The California Central Valley Groundwater-Surface Water Simulation Model

Introduction

CWEMF C2VSim Workshop

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Acknowledgements

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Outline

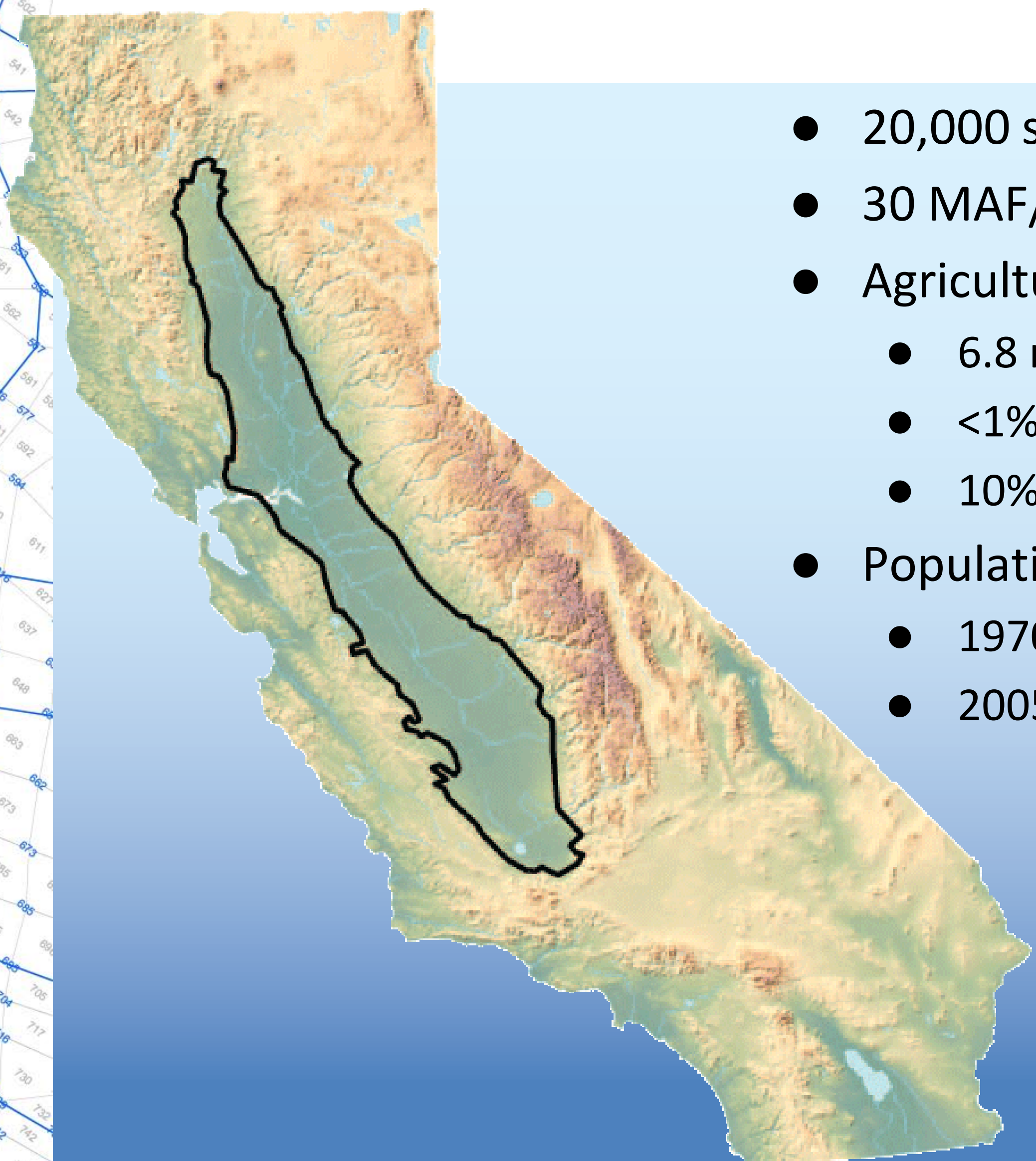
Geology and Geography

Historical and Current Water System

Groundwater Studies & Models

Integrated Water Flow Model

California's Central Valley

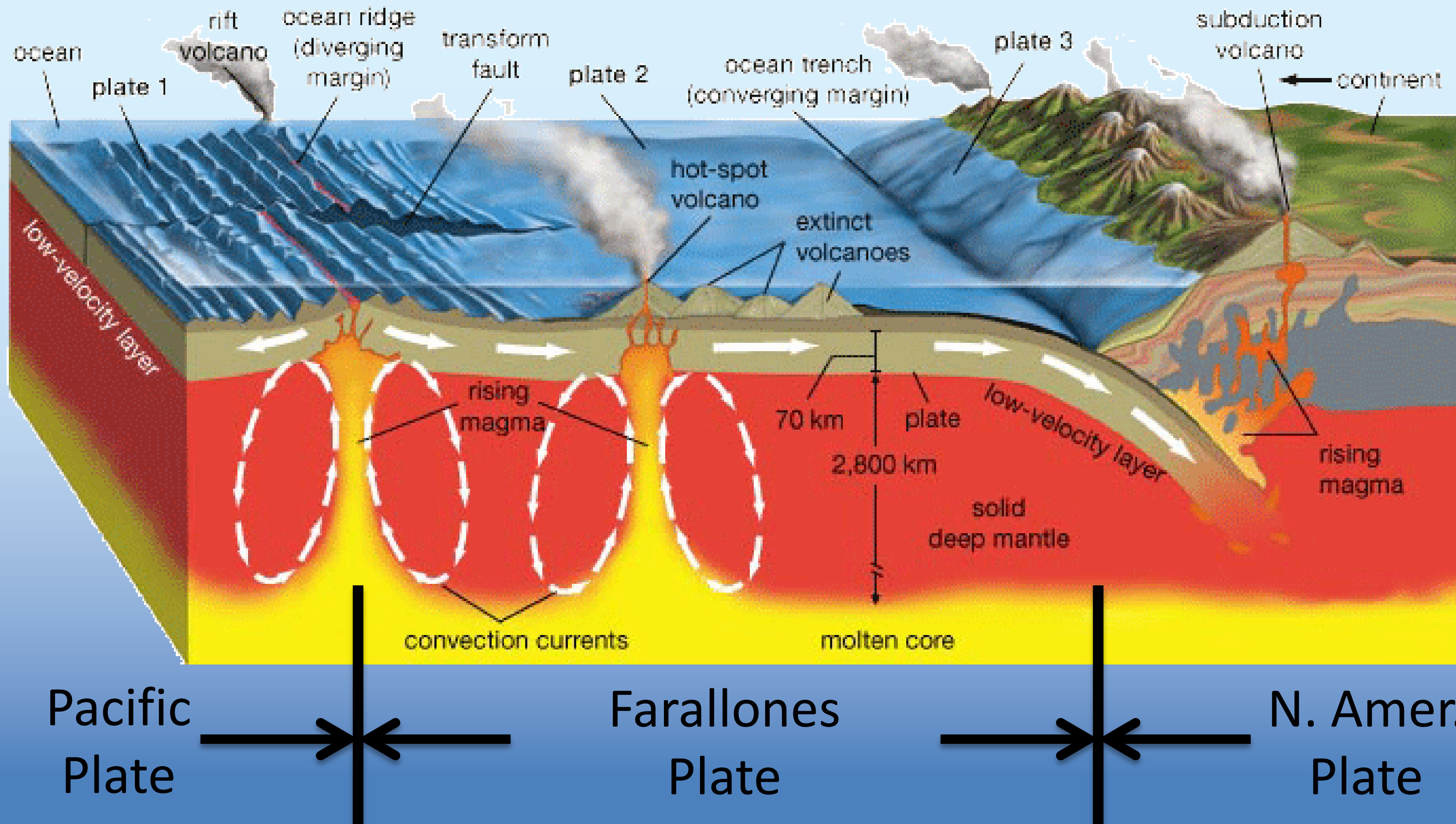


- 20,000 sq. mi. (55,000 sq. km.)
- 30 MAF/yr Surface Water Inflow
- Agricultural Production
  - 6.8 million acres (27,500 sq. km)
  - <1% of US farm land
  - 10% of US crops value in 2002
- Population Growth
  - 1970: 2.9 million
  - 2005: 6.4 million
- Groundwater Pumping
  - ~9 MAF in 2002
  - 10-18% if US pumping
  - Not measured or regulated

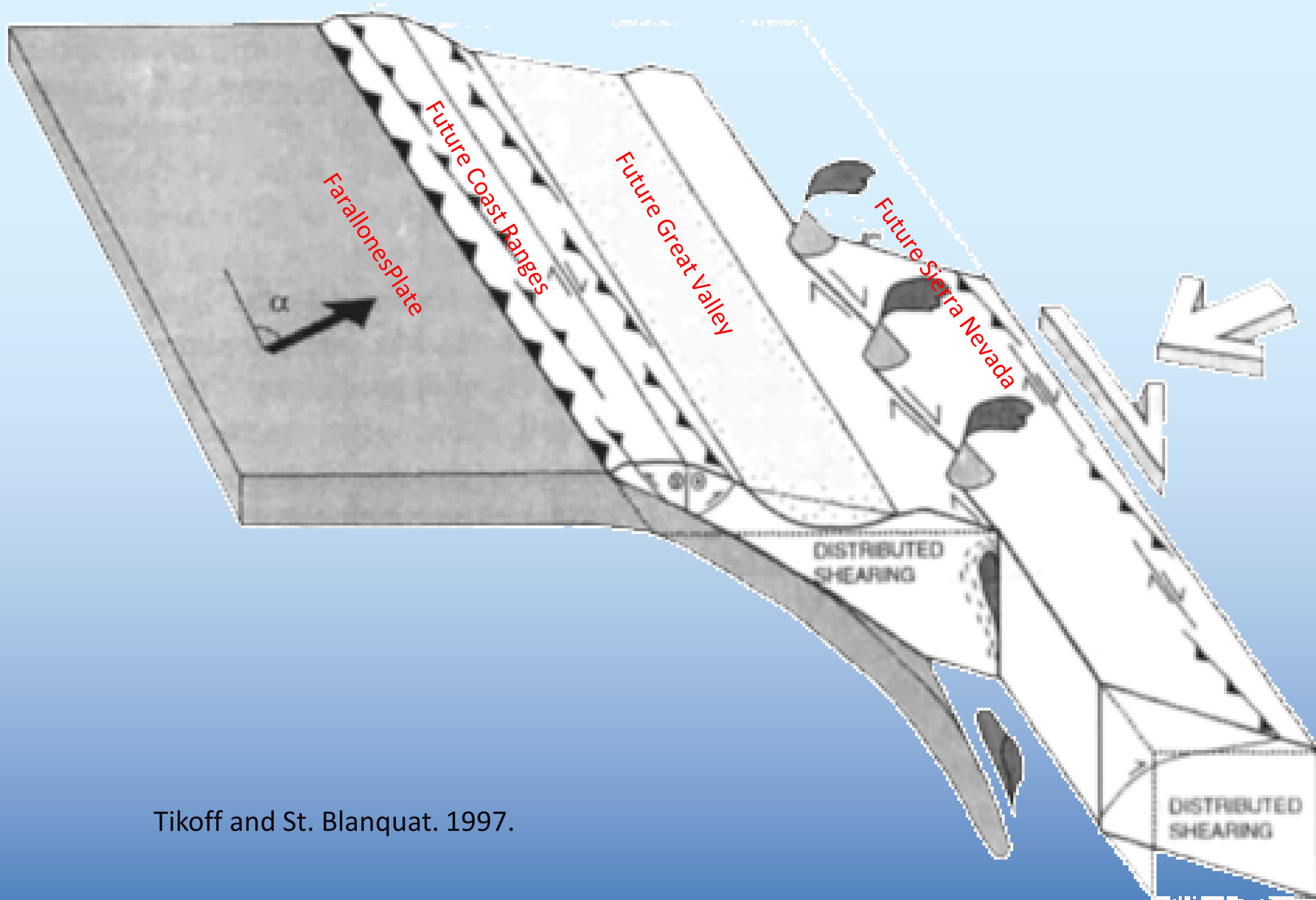
Central Valley Hydrogeology

- Tectonic development
- Alluvial stratigraphy
- Geologic cross-section
- Groundwater studies & models

