. Additional studies near the apex of the fan will provide further insight into the geometry of the stacked IVF deposits believed to exist. This may have a significant influence on the ability to artificially recharge the aquifer.

Additional continuous core data across that fan will also help to better capture the aquifer heterogeneity. One significant improvement in this area would be to add the

sequence bounding paleosols. While this model does not include the paleosols, they may have an impact on the regional or local groundwater flow, acting as no or low flow barriers, as noted on the Kings River fluvial fan (Weissmann *et al.*, 2004).

The groundwater and contaminant transport models generated in this study enhance understanding of the groundwater flow and the potential for contaminant movement through the Modesto area. The models also provide a preliminary understanding of the potential influence these incised-valley fills may have on artificial recharge in the incised-valley fill.

SUMMARY

The coarse-grained continuous nature of the IVFs indicates that the IVF in the Modesto area is capable of acting like a regional conduit for groundwater flow and contaminant transport. Our results support those reported by Weissmann *et al.* (2004) who created groundwater flow and contaminant transport models in studies of similar IVF deposits of the Kings River near Fresno, California. They showed that IVFs significantly influence groundwater flow and contaminant transport specifically by providing the potential for (1) increased groundwater flow and production rates (2) rapid contaminant transport within the incised-valley fill sediments and (3) rapid contaminant movement from the incised-valley fill into the contiguous aquifer sediments. Based on the results of this study, the identified IVF beneath the Modesto area has a similar effect. Continued and more detailed studies on the influence of the IVF will help to fully explore the potential role the IVF plays in artificial aquifer recharge and regional water quality in that area.

Furthermore, implications of these conclusions are directly applicable to the current and continuing USGS investigation into the groundwater status and long term quality, for

which the original model was created. The eastern fluvial fans in the San Joaquin valley have been primarily agricultural land and subjected to substantial amounts of fertilizer application and irrigation since the early 1900's (Gronberg *et al.*, 2004). An investigation of the transport of anthropogenic and natural contaminants to community supply wells by the USGS is already underway in the Modesto area. The main question motivating this USGS investigation of the groundwater status is, "What are the primary man-made and natural contaminant sources, aquifer processes, and well characteristics that control the transport and transformation of contaminants along flow paths to community supply wells in representative water-supply aquifers?" (Gronberg *et al.*, 2004, p.4). The specific objectives of the study are to (1) characterize the regional geologic setting to determine the preferential or most common, groundwater pathways to community supply wells and (2) gain an understanding of the sources of contaminants in the aquifer and the processes that impact the transport and potential transformation of the contaminants (Gronberg *et al.*, 2004). The addition of the IVF into the USGS model will greatly improve the current groundwater model's ability to illustrate the dominant pathways for transport. Areas where contamination of the Tuolumne River can migrate deep into the groundwater would also be highlighted in a groundwater model that incorporates the IVFs. In terms of remediation, it is vital to understand the sources and pathways of the chemicals to better treat or remove the contaminant. The IVF provides a preferential path for water flowing downward through the river bed thus creating a potential conduit for runoff contaminants like fertilizers that will degrade water quality and should be addressed. The realizations developed in this study show that the IVFs significantly influence the groundwater flow by acting as a regional "pipeline" of coarse sediment that creates the potential to provide artificial recharge to the Modesto area and a conduit for contaminants to follow,

increasing the dispersion of particle pathlines into contiguous aquifer sediments and enabling solute plumes to move farther distances more rapidly leaving the aquifer susceptible to widespread contamination.

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Appendix A: Geologic Setting and Stratigraphic Character

INTRODUCTION

Through this study, we intend to show the influence of relatively coarse-grained incised-valley fills (IVFs) on groundwater flow, contaminant transport, and potential artificial recharge in the Modesto, California area. To assess the influence of the IVFs, an investigation of the area geology was conducted to locate and characterize the IVFs and the surrounding sediment.

In this appendix, I first describe the regional geology and stratigraphy. Next, the local geology is described with the findings of geologic investigations using sediment core and driller's well log data. The results of this investigation are then incorporated into four geologic realizations.

BACKGROUND GEOLOGY

San Joaquin Basin and Regional Geologic Setting

The San Joaquin Basin is located within the California's Great Valley, an approximately 700 km long (north to south) by 100 km wide (east to west) valley that is bound on the east by the Sierra Nevada and on the west by the Coast Ranges. The valley is divided into two sub-basins by the Stockton Arch, a buried transverse arch, with the Sacramento Basin in the north and San Joaquin Basin in the south (See Figure 1 from Chapter 2). The basin is underlain by crystalline basement rock and approximately 9 km of Mesozoic and Cenozoic sedimentary rocks and sediments (Bartow, 1988). Structurally, the basin is asymmetric with a gently sloping eastern margin that abuts the Sierra Nevada, and the more steeply sloping western edge adjacent to the Coast Ranges. This study focuses on the Tuolumne River fan, located in the northeast portion of the San

Joaquin Basin (Figure 1). The fan was formed where the Tuolumne River flows west out of the Sierra Nevada into the San Joaquin Basin.

Climate Effects on Quaternary Deposits in the Eastern San Joaquin Valley

Quaternary fluvial fan deposits along the eastern San Joaquin Valley preserve evidence of past phases of aggradation and degradation from varying amounts of sediment supply and discharge in response to recurring glacial periods in the Sierra Nevada (Janda, 1966, Marchand 1977, Huntington 1980, Marchand and Allwardt 1981, Lettis 1988, and Weissmann *et al.* 2002b, 2006). Fluvial fans are differentiated from alluvial fans in this study to emphasize that fluvial fans are characterized by perennial fluvial processes, while alluvial fans are characterized more by ephemeral debris flows or sheetfloods. Similarities among the fluvial fans along the eastern portion of the valley have allowed for basin-scale comparisons of these fans (Weissmann *et al.*, 2006).

Weissmann *et al.* (2002b) investigated the fluvial fan deposits on the Kings River fan and use a sequence stratigraphic model to understand the climatically induced cycles of deposition. In the model, they apply the traditional definition of a sequence as "...a relatively conformable succession of genetically related strata bounded at its top and base by unconformities, or their correlative conformities" (Mitchum, 1977, p. 210). Sequence boundaries in this model are identified as the paleosol surface and respective IVF base that divide the fluvial fan deposits into five stratigraphic units.

In this sequence stratigraphic model, concepts of *accumulation* and *preservation* space (after Blum and Törnqvist, 2000) are used to understand the stratigraphy. Accumulation space is defined as one component of accommodation space and refers to the volume of space available to be filled with sediment and is dependent on the balance of sediment supply and stream discharge as well as channel geometry. Preservation space

is also a component of accommodation space and is the space below the lowest level of sediment removal. In the Kings River and Tuolumne River areas, it is a long-term, preservation space controlled by the local subsidence rate. The five sequences marked distinct periods of regional aggradation and degradation, or accumulation space change. Packages of relatively rapidly deposited fluvial fan deposits separated by paleosols indicate periods of aggradation across the fan, or increased accumulation space, punctuated by periods of degradation and fan incision, or restricted accumulation space and quiescence on the upper parts of the fan. Preservation space was created by constant subsidence in the area, which lowered the deposits below the lowest level of erosion (sequence stratigraphic model described in more detail in the next paragraph). Sequence boundaries in this model are identified as the paleosol surface and respective IVF base that divide the fluvial fan deposits into five stratigraphic units.

Specifically, fluvial fan aggradation or degradation occurred on the Kings River fan as sediment supply to discharge ratios increased or decreased as a result of changes from glacial to interglacial climate. Interglacial periods are marked by limited aggradation, a low accumulation space, and an intersection point located distally on the fan (Figure A1) (Weissmann *et al.*, 2002b). During this portion of the cycle, paleosols formed in the exposed upper fan outside the incised valleys. Glacial periods are characterized by a large amount of laterally extensive aggradation on the fan, a high accumulation space, and an intersection point proximally located near the apex of the fan (Figure A2). Weissmann *et al.* (2002b) indicated that this sequence stratigraphic model can serve as a means to predict facies distributions and stratigraphic relationships in areas exposed to similar conditions.

Due to the similar cyclic depositional character among the fans in the eastern San Joaquin basin, the sequence stratigraphic model described in the Kings River fan study can be applied to other fans in the basin. However climate and sediment supply to stream discharge ratios are not the only controls on the deposition of the fluvial fans in the valley (Weissmann *et al.*, 2006). Factors that control the overall amount of accumulation space available during periods of climate fluctuation and hence sequence development are: (1) the sediment supply to stream discharge ratio, (2) the rate of basin subsidence, (3) the amount of local base level change, and (4) the basin width (Weissmann, *et al.*, 2006). These controls vary within the San Joaquin Basin and influence the sequence geometry on individual fans.

Controls on the Tuolumne River fluvial fan sequence geometry in particular are (1) glacial influence in the drainage basin (2) relatively low subsidence rates (approximately 30cm/ 1000 yrs, Lettis, 1988) due to the river's location in the northern portion of the San Joaquin Valley, and (3) the San Joaquin River as local base level control on Tuolumne River elevation (Weissmann *et al.*, 2006). The Tuolumne River drains the Sierra Nevada which resulted in cycles of significant fluctuations in the sediment supply and stream discharge from Quaternary glaciations. Because the Tuolumne River is in the north, where the San Joaquin Valley is narrower and the subsidence rate is relatively low (30 cm/1000 yrs, Lettis, 1988), sequence thickness and lateral extent were thinner and smaller than found in southern portions of the valley. This resulted in an overall reduction in accumulation and preservation space, which caused the lateral progression of apexes and the thinner fluvial fan units observed here (Weissmann *et al.* 2006; Bennett *et al. in press*; See Figure 2 in Chapter 2). The local base level is connected to the San Joaquin River and ultimately sea level. This resulted in deeper

incision and sediment bypass in the distal portions the fan during interglacial periods, also reducing the overall amount of accumulation space available to be filled.

LOCAL GEOLOGIC INVESTIGATION

Study Area

The study area is delineated by the Sierra Nevada and the San Joaquin River to the east and west, respectively, and by the Stanislaus and Merced Rivers to the north and south (See Figure 3 in Chapter 2). It is approximately 48 km (30 miles) long (west to east) and 19 km (12 miles) wide (north to south). Dissecting the site is the Tuolumne River, which flows east to west through the middle of the study area (See Figure 3 in Chapter 2). Deposits at the site are composed mainly of Cenozoic sedimentary deposits (Marchand and Allwardt, 1981). This study of the Modesto area will focus on the Quaternary Pleistocene fluvial deposits: the Turlock Lake Formation, the Riverbank Formation and the Modesto Formation (See Figure 1 in Chapter 2). A more comprehensive description of the older units in the area can be found in Marchand and Allwardt (1981).

Stratigraphic Units

Each unit of open-fan deposits is bound at the top and bottom by a paleosol and is composed of silty, sandy, and clayey sediments with discrete coarser-grained channel deposits. Nestled among the relatively fine-grained open-fan sediments is the relatively coarse-grained IVF, characterized by a thick basal gravel lag (5 to 9 meters) that gradually fines up to the surface (See Figure 4 in Chapter 2).

Characterization of hydrofacies within the fluvial fan deposits was done by using methods similar to those described in Weissmann *et al.* (2002b) where we utilized several

sources of geologic data, including driller's well logs, geophysical logs, and lithology from continuous core samples. Cooperation with the U.S. Geological Survey (USGS) in Sacramento, California afforded access to several thousand paper copies of the Department of Water Resources (DWR) driller's logs within the study area, geophysical well logs from city wells, and recently obtained, relatively-continuous, soft sediment core. Also available from the USGS are digitized spatial data of the area hydrology, geology, soils, topography, and approximate pumping rates of the city of Modesto municipal wells (S. Phillips, unpublished data, 2005).

Open-fan Deposit Character

Four hydrofacies were identified within the study area from two continuous soft sediment cores collected by the USGS (See Figure 3 in Chapter 2) and well logs from the California Department of Water Resources (DWR) (See Appendix B for detailed descriptions). Included in the core descriptions are a visual estimation of grain size, grain shape, grain sorting, color, primary sedimentary structures, and secondary alterations (including pedogenic alteration). The core descriptions were used to better understand hydrofacies in the proximal (eastern) and distal (western) open-fan deposits. The core data were also used to help generate the fan surfaces used in the IVF fill code in Appendix G. The hydrofacies include: (1) gravel channel deposits (not recovered in these cores but observed in drillers' logs and described by Weissmann *et al.*, 2002b) (2) sand channel deposits (3) silty sands, silty clays, and clay overbank deposits, and (4) pedogenically altered deposits. The core descriptions show that the western extent of the study area contained more fine-grained sediments of the distal fluvial fan deposits, while the eastern extent of the study area contained the more coarse-grained proximal fluvial fan sediments.

Gravel Channel Deposits

Although the gravel channel deposits of the IVF were not seen in these cores, descriptions by Weissmann *et al.* (2002b) indicate that the gravel is composed of clast-supported gravel and cobbles and are commonly found at the channel base.

A few thin intervals of poorly sorted, matrix supported, gravel flood deposits were observed in the core (Figure A3). The matrix is coarse to very coarse sub-angular sand with some granules. The gravel is 1 to 4 cm (0.4 to 1.6 inches). The deposits do not show any primary structures and tend to be heavily iron stained. In both the proximal and distal portions of the fan, these thin gravels are sparse and were located at depth: MREA at 70 meters (230 ft) and MRWA at 55 meters (180 ft). The proximal gravels overall are more coarse than the distal deposits and have less matrix material. The gravel in the distal deposits has fewer large clasts of gravel within the coarse matrix.

Sand Channel Deposits

The channel sand facies (Figure A4) are well sorted, mica rich quartz and feldspathic arenites. The mica is present in large unweathered flakes giving the core a “glittery” appearance. They range in grain size from very fine to coarse sand and are sub-rounded to sub-angular. These channel sands were commonly noted to have a poorly-sorted matrix-supported pebbles at the basal contact. These deposits are typically cross-stratified but were also observed without any primary structures (massive). The channel sand deposits also commonly display a fining upward trend. Proximal fan deposits are more coarsely grained (medium to coarse or very coarse sand) while distal deposits tend to have a finer grain size (very fine to medium grained). Distal deposits showed less evidence of secondary alteration and tended to show more distinct heavy mineral banding along cross-bedding planes.

Overbank Deposits

Overbank deposits (Figure A5) characterized in the cores was silty fine to very fine sand, silty clay, or clayey silt. They are gray to light brown in color with occasional sandy lenses. Slight to no pedogenic alteration was observed. These deposits were commonly thinly laminated, although some massive deposits were observed. Root traces and/or burrows were also observed within the overbank deposits. Iron staining/ mottling was also a very common characteristic among the overbank deposits. Proximal overbank deposits have more silty sands a smaller fraction of silt and clay than was observed in the distal deposits. The distal deposits are most commonly sandy or clayey silt.

Pedogenically Altered Deposits

Reddish colored pedogenically-altered sand with medium to thick clay coats was also present in the cores (Figure A6). Hues range 2.5YR to 10YR in the proximal and 5YR to 10YR (mostly 7.5YR). Value ranges from 4 to 5 in the proximal and 5 to 6 in the distal, and chroma ranges from 3 to 6 in the proximal and 2 to 4 in the distal. These deposits are the most developed paleosols observed in the core samples. Slickensides and root traces are also present in these deposits. Proximal paleosols are better developed with thicker clay coats (thick to medium) and have a stronger reddish coloring. The distal paleosols are less well developed with thinner clay coats (medium to light) and do not always exhibit the distinct reddish coloring seen in the proximal paleosols.

Incised-Valley Fill Geometry

Core was not collected within the targeted IVF deposit. However, Weissmann *et al.* (2002b, 2004) noted that the incised-valley fill could be recognized in driller's logs by a thick gravel or cobble base with overlying sandy facies. These coarse-grained deposits form approximately two-thirds of the fill deposit. Burow *et al.*, (2004) indicated that the

IVF could also be recognized in geophysical logs by a relatively high resistivity and a correspondingly low gamma ray response. This method was adapted and applied to locate and describe the IVF character in the Modesto area using available driller's well logs and geophysical well logs. .

Identification of Incised-Valley Fill with Driller's Well Logs

Approximately 10,000 well logs from the study area were examined. The well logs used for this investigation are the same as those initially filtered by the USGS to develop a database (described in *Burow et al. (2004)*). Logs containing gravels of sufficient thickness (> 3 meters) were assigned a rank of 1 to 4 based on how well the log's description of the stratigraphy resembled the fining-upward prototype characterization of the incised-valley fill. A well assigned a rank of 1 denotes the best representation of the incised-valley fill, with a thick gravel base fining upward to sand then silt and clay, while a well ranked 4 contains thick gravel but does not resemble the ideal fining-upward succession contained within the incised-valley fill deposits. Examples of driller's well logs of various ranks are included in Appendix C. The drilling method and the consistent quality of individual drillers were also used to determine the rank of the well.

Once all of the wells had been ranked, a database of these well logs was generated in ArcGIS to locate the incised-valley fill (Figure A7). Wells were located using reported addresses and descriptors on logs, and then well location coordinates were obtained by plotting them as waypoints in National Geographic TOPO! California. Information that was entered into the database of wells includes (1) the well identification number (2) the rank of the well, (3) the elevation of the well, (4) the depth of the gravel lag deposit, (5) whether or not the well had previously been selected for a USGS database, (6) the

relative depth of the gravel (shallow or deep), and (7) general notes about the log. The results of IVF delineation is described in Chapter 2 and Appendix C.

A potential source for uncertainty in this method of delineating the IVFs is created by using driller's well logs as the primary data set. There is significant uncertainty when identifying the basal gravel lag within the IVF through interpretation of the driller's logs. The quality and accuracy of the logs may be questionable and somewhat unreliable for detailed subsurface correlation. Quality strongly depends on the driller's ability and conscientiousness, and even under the best circumstances, carries significant uncertainty. More easily drilled units, such as sand and clay, may not be noted accurately during drilling, as there is no variation in the rig character or drilling techniques required. However, well logs are successfully used in this study to identify thick gravel deposits. These thick basal gravel lag deposits result in a distinct change in the rig behavior. For this reason, it is assumed that the depth of the gravel units, as well as their thicknesses, will be consistently more correctly described in the log than sand, silt, or clay, thus allowing more reasonable identification of the incised-valley fills.

Construction of Sequence Bounding Surfaces

Prior to generating the groundwater models, digital spatial data were used to generate surfaces for the model layers and for use in FORTRAN codes to insert the IVF in the model. Surfaces depicting the incised channel were developed by (1) adapting the modern Tuolumne River valley from the digital elevation model (DEM) for the Riverbank Formation fan surface and (2) by using ArcGRID to interpolate the older Turlock Lake Formation fan surface (See Appendix D). The present ground surface was assumed to be a sufficient estimate of the Riverbank fan surface outside the IVF, because the Modesto formation that covers the area is only a thin veneer over the fan surface

(Bennett, 2003; Weissmann *et al.*, 2006; Bennett *et al. in press*), . The Turlock Lake Formation surface was developed with data from well logs, digital soil maps, and core data. Surfaces were combined to match the four geologic scenarios described in Chapter 2 (See Table 1 in Chapter 2).

CONCLUSION

Two conclusions come from the analysis of the IVF and surrounding open fan deposits: (1) driller's logs can be used with reasonable success to generally identify the position of IVFs by focusing on presence or absence of thick gravel units and (2) multiple (four) geologic scenarios were developed to help assess the influence of the IVF on regional groundwater flow and assess the impact of model uncertainty.

While the driller's logs were successfully applied, there are still significant improvements that can be made to locating and defining the IVFs. It is unlikely that multiple potential IVFs within the same stratigraphic range (i.e. two potential Modesto Formation IVFs) exist, although were identified. Using four geologic scenarios, the influence of the IVF can be assessed as along with the impact of uncertainty in geologic model. Comparisons among these four scenarios may give insight to the impact of incorrectly developing a conceptual model.

To improve this analysis of the Tuolumne River fluvial fan sediments and stratigraphy, further collection of geologic data is needed. This data collection effort might help constrain the location and the geometry of the IVF. Suggestions for investigation include: seismic studies to delineate the extent of the IVF and additional continuous core data from the area to provide a better definition of the character of the IVF sediments and their variation proximally or distally on the fan. Supplementing the

current characterization of the open-fan deposits from more continuous core would be vital to generate a geostatistical model to illustrate the distribution of hydrofacies and supply information to parameterize the deposits that surround the incised-valley fills. While it would have been ideal to use the core descriptions to generate geostatistical realizations for this study, the data set (inclusive of the two wells described above) was not large enough for proper statistical analysis.

The geologic analysis described in this appendix provides the framework for the groundwater flow and solute transport models described in Chapter 2 of this thesis. The groundwater and contaminant transport models produced are expected to enhance understanding of the groundwater flow and the potential for contaminant movement through the Modesto area. Additionally, the models are also expected to provide a preliminary understanding of the potential influence these incised-valley fills may have on artificial recharge in the incised-valley fill.

Figure A1: Map and cross-sectional view of the balance between aggrading and degrading reaches in deposits on the Kings River. Changes in accumulation space are inferred by a shifting intersection point that marked the aggrading (lower fan) and degrading reaches (incised channel) of the river. (adapted from Weissmann *et al.*, 2002b).