Tectonic Development

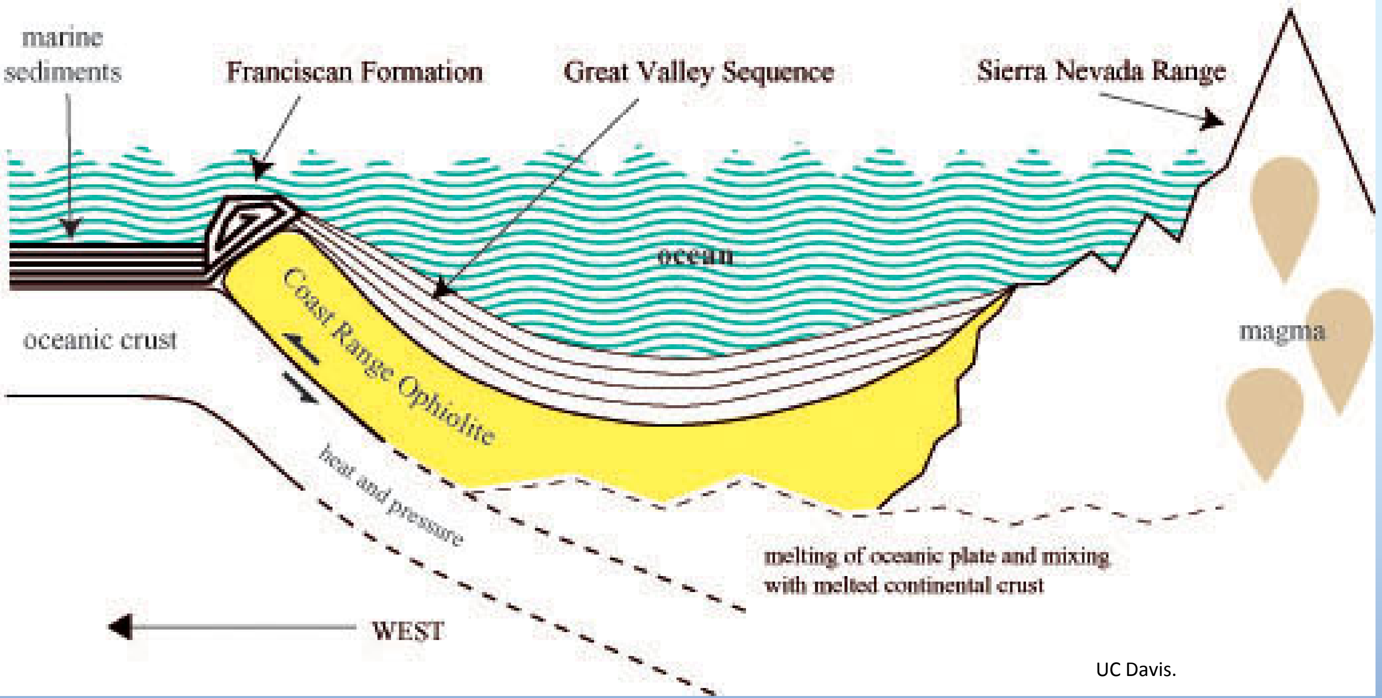


100 million years ago



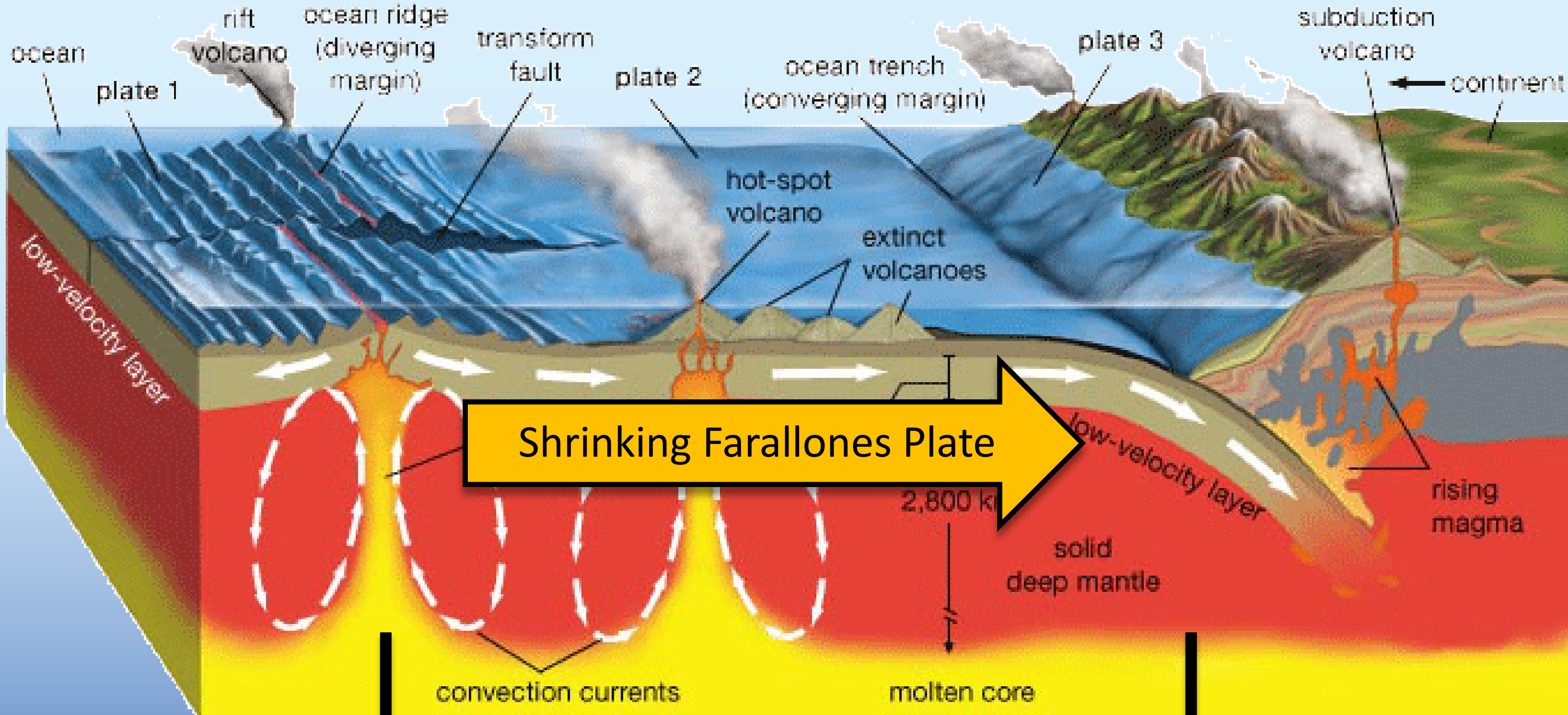
Tikoff and St. Blanquat. 1997.

Early Central Valley



UC Davis.

Tectonic Development



Shrinking Farallones Plate

Pacific Plate

Farallones Plate

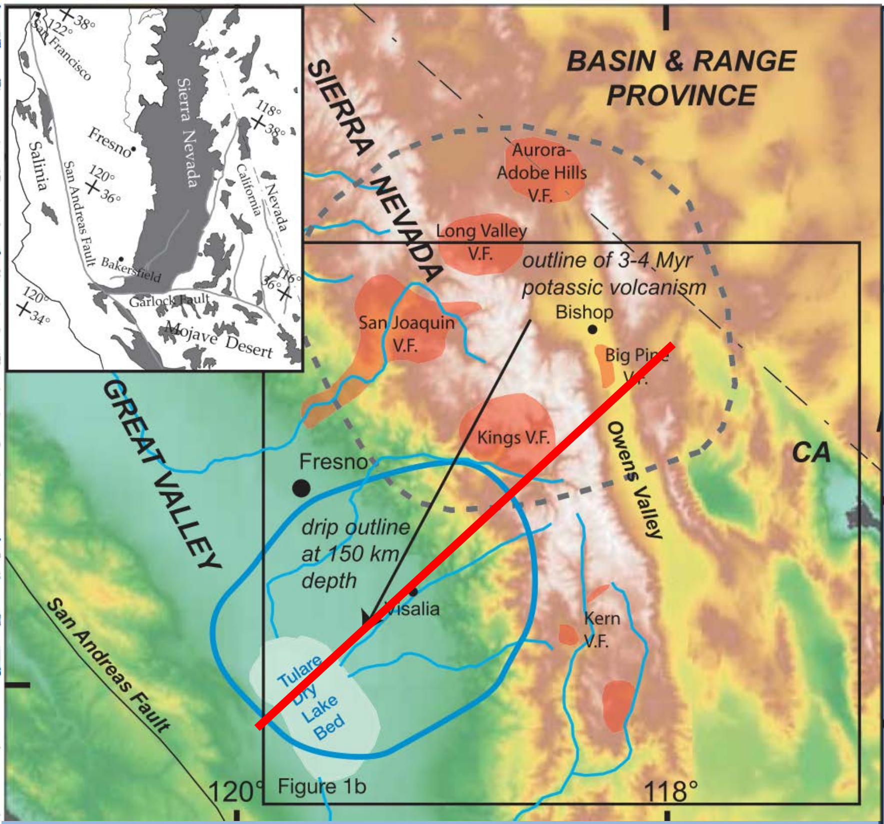
N. Amer. Plate

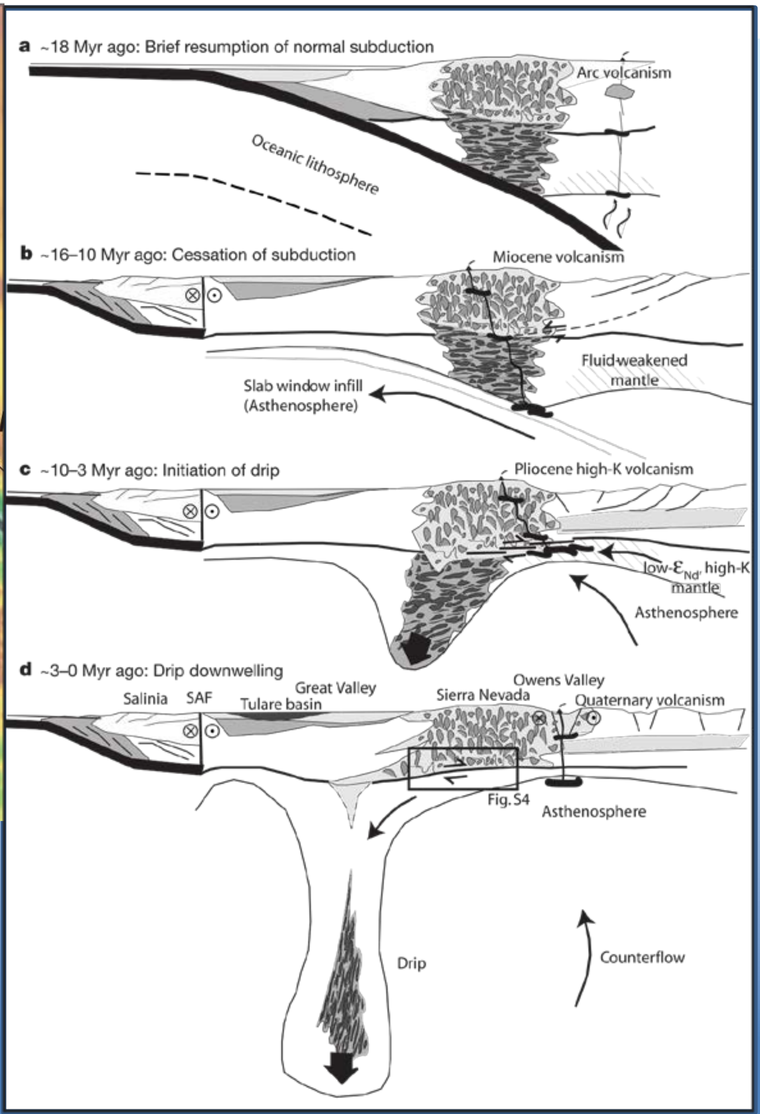
Tectonic Development


Sierra Nevada
Coast Ranges


Tectonic Subsidence

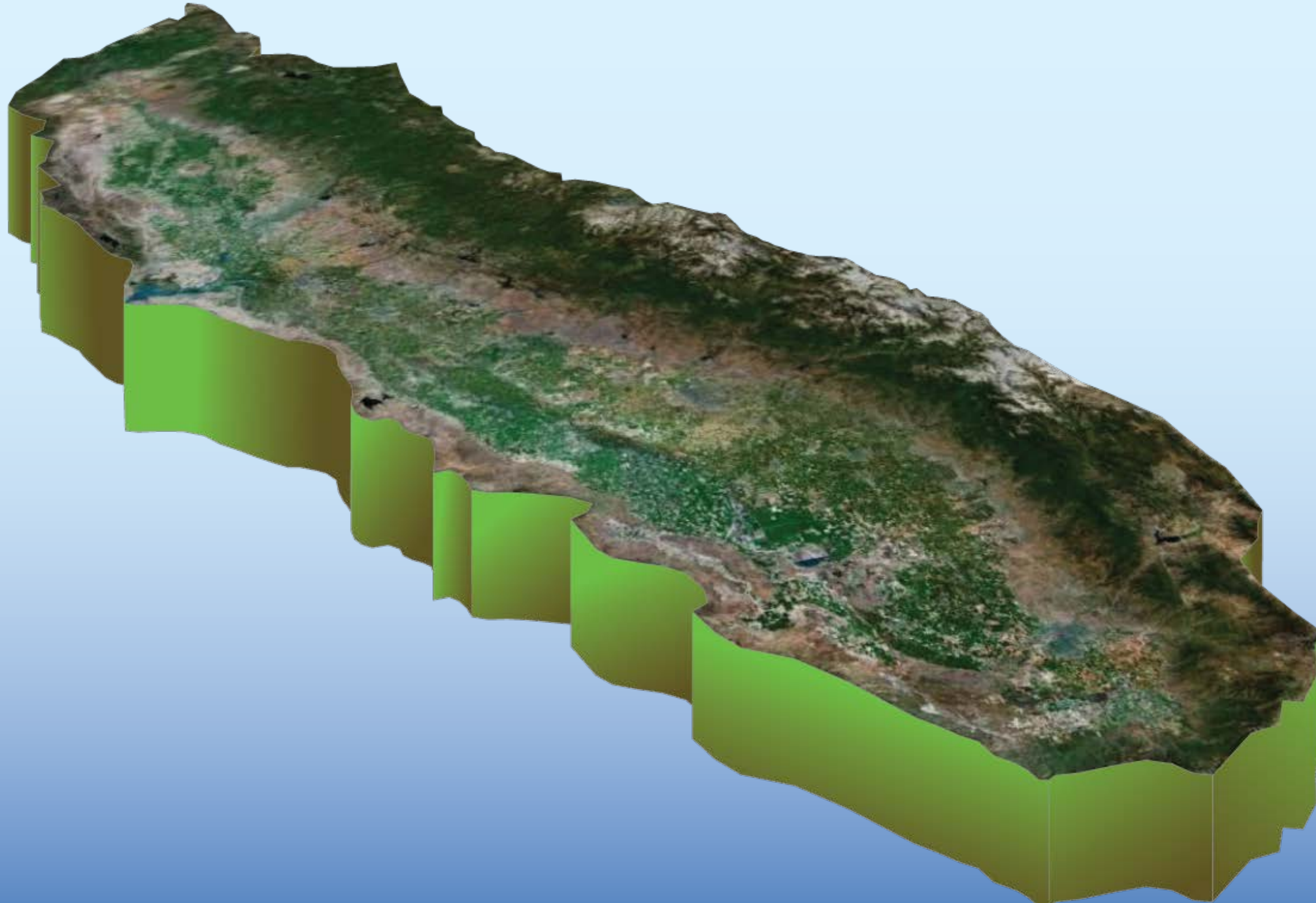
Tectonic Subsidence



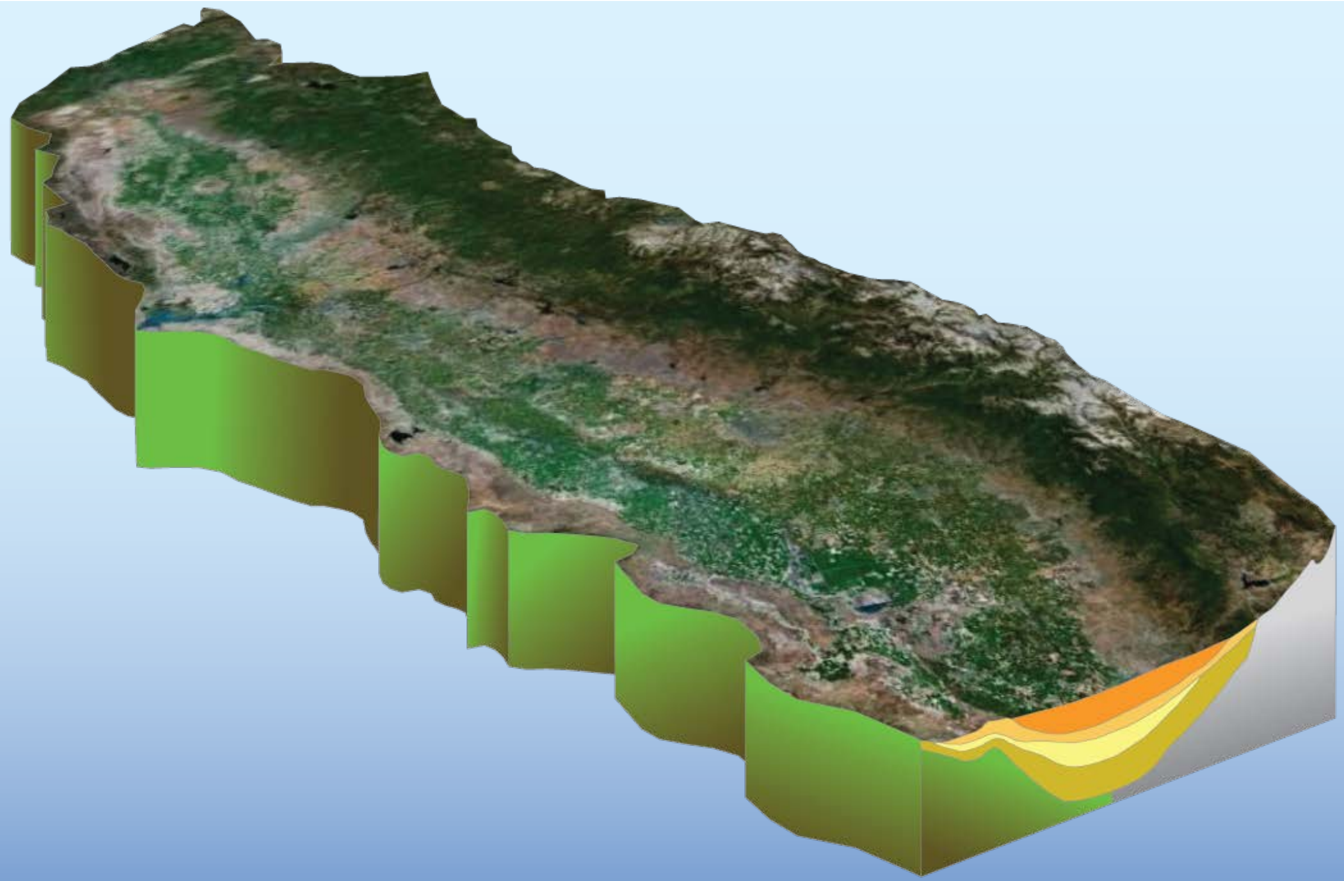


Zandt et al. Nature. September 2004.

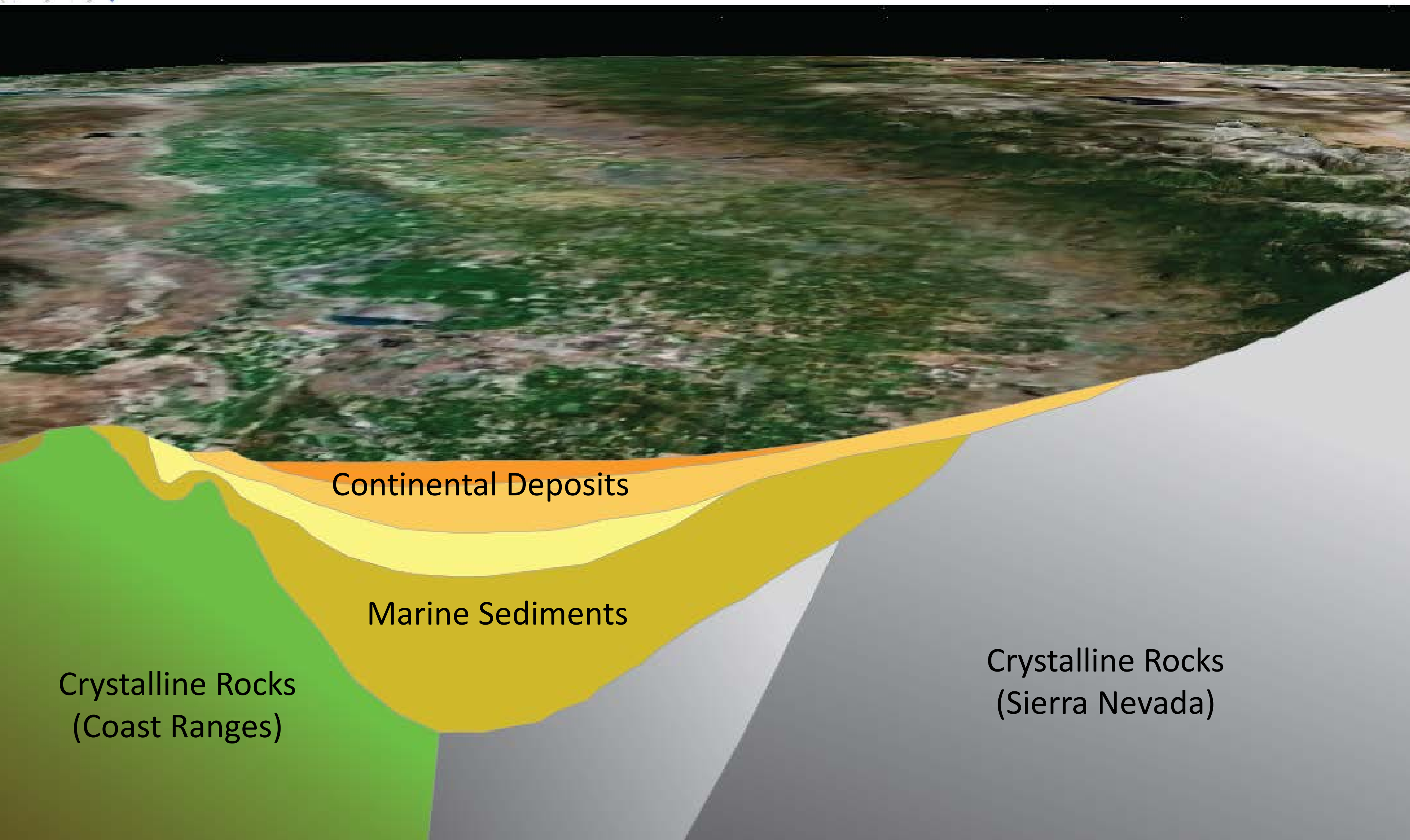
Central Valley Stratigraphy



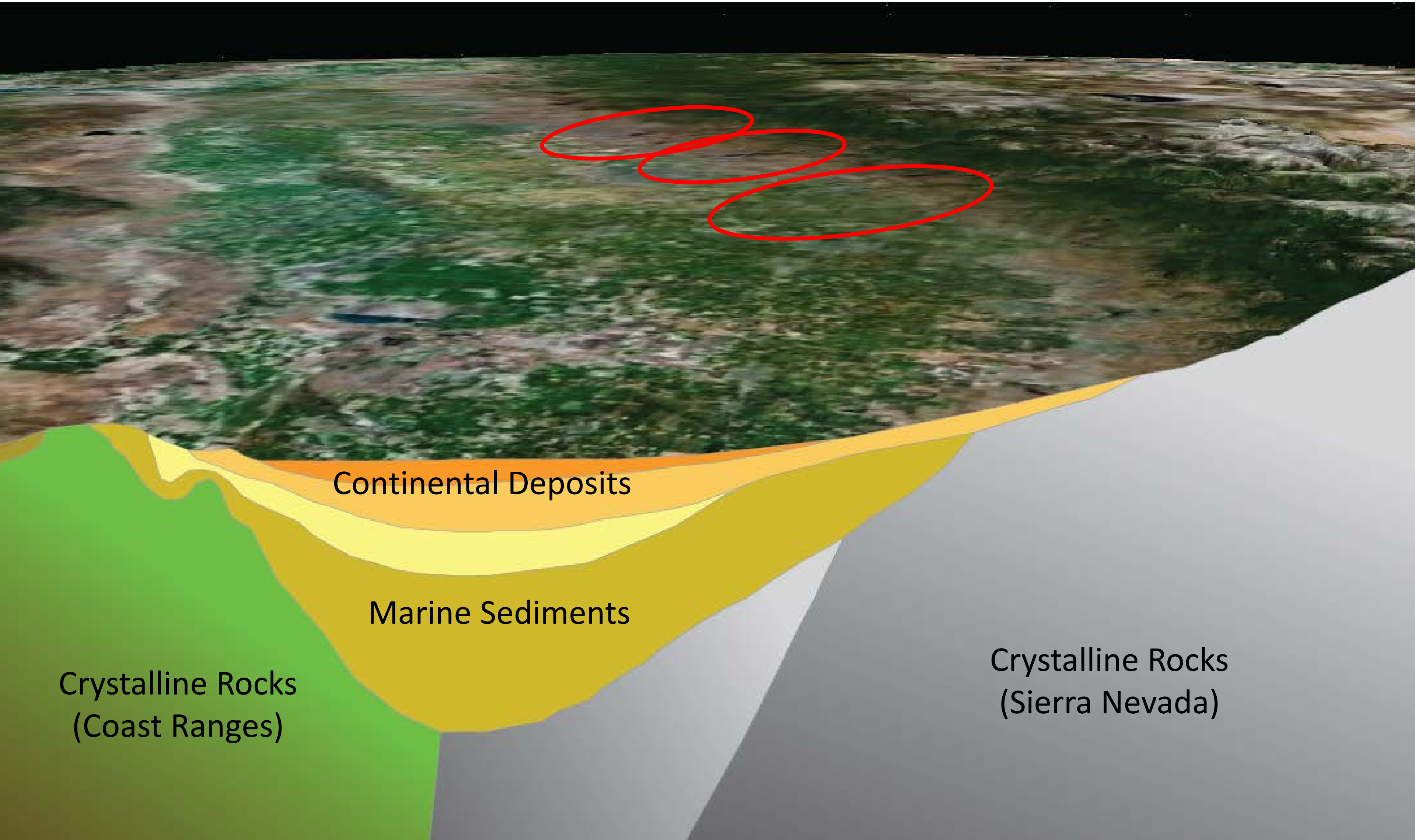
Central Valley Stratigraphy



Current Central Valley



River Fans



Continental Deposits
Marine Sediments
Crystalline Rocks
(Coast Ranges)
Crystalline Rocks
(Sierra Nevada)