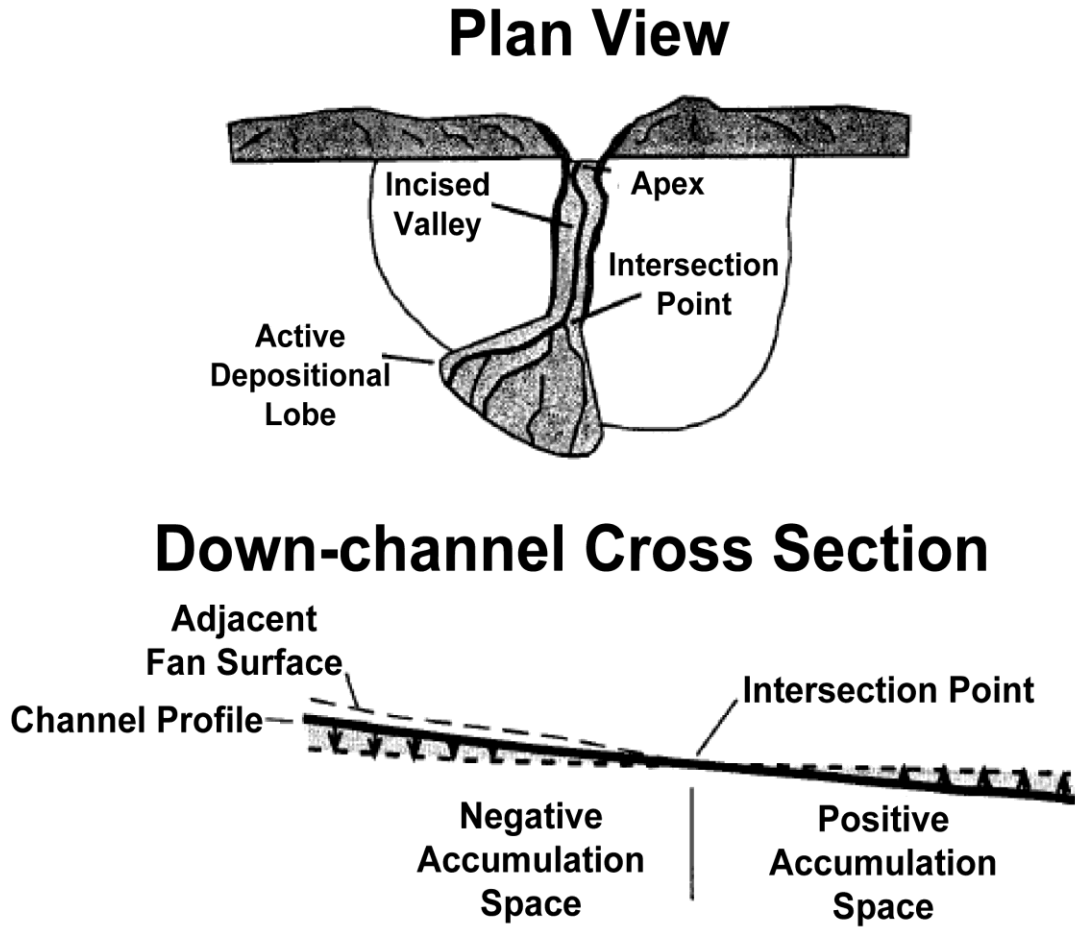


Figure A2: Four diagrams of various depositional regimes through a full glacial to interglacial cycle. The intersection point of the fan, or the transition between aggrading and degrading reaches, will shift up and down the fan as sediment supply:discharge ratios increase and decrease, respectively, with changes from glacial to interglacial episodes. (adapted from Weissmann *et al.*, 2002b).

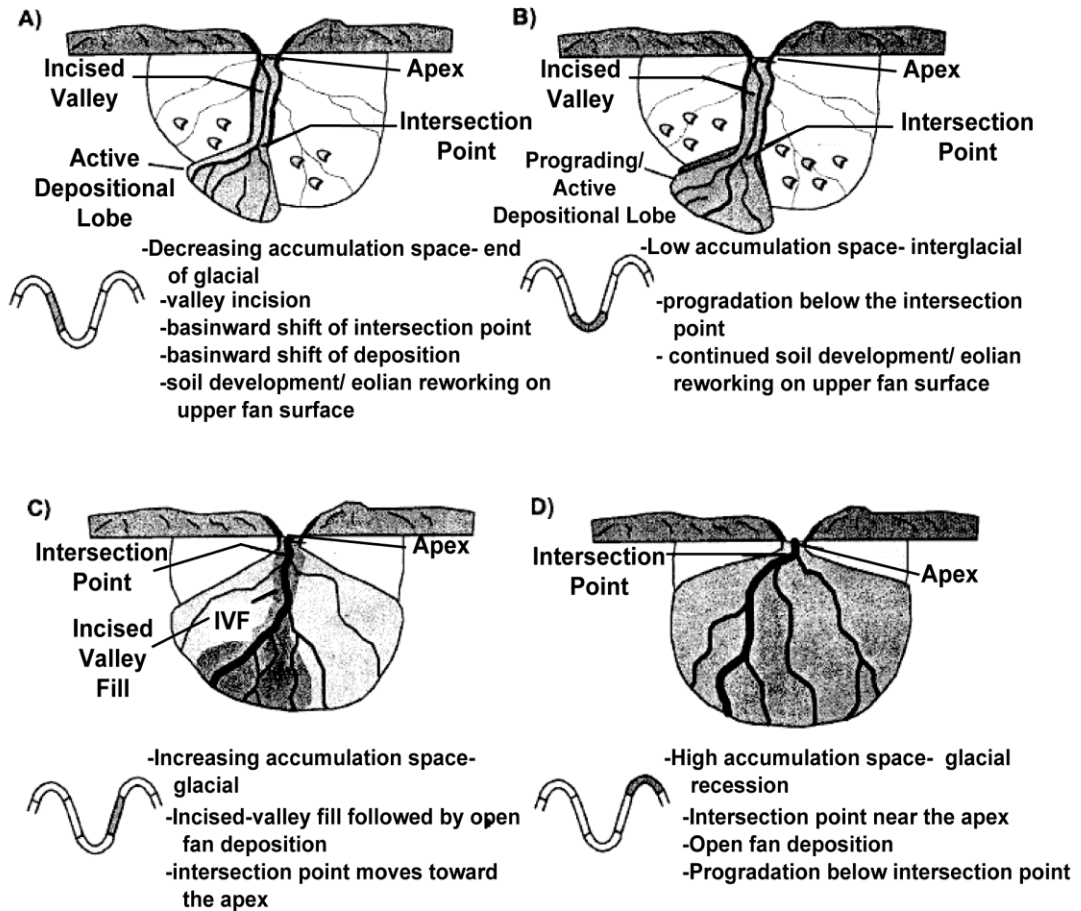


Figure A3: An example of the infrequent matrix-supported gravel facies. This facies represents only a small portion of the core samples and is presumed to be rare. Shown in color.

DISTAL



PROXIMAL



Figure A4: Typical distal and proximal fan examples of the channel sand facies. The distal sediments are typically more fine grained and display less iron staining. Shown in color.

DISTAL



PROXIMAL



Figure A5: Typical distal and proximal fan examples of the overbank silty clay deposits. These deposits are typically composed of silty fine to very fine sand, silty clay, clayey silt. They are usually gray to light brown with some sandy lenses, slight to no pedogenic alteration, and can be thinly laminated or massive. Some deposits displayed root traces or burrows and iron staining or mottling. Shown in color.

DISTAL



PROXIMAL



Figure A6: Typical distal and proximal fan examples of the pedogenically altered facies. This facies is typically reddish in color with significant pedogenic alteration (sand with medium to thick clay coats). Some slickensides and root traces were also noted in descriptions of this facies. Shown in color.

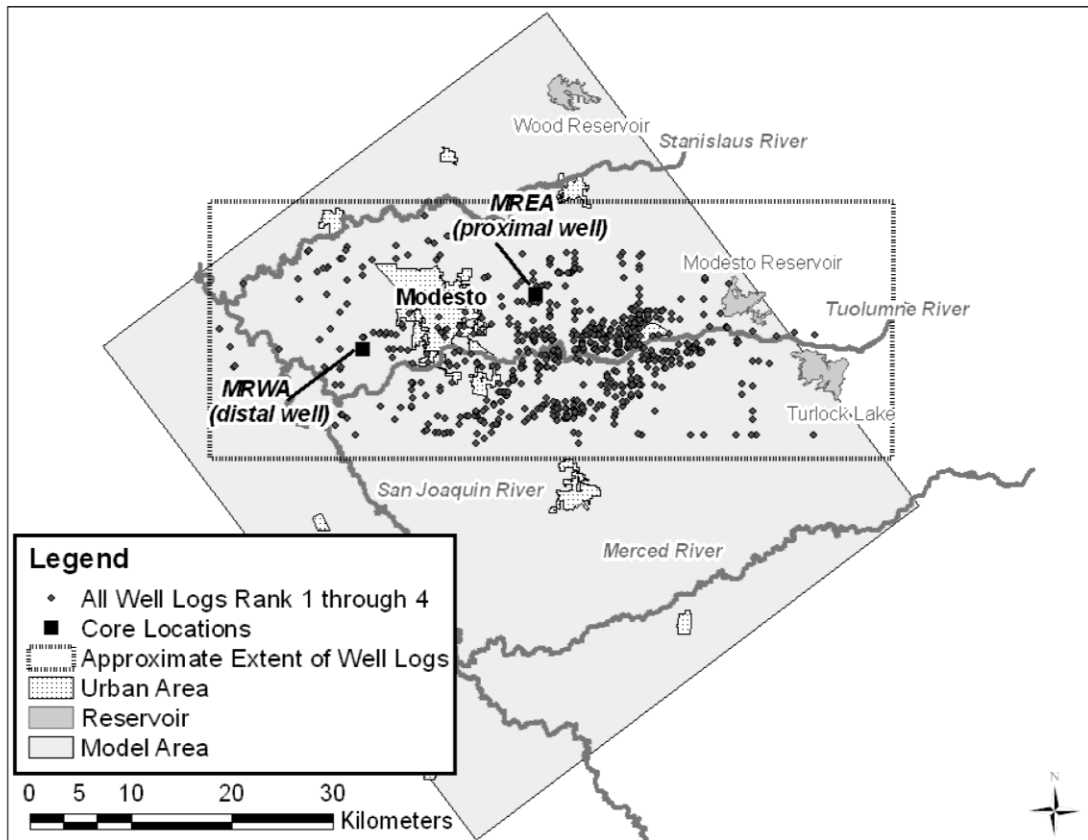
DISTAL



PROXIMAL



Figure A7: All driller's log wells entered in the ArcMap database ranked 1 through 4.



Appendix B: Open Fan Deposit Character Core Description

In order to better understand the character of the open-fan deposits surrounding the incised-valley fill, continuous core, collected by the USGS from two well locations was assessed—one located in a proximal fan position and the other on a distal portion of the fan (See figure 3 in Chapter 2). The proximal well, MREA, was drilled to a depth of 96 m (315 ft) and the distal well, MRWA, was drilled to a depth of 59 m (195 ft). Core was collected in 2.5 cm (1 inch) diameter tubes in 1.5 m (5 ft) increments. The cumulative 155 m (~500 ft) were described with visual assessments of grain size, sorting, shape; lithologic composition; color; primary structures; and secondary alterations. Descriptions verify the western extent of the study area contained more fine-grained sediments of the distal fluvial fan deposits, while the eastern extent of the study area contained the more coarse-grained proximal fluvial fan sediments. See Table B1 and Table B2 for detailed lithologic descriptions for MREA and MRWA, respectively.

Table B1: Lithologic descriptions of the proximally located soft sediment core MREA. The facies column uses a number to denote the hydrofacies and areas where core was not recovered. The numbers include: (0) no core recovered, (1) gravel flood deposits, (2) sandy channel deposits, (3) silty sands, silty clays, and clay overbank deposits, (4) pedogenically altered deposits.

See table on following page.

Table B2: Lithologic descriptions of the proximally located soft sediment core MRWA. The facies column uses a number to denote the hydrofacies and areas where core was not recovered. The numbers include: (0) no core recovered, (1) gravel flood deposits, (2) sandy channel deposits, (3) silty sands, silty clays, and clay overbank deposits, (4) pedogenically altered deposits.

See table on following page.

Appendix C: Drillers' Well Log Analysis

Incised Valley Fill (IVF) Character: Driller's Logs

A relatively coarse grained incised-valley fill (IVF) deposit was identified beneath the city of Modesto using geophysical logs (Burow *et al.* 2004; Figure C1). The logs show a very coarse grained gravel base that gradually fines upward to sand then fine silt and clay. To further investigate the location of the identified IVF in the Modesto area, I evaluated approximately 10,000 driller's well logs from the California Department of Water Resources (provided by the US Geological Survey). While well logs are notorious for irregular quality and potential inaccurate subsurface descriptions, drilling through thick gravel, such as that expected with the IVF basal deposits, would cause a significant change in the drill rig character and possibly require a change in the drill bit. Thus, I assume that thick gravels are consistently more accurately recorded than other deposits within driller' well logs.

However, due to the potential variable quality of well logs, a subjective ranking system from 1 (highest quality) to 4 (lowest quality) was created to filter out the best quality logs. Ranks were also assigned in-between each of these four main categories. The intermediate groups were reserved for the few logs that were slightly greater in quality or slightly lower in quality than the category to which they would be assigned. Subjective ranks were assigned to each well based on the following factors that impact the quality of the logs and thus their rank:

- **Gravel thickness**
 - Gravel 5 meters or greater indicated possible IVF deposits present.
- **Drilling method**
 - Cable tool drilling logs were considered more reliable than mud-rotary logs because the cable tool drilling method produces a sample for the

driller that is not mixed in drilling mud and allows more detail to be described.

- **Stratigraphy—character of the IVF**
 - The fining upward succession of thick gravel overlain by thick sand then silt or clay was expected in IVF deposits (Weissmann *et al.*, 2002b, 2004).
- **Driller**
 - Some drillers consistently recorded more detail than others. Lack of quality for a particular driller was also assessed by the uniqueness of each log. Wells within the same section were noted to have exactly the same stratigraphy recorded by the same driller, which is unlikely in the fluvial fan deposits.
- **Total depth of the log**
 - Some of the logs did not record to the depth of expected incised valley fill bases. Logs from wells that were 60 meters deep or greater were given preference. Some of the logs terminated within the basal gravel, and therefore were not useful for defining the absolute depth of the IVF.
- **Level of detail in the log**
 - The level of detail in a log was measured by the lithologic description and the amount of detail in the vertical succession of units. The presence or absence of color and sediment size descriptors was noted in the ranking process. Some of the driller's produced logs that lacked very little detail vertically. For example, a well with a depth of 100 meters or more was described as 3 or 4 thick units of sand and clay. This resolution makes identification of the IVF much more difficult.

It is important to note that the logs were assigned ranks on a combination of the above factors. No one category outweighed the others consistently in importance. An incomplete log that shows IVF stratigraphy, a log recorded by a driller that consistently produced poor quality logs but that clearly shows the IVF stratigraphy, or a log where the stratigraphy appears slightly irregular could all receive the same ranking. Although this method is subjective, very few wells (<100) that recorded thick gravel units were difficult to describe given the above guidelines. A description of wells ranked 1 through 4 is included below.

Rank 1 Wells

A well assigned a rank of 1 denotes the best representation of the incised-valley fill (Figure C2).

- A thick gravel base fining upward to sand then silt and clay.

- The drilling method was mostly cable tool.
- Several geophysical logs are also included in this category.

Rank 2 Wells

A well assigned a rank of 2 denotes a good representation of the incised-valley fill (Figure C3).

- A moderately thick gravel base fining upward to sand then silt and clay.
- Wells in this category show a slightly less distinct fining upward trend of the IVF: thin sand or sand and clay alternating overlie the gravel.
- The drilling method recorded on the driller's logs was mostly mud-rotary and some cable tool.

Rank 3 Wells

A well assigned a rank of 3 denotes a poor representation of the incised-valley fill (Figure C4).

- A thin sandy gravel base fining upward to clay or sand then silt and clay.
- Wells in this category show a less distinct fining upward pattern of the IVF: thin sand or thick clay overlie the gravel.
- The drilling method recorded on the driller's logs was mostly mud-rotary and some cable tool.

Rank 4 Wells

A well ranked 4 denotes the poorest representation of a possible incised-valley fill (Figure C5).

- Contains relatively thin gravel and does not resemble the ideal fining-upward succession contained within the incised-valley fill deposits.
- The drilling method recorded on the driller's logs was mud-rotary.

Figure C1: Resistivity log of selected test holes near Modesto, San Joaquin Valley, California. (Adapted from Burow, et al., 2004)

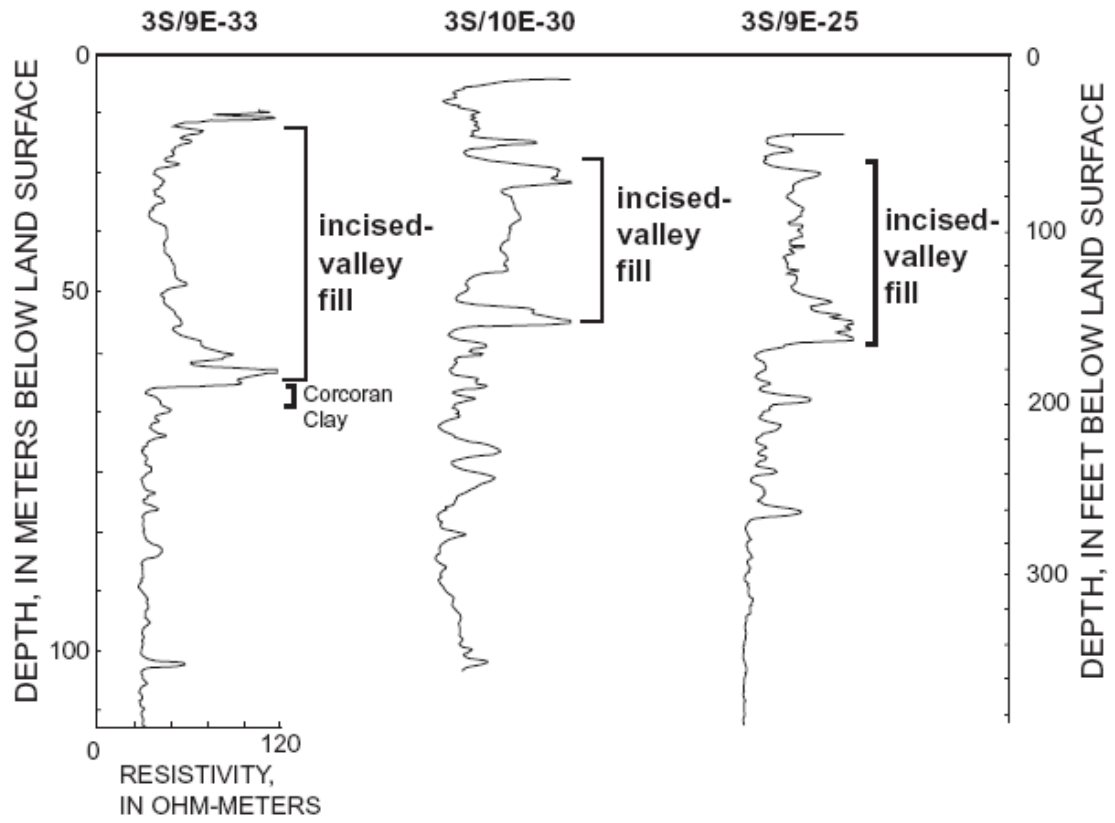


Figure C2: Driller's Well Log: Rank 1 example log. This log was drilled with a cable tool and includes detail as well as the expected IVF stratigraphy. NOTE: The well logs record depth from the surface in feet.

(12) WELL LOG: Total depth — 268ft. Completed depth 264 — ft.

from ft.	to ft.	Formation (Describe by color, character, size or material)		
0	-	5	topsoil	
5	-	7	clay	
7	-	10	silty sand	
10	-	12	sand	
12	-	13	silty clay	
13	-	22	sand	
22	-	33	brn silty clay	FINES
33	-	36	hard clay	FINES
36	-	39	sand & gravel	SAND
39	-	48	set sand	SAND
48	-	66	clay	
66	-	110	coarse sand	
110	-	126	sand & cobbles	GRAVEL
126	-	134	sand & gravel	GRAVEL
134	-	153	sand	GRAVEL
153	-	180	sand & colbbles	GRAVEL
180	-	191	brn. clay	
191	-	193	set sand	
193	-	194	sand & gravel	
194	-	199	brn. clay	
199	-	202	set sand & gravel	
202	-	219	clay	
219	-	221	sand & gravel	
221	-	223	brn. clay	
223	-	225	silty clay	
225	-	230	silty sand & gravel	
230	-	232	brn. clay	
232	-	235	sand & gravel	
235	-	247	red clay	
247	-	253	set silty clay	
253	-	264	red clay	
264	-	268	sand	
268	-	+	clay	
-	-	-	-	
-	-	-	-	
-	-	-	-	
-	-	-	-	
-	-	-	-	
-	-	-	-	
-	-	-	-	
-	-	-	-	
-	-	-	-	
-	-	-	-	

OUTSIDE CORC CLAY AREA

Figure C3: Driller's Well Log: Rank 2 example log.