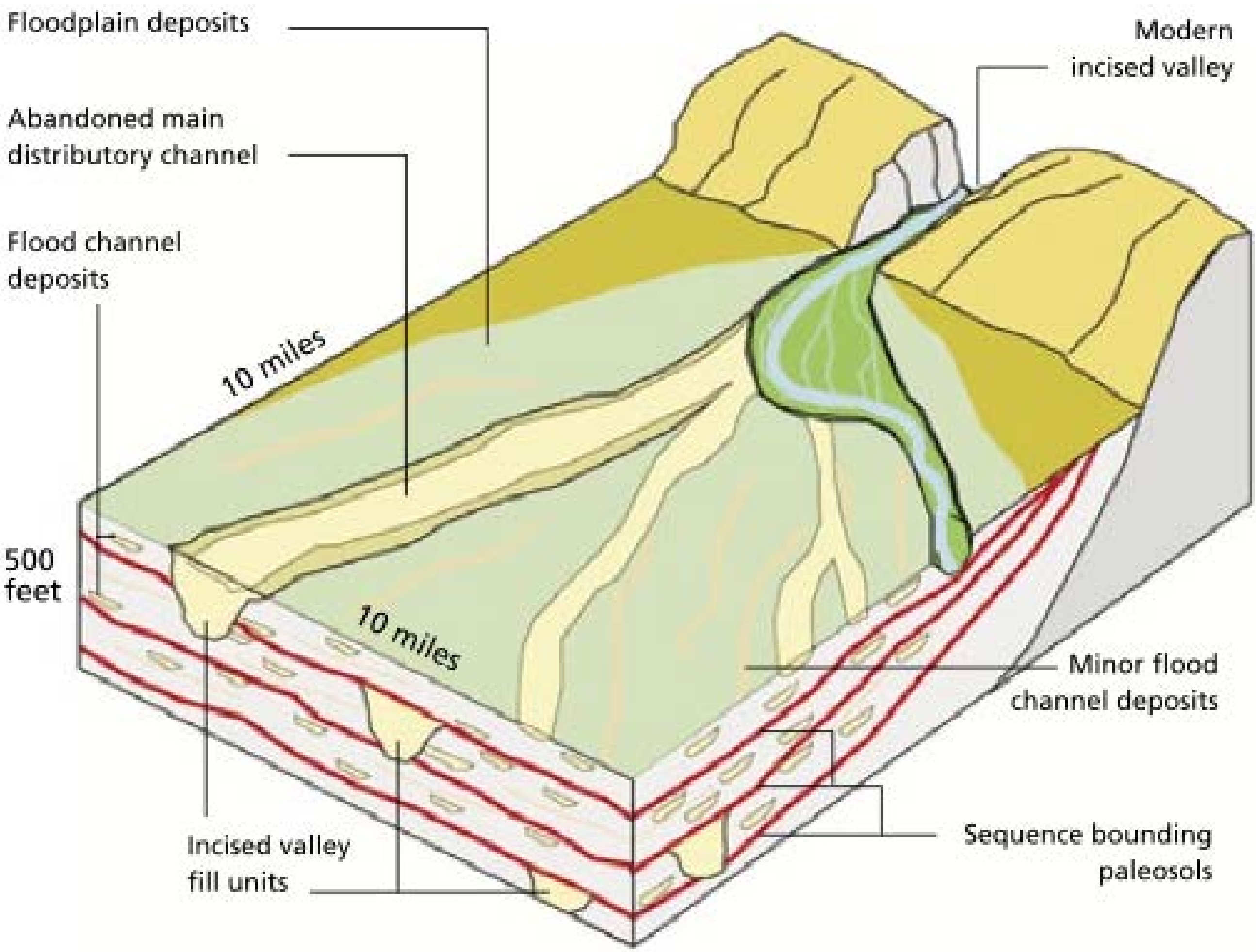


Fig. 2. Schematic diagram of the Kings River alluvial fan and its geologic elements.

Harter et al. 2005.

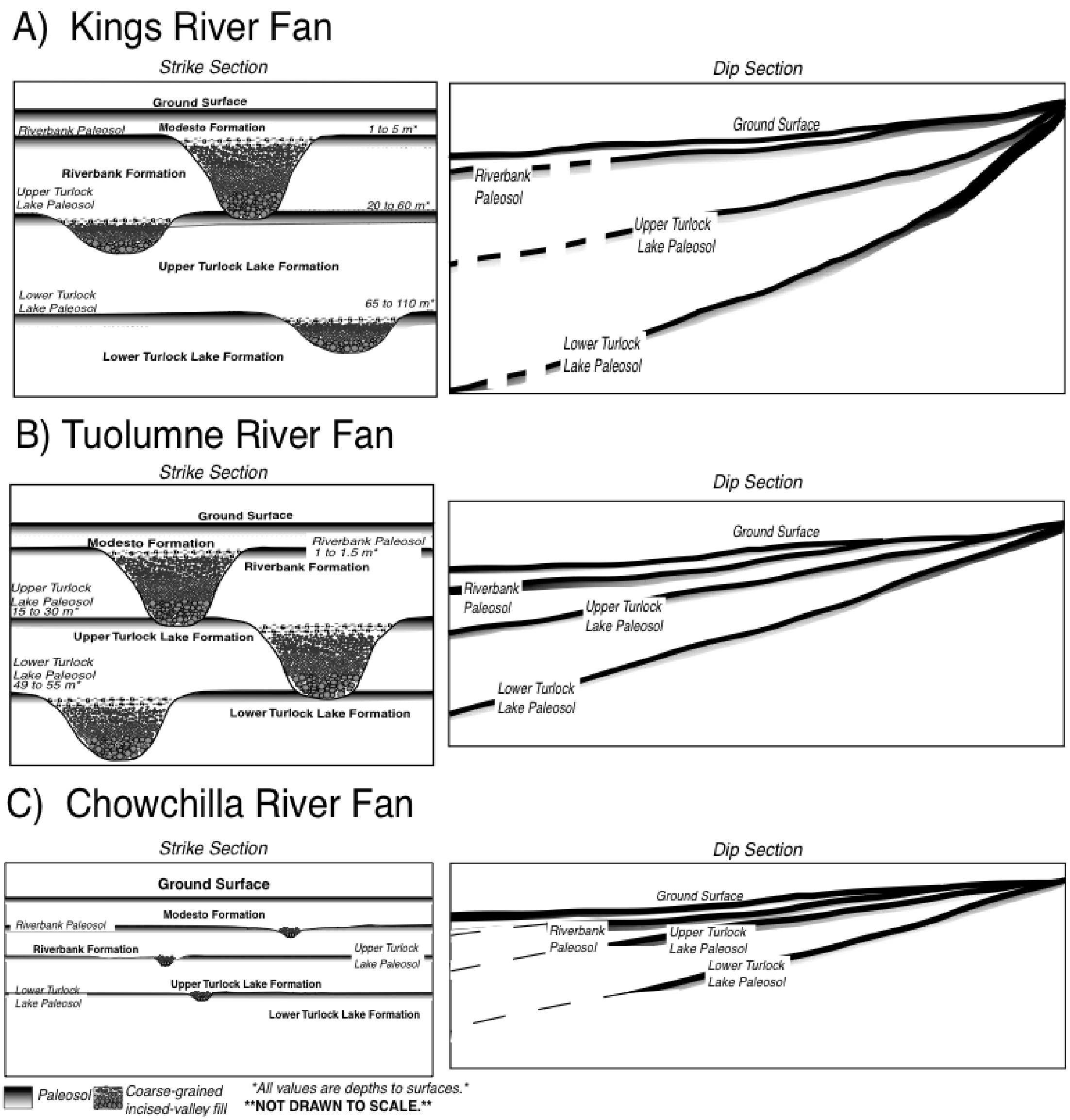
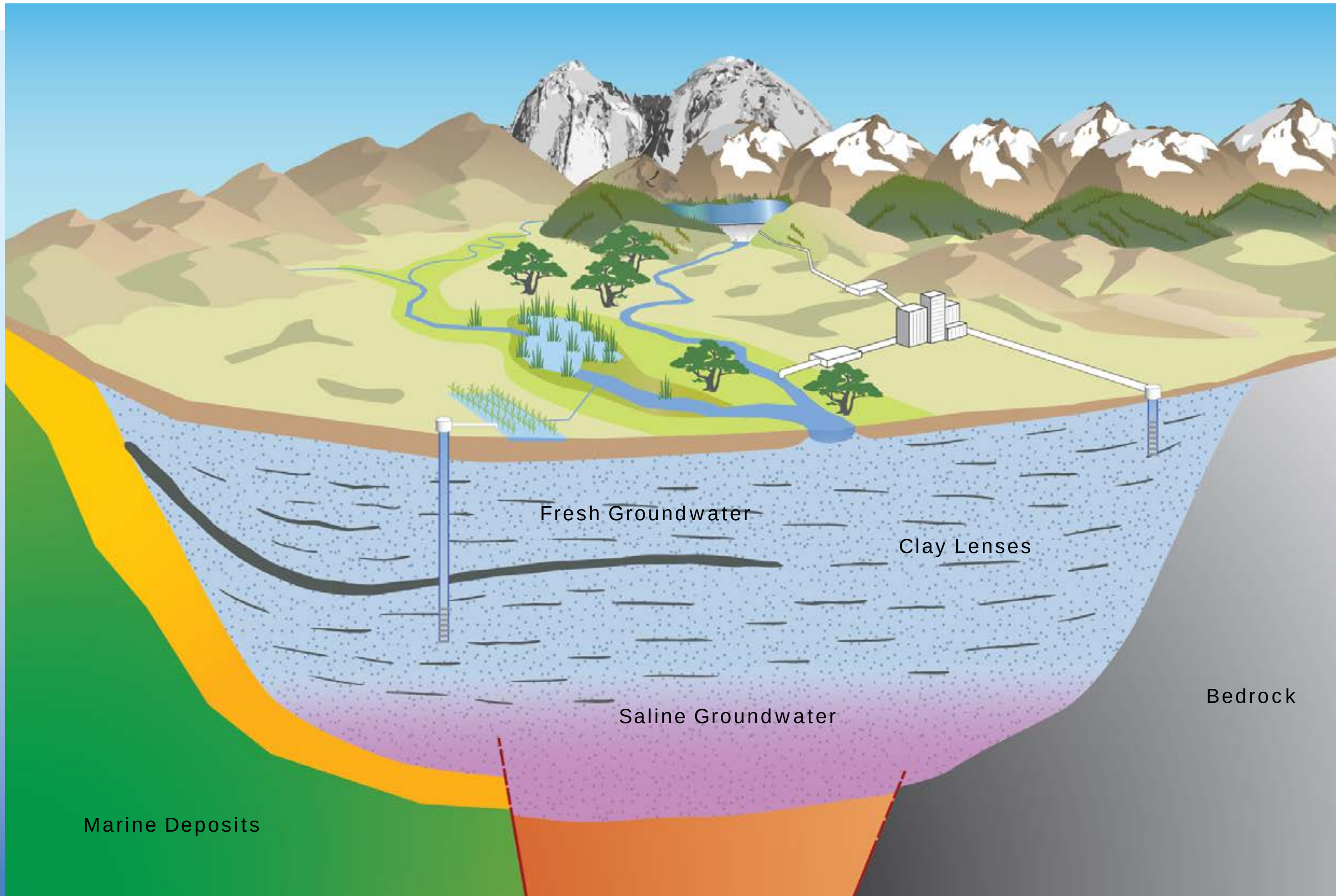