(12) WELL LOG: Total depth 370 ft. Depth of completed well 350 ft.	
from ft.	to ft. Formation (Describe by color, character, size or material)
0 - 2	Silty clay
2 - 7	Clay
7 - 9	Sandy clay
9 - 16	Sand
16 - 20	Gravel and Sand
20 - 22	Sandy gravel
22 - 26	Clayey sand
26 - 39	Clay
39 - 47	Clayey sand
47 - 54	Clayey sand, dense
54 - 58	Clayey sand and gravel, dense
58 - 61	Sand, dense
61 - 65	Clayey sand, red
65 - 75	Clayey sand, tan
75 - 81	Sand
81 - 86	Clayey sand
86 - 95	Sand
95 - 115	Clayey sand
115 - 127	Sandy clay
127 - 132	Gravel
132 - 153	Sand & Gravel, dense
153 - 165	Clay
165 - 171	Clayey Sand & Gravel, hard
171 - 187	Clayey Sand & Gravel, vy hd
187 - 192	Clay, swelling
192 - 212	Clayey Sd & Grvl, vy hd
212 - 214	Sand, loose
214 - 256	Clayey Sd & Grvl, vy hard
256 - 258	Sandy gravel, loose
258 - 295	Clayey sand and gravel
295 - 297	Gravel to 3"
297 - 306	Clayey Sd & Grvl, Grvl 3/8"
306 - 326	Silty sand
326 - 329	Sand, loose
329 - 357	Silty sand w/ layers loose Sd
357 - 370	Clayey sand and gravel
-	-
-	-

FINES

SAND

GRAVEL

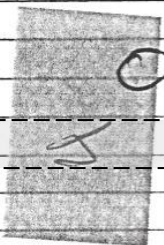
OUTSIDE CORC
CLAY AREA

Figure C4: Driller's Well Log: Rank 3 example log.

(12) WELL LOG: Total depth 200 ft. Depth of completed well 173 ft			
from ft.	to ft.	Formation (Describe by color, character, size or material)	
0	2'	TOP SOIL	
2'	4'	HARD PAN	
4'	13'	SAND	
13'	19'	SAND & GRAVEL	
19'	26'	CLAY	
26'	104'	SAND	
104'	70'	ROCKS	
70'	83'	LOBRICK	
83'	107'	CLAY	FINES
107'	117'	SAND & GRAVEL	
117'	128'	CLAY	SAND
128'	142'	SAND	
142'	155'	CLAY	GRAVEL
155'	167'	SAND	
167'	173'	GRAVEL	
173'	176'	CLAY	
176'	183'	SAND	
183'	200'	CLAY	
		OUTSIDE CORE	
		CLAY	
Work started	JAN 1986	Completed	MAY 1986

Figure C5: Driller's Well Log: Rank 4 example log.

GEOLOGIC LOG		
ORIENTATION (\sphericalangle) <input checked="" type="checkbox"/> VERTICAL <input type="checkbox"/> HORIZONTAL <input type="checkbox"/> ANGLE <input type="checkbox"/> (SPECIFY)		
DEPTH TO FIRST WATER _____ (Ft.) BELOW SURFACE		
DEPTH FROM SURFACE		DESCRIPTION <i>Describe material, grain size, color, etc.</i>
Ft.	to Ft.	
0	7	Soil
7	16	Sand
16	30	clay
30	36	Sand
36	50	Clay & Sand Streaks
50	102	Clay
102	112	Gravel & Rocks
112	118	clay
118	123	Sand
123	150	Clay & Shale
150	167	Gravel & Rocks
167	185	Clay
185	192	Sand & Gravel
192	198	Sandy Clay
198	200	Set up Gravel
200	235	clay
TOTAL DEPTH OF BORING <u>235</u> (Feet)		
TOTAL DEPTH OF COMPLETED WELL <u>210</u> (Feet)		



GRAVEL

Appendix D: Sequence Boundary Surface Generation

The stratigraphy of the area was modeled by generating surfaces of the sequence boundary paleosols. These boundaries include the continuous paleosol surface and the incised valley sides and base.

Riverbank Paleosol with Modesto IVF

To generate the Riverbank paleosol, the ground surface was assumed to be a sufficient estimate of the Riverbank fan surface because the overlying Modesto formation that covers the area is only a thin veneer across the fan surface (*Bennett, 2003; Weissmann et al., 2006; Bennett et al. in press*). This assumption allowed the Riverbank paleosol surface to be created using the modern 30-meter DEM.

1. The DEM raster file, or grid, was clipped manually in ArcMap with the N-Bands Raster Clipper tool, which can be downloaded from the ESRI website (Multi-Bands Raster Clipper v1.2 for ArcMap 9.x at <http://arcscripts.esri.com/details.asp?dbid=13474>).
2. Because the file size of the 30-meter DEM grid was very large, the 30-meter resolution of the DEM was increased using the AGGREGATE expression in ArcMap Spatial Analyst.
 - a. In spatial analyst, select raster calculator and type in the following map algebra syntax: `aggregate ([name of grid], [cell factor], [aggregation type], truncate, data)`.
 - b. The cell factor (13.333) was calculated to make the cell size 400 meters ($400/30=13.333$).
 - c. The aggregation type “mean” was chosen as the method for calculating the output value of each cell.

- d. “Truncate” refers to how the calculator will manage boundaries. The truncate option reduces the number of rows and/or columns by one. This option allows truncation of the input grid at the bottom and right boundaries so that the number of rows and columns will be a multiple of the cell factor. This means that the output grid may be smaller than the input. In the case of the input 30-meter DEM, the grid was clipped sufficiently large enough to account for the potential shortening by this function.
 - e. The “data” parameter specifies that if the 30-meter DEM had a NoData value, it would be ignored in the calculation of the new output grid.
3. The new coarser grid was converted to a point shapefile in Arc GRID with the GRIDPOINTSHAPE function or in ArcMap Spatial Analyst.
- a. The syntax required for this is: GRIDPOINTSHAPE ([name of grid to be converted]).
 - b. An alternate method is available in ArcMap to convert the raster file to a point shape file. In the Spatial Analyst menu, select “Convert” then select “Raster to Feature”. Be sure the “Output geometry type” is point. The “field” specified should be the column with the elevation data.
4. Using the shapefile of rank 1 and 2 wells delineating the presence of the Modesto Formation IVF basal gravel between 24 to 38 m (80 to 125 ft) (Appendix A), polygon shapefiles of the proposed incised valleys (both the IVF scenarios, the small Modesto Formation valley, and the larger valley) were created. The width of the valley was approximated from measurements of the modern valley: 0.7 to 1.6 kilometers. Because there was little information on the actual IVF width, we

assume that the current valley is a good representation of the geometry of past interglacial incised-valleys.

5. The polygon shapefiles were then converted to point shapefiles.
 - a. To do this, the polygons were first converted to grids (raster files). In Spatial Analyst, select “Convert” then “Feature to Raster”. The grid cell size specified was 200 meters.
 - b. To convert the raster file to a point shape file, return to the same menu, only this time select “Raster to Feature”. Be sure to convert the file to a point shapefile. The “field” specified for the conversion does not matter because raster file did not have any relief. The elevation of the valley bottom will be manually added in the following steps. The result is a grid with rows and columns of points (or ghost wells) spaced 200 meters apart delineating the location of the IVF.
6. Once the IVFs were delineated as a 200-meter spaced point shapefile, elevations of “ghost” wells were assigned to the valley bottom with a gradient of 0.0004 (“ghost” wells were used to enforce our conceptual model of the incised valley geometry). The gradient value was obtained from measurements of the modern interglacial river gradient in Weissmann et al. (2006). To assign the elevations, the rank 1 and 2 well shapefile was plotted with the ghost well point shapefile. Rank 1 and 2 wells with elevations that matched the expected gradient of the basal gravel were used as anchors to calculate and then assign elevations to the “ghost” wells situated between them (see description of RB valley below and Figure D1 for image of implementation of “ghost” wells).

7. To insert the IVF point into the Riverbank paleosol surface, the polygon coverage was used to select all points in the DEM within the area of the Modesto IVF polygon.
 - a. In ARC Map the “Select by Location” feature was used to select all points that “are contained by” the polygon. A buffer of 50 meters was applied. Once the points were selected, they were removed.
8. The Modesto IVF point shapefile was then used to fill in the valley floor elevation points.
9. The point shapefile that resulted from the merging of the DEM and the Modesto IVF was then used to generate a grid of the surface in ArcMap Geostatistical Wizard using the Local Polynomial Function. A cell size of 300 meters was chosen. The resulting surfaces are shown below in figures 1 through 4.

Upper Turlock Lake Paleosol with Riverbank IVF

The Upper Turlock Lake (UTL) surface was not generated from a preexisting surface, and therefore was created in a series of steps with multiple sources of data.

1. First, the elevation of the Corcoran clay was used to estimate the elevation of the Turlock Lake surface. The Corcoran clay elevation was estimated by sorting out "blue clay" or "blue silt" from the USGS texture database (described in *Burow et al.*, 2004). These data were saved in an individual database and plotted in ArcMap using the plot XY data option. In ArcMap, points were selected by depth ("Select by attributes"). An estimated depth of 60 meters (~200 feet) for the Corcoran Clay was obtained from *Burow et al.* (2004), so a range of 55 to 67 meters (180 to 220 feet) was applied to select the Corcoran Clay. The elevations were calculated from the "land surface elevation" minus the "top depth" of the

Corcoran clay. Because this database search limited the depth range for the Corcoran clay, most of the points plotted were clustered in a band that runs the length of the study area approximately 100km east of the San Joaquin River.

2. To determine the elevation of the upper Turlock Lake (UTL) paleosol, the thickness between the Corcoran Clay and the Turlock Lake paleosol was added to each of the points in the Corcoran Clay database, using the "calculate values" feature in the ARC Map attributes table. MRWA, the core drilled in the distal portion of the fan, is located in the area where most of the Corcoran Clay points were identified in the database; therefore the thickness added to the Corcoran Clay points was obtained from the MRWA core descriptions. The MRWA thickness between the UTL top and the top of the Corcoran Clay was estimated to be 23.5 meters (77 feet). Estimates from Lettis (1982) verify that this is a reasonable value.
3. Once all of the Corcoran Clay data points had been converted to UTL top elevations, other data points were added. Supplementary points added to the database of UTL elevations include (1) the land surface elevations of the outcropping UTL from soil maps (*Weissmann et al.*, 2006) and (2) the elevation of the UTL approximated in the two cores described (MREA and MRWA). The combination of these data in a point shapefile (Figure D2) was used as the input to generate the UTL surface in Arc GRID.
4. In Arc GRID, the TREND surface interpolation function was used to make the UTL surface, which uses a polynomial regression technique to fit a least squares surface to the data set. This function was chosen because it creates a smooth surface in a raster file format. Because this method attempts to find a best fit for

the entire surface, the resulting surface may not go through many of the input data points. A low root-mean square (RMS) error (~7.928) and general shape of the surface were used as indicators of the generated surface's accuracy.

- a. The syntax used in ARC GRID is as follows:
 - i. **TREND (<point_cover | point_file>, {item}, {order}, {xmin, ymin, xmax, ymax})**
 - ii. The <point cover> is the point shapefile of UTL elevations that was used to generate the surface.
 - iii. The item is the elevation of the UTL surface in the shapefile that will be used to make the surface.
 - iv. The order used was 2. This was used after experimentation with other orders, which produced unrealistic representation of the surface.
 - v. The coordinates for the area to be interpolated were (-125696, 1564302, -35442, 1663440) in NAD 1983 Albers projection.
- b. The elevation of the TREND surface/ grid was checked with the Riverbank surface to be sure that they do not intersect, as realistically, the UTL would not overlie the younger Riverbank Formation. To ensure that the UTL was not above the Riverbank in any locations, ArcMap's "Raster Calculator" in Spatial Analyst was used.
 - i. In Raster Calculator, the following expression was used:
 1. $\text{con}([\text{UTL grid}] \leq [\text{Riverbank grid}], [\text{UTL grid}], [\text{Riverbank grid}])$.

2. This conditional statement says that if the UTL grid is less than or equal to the Riverbank, then the output grid should be assigned the UTL grid elevation, if not, the output grid should be assigned the Riverbank elevation.
5. The raster file of the UTL fan surface that was created in TREND was then converted to a point shapefile in ArcMap in Spatial Analyst (see above in step 3b of the **Riverbank Paleosol with Modesto IVF**).
6. Similarly to the methods described above for the Riverbank paleosol surface, polygon shapefiles of the proposed Riverbank incised valleys were used create “ghost” wells assigned elevations of the IVF bottom gradient (Figure D1). The IVFs were added to the UTL fan surface (See steps 4-9 in **Riverbank Paleosol with Modesto IVF**).
 - a. One difference between the generation of this valley bottom and the Modesto valley is the correction for subsidence. Because the Riverbank Formation is older (~130 to 450 ka) (Lettis, 1988; Weissmann *et al.*, 2002b), the impacts of subsidence were calculated into the gradient. The valley bottom was assigned a gradient of 0.0017. Subsidence was calculated from a rate of 0.2 mm/yr, or 0.0002 m/yr (Lettis, 1988) over a span of approximately 330 ka. This results in about 66 meters of subsidence, which increases the slope by 0.0013. When added to the modern valley gradient of 0.0004 is equal to 0.0017.
7. The resulting surfaces are shown below in figures D3 through D6.

Figure D1: This figure shows a map view of the use of ghost wells used to delineate the IVF. In this example, the black dots show the ghost wells used to delineate the RB IVF. The surrounding gray dots represent the elevation of the paleosol surface. This point data was used to interpolate the Turlock Lake sequence boundary surface.

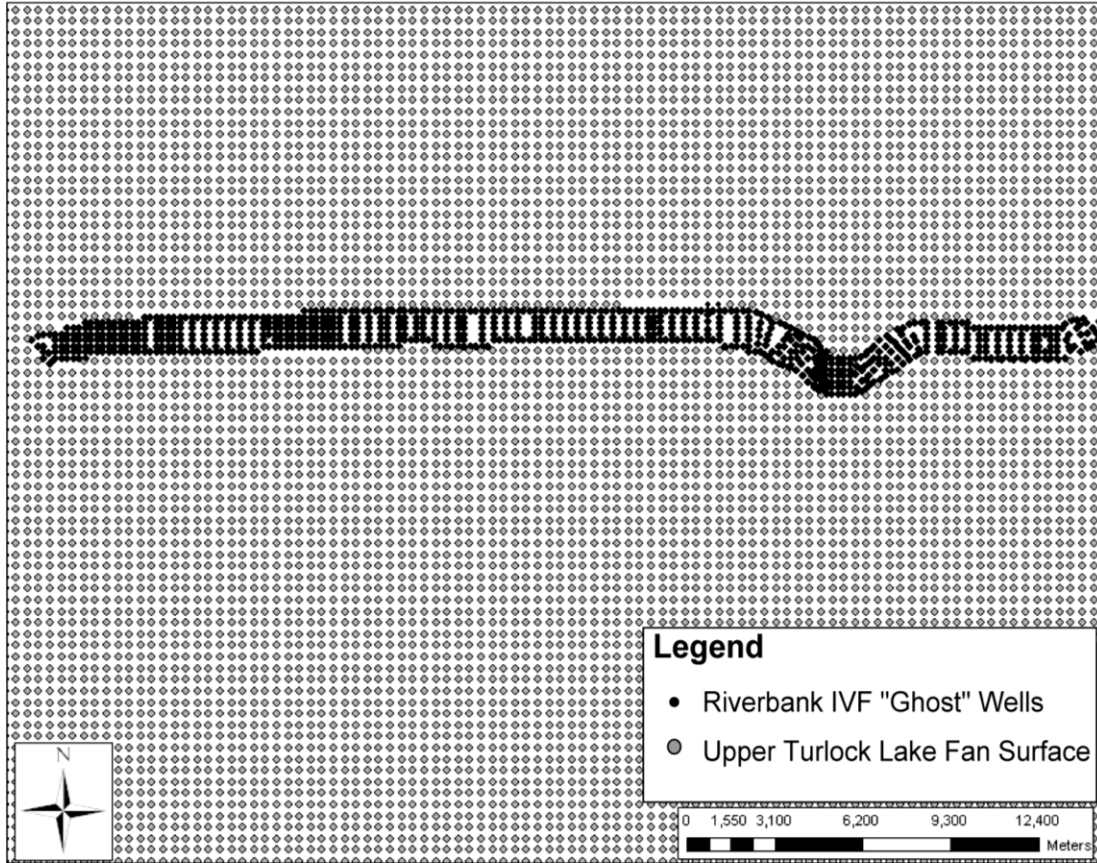


Figure D2: This map shows the location of the Corcoran Clay wells found in the USGS database. The dense clusters of points in the eastern portion of the map mark areas where the Turlock Lake formation outcrops. These points were used to interpolate the UTL sequence boundary surface.

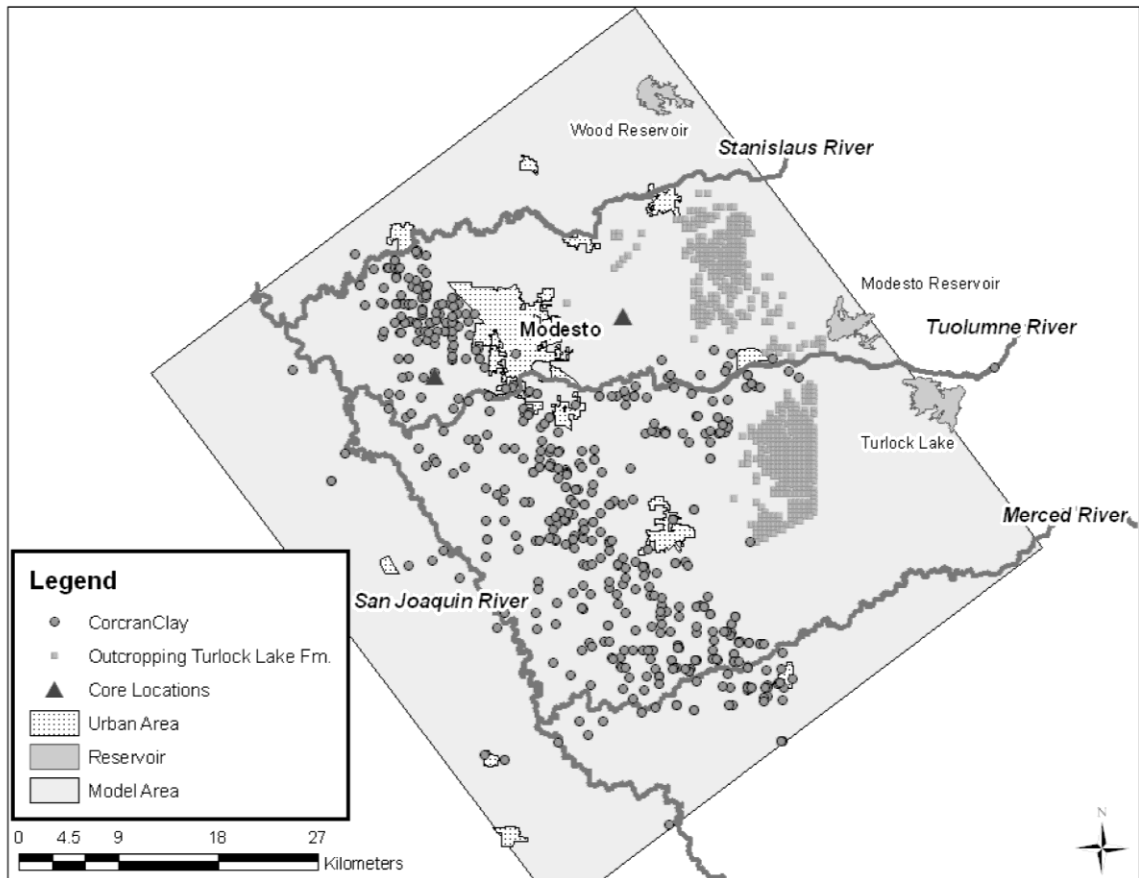


Figure D3: The Riverbank Formation surface with the Tuolumne River large Modesto IVF above the upper Turlock Lake Formation surface with the Tuolumne River Riverbank IVF (RBML). NOTE: Surfaces are exploded 100 meters.

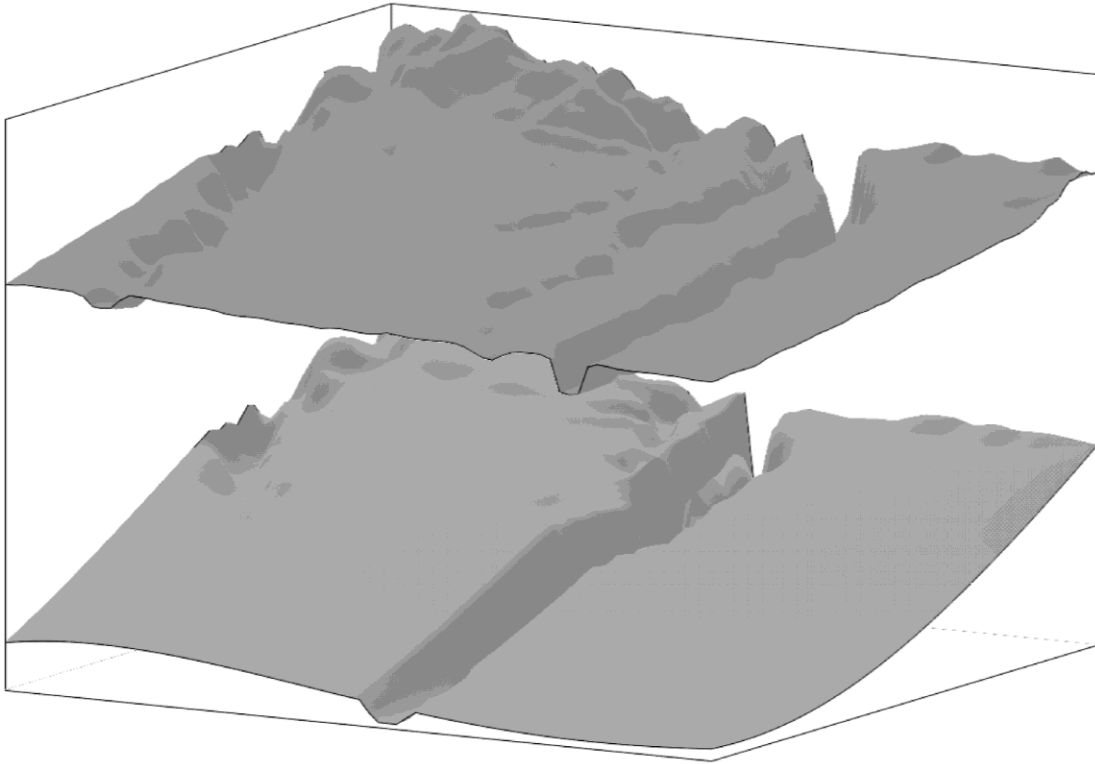


Figure D4: The Riverbank Formation surface with the Tuolumne River small Modesto IVF above the upper Turlock Lake Formation surface with the Tuolumne River Riverbank IVF (RBMS). NOTE: Surfaces are exploded 100 meters.