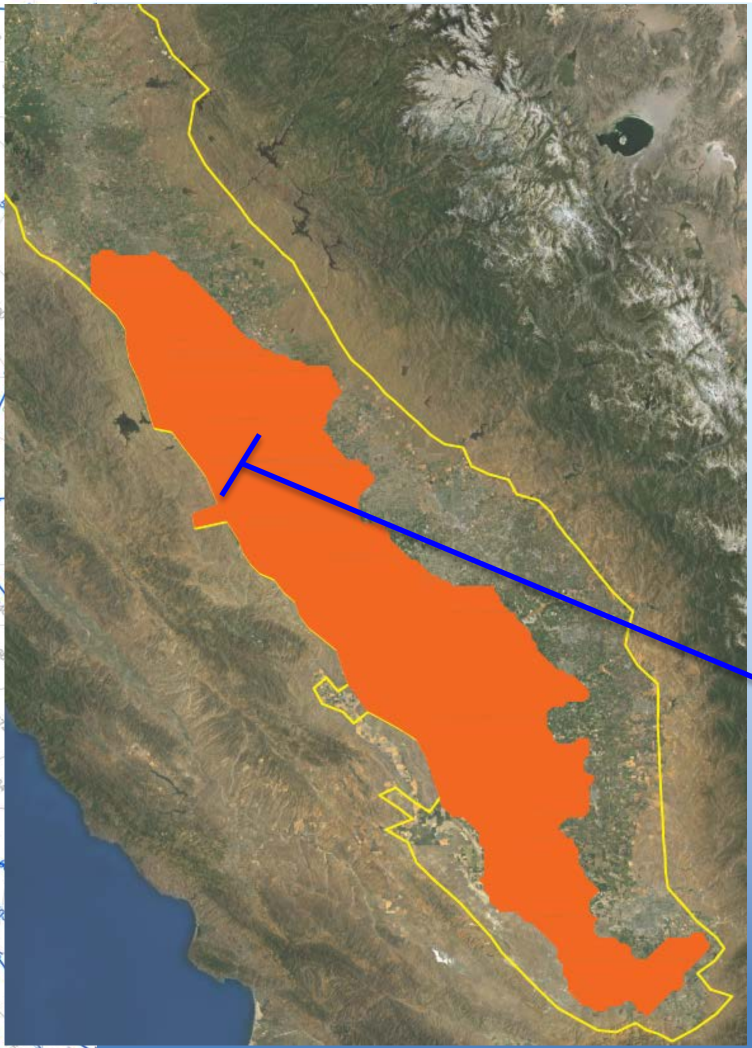
Fig. 6. Schematic cross-sections through: (**A**) the Kings River fluvial fan (based on Weissmann *et al*. 2002*a*, 2004); (**B**) the Tuolumne River fluvial fan (based on Burow *et al*. 2004); and (**C**) the Chowchilla River fluvial fan (based on Helley 1966).

Weissmann et al. 2005.

Hydrogeology



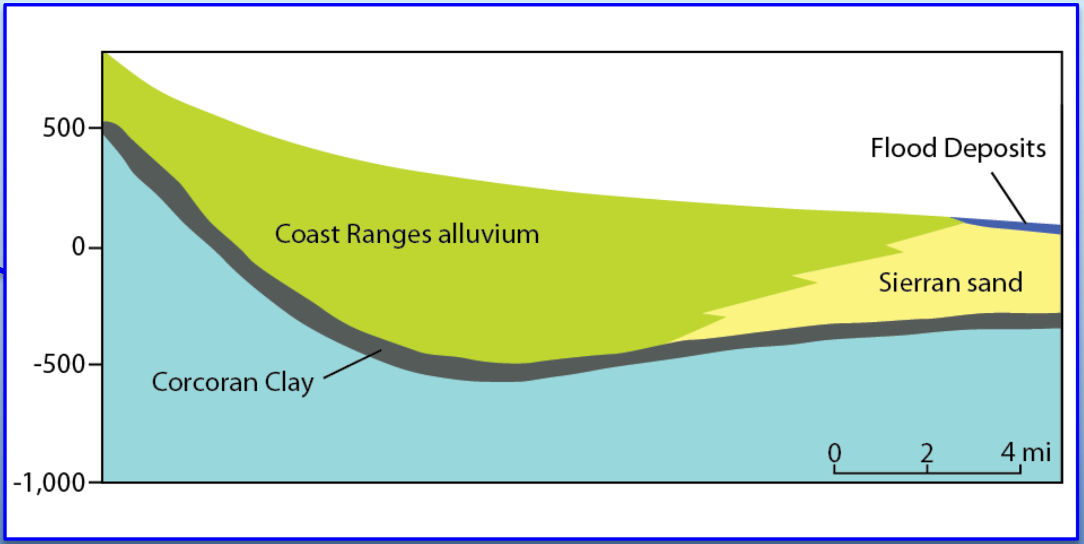
Corcoran Clay



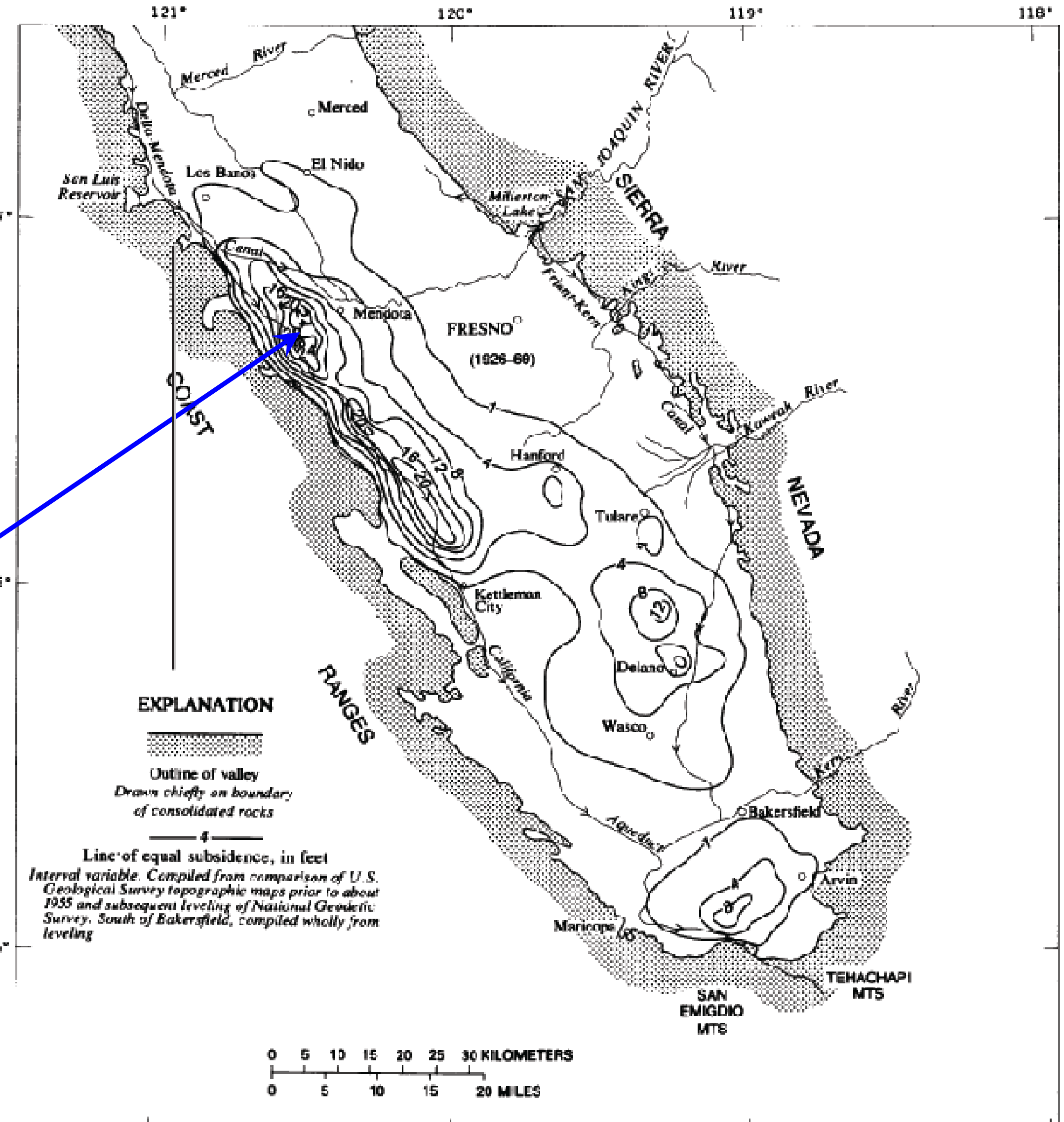
Buried remnant of a Pleistocene lake bed