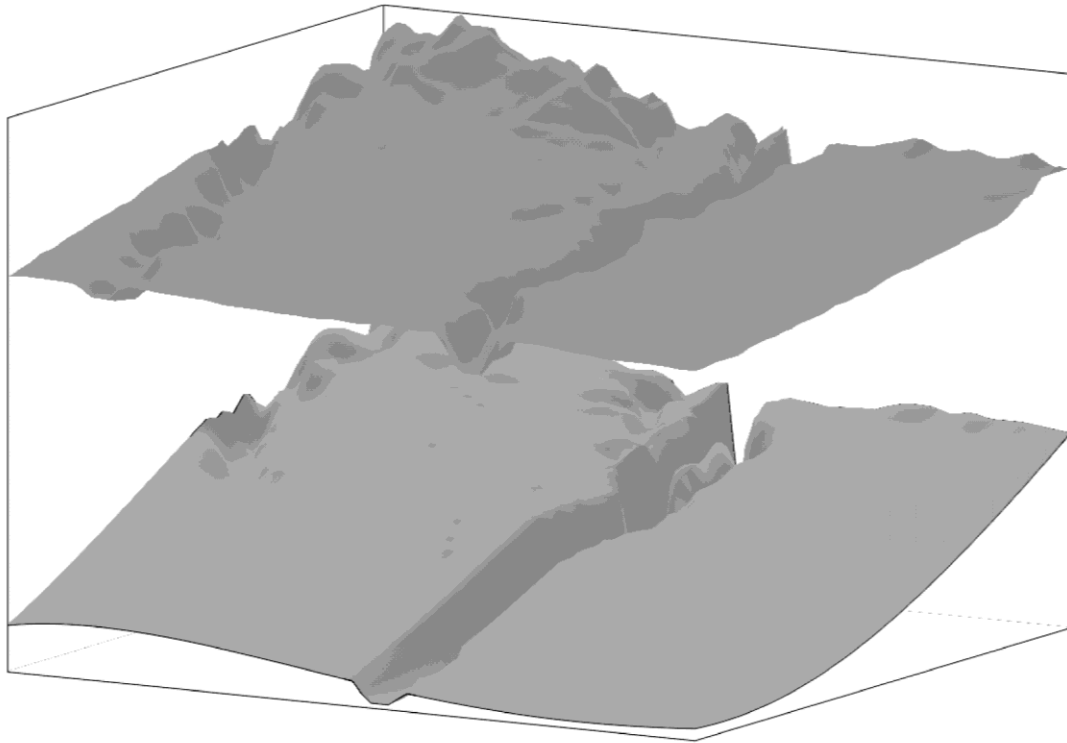


Figure D5: The Riverbank Formation surface with the Tuolumne River large Modesto IVF above the upper Turlock Lake Formation surface with the Tuolumne River Riverbank IVF and the Stanislaus River Riverbank IVF (RBSTML). NOTE: Surfaces are exploded 100 meters.

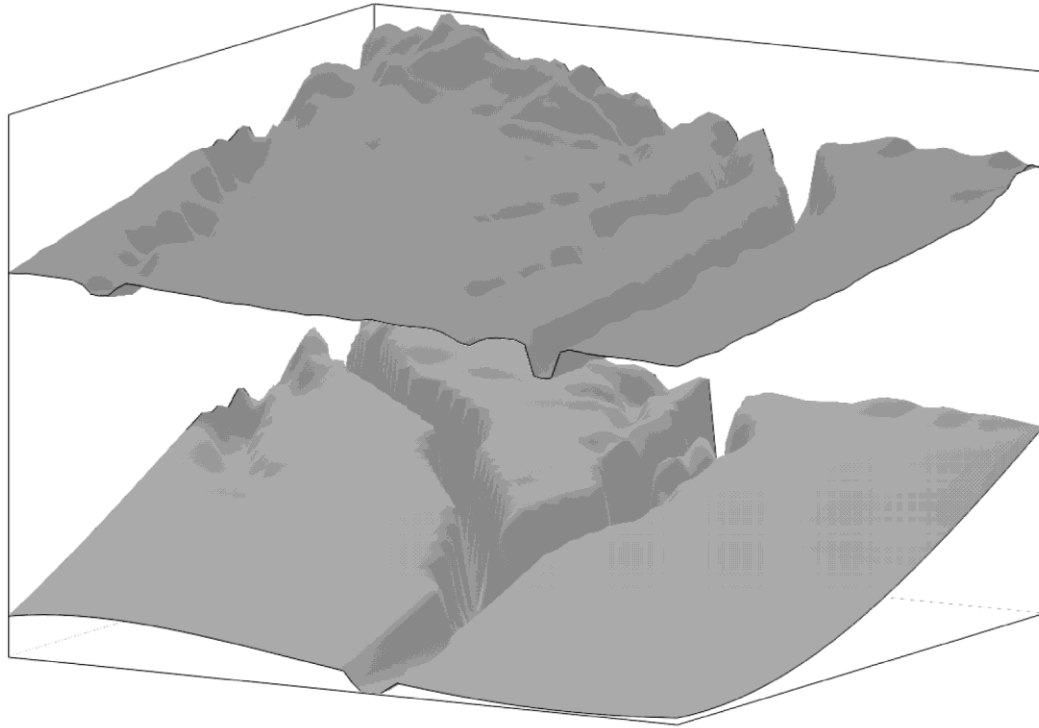
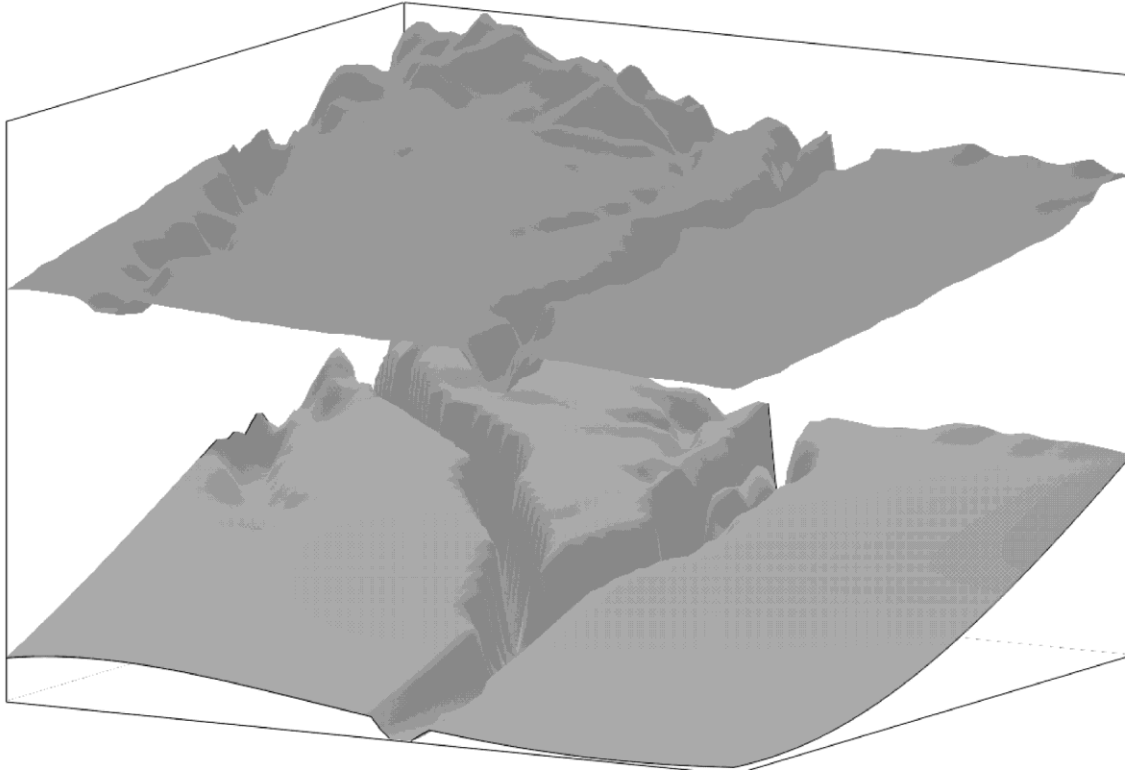


Figure D6: The Riverbank Formation surface with the Tuolumne River small Modesto IVF above the upper Turlock Lake Formation surface with the Tuolumne River Riverbank IVF and the Stanislaus River Riverbank IVF (RBSTMS). NOTE: Surfaces are exploded 100 meters.



Appendix E: USGS Model

Details of the USGS model are described in Chapter 2 of this thesis. The following appendix details how the original USGS MODFLOW model was opened. To open the original USGS MODFLOW model:

Open the MODFLOW model from the USGS one layer at a time.

Alterations to the original model file include:

- (1) changing number format : mostly done in Excel or by using the “Search and replace” feature in EditPadPro
 - a. reducing the number of digits (0.990000E0002 to 0.0099)
 - b. also adding a 0 after floating points (123. to 123.0—
CAREFUL: some values lost spaces between them by doing this. To rectify problem search for “.00.” and replace with “.0 .0”)
- (2) reducing the number of spaces in between numbers: done in Excel and the “Search and replace” feature in EditPadPro--(save as a comma delimited file and then replace commas with spaces)
 - a. e.g.- from 5 or more to just one
- (3) Reducing the number of hard returns within a row of data (files are set up so that they list data by row (153 rows) for each layer (16 layers). There are also 137 columns. To complete step 3, I used a script that Anthony wrote in Matlab—see “dat_read.m” in
C:\users\Amy\May312005\USGSModelFiles\Tuolumne060605\USGS
_used_4_final_model.

- (4) ALSO MAKE EXTERNAL FILES INTERNAL—I cut and pasted all of the external files into the .bcf file. GMS would not read the external files.

To generate Kdatasets.gpr

Once the model will read the discrete (.dis) and (.bcf) file by using the above methods, the K values must be imported separately. GMS would only read one layer of K data at a time. (I think this is because they are read in as 3D data sets, which makes K values in all other layers zero.)

- (1) Open the MODFLOW model in GMS with the K, Leakance, and Wetdry values for ALL layers “INTERNAL”. MODFLOW will only read the first layer with values into the model. This means that ONLY the K, leakance, and wetdry values for layer 1 will be read into GMS when it opens.
- (2) Once GMS opens, save this model as “Kdataset.gpr”—CLOSE THE MODEL
- (3) Go into the “Kdataset.mfs” file using Microsoft Explorer to set the origin (ORG -83756.2 1573010 0.0) and the rotation angle (ROT 37).
- (4) Re-open the model “Kdataset.gpr”.
- (5) Click on the 2D grid module.
- (6) Click on the “Grid” dropdown menu and “Create grid”. Enter the following:
 - a. X origin: -83756.2 Y origin: 1573010 Z origin: 0.0
 - b. Length: 54800 Length: 61200
 - c. Number of cells: 137 Number of cells: 153
 - d. IN BOTTOM RIGHT CORNER, FILL IN ROTATION ANGLE: 37

- (7) Go into the 3D grid module and click on the “MODFLOW” dropdown menu. Select “BCF Package” and view AND export the K, leakance, and wetdry values for Layer 1. EXPORT the values from “Layer to 2D data set”—File names should be something like “layer1_k”, “layer1_leak”, and “layer1_wetdry”.
- (8) Go into the 2D grid module and right click on each of the 2D data sets just generated, and EXPORT the data as and ASCII file (CAREFUL—the default file type is Binary—BE SURE TO CHANGE THIS!!!).
- (9) Once the data have been saved as ASCII files they can be imported into any model later (see step 13). After data has been saved, SAVE “Kdataset.gpr” and CLOSE out of the model.
- (10) Open the original MODFLOW .bcf file. This time, delete all of the values for layer 1 (including K, leakance, and wetdry). Fill in “CONSTANT 0.0 (free) 0” for each of those data sets. Now Layer 2 data should be the first data set visible in the .bcf file. Save and close this file.
- (11) Open a new GMS file. Open the original MODFLOW file (.nam) . (This step is similar to step 1).
- (12) Repeat steps 7-10 for each successive layer. NOTE: Only Layers 1 through 7 have “wetdry” data. Layers 8 through 16 are confined and have transmissivity values, NOT hydraulic conductivity values.
- (13) Once all of the ASCII files have been generated, they can be opened in GMS as 3D data sets.
- (14) Open “Kdataset.gpr” then go to “File—Open” and select the ASCII file to import. Once all files are open as 3D data sets, they will need to be converted

into 2D data sets (next step). *This is necessary because importing a 3D data set into the BCF package will make all values in other layers zero.

Transforming to a 2D ensures that only the values of the 2D layer to which you import the data will be changed.*

(15) To convert from 3D to 2D, click on the file to be converted so that the text is bolded.

(16) Go to the “Data” dropdown menu and select “3D data to 2D data”.

(17) **BETTER WAY: Go into the 3D grid module and click on a data set.**

Go to the DATA drop down menu. Select “3D data to 2D data”. In dropdown box, select “Value from k layer” then in the adjacent box, match the layer of K values to the layer specified in the data set to be converted. Save the file as, for example: “lay1_layer1_k” or “lay8_layer8_trans”. This results in a 2D array ASCII file when exported. OLD WAY—DID NOT WORK: Make sure the file you want to convert is selected, and that the “Maximum value in the ij column” is selected and click “OK”. When a 2D data set is saved as a 3D data set, a value of zero is filled in for all unknown numbers. Any K, leakance, or wetdry number for a given layer will be greater than 0, therefore the maximum number in the ij column will be K (or leakance, or wetdry) for the layer file being converted.

(18) SAVE the new 2D file with the old 3D file name.

(19) Once all of the layers have been converted into 2D grid, go back to the 3D grid module and click on the MODFLOW dropdown menu. Go to the “BCF Package” and begin importing the 2D data to each layer.

- a. NOTE: to do this go into each layer (1-7) and (1) click “hydraulic conductivity”, “leakance” or “wetdry” (2) select the appropriate layer (3) click “2D data set to layer” and pick the data set you want to fill in.
DO NOT FILL IN HYDRAULIC CONDUCTIVITY FOR LAYERS 8 THROUGH 16.
 - b. FOR (8-16) fill in the “transmissivity” and the “leakance” ONLY
- (20) SAVE ALL WORK PERIODICALLY.

To open sequence boundary surfaces in GMS

- (1) in 2D scatter point module
- (2) Select “File” then “Open”
- (3) “Import as scatter points”
- (4) assign scatter point file a name
- (5) with this data set active, go to “Interpolation” drop down menu
- (6) Select “Interpolate -> 2D grid”
- (7) Select interpolation method
 - a. “Inverse distance weighted” and leave default options
 - i. “Nodal Function” should stay as “Gradient plane”
 - ii. “Computation of nodal function coefficients” should stay as “Use subset of points”
 - iii. “Computation of interpolation weights” should stay as “Use subset of points”
- (8) repeat until all data files have been opened in GMS

(9) Next, export the 2D grid data to an ASCII file and save for use within the code.

Appendix F: Model Generation

The following documentation details the inputs for the model adapted from the USGS. The initial model from the USGS was developed by Steve Phillips (Steve Phillips, Hydrologist; U.S. Geological Survey, 6000 J Street, Placer Hall, Sacramento, CA 95819-6129; sPhillip@usgs.gov; phone: 916-278-3002; fax -3071).

A. Flow Package

The Layer Property Flow (LPF) was chosen to allow more flexibility in entering parameters (the Block-Centered Flow (BCF) package was used in the USGS model). Values such as the vertical hydraulic conductivity were incorporated into the model without conversion of the original “vcont” values (or K_v / thickness), but rather through the K_h/K_v ratio that calculates the vertical conductance based on the layer elevations.

B. Solver

Preconditioned Conjugate Gradient 2 (PCG2) solver was used for this model (the USGS model also used the PCG2 solver). The initial solution for the adapted model was generated using the geometric multigrid (GMG) solver and starting heads all equal to the elevation of layer 1. The solution generated using the GMG was then used as a starting head and allowed the rest of the models to be solved with the PCG2 solver.

C. Discretization

Changes to the discretization of the USGS model were made in layers where the IVFs are located (approximately layers 2 through 7 in the old model) (See Figure 10 in Chapter 2). The new discretization is finer and better models the IVFs. The adapted model layers 2 through 16 (old layers 2 through 7) use the IVF base as a layer surface. The original layers 2 through 7 in the USGS model were assigned as a percent thickness between the ground surface elevation and the top of the Corcoran Clay layer. In the

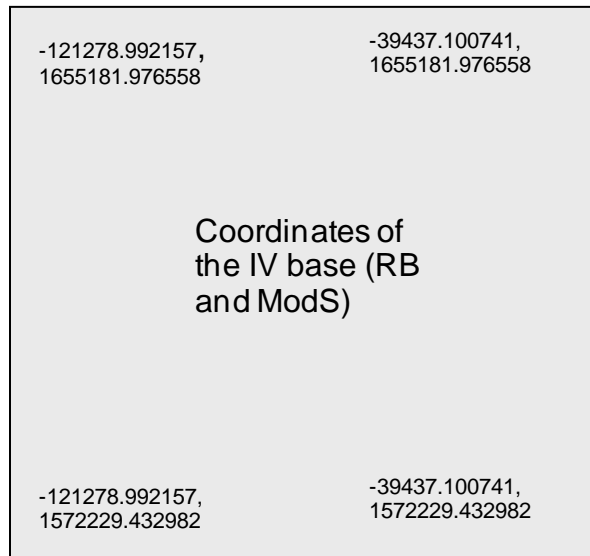
adapted model, the slope of the layers 2 through 5 match the Modesto small IVF base and 6 through 16 match the slope of the Riverbank IVF base.

One problem that arose with the new discretization was the new layers intersected with some of the older layers due to varying gradients. To fix this, layers 17 through 22 (USGS model layers 8 through 11) were slightly altered in the eastern portion of the model to prevent intersection of layer elevations. Layers 23 through 27 (USGS layers 12 through 16) were well below the IVF and were not affected by the gradient of the new surfaces, thus the original USGS top and bottom elevations were preserved in the adapted model.

The following instructions describe how the modified model was discretized.

- 1) Open a new model in GMS 5.0.
 - a) Create a 3D grid with at least 8 layers.
 - b) In the MODFLOW super file, be sure to set the correct origin and rotation
 - i) Rotation 37 degrees,
 - ii) ORIG
 - (1) (x) -83795.7
 - (2) (y)1572727.3
 - (3) (z)0.0 (from well code)
 - iii) length
 - (1) (x length) 54800
 - (2) (y length) 61200
 - iv) Cells 400 by 400m
 - v) (x) 137 columns (y) 153 rows
 - c) Be sure the LPF package is activated.

- d) Import the top and bottom elevation from the old model. Import layers 11-16 of the old model as the basal layers of this model. (export data and import to my model)
- 2) Use the base of IVF to determine the dip of the upper most grid layers.
- i) To do this, use the IVF base grid surface (same as the data used for the calculations of the gravel, sand and fines top elevation of the IVF).
 - (1) Generate in Arc GRID using the TREND function
 - (2) Assign coordinates so that the surface generated will cover the entire model area.



- (a) RIVERBANK VALLEY and MODESTO VALLEY surface
 - (i) Resample original 12m cell surface from initial IV base (used in code and to make gravel, sand , and fines surfaces) to 50m cells
 - 1. In ArcMap Toolbox—Data Management—Raster—Resample
 - (ii) Convert raster to point file in Arc GRID
 - (iii) Make TREND surface with 50m cells in Arc GRID

(iv) Resample trend surface to 300m cells

1. In ArcMap Toolbox go to—Data Management—Raster—Resample

(v) Check Riverbank surfaces using the raster calculator in ArcMap Spatial Analyst to find the absolute difference between the surfaces to be sure there is not a significant difference.

1. The maximum difference between the initial 12 m and the resampled 50m grid is minimal (calculates 0).
2. The maximum difference between the 50m grid and the trend surface is 0.012m.
3. The maximum difference between the 50m trend surface and the resampled 300m surface is 0.095m.
4. Difference between the original 12m cell surface and the final 300m surface was ~0.01m.

(vi) Check MODESTO surfaces using the raster calculator in ArcMap Spatial Analyst to find the absolute difference between the surfaces to be sure there is not a significant difference.

1. The maximum difference between the initial 12 m and the resampled 50m grid is 0.05m.
2. The maximum difference between the 50m grid and the trend surface is 0.017m.
3. The maximum difference between the 50m trend surface and the resampled 300m surface is 0.019m.

4. Difference between the original 12m cell surface and the final 300m surface was ~0.053m.

ii) INTERSECTION OF SURFACES: The Riverbank valley base and Modesto valley base surfaces intersect in the southern portion of the model grid. To fix this, there are two steps using the raster calculator in ArcMap will be used.

(1) Initial adjustment: The following conditional statement was used to calculate the new surface:

(a) $\text{con}(\text{RIVERBANK} \geq \text{MODESTO}, \text{MODESTO} - 5, \text{RIVERBANK})$

(2) Thin cells-- To fix thin areas between the Modesto IV base surface and the Riverbank IV base surface...

(a) $m-r = [\text{MODESTO}] - [\text{RIVERBANK}]$

(b) $\text{RIVERBANK below MODESTO fix thin cells} = \text{con}([\text{m-r}] < 5, [\text{MODESTO}] - 5, [\text{RIVERBANK}])$

iii) Convert raster file to ASCII file in ARC toolbox then import to GMS as scatter points and reinterpolate to the 2D grid using natural neighbor.

iv) Add layers between the Modesto IVF base and the Riverbank IVF base to make discretization fine enough to capture IVF character (minimum 0.5m thick cells)

v) Both of the IVF base surfaces intersect the Corcoran clay and layers 9 through 11. Use the GMS model checker to auto fix layer errors. In GMS model checker:

(1) Set a minimum thickness of 0.5 m for cell thickness.

- (2) Fix layer errors from the top down and preserve the top layers (this is the best way to preserve the known data surfaces: the Modesto IVF, the Riverbank IVF and the Corcoran Clay)

D. Boundaries

The southern and western general head boundary cells in the modified model are the same as in the USGS model. Changes in the GHB conditions were made to the rivers in the central portion of the model and the northeastern boundary. The upper reaches of the Stanislaus, Tuolumne, and Merced Rivers in layer 1 were changed from specified fluxes to general head cells. The GHB condition was removed in several cells (~250) in the northern portion of the model.

The specified flux cells that represent the Stanislaus, Tuolumne, and Merced Rivers in layer 1 of the USGS model were changed to GHB cells in the adapted model (See Figure 8 in Chapter 2). The head elevations at these new locations were assigned based on the ground surface elevation. Using National Geographic TOPO! California, waypoints were marked along the river and imported into ArcMap and plotted as XY data. This point file was then opened in GMS5.0 and used to assign head elevations to the new GHB cells delineating the upper reaches of the rivers. These new head elevations were then added to the input file for the GHB code.

In the USGS model, lack of boundary cells along the rivers was justified because the rivers are disconnected from the aquifer in the area. However, the lack of a boundary in this portion of the model causes unrealistic volumes of water to collect within the river valleys. To maintain the condition that the rivers are not connected to the aquifer in the eastern portion of the model, conductances of the newly assigned GHB cells were reduced. Conductances were assigned using the same calculations as the original river

cells (explained below), but without the vertical K river multiplier (vkrivmult) of 10, which lowered the cell conductances to reflect the disconnected surface and groundwater in the area. The cell conductances that were calculated this way include all of the GHB cells delineating the rivers to the eastern extent: cell *I 20 J78* on the Stanislaus River, *I 53 J 61* on the Tuolumne River, and *I 136 J73* on the Merced River (Table F1). The eastern most GHB cells along the river have even lower conductivities to represent the more consolidated geologic deposits in that area. These cells were not only calculated without the vertical K river multiplier but also divided by 2 (Table F2). This allows unrealistic volumes of water to fill the river valley, 5 to 8 meters at most. This condition is also present in the USGS model. To attempt to rectify this unrealistic situation, five cells were added to the head of the Tuolumne River, extending the GHB to the edge of the model. These cells are in Table 2. This helped to reduce the amount of water gained by the stream in the model, but did not correct the problem completely. The river in the adapted model still maintains losing and gaining reaches which is the most parsimonious condition that could be achieved for the model in this study.

In the northeastern-most portion of the USGS model, GHB cells are dry down to an elevation of 10 to 17 meters (33 to 56 feet). To avoid the drying of boundary cells, some of the boundary cells assigned in the original USGS model were removed from layer 1 through layer 4 in the adapted model. The exact cells where the GHB condition was removed include:

- **Layer 1: I 1; J 76 to 153**
- **Layer 2: I 1; J 81 to 153**
- **Layer 3: I 1; J 96 to 153**
- **Layer 4: I 1; J 111 to 153**

General head boundaries were assigned using an adaptation of a code used to develop general head boundaries for the USGS model. Head elevations and cell

conductances were assigned using a code adapted from the 16 layer USGS model to the 27 layer model used in this study. This code accounts for the location of the boundary (i.e. north and south lateral boundary, the San Joaquin River in the west, or the river cells in the top active layer).

Head was calculated with a vertical gradient of 0.05 meters of head per meter of depth. The head decreases from layer 1 to layer 17. Initial head values for layer 1 GHB were determined from stream gage data and the area topography (*S. Phillips*, pers. comm., 8/1/05). Layer 18 was set equal to layer 17 to prevent an unrealistic (at this model scale) head change between the low conductivity Corcoran Clay layer and the layer below it. The head was set to increase from layer 19 down to layer 27 in order to generate upward flow in these layers. The gradient of 0.05 meters of head per meter of depth (thickness) was added to the initial start head (values from layer 18). In a manner similar to the USGS approach, this increasing head value was constrained with the sub-condition that the calculated head value could not exceed the assigned head value in layer 1. If this condition occurred, the calculated head value for that layer would be ignored and the cell would be assigned a head equal to the head in layer 1).

Downward flow

$$\mathbf{ghbhead = ghbhead - (totthick * gradient)} \quad (1)$$

[for layers 1 through 18 where head in layer 18 = head in layer 17]

Upward flow

$$\mathbf{ghbhead = ghbhead + (totthick * gradient)} \quad (2)$$

[for layers 19 through 27]

where *ghbhead* is the head assigned to the GHB cell, and *totthick* is the thickness from the center of the cell in layer 1 (for the downward flow) or layer 19 (for the upward flow) to the center of the layer for which the GHB head value is being calculated.

The conductance (*ghbcond*) through the GHB cells was determined depending on the location of the cell in the model: the top layer river cells had different conductance calculations than the rest of the GHB cells. In general, conductance is calculated using two variables: (1) the horizontal hydraulic conductivity assigned to the cell and (2) the cell thickness. Constants also included in the calculation are: (1) cell size (400m) and (2) general head boundary distance (400m).

Preserve Regional Lateral Flow from the East

$$\mathbf{ghbcond = KH*thick*cellsize/ ghbdist} \quad \mathbf{(3)}$$

(For GHB cells assigned to northern and southern boundaries and western boundary below layer 1)

GHB cells that delineate rivers in layer 1 allow a small amount of vertical flow, while below layer 1 along the western model edge and for all layers along the north and south extent of the model, the boundary reflects the overall lateral flow from the east. To implement vertical flow, the conductance through layer 1 GHB cells at the location of the rivers was calculated using the vertical hydraulic conductivity, riverbed thickness (1m), river width (25m), and a vertical conductivity multiplier of 10.

Preserve Local Vertical Flow from Rivers

$$\mathbf{ghbcond = KV * ((cellsize*rivwidth) /bedthick)* vkrivmult} \quad \mathbf{(4)}$$

(For GHB cells assigned to rivers in layer 1)

E. Hydraulic Conductivity data

See IVF Fortran code and Vertical Hydraulic Conductivity and Anisotropy Factor Fortran code

Horizontal Hydraulic Conductivities

Horizontal hydraulic conductivities were assigned using the IVF Fortran code (See Appendix G). This code assigns the IVF of the various scenarios based on the elevation at the center of a cell. The output file from this code preserves the general geometry and slope of the valley; however, some manual editing was needed for the hydraulic conductivity of the IVF Fortran output file. The main areas where edits were made are at the head and the mouth of the valley: the head of the valley from j137 to approximately j116 and the end of the valley from j49. The mouth of the valley, in particular lack fines at the top of the valley. General summary of where and why changes were made to the IVF HK files include:

- The stratigraphy at head of the valley was not as well defined as it was farther down valley. For example, the sand pinched out in some areas of the valley (e.g. J134 in the RBMS and RBSTMS model). The upper reaches of the IVF were edited to preserve the stratigraphy and lateral continuous nature of the valley.
- Lateral valley continuity was disrupted most commonly at bends in the river valley. In this case, the valley needed to be widened by a cell width (or 2 cell widths at the most) in areas to maintain connectivity (e.g. J116 in the Modesto small IVF).
- In all of the models, the Tuolumne River Riverbank IVF (RB) has fines largely nonexistent. Fines were added to the areas where they did not exist. The fines are likely under represented because the lower limit elevation of the fines may be slightly higher than the center of the cell. The unit may be too thin to be preserved with the discretization.

The need for manual edits of the IVF Kh file may have been caused by using a different surface generation method for the sequence boundary surfaces (surfaces including the IVF used in the IVF code) than was used to make the IVF base surface (which was used to make the upper layers of the model and in the IVF code to designate the location and Kh of cells in the IVF). Due to limited data, Arc GRID TREND was chosen as the surface generation tool for the IVF bottom surface that was entered in the model discretization. TREND was chosen over the ArcMap Geostatistical Wizard, which was used to create the sequence boundary surfaces, to allow manual designation of the

output surface extent (step 2i2 above). The ArcMap Geostatistical Wizard will only extrapolate a surface to a predetermined extent outside of the input data points. Manually assigning the extent of the output surface provided the flexibility to create a surface large enough to cover the model extent. Using the same method of surface generation for both the sequence boundary surface and the IVF base surface for the new model discretization would be ideal, but it was not possible in this case due to a lack of input data points, which prevented the ArcMap Geostatistical Wizard from generating a surface large enough to cover the model area. Minimal lateral and vertical shifting of the valley mostly in the eastern portion of the model was the result of this discrepancy.

Vertical Hydraulic Conductivities

Because the LPF package is used for this model, a leakance value ($v_{cont} = K_v/\text{thickness}$) is not specified. Instead, this model uses an anisotropy factor (K_h/K_v). To calculate this number for the model, a FORTRAN code (See Appendix H) was generated to first, calculate the vertical conductivity from the leakance parameter in the USGS data. This vertical conductivity was assigned to cells in the newly discretized model using the same method as the horizontal hydraulic conductivity: if the new model's cell centered elevation falls between the top and bottom layer elevations of the coarser USGS model the K_v from the USGS model will be assigned to the adapted model. Then, the vertical hydraulic conductivity was used to calculate the anisotropy factor (K_h/K_v).

F. Recharge

All of the original recharge values from the USGS land-use approach were maintained in the model (Burow *et al.*, 2004). Recharge values range from 0 to 0.005 m/d or 1.825 m/yr (0.0164 ft/day or 5.986 ft/yr).

G. Evapotranspiration

The original ET values were maintained in the new model: maximum evaporation rate of 1.6 m/yr at land surface and the maximum extinction depth is 2.1 meters below the land surface. These values were assigned based on the water budget in Burow *et al.* (2004).

H. Wells

Pumping wells in this model are the same wells used for the USGS model and include: urban-supply, agricultural, and water-table-control, or have known "drainage". Pumping from the wells was calculated using the same FORTRAN code as was used for the USGS model. Appropriate layer numbers were changed for the newly discretized model (see code). The well code had to be run to produce a separate well file for each model scenario, as several wells intersect the IVF.

I. Reservoirs

Wood Reservoir, Modesto Reservoir, and Turlock Lake are all preserved in the adapted model. The reservoir file was used with the adapted model without any changes to the file format. The vertical conductance of the reservoir, however, was reduced. The values of 0.003 and 0.006 m²/day were divided by 1.2 (value obtained by manually testing various vertical conductances to constrain the best value). The resulting vertical conductances are 0.0025 and 0.005 m²/day.

The only other small alteration made in the file is in the heading. The unit number that specifies where the cell-by-cell flow should be recorded was changed to zero. This is the second number in the initial line of the reservoir data array.

Table F1: Cells where the conductance in the upper reaches of the Tuolumne River were reduced by 10 and then 2. It is assumed that the lithologic units here are more consolidated, therefore their conductance is lower.

i	j	k	head	original conductance	New Conductance (Divide by 10 then 2)
87	121	1	28	163.93	81.96500245
87	122	1	28	233.15	116.575
88	123	1	28	391.37	195.6849976
89	124	1	29	438.96	219.4800049
89	125	1	29	128.64	64.3200012
90	126	1	30	277.76	138.8799927
91	126	1	30	204.3	102.15
92	127	1	31	153.32	76.66000365
93	128	1	31	130.46	65.2299988
94	129	1	32	122.12	61.05999755
95	130	1	33	119.37	59.68499755
96	131	1	33	127.74	63.8700012
97	131	1	34	122.28	61.14000245
98	132	1	34	125.52	62.75999755
99	133	1	35	249.4916	124.7457861
99	134	1	36	269.4419	134.7209548
100	135	1	37	227.6779	113.8389331
100	136	1	37	304.0255	152.0127616
101	137	1	37	266.2508	133.1253762

Table F2: Table listing the cells added to the head of the Tuolumne River to attempt to reduce the amount of water within the river valley.

i	j	k	head	Conductance	Kh	Kh/Kv	Kv	con
99	133	1	35	249.4947	86.4	3463	0.024949	249.4947
99	134	1	36	269.4443	86.4	3206.6	0.026944	269.4443
100	135	1	37	227.674	86.4	3794.9	0.022767	227.674
100	136	1	37	304.022	86.4	2841.9	0.030402	304.022
101	137	1	37	266.2558	86.4	3245	0.026626	266.2558

Appendix G: Incised-Valley Fill FORTRAN Code

A. IVF Code Information

1. Use IVF_CODE to assign the original Kh from the USGS model to the cell in the adapted model with the same elevation as the USGS model cell. Be sure to use the code specific to the geologic scenario: without ST or with ST.
2. Files Needed
 - a. Elevation data exported from the GMS 5.0.
 - b. Kh data from the USGS in ASCII form exported from GMS (no IVF, this code will add them)
 - c. Gravel, sand, and fines top elevations for the IVF
 - d. File to delineate where the Tuolumne River Riverbank IVF and Stanislaus Riverbank IVF are located. This file assigns the Stanislaus IVF a value of 3 and the Tuolumne River IVF a value of 2.
3. Writes
 - a. This will output a new Kh data set for each geologic scenario.

B. IVF Developing Stratigraphy and Assigning Hydraulic Conductivities

1. Development of Top Surfaces of gravel, sand, and fines.
 - a. This code relies on the stratigraphy of the area to identify a cell located within the IVF. The code uses a series of logical statements to determine whether the IVF is within the IVF, and if it is, what part of the IVF is the cell located in based on elevation. To do this, the code uses the grid surfaces developed in Appendix D, as well as grid surfaces of the top of the gravel, sand, and fines fractions of the IVF.
 - b. These surfaces were generated by:

- i. First, creating grid surfaces for the IV base.
 1. Use the point shapefile of each IVF with the valley gradient assigned to generate a surface in Arc GRID using TREND.
 2. The syntax used is:
 - a. **TREND (<point_cover | point_file>, {item}, {order}, {xmin, ymin, xmax, ymax})**
 - b. The <point cover> is the point shapefile of IV basal elevations that was used to generate the surfaces in Appendix D.
 - c. The item is the elevation of the IVF base in the shapefile that will be used to make the surface.
 - d. The order used was 1.
 - e. The coordinates for the area to be interpolated were (-125695, 1607364, -35303, 1632550) in NAD 1983 Albers projection.
- ii. Obtain the entire thickness of the valley
 3. Using the Raster Calculator function in ArcMap's Spatial Analyst, the thickness of the valley was calculated with the following equation:
 - a. **Total IV Thickness = abs ([fan surface (UTL or RB)] - [bottom of IV surface])**
 - b. The fan surface was either the Riverbank or the UTL fan surface WITHOUT the IVF.

- c. The bottom of the IV surface was the Riverbank Tuolumne River, Riverbank Stanislaus River, Modesto Large, or Modesto Small gravel base surface generated in step “i”.
- 4. Percent thickness of each fraction of the IVF (gravel, sand, and fines) were calculated using the grid files in the raster calculator:
 - a. **Gravel thickness**= 0.4* [valley thickness]
 - b. **Sand thickness**= 0.45* [valley thickness]
 - c. **Fines thickness** = 0.15* [valley thickness]
- 5. Using the thickness calculated above, the elevation of the top of the gravel, sand, and fines surfaces were created by adding that thickness to the valley bottom (for the gravel) or to the elevation of the top of the unit below (for the sand and the fines)
 - a. **Gravel top surface elevation** = [bottom of IV valley] + [gravel thickness]
 - b. **Sand top surface elevation** = [gravel top elevation] + [sand thickness]
 - c. **Fines top surface elevation** = [sand top elevation] + [fines thickness]

2. Hydraulic Conductivity Values

- b. The hydraulic conductivity values assigned to the IVF were obtained from Weissmann *et al.* (2004).

- i. Gravel was assigned a Kh of 864 m/d (or 1×10^{-2} m/s)
- ii. Sand was assigned a Kh of 86.4 m/d (or 1×10^{-3} m/s)
- iii. Fines were assigned a Kh of 0.0864 m/d (or 1×10^{-6} m/s)

C. Preparing the files for use in the FORTRAN code

The resulting Riverbank and UTL surfaces with IVFs were used in a FORTRAN code to assign the hydraulic conductivities of the IVF. To preserve a consistent file format and interpolate the ArcMap generated grid to the model grid for the FORTRAN code, the surfaces were opened in GMS 5.0 and interpolated to an existing model grid.

1. To open the surfaces in GMS 5.0, the raster files were converted into an ASCII file.
 - a. In Arc Toolbox, look in Conversion Tools, then select “Raster to ASCII” tool.
2. In GMS 5.0, the USGS grid must be defined.
 - a. The grid is 153 rows by 137 columns of 400 meter² cells.
 - b. In the 2D grid module, select the Grid dropdown menu, then “create Grid”.
 - i. Origin (x) -83795.7 (y) 1572727.3
 - ii. Length (x length) 54800 (y length) 61200
 - iii. Number of Cells: (x) 137 columns (y) 153 rows
 - iv. Rotation: 37
3. Next, the ASCII file was opened in GMS 5.0 as 2D scatter points.
4. The 2D scatter points were then interpolated to the grid generated by the USGS.
 - a. In the 2D grid module, go to the “Interpolation” drop down menu, and select interpolate to 2D grid.

- b. Inverse distance weighted was used to interpolate the surface. A maximum of 1 meter difference in the actual versus interpolated surface was noted based on a random sampling of points.
- 5. The newly interpolated surfaces were then exported as ASCII files to be used in the IVF FORTRAN code to assign hydraulic conductivity values.
 - a. Some file manipulation was necessary prepare the ASCII files from GMS for the code. The exported GMS ASCII files each contain a header providing information the type of data set the file is, the file name, and the number of data points (see sample below). This as well as the list of 1's and 0's, denoting active and inactive cells respectively, needed to be removed.

b. **Sample GMS Header**

```

DATASET
OBJTYPE "grid2d"
BEGSCL
ND 20961
NC 20961
NAME "elevation2"
TS 0 0

```

AND for 3 dimensional grids

```

DATASET
OBJTYPE "grid3d"
BEGSCL
ND 565947
NC 565947
NAME "gmsfil"
TS 0 0

```

D. IVF FORTRAN CODE

1. General Description of Code

- a. The IVF code uses a series of conditional statements to assign hydraulic conductivity values to cells of the model located within the IVF. Figure

G1 shows a flow chart of conditional statements that must be met to assign the predetermined Kh values for the IVF. The elevation of the center of the cell was used to determine (1) if the cell was in the IVF and (2) based on the location, which Kh value it should be assigned. Cells outside of the IVF were assigned Kh values from the USGS model. Cells within the IVF were assigned a Kh value for gravel (864 m/d), sand (86.4 m/d), or fines (0.084 m/d) (Figure G2). For example, if the cell were above the Turlock Lake surface, below the Riverbank surface, above the top of the gravel elevation and below or equal to the bottom elevation of the top of the sand, then the cell is in the IVF and would be assigned a Kh of sand. As is illustrated in figure G2, the fines represent a small fraction of the total IVF thickness and the likelihood of the center of the cell falling either below or above this relatively thin interval is high, thus the fines are under represented in this model.

Figure G1: A flow chart of the conditional statements used to define the Kh of the IVF based on its stratigraphic position. This example uses the Modesto large IVF and the Tuolumne River Riverbank IVF (RBML).