Deposited 615,000 - 750,000 years ago

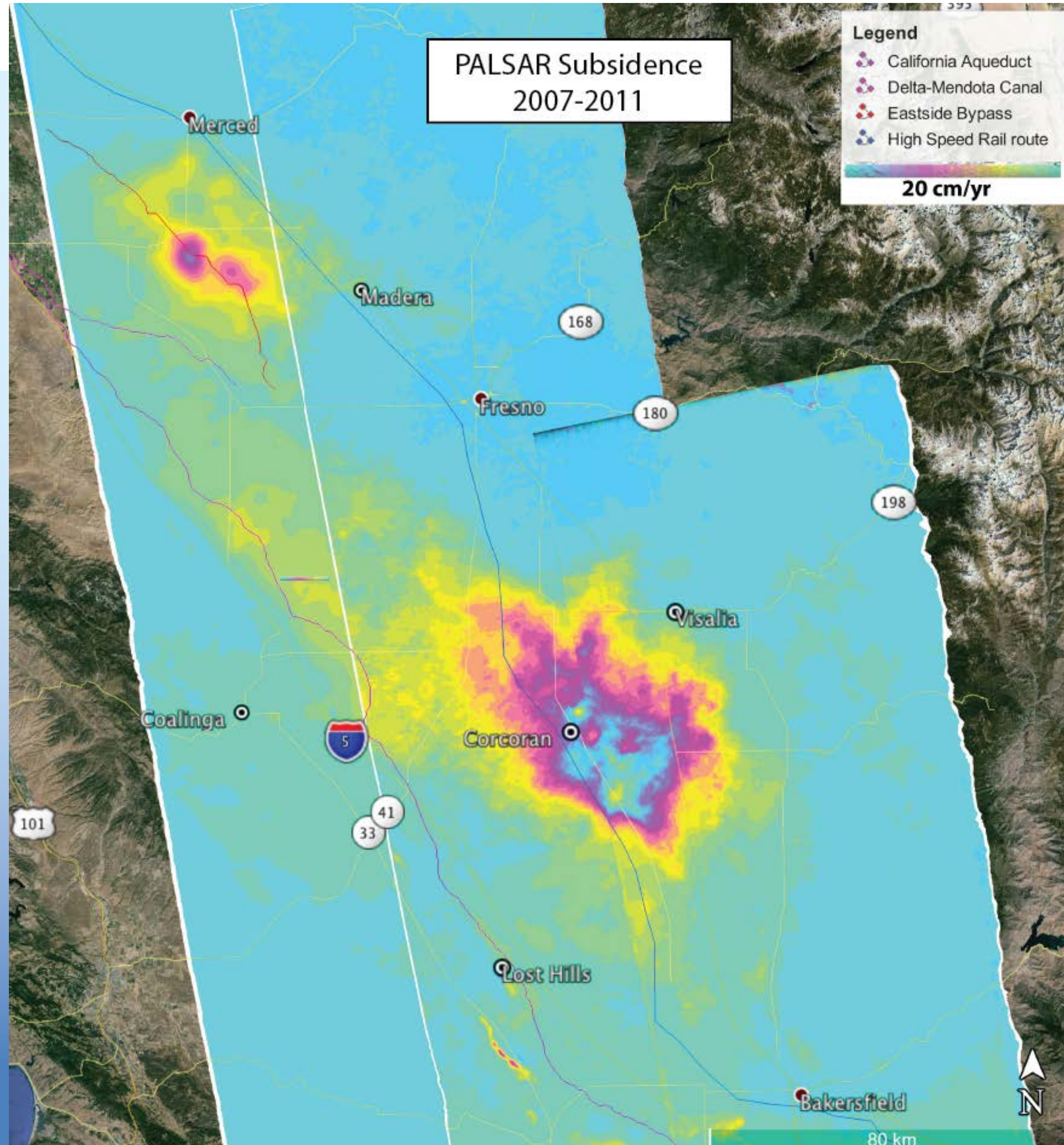
Deformed by tectonic subsidence



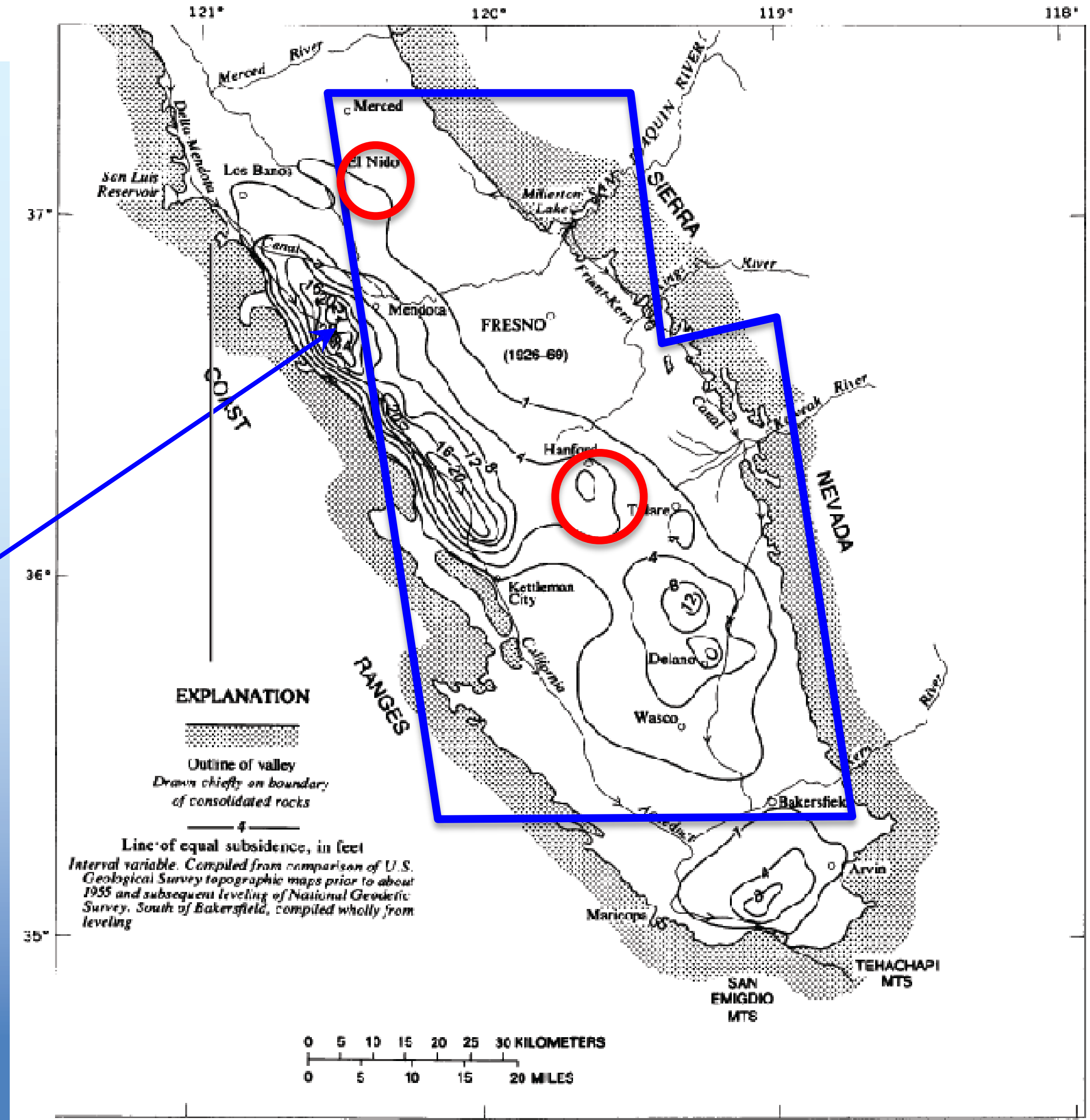
Land Surface Subsidence



Land Surface Subsidence



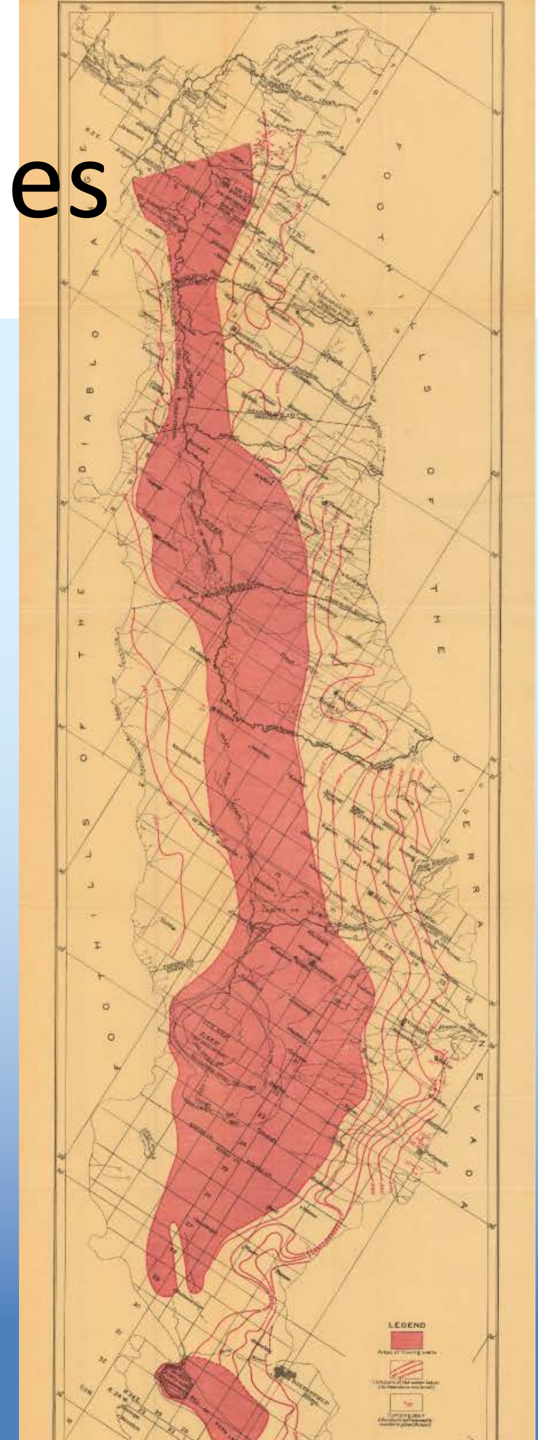
Land Surface Subsidence



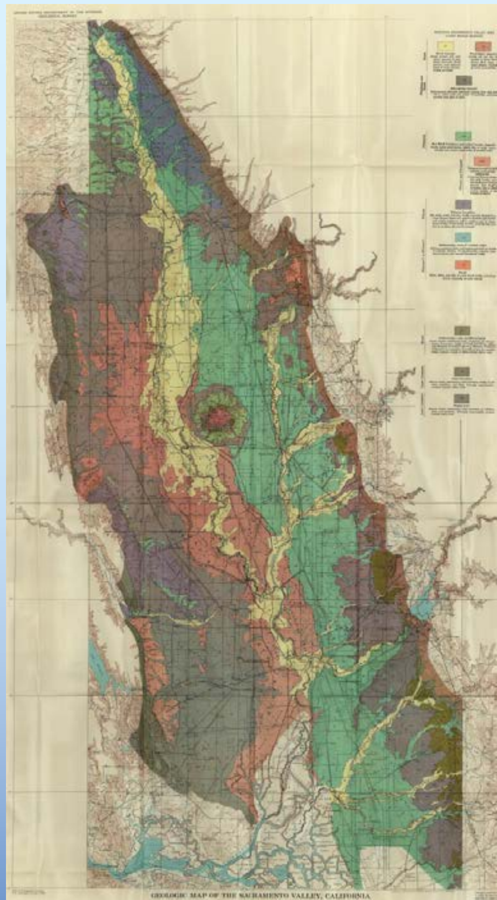
Groundwater Studies

Bryan, 1923. Geology and ground-water resources of Sacramento Valley, California.

Mendenhall et al. 1916. Ground water in San Joaquin Valley, California.

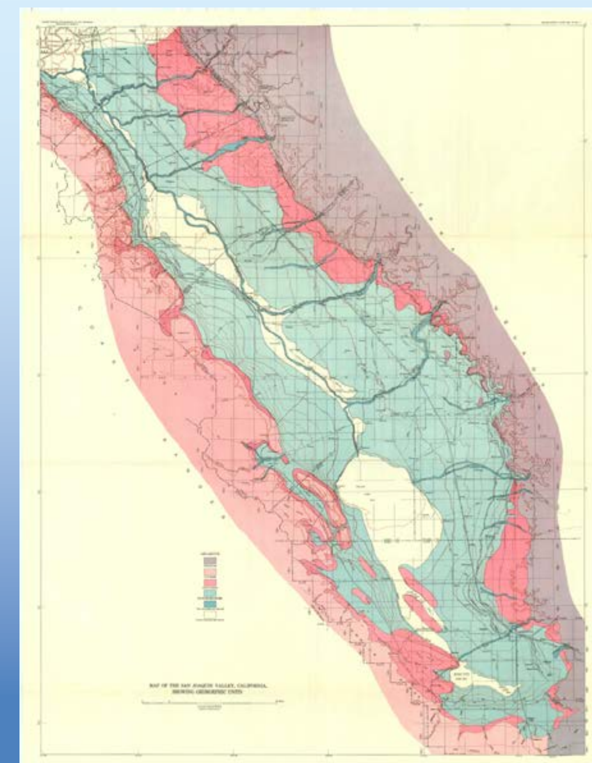


Groundwater Studies



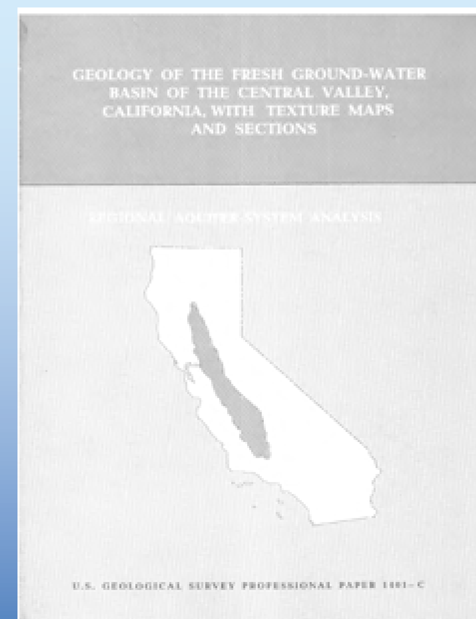
Olmsted and Davis. 1961. Geologic features and ground water storage capacity of the Sacramento Valley, California.

Davis et al. 1959. Ground-water conditions and storage capacity in the San Joaquin Valley California.



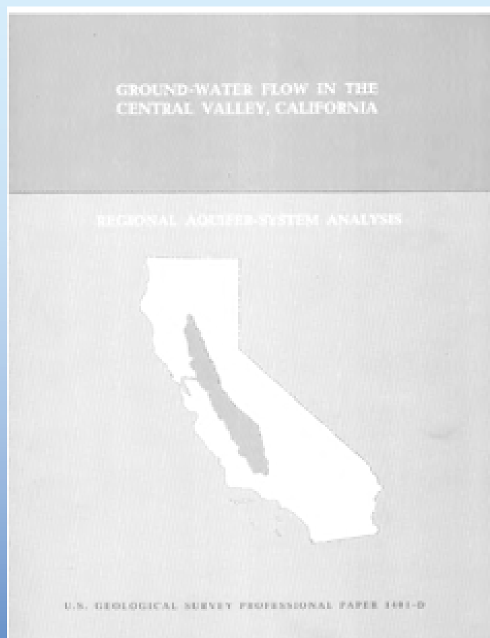
Groundwater Studies

Page. 1986. Geology of the fresh ground-water basin of the Central Valley, California.

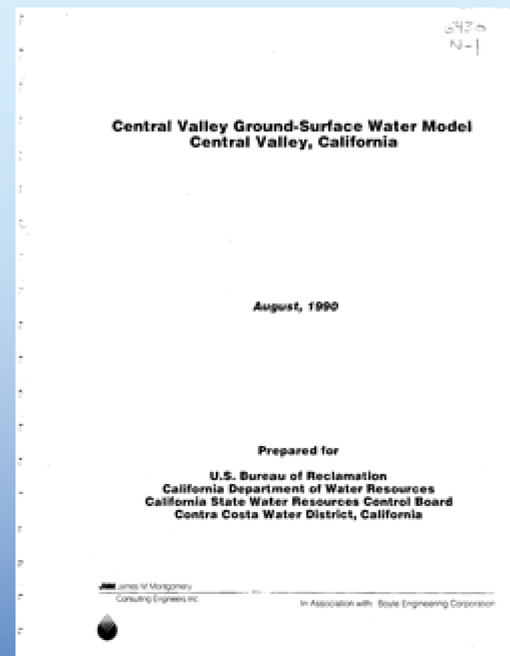


Regional Models

Williamson et al. 1989. Ground-water flow in the Central Valley, California.