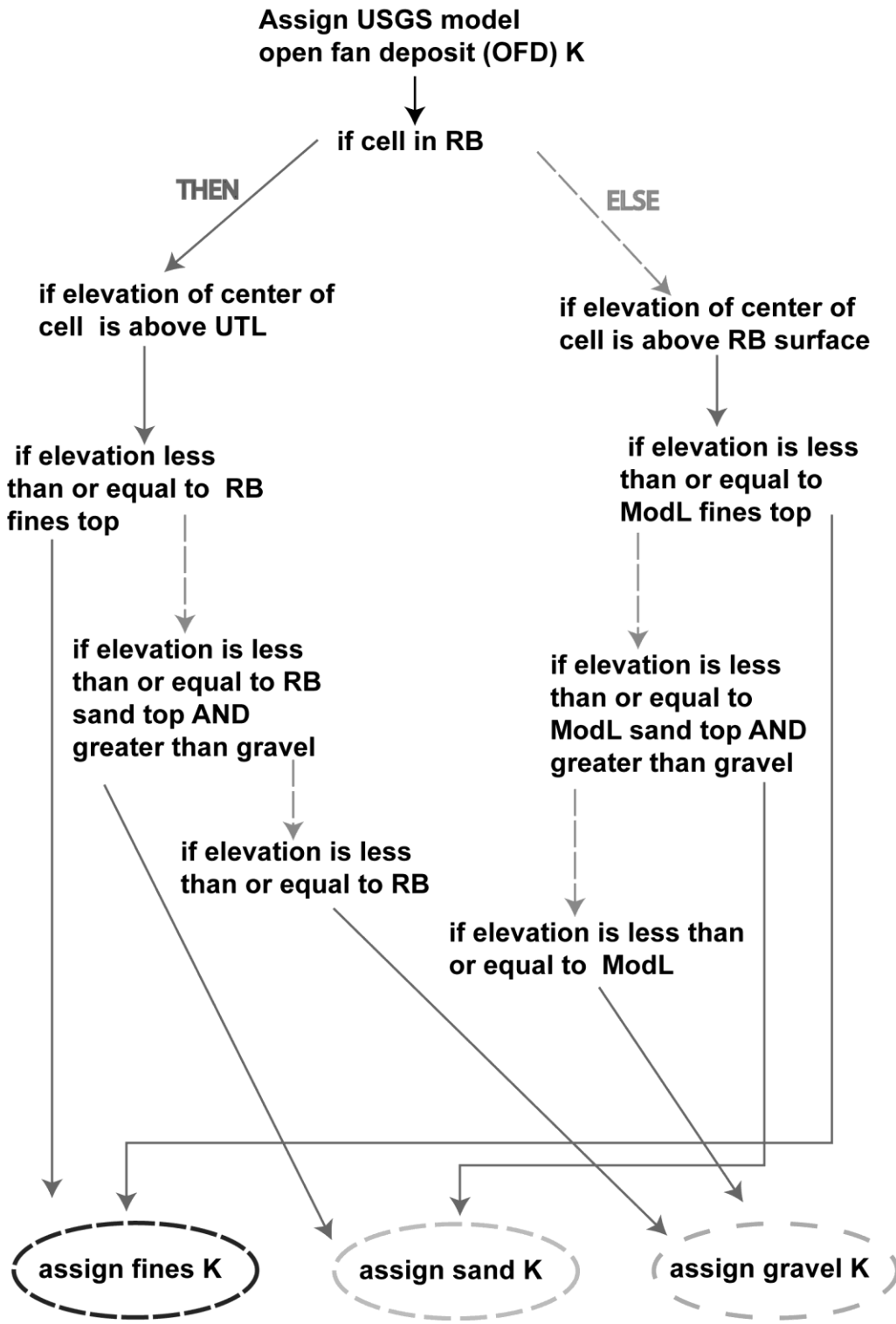
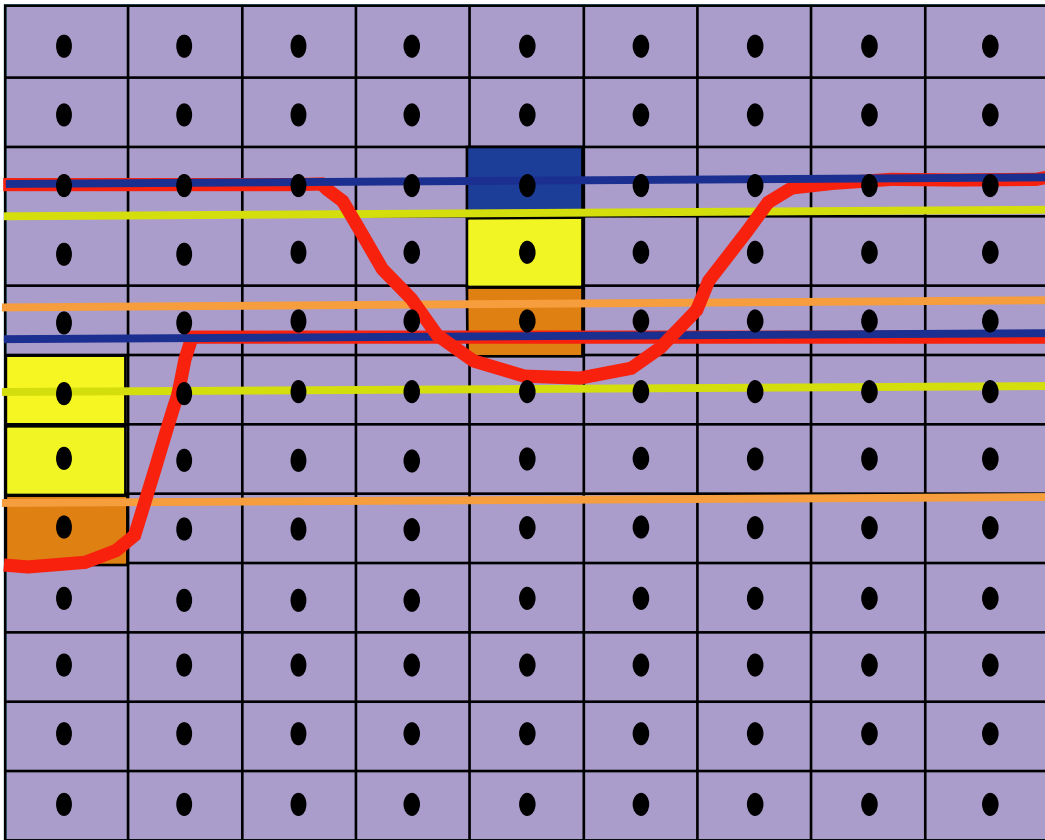


Figure G2: Cells located within the IVF were assigned a Kh based on the elevation of the center of the cell relative to the sequence boundary surfaces (in red), gravel (in orange), sand (in yellow), and fines (in blue) surfaces within the IVF. Shown in color.



2. No IVF
 a. FORTRAN code

```

program noIVF

c Program to create an output file to be
c used in 3D realization for a GMS 5.1
c groundwater model.
c DO NOT USE WITHOUT ADJUSTMENT FOR SPECIFICS
c
c PARAMETERS:
c gk = gravel hydraulic conductivity**;
c sk = sand conduct; fk = fines conduct**;
c pk=paleosol conduct**
c **from King's River model Weissmann, Zhang, Fogg, Mount (2004)
c HK1_40 = open fan deposit conduct from USGS model; nzusgs= vertical
discretization of USGS model;
c nx= number of rows
c ny= number of columns
c nz= my vertical discretization;
c
  
```

```

c Elevation from newly discretized USGS model (40 layers)= elevfil
c Riverbank top = rsfil
c Riverbank bottom of paleosol = rpfil
c Upper Turlock Lake top = usfil
c UTL base of paleosol = upfil
c Mod IV (large or small) fines top surface= mfsfil; mssfil = sand;
mgsfil = gravel
c ModS IV fines top surface= mfsfil (ONLY CHANGE TO MODESTO SMALL WHEN
FILE CHANGED IN PARFIL); mssfil = sand; mgsfil = gravel
c RB IV fines top surface= rfsfil; rssfil = sand; rgsfil = gravel
c ST IV fines top surface= stffil; stsfil = sand; stgfil = gravel (ONLY
WHEN PRESENT IN PARFIL)
c HK1_40fil= 3D array file of all the K values from newly discretized
USGS model
c HK_IVF = new file of horizontal hydraulic conductivities with IVF K
values included
c
c
c EDIT 080905 Changed the HK1_40 to HK1_36.  nzz=36 Using newly
discretized HK data...
c ...nzz=33 FInal model will have 33 layers.
c
c

```

```

c Declaration of variables

```

```

c      integer nznewd, nxy, nxyz, nxyzusgs

```

```

parameter nx=153
parameter ny=137
parameter nz=27
parameter nzz=16
parameter nxy=nx*ny
parameter nxyz=nx*ny*nz
parameter nxyzz=nx*ny*nzz

```

```

real elev(nxyzz)
real elev2(nxyz)
real HK1_16(nxyzz)
real HK1_27(nxyz)

```

```

character*40 elevfil
character*40 elev2fil
character*40 HK1_16fil
character*40 HK1_27fil
character*40 parfill

```

```

dx=400.
dy=400.
dz=0.5

```

```

c Where are the data?????????

```

```

print*, 'input par file name?:' ! Open input and output files
read(5, '(a40)') parfill
print*, 'input file name:', parfill
open(1, file=parfill, status='old')

read(1, '(a40)') elevfil
read(1, '(a40)') elev2fil
read(1, '(a40)') HK1_16fil
read(1, '(a40)') HK1_27fil

close(1)
c

open(18, file='dbg.txt', status='unknown')
open(19, file='elevations', status='unknown')

c Read data from ASCII file to fill arrays. Sequence boundaries!
print*, 'reading Parfil including ASCII files from GMS--read elev'
c read(*, '(a40)') eleva
open(1, file=elevfil, status='old', form='formatted')
c print*, '1st doloop'
c do i=1, 7
c read (1, '(a40)') junk
c enddo
c do k=1, nzz
c do j=1, ny
c do i=1, nx
c ijk= i+((k-1)*nx*ny)+((j-1)*nx)
c read (1, *) elev(ijk)
c enddo
c enddo
c enddo
close(1)

print*, 'open elev2fil'
open(2, file=elev2fil, status='old', form='formatted')
do k=1, nz
do j=1, ny
do i=1, nx
ijk= i+((k-1)*nx*ny)+((j-1)*nx)
read(2, *) elev2(ijk)
enddo
enddo
enddo
close(2)

print*, 'open HK1_16fil'
open (17, file=HK1_16fil, status='old', form='formatted')

do k=1, nzz
do j=1, ny
do i=1, nx

```



```

                                ijk=i+((k-1)*nx*ny)+((j-1)*nx)
                                read(17,*) HK1_16(ijk)
                                enddo
                            enddo
                    enddo

                close(17)

c fill in gms final grid array with proper hydraulic conductivity

                do k=1,nz
                    do j=1,ny
                        do i=1,nx
                            ij=i+((j-1)*nx)
                            ijk=((k-1)*nx*ny)+i+((j-1)*nx)

c Fill in USGS K values for bottom cells (USGS cells 12 through 16)
                            if(k.ge.23) then
                                kusgs=k-11
                                ijkusgs=((kusgs-1)*nx*ny)+i+((j-1)*nx)
                                HK1_27(ijk)=HK1_16(ijkusgs)
                            else

c Calculate elevation of cell and fill in USGS value as 'default'
c     ijk2 = cell number located below ijk
c     elevation = elevation of center of cell for rediscretized grid
                                ijk2=(k*nx*ny)+i+((j-1)*nx)
                                elevation = ((elev2(ijk)-
elev2(ijk2))/2)+elev2(ijk2)

c Find out which usgs cell we are in and assign usgs K value
                                do kk=1,12
                                    ijkk=((kk-1)*nx*ny)+i+((j-1)*nx)
                                    ijkk2=(kk*nx*ny)+i+((j-1)*nx)
                                    if(elevation.le.elev(ijkk).and.elevation.gt.elev
*
                                        (ijkk2)) then
                                            HK1_27(ijk)=HK1_16(ijkk)
                                    write(15,'(4i4)') i,j,k,kk
                                    endif
                                enddo
                            endif
                        enddo
                    enddo
                enddo

c Prepare the gms input files

                print*, 'printing gms files'
                open(20,file=HK1_27fil,status='unknown')

c writing GMS full grid file

```

```

do k=1,nz
  do j=1,ny
    do i=1,nx
      ijk=i+((j-1)*nx)+((k-1)*nx*ny)
      write(20,'(E9.4)') HK1_27(ijk)
    enddo
  enddo
enddo

print*,'gms files noIVF completed'
print*,'Goodbye!'

close(20)
close(18)
close(19)

print*,'*****'
print*,'GMS files written.'
print*,'*****'
print*,'(:'

stop
end

```

3. With the Riverbank IVF from the Stanislaus River

a. FORTRAN code

```

program IVF code wST

c Program to create an output file to be
c used in 3D realization for a GMS 5.1
c groundwater model.
c DO NOT USE WITHOUT ADJUSTMENT FOR SPECIFICS
c
c PARAMETERS:
c gk = gravel hydraulic conductivity**;
c sk = sand conduct; fk = fines conduct**;
c pk=paleosol conduct**
c **from King's River model Weissmann, Zhang, Fogg, Mount (2004)
c HK1_27 = open fan deposit conduct from USGS model; nzusgs= vertical
discretization of USGS model;
c nx= number of rows
c ny= number of columns
c nz= my vertical discretization;
c
c Elevation from newly discretized USGS model (40 layers)= elevfil
c Riverbank top = rsfil
c Riverbank bottom of paleosol = rpfil
c Upper Turlock Lake top = usfil
c UTL base of paleosol = upfil

```

```

c Mod IV (large or small) fines top surface= mfsfil; mssfil = sand;
mgsfil = gravel
c ModS IV fines top surface= mfsfil (ONLY CHANGE TO MODESTO SMALL WHEN
FILE CHANGED IN PARFIL); mssfil = sand; mgsfil = gravel
c RB IV fines top surface= rfsfil; rssfil = sand; rgsfil = gravel
c ST IV fines top surface= stffil; stsfil = sand; stgfil = gravel (ONLY
WHEN PRESENT IN PARFIL)
c HK1_27fil= 3D array file of all the K values from newly discretized
USGS model
c HK_IVF = new file of horizontal hydraulic conductivities with IVF K
values included
c
c TO USE...
c (1) If changing vertical discretization: Check Lines 361 and 362
c (2) Edit 'parfil.par' to edit input files.
c

```

```

c Declaration of variables

```

```

c      integer nznewd, nxy, nxyz, nxyzusgs

```

```

parameter nx=153
parameter ny=137
parameter nz=27
parameter nzz=16
parameter nxy=nx*ny
parameter nxyz=nx*ny*nz
parameter nxyzs=nx*ny*nz

```

```

c      nxy=nx*ny
c      nxyz=nx*ny*nz
c      nxyzusgs=nx*ny*nzusgs

```

```

real rs(nxy), rp(nxy), mfs(nxy), mss(nxy), mgs(nxy)
real us(nxy), up(nxy), rfs(nxy), rss(nxy), rgs(nxy)
real st3rb2(nxy)
real stf(nxy)
real sts(nxy)
real stg(nxy)
real elev(nxyz)
real elev2(nxyz)
real HK1_16(nxyz)
real HK_IVF(nxyz)

```

```

character*40 elevfil
character*40 elev2fil
character*40 usfil
character*40 upfil
character*40 rfsfil
character*40 rssfil
character*40 rgsfil
character*40 stffil
character*40 stsfil

```

```

character*40 stgfil
character*40 rsfil
character*40 rpfil
character*40 mfsfil
character*40 mssfil
character*40 mgsfil
character*40 st3rb2fil
character*40 HK1_16fil
character*40 HK_IVFfil
character*40 parfill1

c   character*40 parfill1, junk

c   K values for facies from Weissmann junk

      gk=864
      sk=86.4
      fk=0.0864
c   pk=0.0000001

      dx=400.
      dy=400.
      dz=0.5

c   Where are the data????????

print*, 'input par file name?:' ! Open input and output files
read(5, '(a40)') parfill1
print*, 'input file name:', parfill1
open(1, file=parfill1, status='old')

read(1, '(a40)') elevfil
read(1, '(a40)') elev2fil
read(1, '(a40)') usfil
read(1, '(a40)') upfil
read(1, '(a40)') rfsfil
read(1, '(a40)') rssfif
read(1, '(a40)') rgsfil
read(1, '(a40)') stffil
read(1, '(a40)') stsfif
read(1, '(a40)') stgfil
read(1, '(a40)') rsfil
read(1, '(a40)') rpfil
read(1, '(a40)') mfsfil
read(1, '(a40)') mssfil
read(1, '(a40)') mgsfil
read(1, '(a40)') st3rb2fil
read(1, '(a40)') HK1_16fil
read(1, '(a40)') HK_IVFfil

close(1)

c

```

```

open(18,file='dbg.txt',status='unknown')
open(19,file='elevations',status='unknown')

c Read data from ASCII file to fill arrays. Sequence boundaries!
  print*, 'reading Parfil including ASCII files from GMS--read elev'
c read(*, '(a40)') eleva
  open(1,file=elevfil,status='old', form='formatted')
c print*, '1st doloop'
c do i=1, 7
c     read (1,'(a40)') junk
c     enddo
          do k=1,nzz
            do j=1,ny
              do i=1,nx
                ijk= i+((k-1)*nx*ny)+((j-1)*nx)
                read (1,*) elev(ijk)
              enddo
            enddo
          enddo
        close(1)

  print*, 'open elev2fil'
  open(2,file=elev2fil,status='old', form='formatted')
    do k=1,nz
      do j=1,ny
        do i=1,nx
          ijk= i+((k-1)*nx*ny)+((j-1)*nx)
          read(2,*) elev2(ijk)
        enddo
      enddo
    enddo
  close(2)

c Open and read Upper Turlock Lake surface with Riverbank Valley
  print*, 'open usfil'
c read(*, '(F15.5)') utl_rbl_300
  open(3,file=usfil,status='old', form='formatted')

          do j=1,ny
            do i=1,nx
              ij=i+((j-1)*nx)
              read(3,*) us(ij)
            enddo
          enddo
        close(3)

  print*, 'open upfil'
  open(4,file=upfil,status='old', form='formatted')

          do j=1,ny
            do i=1,nx
              ij=i+((j-1)*nx)
              read(4,*) up(ij)
            enddo
          enddo

```

```

close(4)

print*, 'open rfsfil'
open(5,file=rfsfil,status='old', form='formatted')

      do j=1,ny
        do i=1,nx
          ij=i+((j-1)*nx)
          read(5,*) rfs(ij)
        enddo
      enddo

close(5)

print*, 'open rssfil'
open(6,file=rssfil,status='old', form='formatted')

      do j=1,ny
        do i=1,nx
          ij=i+((j-1)*nx)
          read(6,*) rss(ij)
        enddo
      enddo

close(6)
print*, 'open rgsfil'
open(7,file=rgsfil,status='old', form='formatted')

      do j=1,ny
        do i=1,nx
          ij=i+((j-1)*nx)
          read(7,*) rgs(ij)
        enddo
      enddo

close(7)

print*, 'open stffil'
open(8,file=stffil,status='old', form='formatted')
      do j=1,ny
        do i=1,nx
          ij=i+((j-1)*nx)
          read(8,*) stf(ij)
        enddo
      enddo

close(8)

print*, 'open stsfil'
open(9,file=stsfil,status='old', form='formatted')
      do j=1,ny
        do i=1,nx
          ij=i+((j-1)*nx)
          read(9,*) sts(ij)
        enddo

```

```

        enddo

close(9)

print*, 'open stgfil'
open(10,file=stgfil,status='old', form='formatted')
    do j=1,ny
        do i=1,nx
            ij=i+((j-1)*nx)
            read(10,*) stg(ij)
        enddo
    enddo

close(10)

print*, 'open rsfil'
open(11,file=rsfil,status='old', form='formatted')

    do j=1,ny
        do i=1,nx
            ij=i+((j-1)*nx)
            read(11,*) rs(ij)
        enddo
    enddo

close(11)

print*, 'open rpfil'
open(12,file=rpfil,status='old', form='formatted')

    do j=1,ny
        do i=1,nx
            ij=i+((j-1)*nx)
            read(12,*) rp(ij)
        enddo
    enddo

close(12)

print*, 'open mfsfil'
open(13,file=mfsfil,status='old', form='formatted')

    do j=1,ny
        do i=1,nx
            ij=i+((j-1)*nx)
            read(13,*) mfs(ij)
        enddo
    enddo

close(13)

print*, 'open mssfil'
open(14,file=mssfil,status='old', form='formatted')

    do j=1,ny
        do i=1,nx

```

```

                ij=i+((j-1)*nx)
                read(14,*) mss(ij)
            enddo
        enddo

close(14)

print*, 'open mgsfil'
open(15,file=mgsfil,status='old', form='formatted')

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(15,*) mgs(ij)
            enddo
        enddo

close(15)

print*, 'open st3rb2fil'
open (16,file= st3rb2fil, status='old', form='formatted')

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(16,*) st3rb2(ij)
            enddo
        enddo

close(16)

print*, 'open HK1_16fil'
open (17,file=HK1_16fil,status='old', form='formatted')

        do k=1,nzz
            do j=1,ny
                do i=1,nx
                    ijk=i+((k-1)*nx*ny)+((j-1)*nx)
                    read(17,*) HK1_16(ijk)
                enddo
            enddo
        enddo

close(17)

```

c fill in gms final grid array with proper hydraulic conductivity

```

do k=1,nz
    do j=1,ny
        do i=1,nx
            ij=i+((j-1)*nx)
            ijk=((k-1)*nx*ny)+i+((j-1)*nx)

```



```

c Fill in USGS Kh values for bottom cells (USGS cells 12 through 16)
  if(k.ge.23) then
    kusgs=k-11
    ijkusgs=((kusgs-1)*nx*ny)+i+((j-1)*nx)
    HK_IVF(ijk)=HK1_16(ijkusgs)
  else

c Calculate elevation of cell and fill in USGS value as 'default'
c   ijk2 = cell number located below ijk
c   elevation = elevation of center of cell for rediscrretized grid
    ijk2=(k*nx*ny)+i+((j-1)*nx)
    elevation = ((elev2(ijk)-elev2(ijk2))/2)+elev2(ijk2)

c Find out which usgs cell we are in and assign usgs K or T value
  do kk=1,12
    ijkk=((kk-1)*nx*ny)+i+((j-1)*nx)
    ijkk2=(kk*nx*ny)+i+((j-1)*nx)

    if(elevation.le.elev(ijkk).and.elevation.gt.elev
*      (ijkk2)) then
      HK_IVF(ijk)=HK1_16(ijkk)
    write(15,'(4i4)') i,j,k,kk
    endif
  enddo

c Fill in UTL Formation Paleosol
c   if(elevation.le.us(ij).and.elevation.ge.up(ij)) gms(ijk)= pk

c Fill in Riverbank Formation Paleosol ModL IV
c   if(elevation.le.rs(ij).and.elevation.ge.rp(ij)) gms(ijk)= pk

c fill in Riverbank formation with RB IV (st3rb2 = 2 = inside tuol rb
valley)
  if(st3rb2(ij).eq.2) then
    if(elevation.lt.rfs(ij).and.elevation.gt.us(ij)) then
      if(elevation.le.rfs(ij).and.elevation.gt.rss(ij)) then
        HK_IVF(ijk)= fk
      else if (elevation.le.rss(ij).and.elevation.gt.rgs(ij))
then
        HK_IVF(ijk)= sk
        write(15,'(a6,e9.4)') 'sands ',gms(ijk)
      else if(elevation.le.rgs(ij)) then
        HK_IVF(ijk)= gk
      endif
    endif
  endif
endif

c Fill in the Riverbank formation with ST IV
  if(st3rb2(ij).eq.3) then
    if(elevation.lt.stf(ij).and.elevation.gt.us(ij)) then
      if (elevation.le.stf(ij).and.elevation.gt.sts(ij))
then
        HK_IVF(ijk)= fk
      else if (elevation.le.sts(ij).and.elevation.gt.stg(ij))
then
        HK_IVF(ijk)= sk

```

```

                                else if (elevation.le.stg(ij)) then
                                    HK_IVF(ijk)= gk
                                endif
                            endif
                        endif
                    endif

c Fill in the Modesto formation with Mod IVF
                    if(elevation.gt.rs(ij)) then
                        if (elevation.le.mfs(ij).and.elevation.gt.mss(ij)) then
                            HK_IVF(ijk)= fk
                        else
                            if(elevation.le.mss(ij).and.elevation.gt.mgs(ij)) then
                                HK_IVF(ijk)= sk
                            else if (elevation.le.mgs(ij)) then
                                HK_IVF(ijk)= gk
                            endif
                        endif
                    endif
                endif
            enddo
        enddo

c Prepare the gms input files

        print*, 'printing gms files'
        open(20,file=HK_IVFfil,status='unknown')

c writing GMS full grid file

        do k=1,nz
            do j=1,ny
                do i=1,nx
                    ijk=i+((j-1)*nx)+((k-1)*nx*ny)
                    write(20,'(E9.4)') HK_IVF(ijk)
                enddo
            enddo
        enddo

        print*, 'gms files completed'
        print*, 'Goodbye!'

        close(20)
        close(18)
        close(19)

        print*, '*****'
        print*, 'GMS files written.'
        print*, '*****'
        print*, '(:'

```

```
stop
end
```

4. Without the Riverbank IVF from the Stanislaus River a. FORTRAN code

```
program IVF code noST

c Program to create an output file to be
c used in 3D realization for a GMS 5.1
c groundwater model.
c DO NOT USE WITHOUT ADJUSTMENT FOR SPECIFICS
c
c PARAMETERS:
c gk = gravel hydraulic conductivity**;
c sk = sand conduct; fk = fines conduct**;
c pk=paleosol conduct**
c **from King's River model Weissmann, Zhang, Fogg, Mount (2004)
c HK1_40 = open fan deposit conduct from USGS model; nzusgs= vertical
discretization of USGS model;
c nx= number of rows
c ny= number of columns
c nz= my vertical discretization;
c
c Elevation from newly discretized USGS model (40 layers)= elevfil
c Riverbank top = rsfil
c Riverbank bottom of paleosol = rpfil
c Upper Turlock Lake top = usfil
c UTL base of paleosol = upfil
c Mod IV (large or small) fines top surface= mfsfil; mssfil = sand;
mgsfil = gravel
c ModS IV fines top surface= mfsfil (ONLY CHANGE TO MODESTO SMALL WHEN
FILE CHANGED IN PARFIL); mssfil = sand; mgsfil = gravel
c RB IV fines top surface= rfsfil; rssfil = sand; rgsfil = gravel
c ST IV fines top surface= stffil; stsfil = sand; stgfil = gravel (ONLY
WHEN PRESENT IN PARFIL)
c HK1_40fil= 3D array file of all the K values from newly discretized
USGS model
c HK_IVF = new file of horizontal hydraulic conductivities with IVF K
values included
c
c
c EDIT 080905 Changed the HK1_40 to HK1_36. nzz=36 Using newly
discretized HK data...
c ...nz=33 FInal model will have 33 layers.
c
c
c Declaration of variables
```

```

c      integer nznewd, nxy, nxyz, nxyzusgs

      parameter nx=153
      parameter ny=137
      parameter nz=27
      parameter nzz=16
      parameter nxy=nx*ny
      parameter nxyz=nx*ny*nz
      parameter nxyzz=nx*ny*nzz

c
c      nxy=nx*ny
c      nxyz=nx*ny*nz
c      nxyzusgs=nx*ny*nzusgs

      real rs(nxy), rp(nxy), mfs(nxy), mss(nxy), mgs(nxy)
      real us(nxy), up(nxy), rfs(nxy), rss(nxy), rgs(nxy)
      real st3rb2(nxy)
c      real stf(nxy)
c      real sts(nxy)
c      real stg(nxy)
      real elev(nxyz)
      real elev2(nxyz)
      real HK1_16(nxyz)
      real HK_IVF(nxyz)

      character*40 elevfil
      character*40 elev2fil
      character*40 usfil
      character*40 upfil
      character*40 rfsfil
      character*40 rssfil
      character*40 rgsfil
c      character*40 stffil
c      character*40 stsfil
c      character*40 stgfil
      character*40 rsfil
      character*40 rpfil
      character*40 mfsfil
      character*40 mssfif
      character*40 mgsfil
      character*40 st3rb2fil
      character*40 HK1_16fil
      character*40 HK_IVFfil
      character*40 parfill

c      character*40 parfill, junk

c      K values for facies from Weissmann junk

      gk=864
      sk=86.4
      fk=0.0864
c      pk=0.0000001

```

```

dx=400.
dy=400.
dz=0.5

```

c Where are the data???????

```

print*, 'input par file name?:' ! Open input and output files
read(5, '(a40)') parfill1
print*, 'input file name:', parfill1
open(1, file=parfill1, status='old')

```

```

read(1, '(a40)') elevfil
read(1, '(a40)') elev2fil
read(1, '(a40)') usfil
read(1, '(a40)') upfil
read(1, '(a40)') rfsfil
read(1, '(a40)') rssfil
read(1, '(a40)') rgsfil
c read(1, '(a40)') stffil
c read(1, '(a40)') stsfil
c read(1, '(a40)') stgfil
read(1, '(a40)') rsfil
read(1, '(a40)') rpfil
read(1, '(a40)') mfsfil
read(1, '(a40)') mssfil
read(1, '(a40)') mgsfil
read(1, '(a40)') st3rb2fil
read(1, '(a40)') HK1_16fil
read(1, '(a40)') HK_IVFfil

```

```

close(1)

```

c

```

open(18, file='dbg.txt', status='unknown')
open(19, file='elevations', status='unknown')

```

c Read data from ASCII file to fill arrays. Sequence boundaries!

```

print*, 'reading Parfil including ASCII files from GMS--read elev'
c read(*, '(a40)') eleva
open(1, file=elevfil, status='old', form='formatted')
c print*, '1st doloop'
c do i=1, 7
c read(1, '(a40)') junk
c enddo
c do k=1, nzz
c do j=1, ny
c do i=1, nx
c ijk= i+((k-1)*nx*ny)+((j-1)*nx)
c read(1, *) elev(ijk)
c enddo
c enddo
c enddo
close(1)

```

```

print*, 'open elev2fil'
open(2,file=elev2fil,status='old', form='formatted')
  do k=1,nz
    do j=1,ny
      do i=1,nx
        ijk= i+((k-1)*nx*ny)+((j-1)*nx)
        read(2,*) elev2(ijk)
      enddo
    enddo
  enddo
close(2)

c   Open and read Upper Turlock Lake surface with Riverbank Valley
print*, 'open usfil'
c   read(*, '(F15.5)') utl_rb1_300
open(3,file=usfil,status='old', form='formatted')

  do j=1,ny
    do i=1,nx
      ij=i+((j-1)*nx)
      read(3,*) us(ij)
    enddo
  enddo
close(3)

print*, 'open upfil'
open(4,file=upfil,status='old', form='formatted')

  do j=1,ny
    do i=1,nx
      ij=i+((j-1)*nx)
      read(4,*) up(ij)
    enddo
  enddo
close(4)

print*, 'open rfsfil'
open(5,file=rfsfil,status='old', form='formatted')

  do j=1,ny
    do i=1,nx
      ij=i+((j-1)*nx)
      read(5,*) rfs(ij)
    enddo
  enddo
close(5)

print*, 'open rssfil'
open(6,file=rssfil,status='old', form='formatted')

  do j=1,ny
    do i=1,nx
      ij=i+((j-1)*nx)

```

```

                read(6,*) rsg(ij)
            enddo
        enddo

close(6)
print*, 'open rgsfil'
open(7,file=rgsfil,status='old', form='formatted')

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(7,*) rgs(ij)
            enddo
        enddo

close(7)

print*, 'open rsfil'
open(11,file=rsfil,status='old', form='formatted')

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(11,*) rs(ij)
            enddo
        enddo

close(11)

print*, 'open rpfil'
open(12,file=rpfil,status='old', form='formatted')

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(12,*) rp(ij)
            enddo
        enddo

close(12)

print*, 'open mfsfil'
open(13,file=mfsfil,status='old', form='formatted')

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(13,*) mfs(ij)
            enddo
        enddo

close(13)

print*, 'open mssfil'
open(14,file=mssfil,status='old', form='formatted')

```

```

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(14,*) mss(ij)
            enddo
        enddo

close(14)

print*, 'open mgsfil'
open(15,file=mgsfil,status='old', form='formatted')

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(15,*) mgs(ij)
            enddo
        enddo

close(15)

print*, 'open st3rb2fil'
open(16,file=st3rb2fil, status='old', form='formatted')

        do j=1,ny
            do i=1,nx
                ij=i+((j-1)*nx)
                read(16,*) st3rb2(ij)
            enddo
        enddo

close(16)

print*, 'open HK1_16fil'
open(17,file=HK1_16fil,status='old', form='formatted')

        do k=1,nzz
            do j=1,ny
                do i=1,nx
                    ijk=i+((k-1)*nx*ny)+((j-1)*nx)
                    read(17,*) HK1_16(ijk)
                enddo
            enddo
        enddo

close(17)

```

c fill in gms final grid array with proper hydraulic conductivity

```

do k=1,nz
    do j=1,ny
        do i=1,nx
            ij=i+((j-1)*nx)
            ijk=((k-1)*nx*ny)+i+((j-1)*nx)

```



```

c Fill in USGS K values for bottom cells (USGS cells 12 through 16)
  if(k.ge.23) then
    kusgs=k-11
    ijkusgs=((kusgs-1)*nx*ny)+i+((j-1)*nx)
    HK_IVF(ijk)=HK1_16(ijkusgs)
  else

c Calculate elevation of cell and fill in USGS value as 'default'
c   ijk2 = cell number located below ijk
c   elevation = elevation of center of cell for rediscrretized grid
    ijk2=(k*nx*ny)+i+((j-1)*nx)
    elevation = ((elev2(ijk)-elev2(ijk2))/2)+elev2(ijk2)

c Find out which usgs cell we are in and assign usgs K or T value
  do kk=1,12
    ijkk=((kk-1)*nx*ny)+i+((j-1)*nx)
    ijk2=(kk*nx*ny)+i+((j-1)*nx)

    if(elevation.le.elev(ijkk).and.elevation.gt.elev
*      (ijk2)) then
      HK_IVF(ijk)=HK1_16(ijkk)
    write(15,'(4i4)') i,j,k,kk
    endif
  enddo

c Fill in UTL Formation Paleosol
c   if(elevation.le.us(ij).and.elevation.ge.up(ij)) gms(ijk)= pk

c Fill in Riverbank Formation Paleosol ModL IV
c   if(elevation.le.rs(ij).and.elevation.ge.rp(ij)) gms(ijk)= pk

c fill in Riverbank formation with RB IV (st3rb2 = 2 = inside tuol rb
valley)
  if(st3rb2(ij).eq.2) then
    if(elevation.lt.rfs(ij).and.elevation.gt.us(ij)) then
      if(elevation.le.rfs(ij).and.elevation.gt.rss(ij)) then
        HK_IVF(ijk)= fk
      else if (elevation.le.rss(ij).and.elevation.gt.rgs(ij))
then
        HK_IVF(ijk)= sk
        write(15,'(a6,e9.4)') 'sands ',gms(ijk)
      else if(elevation.le.rgs(ij)) then
        HK_IVF(ijk)= gk
      endif
    endif
  endif

c Fill in the Modesto formation with Mod IVF
  if(elevation.gt.rs(ij)) then
    if (elevation.le.mfs(ij).and.elevation.gt.mss(ij)) then
      HK_IVF(ijk)= fk
    else
if(elevation.le.mss(ij).and.elevation.gt.mgs(ij)) then
      HK_IVF(ijk)= sk
    else if (elevation.le.mgs(ij)) then

```

```

                                HK_IVF(ijk)= gk
                                endif
    endif
endif
    enddo
    enddo
enddo

```

c Prepare the gms input files

```

print*, 'printing gms files'
open(20,file=HK_IVFfil,status='unknown')

```

c writing GMS full grid file

```

do k=1,nz
  do j=1,ny
    do i=1,nx
      ijk=i+((j-1)*nx)+((k-1)*nx*ny)
      write(20,'(E9.4)') HK_IVF(ijk)
    enddo
  enddo
enddo

```

```

print*, 'gms files completed'
print*, 'Goodbye!'

```

```

close(20)
close(18)
close(19)

```

```

print*, '*****'
print*, 'GMS files written.'
print*, '*****'
print*, '(:'

```

```

stop
end

```

Appendix H: Code to Calculate Kv and Kh/Kv

```
program KVcalc

c Program to create an output file to be
c used in 3D realization for a GMS 5.1
c groundwater model.
c DO NOT USE WITHOUT ADJUSTMENT FOR SPECIFICS
c
c NOTE: This code uses a parameter file.
c
c PARAMETERS:
c
c nx= number of rows
c ny= number of columns
c nz= my vertical discretization;
c nzusgs= number of layers in original USGS model from Steve Phillips in July of 2004
c
c Elevation from original USGS 16 layer model= elevfil
c Elevation from red discretized 27 layer model= elev2fil
c
c This program is intended to generate KV and Kh/Kv parameters for the 27 layer model generated
c * from the red discretization of a 16 layer USGS model.
c kvert.dat = vertical K calculated from the vcont values in the original USGS model (kvert= vcont/
thickness)
c      thickness= the distance between the center of the two cells for which kvert is being calculated
c khkv.dat = kvert from original USGS reassigned to my layers (kvert is based on the material, not the cell
thickness)
c vcont.dat = leakance from the original USGS model

c Declaration of variables

      parameter nx=153
      parameter ny=137
      parameter nzusgs=16
      parameter nz=27
      parameter nxy=nx*ny
      parameter nxyz=nx*ny*nz
      parameter nxyzusgs=nx*ny*nzusgs

      real elev(nxyzusgs)
      real elev2(nxyz)
      real vcont(nxyzusgs)
      real corc01(nxy)
      real thick(nxyzusgs)
      real kh(nxyz)
      real hlfthick(nxyzusgs)
      real kv1_16(nxyzusgs)
      real kv1_27(nxyz)
      real khkv(nxyz)

      character*40 elevfil
      character*40 elev2fil
```

```

character*40 vcontfil
character*40 corc01fil
character*40 thickfil
character*40 khfil
character*40 hlfthickfil
character*40 kv1_27fil
character*40 khkvfil
character*40 parfill

```

c Open parfil (input)

```

print*, 'input parfile name?:'
read(5, '(a40)') parfil1
print*, 'input file name:', parfill
open(1, file=parfill, status='old')

read(1, '(a40)') elevfil
read(1, '(a40)') elev2fil
read(1, '(a40)') vcontfil
read(1, '(a40)') corc01fil
read(1, '(a40)') thickfil
read(1, '(a40)') khfil
read(1, '(a40)') hlfthickfil

close(1)

```

c Read data from ASCII file to fill arrays.

```

print*, 'reading Parfil'
open(1, file=elevfil, status='old', form='formatted')
    do k=1, nzusgs
        do j=1, ny
            do i=1, nx
                ijk= i+((k-1)*nx*ny)+(j-1)*nx
                read (1, *) elev(ijk)
            enddo
        enddo
    enddo
close(1)

open(2, file=elev2fil, status='old', form='formatted')
    do k=1, nz
        do j=1, ny
            do i=1, nx
                ijk= i+((k-1)*nx*ny)+(j-1)*nx
                read (2, *) elev2(ijk)
            enddo
        enddo
    enddo
close(2)

open (17, file=vcontfil, status='old', form='formatted')
    do k=1, nzusgs
        do j=1, ny
            do i=1, nx

```

```

            ijk=i+((k-1)*nx*ny)+((j-1)*nx)
            read(17,*) vcont(ijk)
        enddo
    enddo
enddo

close(17)

open (3,file=corc01fil,status='old', form='formatted')
do j=1,ny
do i=1,nx
    ij=i+((j-1)*nx)
    read(3,*) corc01(ij)
enddo
enddo

close(3)

open (4,file=thickfil,status='old', form='formatted')
do k=1,nzusgs
do j=1,ny
do i=1,nx
    ijk=i+((k-1)*nx*ny)+((j-1)*nx)
    read(4,*) thick(ijk)
enddo
enddo
enddo

close(4)

open (5,file=khfil,status='old', form='formatted')
do k=1,nz
do j=1,ny
do i=1,nx
    ijk=i+((k-1)*nx*ny)+((j-1)*nx)
    read(5,*) kh(ijk)
enddo
enddo
enddo

close(5)

open (6,file=hlftickfil,status='old', form='formatted')
do k=1,nzusgs
do j=1,ny
do i=1,nx
    ijk=i+((k-1)*nx*ny)+((j-1)*nx)
    read(6,*) hlftick(ijk)
enddo
enddo
enddo

close(6)

```

c Calculate Kv for the 16 layer USGS model from the vcont values.

c ijk2 = cell number located below ijk

print*, 'Create KV1_16'

```

do k=1,nzusgs
  do j=1,ny
    do i=1,nx
      ijk=((k-1)*nx*ny)+i+(j-1)*nx
      ijk2=(k*nx*ny)+i+(j-1)*nx

      if((k.eq.7.or.k.eq.8).and.(corc01(ij).eq.1)) then
        k8=8
        kcorc=0.0013
c      ijk8=(k8*nx*ny)+i+(j-1)*nx
        kv1_16(ijk)=vcont(ijk8)*hlfthick(ijk8)
c      kv1_16(ijk)=kcorc
      else
        kv1_16(ijk) = vcont(ijk)*(hlfthick(ijk)+hlfthick(ijk2))
      endif

      open(15,file='kv1_16.dat',status='unknown')
      write(15,'(E14.5)') kv1_16(ijk)

      enddo
    enddo
  enddo
close(15)

c Calculate KV1_27 from the vcont values in the original USGS model.
print*,'Create KV1_27 and KH/KV'

do k=1,nz
  do j=1,ny
    do i=1,nx
      ij=i+(j-1)*nx
      ijk=((k-1)*nx*ny)+i+(j-1)*nx
      ijk2=(k*nx*ny)+i+(j-1)*nx

c Fill in values for KV1_27 with USGS values for bottom layers 23 through 27 (USGS cells 12 through 16)
c These cells are the same size and thickness as in the original model.
c KV can be directly assigned after multiplying by the thickness.
c kusgs = the layer number in the USGS model
c ijkusgs = reading array at the specified layer in USGS model
c ijkusgs2 = reading array at the layer below ijkusgs

c print*,'Fill in USGS KV1_27 values for bottom layers'
      if(k.ge.23) then
        kusgs=k-11
        ijkusgs=((kusgs-1)*nx*ny)+i+(j-1)*nx
c      ijkusgs2= ((kusgs)*nx*ny)+i+(j-1)*nx
        kv1_27(ijk)=kv1_16(ijkusgs)

      else
c Calculate elevation of center of cell and fill in correlative USGS value
c elevation = elevation of center of cell for rediscrretized grid

        elevation = ((elev2(ijk)-elev2(ijk2))/2)+elev2(ijk2)

c Find out which USGS cell we are in and assign KV value calculated from vcont
c Layer 8 is the Corcoran clay in the USGS model. KV is calculated differently according to...
c ...'kvc_calib_merten.f' from the USGS model.
c print*,'Find out which usgs cell we are in and assign Kv1_27'

```

```

        do kk=1,12
            ijk=((kk-1)*nx*ny)+i+(j-1)*nx
            ijk2=(kk*nx*ny)+i+(j-1)*nx

            if(elevation.le.elev(ijk).and.elevation.gt.elev
*              (ijk2)) then
                kv1_27(ijk)=kv1_16(ijk)
            endif
        enddo

c      write(15,'(4i4)') i,j,k,kk
    endif

        enddo
    enddo
enddo

c Calculate Kh/Kv
print*, 'Calc Kh/Kv'
do k=1,nz
    do j=1,ny
        do i=1,nx
            ijk=((k-1)*nx*ny)+i+(j-1)*nx

            if(kv1_27(ijk).eq.0) then
                khkv(ijk) = kh(ijk)/ 0.0000001
            else
                khkv(ijk)= kh(ijk)/ kv1_27(ijk)
            endif

        enddo
    enddo
enddo

c writing GMS full grid file
print*, 'writing GMS full grid file'
open(18,file='kv1_27fil.dat',status='unknown')
open(20,file='khkv.dat',status='unknown')

        do k=1,nz
            do j=1,ny
                do i=1,nx
                    ijk=i+(j-1)*nx)+(k-1)*nx*ny
                    write(18,'(E14.5)') kv1_27(ijk)
                    write(20,'(E14.5)') khkv(ijk)

                enddo
            enddo
        enddo

print*, 'gms files completed'
print*, 'Goodbye!'