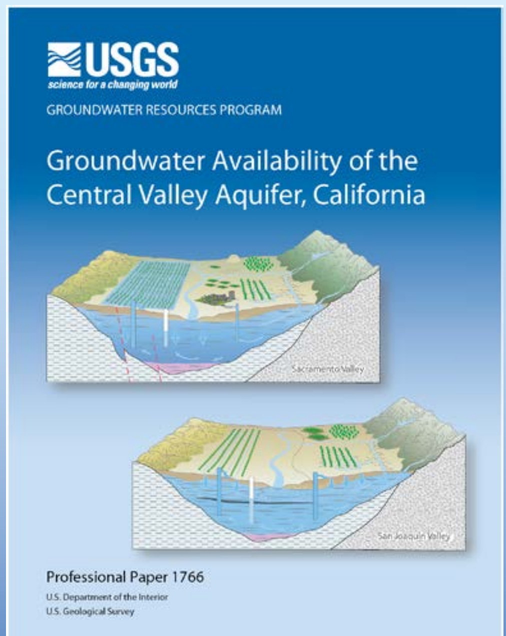
JM Montgomery Engineers. 1990. California Central Valley Ground-Surface Water Model (CVGSM) Manual.

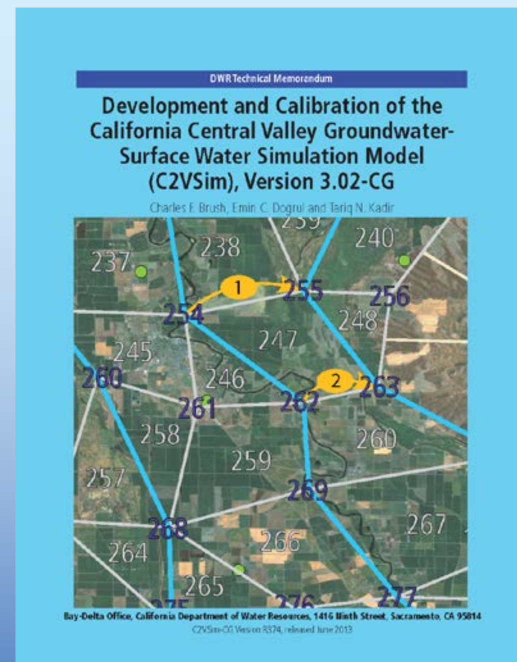


Regional Models

Faunt et al. 2009. Groundwater availability of the Central Valley aquifer, California.

DWR. 2012. California Central Valley Groundwater-Surface Water Simulation Model (C2VSim).





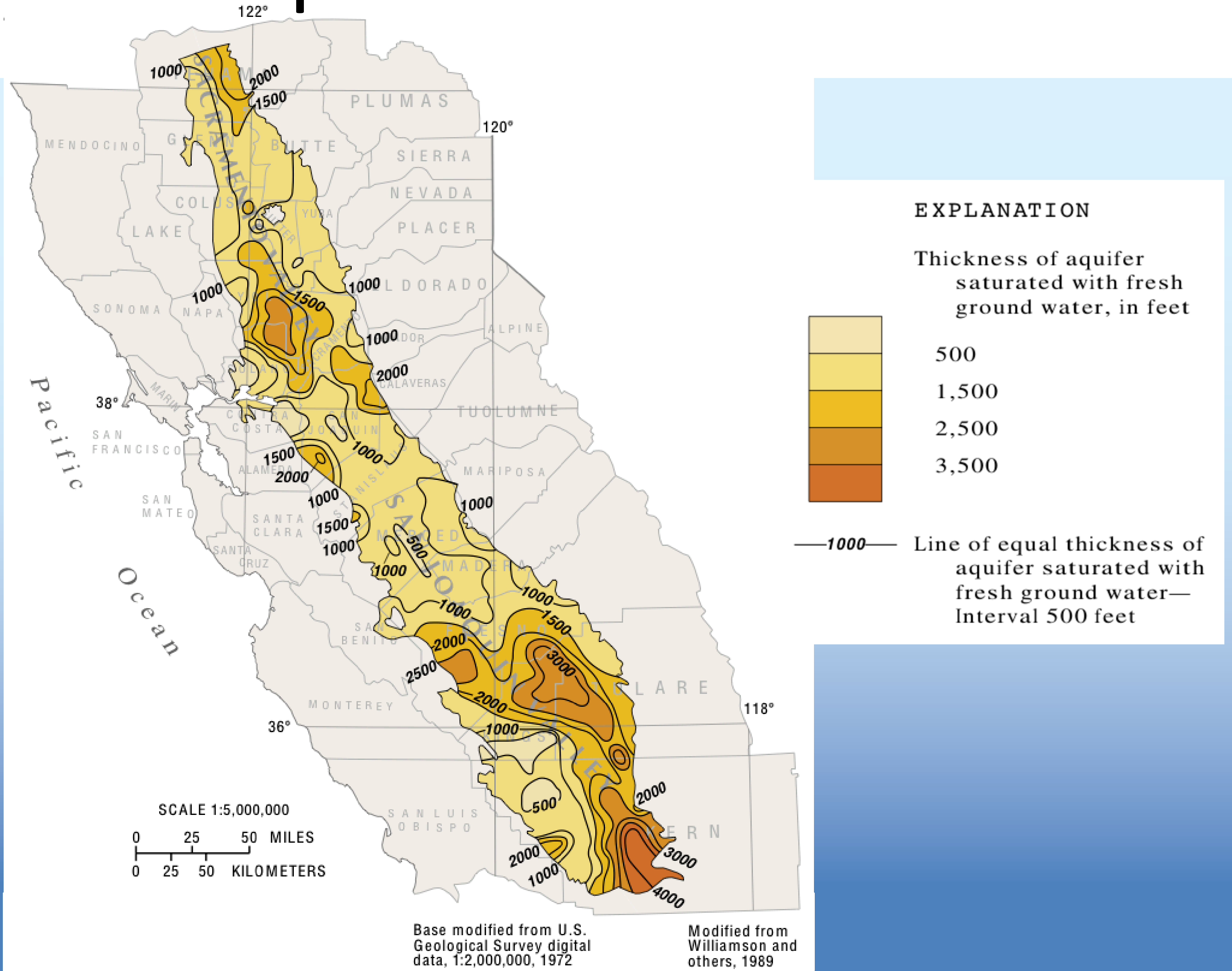
Faults

- Can act as flow barriers
- Several mapped on basement
- Vertical extent generally unknown

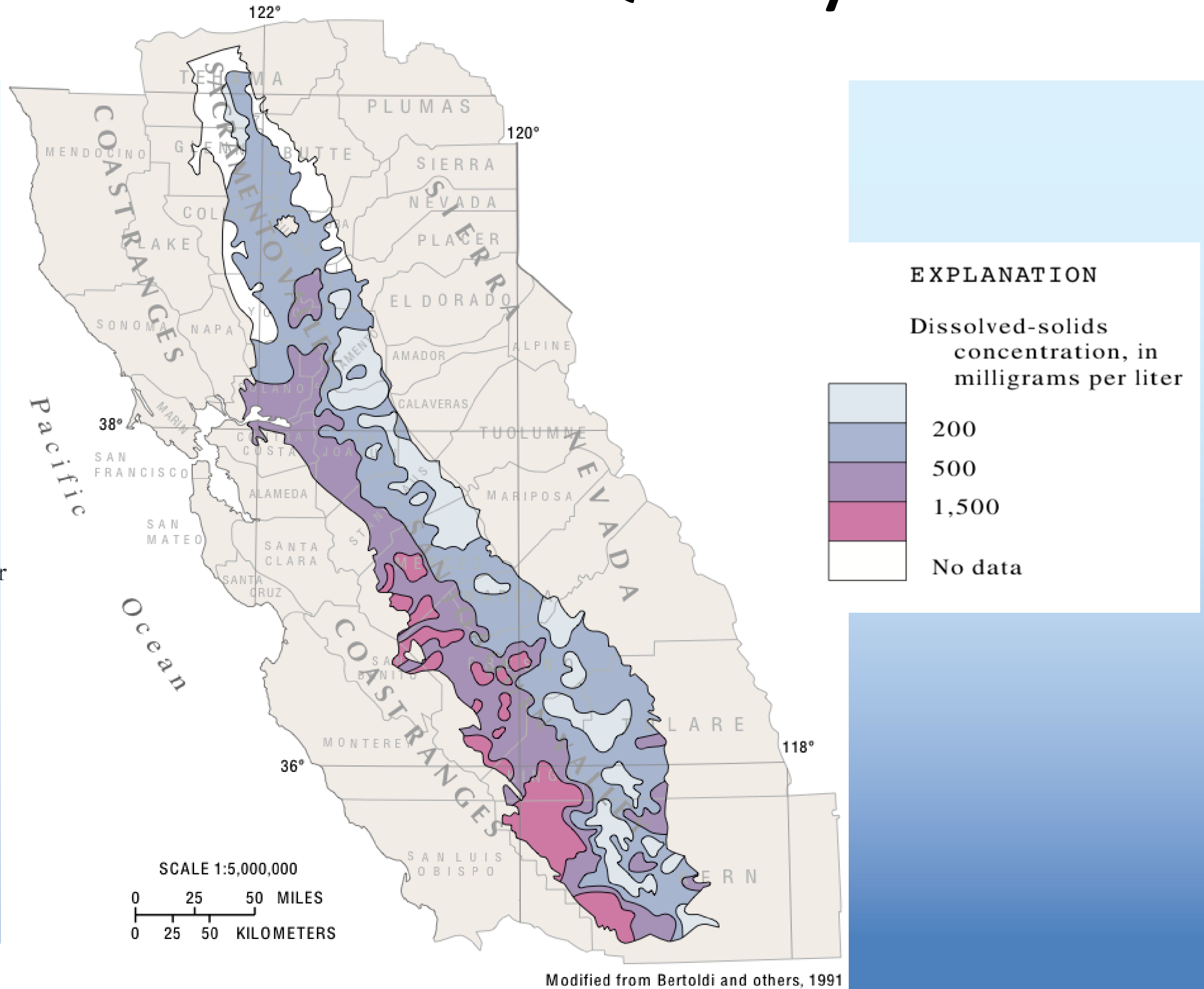
Faults

- Battle Creek Fault
- **Red Bluff Arch**
- Plainfield Ridge Anticline
- Pittsburgh – Kirby Hills – Vaca Fault
- Vernalis Fault
- Graveley Ford Faults
- Visalia Fault
- Pond-Poso Creek Fault
- Edison Fault
- **White Wolf Fault**