```

```
close(18)
close(19)
close(20)
```

```
print*, '*****'
print*, 'GMS files written.'
print*, '*****'
print*, '('
```

```
stop
end
```


Appendix I: General Head Boundary Code

```
PROGRAM ghb_all
c   MODIFIED from USGS kvc_calib_merten.f from Steve Phillips July 11, 2005 via e-mail.
c   Used to remake ghb files with new discretization for use in lpf model.
c   Deleted beginning of program--only need to calc. the ghb file for model.
c   ***Lines that begin with asterisks are edits by Amy Lansdale.
c
c
c   ***TO USE: (1) ALWAYS check input horizontal hydraulic conductivity file #29 on line 61
c           (2) Change input Kv file #99 in line 64
c
c   ***Changed numbers of layers and added some variables.
      integer row,col,nsteps,lay,iunit,nghb,ghbloc(200,200),
+ bound(200,200,20),corc01(200,200)
      real KH(153,137,27),KV1_27(153,137,27),KH2(153,137,27)
+ ,thick(153,137,27),ghbhead(200,200,80),ghbcond(200,200,80),
+ botelev(153,137,40),top(153,137,40),head,ghbdist,
+ persat(153,137,40)

c
c ... grid geometry
      nrow=153
      ncol=137
      nlay=27
      ny=137
      nx=153
      nz=27

c
      ncorr=0
      print*, 'initialize variables'
c   initialize variables
5 do 10 lay=1,nlay
      do 10 row=1,nrow
          do 10 col=1,ncol
              ghbhead(row,col,lay)=0.
              ghbcond(row,col,lay)=0.
              KH2(row,col,lay)=0.
              persat(row,col,lay)=0.

10 continue

      open(95,file='ghb27fil.ghb')
      open(101,file='KH2fil.dat')

c   open files and read in external data

      print*, 'open ghb_locations.dat'
      open(94,file='ghb_locations3.dat')

      read(94,')
          do 40 row=1,nrow
```

```

        read(94,'(200i1)') (ghbloc(row,col),col=1,ncol)

40 continue

c *****THIS MUST BE CHANGED FOR EACH GEOLOGIC SCENARIO OF IVF (rbmodL, rbstmodL,
rbmods, rbstmods).*****
    print*, 'open HK_IVFfil, thick, and KV1_27'
c ***This input HK file should be the HK file for each of the various IVF scenarios. CHECK before each
run of this code.
    open(29,file='Khrbstmless50finalnodat.dat')
c *** "Thickin" should be recalculated for various discretizations. See "Thickness.f" code to calculate.
    open(30,file='thick27.dat')
    open(99,file='kv1_27rbstmless50.dat')

    do 20 lay=1,nlay
    do 20 row=1,nrow

        read(29,*) (KH(row,col,lay),col=1,ncol)
        read(30,*) (thick(row,col,lay),col=1,ncol)
        read(99,*) (KV1_27(row,col,lay),col=1,ncol)

20 continue

c ***Calculate the K vertical for layer 1 to 2 and 2 to 3 (original layer 1 to 2) only (needed below in USGS
code) using the harmonic mean...
c    print*, 'Calc KH2'

    do 80 lay=1,nlay
    do 90 row=1,nrow
        do 100 col=1,ncol
c ...***check to see if KH value is equal to zero to prevent zero divide. Make KH a very small number.
c ...***most of the cells with zeros are inactive.
            if (KH(row,col,lay).eq.0) then
                KH2(row,col,lay)= 0.0000000000000001
            elseif (KH(row,col,lay).ne.0) then
                KH2(row,col,lay)= KH(row,col,lay)
            endif

100    continue
90    continue
80    continue

    print*, 'Write KH2'

    do 175 lay=1,nlay
    do 175 row=1,nrow
        do 175 col=1,ncol
            write(101,'(3i5,g20.12)') lay,row,col, KH2(row,col,lay)

```

175 **continue**

close(101)

print*, 'ghb calc'

```
c *** generate ghb file; ghbloc indicates boundary type (4&5 are lateral,
c *** 2 is river)
c
c ... Vertical gradient of 0.05 specified along N and S lateral boundaries;
c ... downward to layer 33 (**was 9 in original model), and upward below 33 (**was 9 in original
model)
c ... -- max head below 33 (**was 9 in original model) = water table
c
c      constants:
c      bedthick=1.0
c      cellsize=400.
c      rivwidth=25.
c      ghbdist=400.
c      nghb=0
c      gradient=0.05
c      vkrivmult=10.

      open(93,file='ghb27in1_finalEDIT.dat')
      open(105, file='totthick.dat')
c      open(106, file='totthick2.dat')

200 read(93,*,end=290) lay,row,col,head

c      print*, 'downstream river segments and western boundary'
c ... downstream river segments and western boundary
      if((ghbloc(row,col).eq.2.and.lay.eq.1).or.ghbloc(row,col).eq.5)
      & then
          nghb=nghb+1
          ghbhead(row,col,lay)=head

c ****Changed the original:
c      ghbcond(row,col,lay)=vcont(row,col,lay)*((thick(row,col,lay)/
c      2.)+(thick(row,col,lay+1)/2.))*((cellsize*riv width)/bedthick)
c      *vkrivmult to...see below...
      if(ghbloc(row,col).eq.2.and.lay.eq.1) then
          ghbcond(row,col,lay)= KV1_27(row,col,lay)*((cellsize*rivwidth)
      & /bedthick)*vkrivmult

c ***Layer in following if statement (now layer 16) was 7 (lay above C.C) in original code...
c ..."REMOVE" is the line that was used to calc K. Not needed here because all values in...
c... KH file are actual conductivities, not K and T values as was true..
c...in original code (lay 8-16 were T values). K values were calc by dividing by thickness in GMS.
```

```

    else
      ghbcond(row,col,lay)=KH2(row,col,lay)*thick(row,
& col,lay)*cellsize/ghbdist
    endif
c ***REMOVED KH(row,col,lay)=KH(row,col,lay)/thick(row,col,lay)

c ... north and south lateral boundary
c print*, 'north and south lateral boundary'

    else if(ghbloc(row,col).eq.4) then
      nghb=nghb+1

c ... conductance first
c ... ***layer was 7, change to layer 16 which is equivalent to the layer above CC
c print*, 'conductance first'
c ***below conditional statement separates the unconfined portions of the a quifer (above Corcran clay)
from the confined...
c... portions of the model (Corcran clay and below). Because ALL of my KH values are K values...
c... not K and T values, I maintianed the USGS code format but multiply by thickness in both portions of
the statement.
      if(lay.le.16) then
        ghbcond(row,col,lay)=KH2(row,col,lay)*thick(row,col,lay)*
& cellsize/ghbdist
      else
        ghbcond(row,col,lay)=KH2(row,col,lay)*thick(row,col,lay)*cellsize/
& ghbdist
      endif

c print*, 'now head'

cc ... now head
totthick=0
c ****Edit the application of a gradient to the head from the methods used in the USGS.
c ****The gradient is subtracted (to generate downward flow) and applied from layer 1 to
c ****...17 (the Corcoran Clay). Then the layer below the Corcoran clay (where the most
c ****...pumping occurs), is set equal to the head in the Corcoran Clay.
      if(lay.eq.1) then
        ghbhead(row,col,lay)=head
210 continue
      else if(lay.le.17) then
        do 220 k=1,lay
          if(k.eq.1) then
            thickness=thick(row,col,k)/2.
          else if(k.eq.lay) then
            thickness=thick(row,col,k)/2.
          else
            thickness=thick(row,col,k)
          endif
          totthick=totthick+thickness
        220 continue
        ghbhead(row,col,lay)=ghbhead(row,col,1)-(totthick*gradient)
      write (105,*) lay,row,col,totthick
c totthick=0

```

```

c ****The original USGS gradient had the head in the Corcoran clay higher than...
c **** ...the head in the cells above it. Added this IF/THEN statement to rectify that.
  else if(lay.eq.18) then
    ghbhead(row,col,lay)=ghbhead(row,col,17)
  write (105,*) lay,row,col

  else

c ... ****Change to layer 19. Below layer 18, the gradient is positive (generates an upward flow).
  do 240 k=19,lay
    if(k.eq.19) then
      thickness=thick(row,col,k)/2.
    else if(k.eq.lay) then
      thickness=thick(row,col,k)/2.
    else
      thickness=thick(row,col,k)
    endif
    totthick=totthick+thickness

    write (106,*) lay,row,col,totthick

240  continue
    ghbhead(row,col,lay)=ghbhead(row,col,18)+(totthick*gradient)
  write (105,*) lay,row,col,totthick
c    totthick=0

    if(ghbhead(row,col,lay).gt.ghbhead(row,col,1))
    &  ghbhead(row,col,lay)=ghbhead(row,col,1)
    endif
  endif

  write (105,*) lay,row,col,totthick

  goto 200

c    output ghb file, rivers first
c

290  k=1
c **** Change the iunit to 40 (was 2 in the old code). This is where flow budget will be recorded.
c **** When the file is opened by GMS and resaved, it will rewrite 40.
    iunit=40
    np=0
    write(95,'(2i5)') nghb,iunit
    write(95,'(2i5)') nghb,np
    do 300 i=1,nrow
      do 300 j=1,ncol
        if(ghbloc(i,j).eq.2.) write(95,'(3i5,2g20.12)') k,i,j,
        &  ghbhead(i,j,k),ghbcond(i,j,k)
300 continue
      do 350 k=1,nlay
        do 350 i=1,nrow
          do 350 j=1,ncol
            if(ghbloc(i,j).eq.4.or.ghbloc(i,j).eq.5) write(95,'(3i5,2g20

```

```
& .12) k,ij,ghbhead(ij,k),ghbcond(ij,k)
350 continue
    print*, '*****'
    print*, 'Files written.'
    print*, '*****'
    stop
end
```

Appendix J: Well Code

```

      program wel_calib_all
c ***Lines that begin with astericks are edits by Amy Lansdale from the original code by Steve Phillips.
c *****TO USE: Change file #34 in line 36 to input horizontal hydraulic conductivity.
c
c
c   SPP 12/04 -- modified to distribute pumpage to adjacent layers for
c   wells pumping > spec rate in cells with < spec % of coarse materials
c   SPP 02/03 -- now called by runss_calib.sh
c   SPP 12/02 -- creates well file for MERSTAN SS model
c
c***Changed the array sizes to accomodate the 40 layer model. (Number of layers was set to 20 for the 16
layer model.)
      integer row,col,lay,ibound(200,200),icorc(200,200)
      real pumpage,tperf,bperf,x,y,bot(200,200,40),
& HK(200,200,40),tequiv(40),pumplay(40)
      character wellid*8,runtyp*1,onlycorc*1
c
      nrow=153
      ncol=137
      nlay=27
      xorigin=-83795.7
      yorigin=1572727.3
      nwells=0
      totpump=0.
      onlycorc='y'
c
c   read if single or multiple run, passed from script
c   read(*,*) runtyp
c   runtyp='s'
c
      open(30,file='wel.in')
      open(31,file='elevbot1_27nodat.dat')
      open(35,file='elevtop1_27nodat.dat')
      open(32,file='ibound.40')
      open(33,file='corc01.32')
c *****THIS FILE MUST BE CHANGED FOR EACH GEOLOGIC SCENARIO OF IVF (rbmodL,
rbstmodL, rbmods, rbstmods).*****
      open(34,file='KHrbstm1plus50finalnodat.dat')
c   output files
      open(40,file='wel.tmp')
      open(41,file='wel27.wel')

c *****K and T input files--REMOVED ALL 07/21/05

c
c   read first array for "bot", which is top layer 1, ibound, icorc
      read(32,')
      do 100 i=1,nrow
          read(35,*) (bot(i,j),j=1,ncol)
          read(32,*) (ibound(i,j),j=1,ncol)
          read(33,*) (icorc(i,j),j=1,ncol)
      100 continue
c
c   read rest of bottoms, and k
```

```

do 150 l=1,nlay

do 150 i=1,nrow
  read(31,*) (bot(i,j,l+1),j=1,ncol)
c      iunit=50+l
c      read(iunit,*) (HK(i,j,l),j=1,ncol)
150 continue
c
c  read texture
do 160 lay=1,nlay

do 160 row=1,nrow
  read(34,*) (HK(row,col,lay),col=1,ncol)
160 continue
c
c  read through list of wells one by one, determine equivalent transmissivities
c  to distribute by layer, and build well file
c ... *** a gain, note that "bot" array starts with top of layer 1 ***
c
  read(30,(' '))
200 read(30,*,end=99) wellid,x,y,tperf,bperf,pumpage
c
c  transform coordinates, and calculate row & column
c
  delta x=xorigin-x
  delta y=y-yorigin
  tdelta x=delta x
  xdist=((delta y*.601815023152048)-(delta x*.798635510047293))
  ydist=((delta y*.798635510047293)+(tdelta x*.601815023152048))
  col=int(xdist/400.)+1
  row=153-int(ydist/400.)
c
c  sweep through layers, calculating effective transmissivity based on thickness
c  of screened interval within each layer and K value for layers 1-7; layers 8-16
c  "K" values are "T" already
c
c
  if(ibound(row,col).ne.0) then
    sumtequiv=0.
  do 500 lay=1,nlay
    if((tperf.gt.bot(row,col,lay+1)).and.(bperf.lt.bot(row,col,lay))) then
      if(tperf.lt.bot(row,col,lay)) then
        z1=tperf
      else
        z1=bot(row,col,lay)
      endif
      if(bperf.gt.bot(row,col,lay+1)) then
        z2=bperf
      else
        z2=bot(row,col,lay+1)
      endif
c ...      The old way
c          tequiv(lay)=K(row,col,lay)
c          if(lay.le.7) tequiv(lay)=tequiv(lay)*(z1-z2)
c          sumtequiv=sumtequiv+tequiv(lay)
c ...      The new way

```


c****Change old layer 7 in USGS model to layer 16, which is still the layer above the Corcran Clay in the newly...
c...discretized model.

```

                if(lay.le.16) then
                    tequiv(lay)=HK(row,col,lay)*(z1-z2)
                else
                    tequiv(lay)=HK(row,col,lay)*((z1-z2)/
&                (bot(row,col,lay)-bot(row,col,lay+1)))
                endif
                sumtequiv=sumtequiv+tequiv(lay)
            else
                tequiv(lay)=0.
            endif
        500 continue
    c
    c        now distribute pumpage by layer, write to file, and read next well
    c
    c $$$ option 1: correct for wells screened only in corcoran
    c
    c    if(onlycorc.eq.'y') then
    c
    c ... first check for wells screened only in corcoran (unrealistic) and,
    c    if so, distribute pumpage to layers 7 - 9
    c****Change 8 (USGS Corcran Clay) to 17, 7 (USGS lay abv Corcran Clay) to 16,...
    c ...and 9 (USGS lay blw Corcran Clay) to 18.
        if((tequiv(17).ne.0.).and.(tequiv(16).eq.0.).and.(tequiv(18).eq.
& 0.)) then
            if(icorc(row,col).ne.0) then
                thick16=bot(row,col,16)-bot(row,col,18)
                tequiv16=HK(row,col,16)*thick16
                tequiv17=HK(row,col,17)
                tequiv18=HK(row,col,18)
                sumtequiv=tequiv16+tequiv17+tequiv18
                tequiv(16)=1.
                tequiv(18)=1.
            c    Layer 16 (USGS layer 7)
                pump=pumpage*(tequiv16/sumtequiv)
                write(40,(3i5,g15.6)) 16,row,col,pump
                nwells=nwells+1
                totpump=totpump+pump
            c    Layer 17 (USGS layer 8--CC)
                pump=pumpage*(tequiv17/sumtequiv)
                write(40,(3i5,g15.6)) 17,row,col,pump
                nwells=nwells+1
                totpump=totpump+pump
            c    Layer 18 (USGS layer 9)
                pump=pumpage*(tequiv18/sumtequiv)
                write(40,(3i5,g15.6)) 18,row,col,pump
                nwells=nwells+1
                totpump=totpump+pump
            else
                pump=pumpage
            c    Layer 17 (USGS layer 8)
                write(40,(3i5,g15.6)) 17,row,col,pump
                nwells=nwells+1
                totpump=totpump+pump
            endif
        else

```

```

c
c ... Check for other wells pumping in single layer at > specified rate and
c      within cells with < specified % coarse; if so, distribute pumpage
c      proportionally to adjacent layers. If adjacent layers already pumping,
c      activate nearest layers above and below.
c
c $$$ Specified values:
c
      specrate=-1000.
      specpct=0.8007E+01
c*****Change 'specpct=10.' which refers to the coarse\fine fraction from the initial USGS input...
c.....to 'specpct=0.8007E+01'. This is the calculated HK of a cell with a coarse\fine fraction of 10...
c.....CALCULATE HK from htextr (corase\fine fraction)-->
c.....htextr=10; fcoarse=10/100=0.1; ffine=1-0.1=0.9...
c.....To calc. use arithmetic mean from page 6 in 'kvc_calib-merten.f'-->
c.....Ksand and Kclay from 'kvc_calib_merten_s.dat'
c ....HK = (ffc coarse)(Ksand)+(ffine)(Kclay)= (0.1*80)+ (0.9*0.008)= 8.0072 = 0.8007E+01

c $$$
580  do 590 lay=1,nlay
      pumplay(lay)=0.
590  continue
      do 600 lay=1,nlay
        if(tequiv(lay).ne.0.) then
          pumplay(lay)=pumpage*(tequiv(lay)/sumtequiv)
          if((pumplay(lay).lt.specrate).and.(HK(row,col,lay)
&      .lt.specpct)) then
            thick=bot(row,col,lay)-bot(row,col,lay+1)
            tequiv(lay)=HK(row,col,lay)
            if(lay.le.16) tequiv(lay)=tequiv(lay)*(thick)
            sumtequiv=tequiv(lay)
c      activate closest non-pumping layers, recalculating tequiv
            l=lay-1
610      if(tequiv(l).eq.0.) then
              thick=bot(row,col,l)-bot(row,col,l+1)
              tequiv(l)=HK(row,col,l)
              if(l.le.16) tequiv(l)=tequiv(l)*(thick)
              sumtequiv=sumtequiv+tequiv(l)
            else
              thick=bot(row,col,l)-bot(row,col,l+1)
              tequiv(l)=HK(row,col,l)
              if(l.le.16) tequiv(l)=tequiv(l)*(thick)
              sumtequiv=sumtequiv+tequiv(l)
              l=l-1
            goto 610
          endif
          l=lay+1
620      if(tequiv(l).eq.0.) then
              thick=bot(row,col,l)-bot(row,col,l+1)
              tequiv(l)=HK(row,col,l)
              if(l.le.16) tequiv(l)=tequiv(l)*(thick)
              sumtequiv=sumtequiv+tequiv(l)
            else
              thick=bot(row,col,l)-bot(row,col,l+1)
              tequiv(l)=HK(row,col,l)
              if(l.le.16) tequiv(l)=tequiv(l)*(thick)
              sumtequiv=sumtequiv+tequiv(l)
              l=l+1

```

```

        goto 620
    endif
endif
endif
600 continue
c
c ... Write out pumpage
c
        do 650 lay=1,nlay
    if(tequiv(lay).ne.0.) then
        pump=pumpage*(tequiv(lay)/sumtequiv)
        write(40,'(3i5,g15.6)') lay,row,col,pump
        nwells=nwells+1
        totpump=totpump+pump
    endif
650 continue
endif
endif
    goto 200
c
c end of input file has been reached, so write headers to well file,
c and transfer previous output to this file
c
99 nunit=2
nparam=0
rewind (40)
write(41,'(2i5)') nwells,nunit
write(41,'(2i5)') nwells,nparam
do 1000 i=1,nwells
    read(40,'(3i5,g15.6)') lay,row,col,pump
    write(41,'(3i5,g15.6)') lay,row,col,pump
1000 continue
write(*,'(a,g20.6)') 'total pumpage = ',totpump

print*, '*****'
print*, 'Files written.'
print*, '*****'
stop
end

```