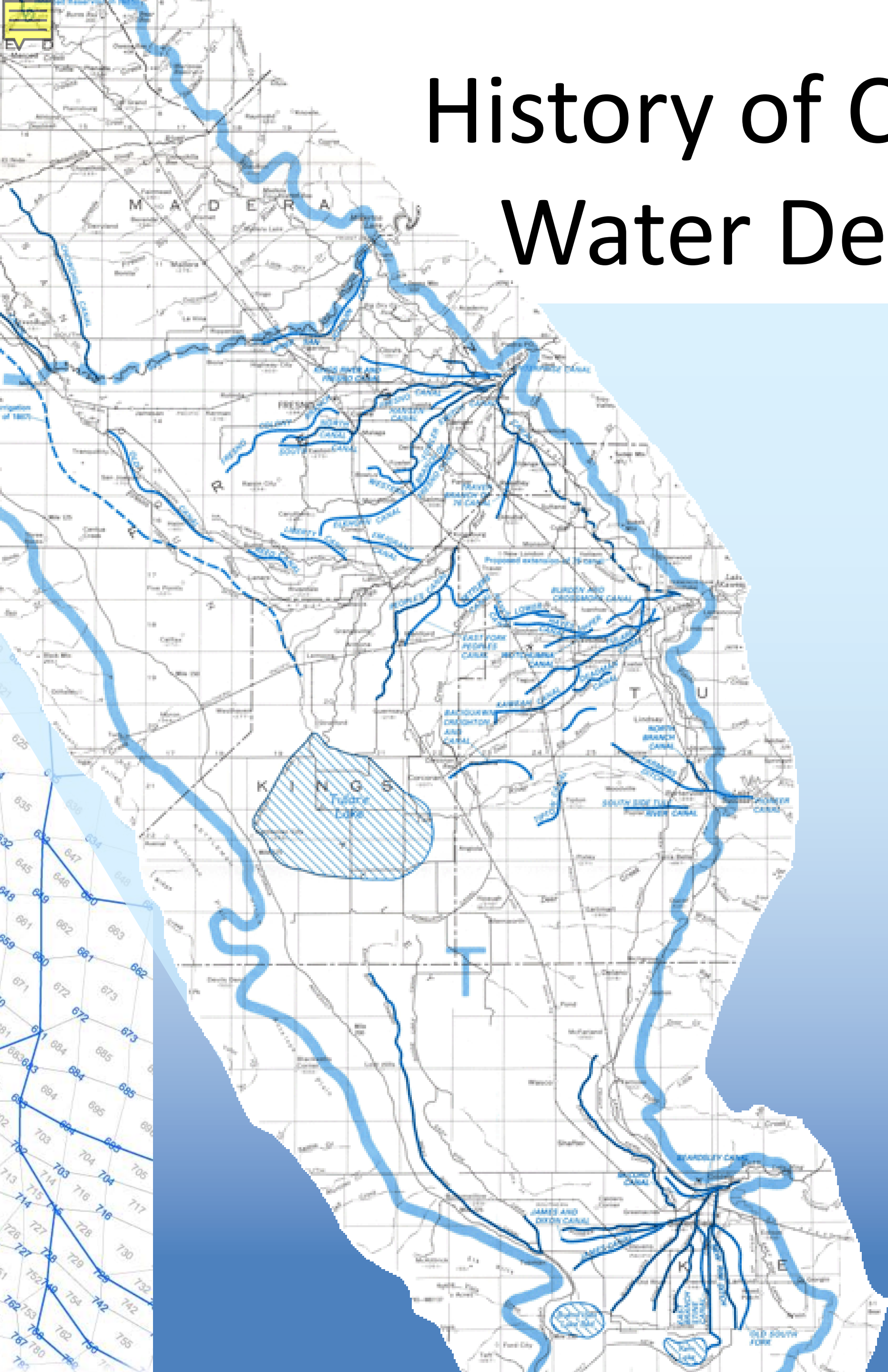
Aquifer Thickness



Water Quality



History of Central Valley Water Development

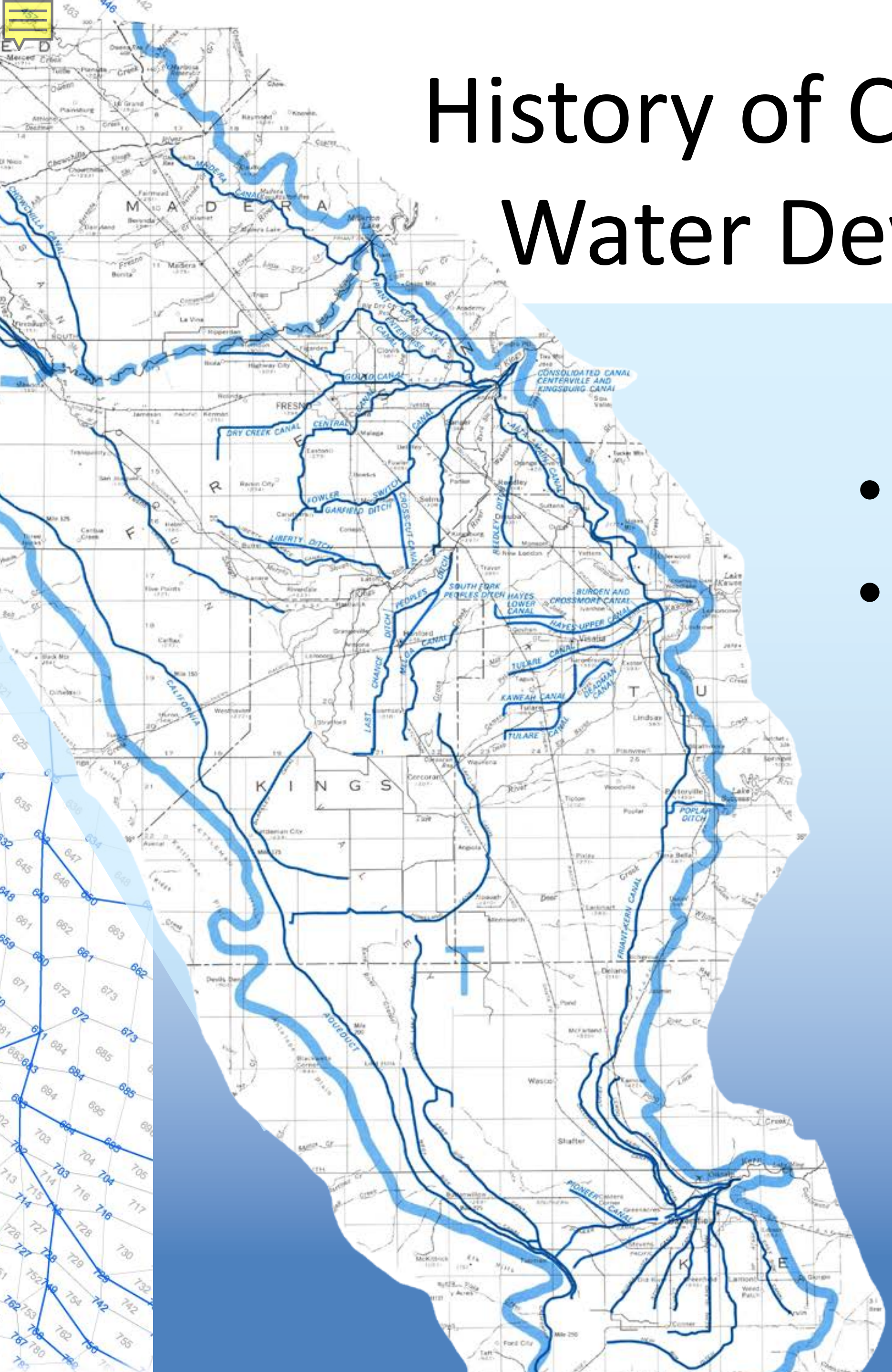


1800s

- Water development to support hydraulic mining
- Converted to irrigation after 1886
- Local diversions and irrigation canals within a watershed

Nady and Larragueta. 1983. Development of Irrigation in the Central Valley. USGS Hydrologic Atlas 649, plate 1.

History of Central Valley Water Development

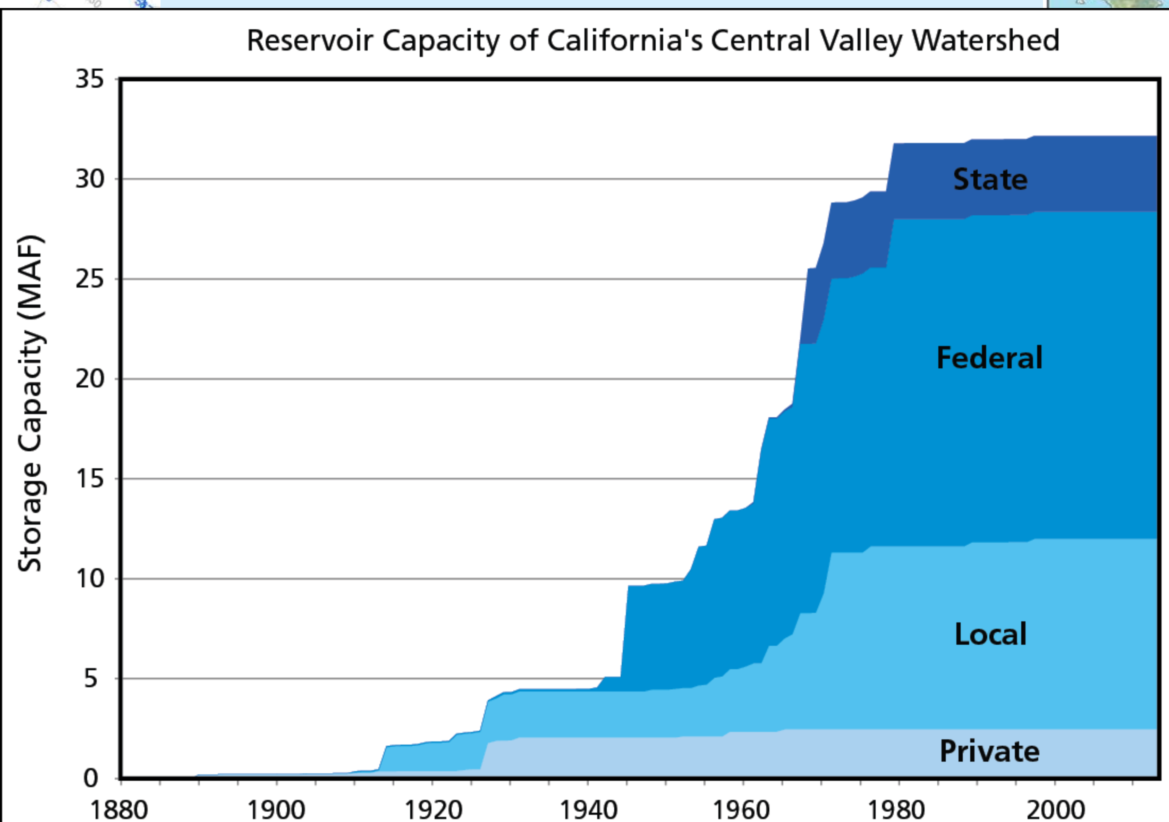


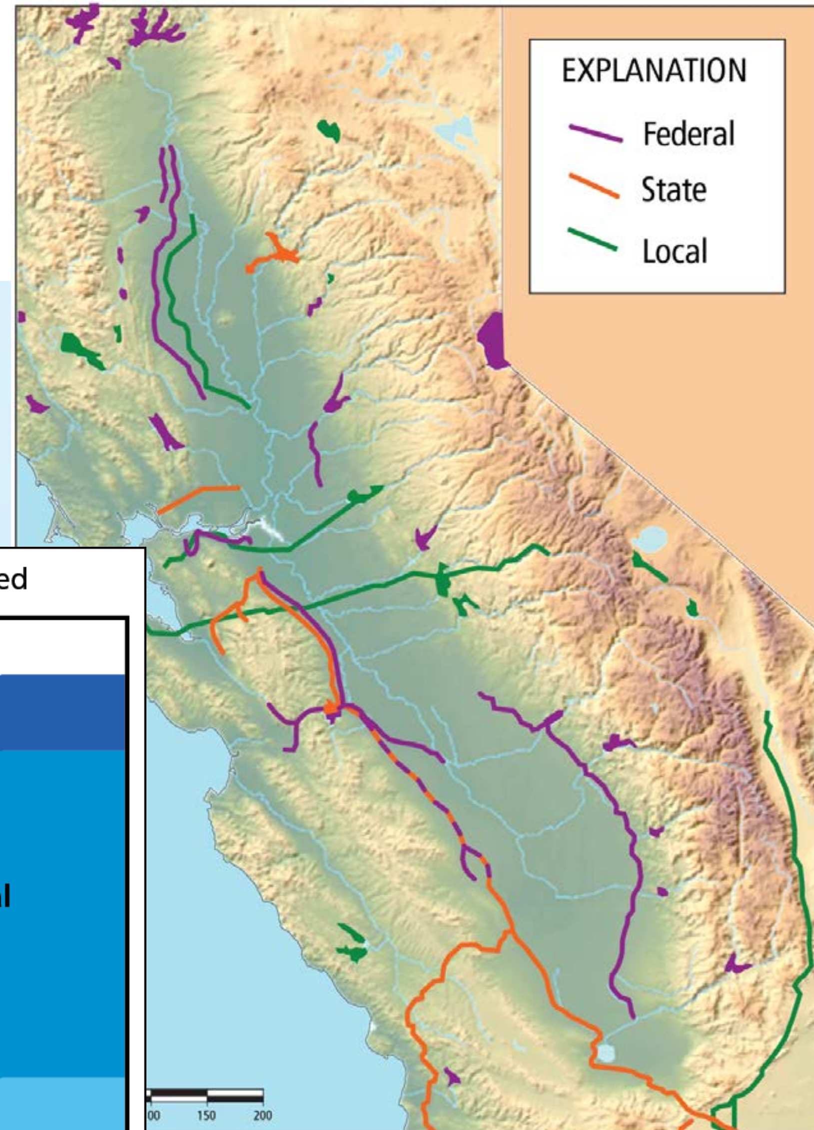
1980

- Groundwater pumping
- Inter-basin Transfers
  - Hetch-Hetchy Aqueduct
  - Mokelumne Aqueduct
  - Central Valley Project
  - State Water Project

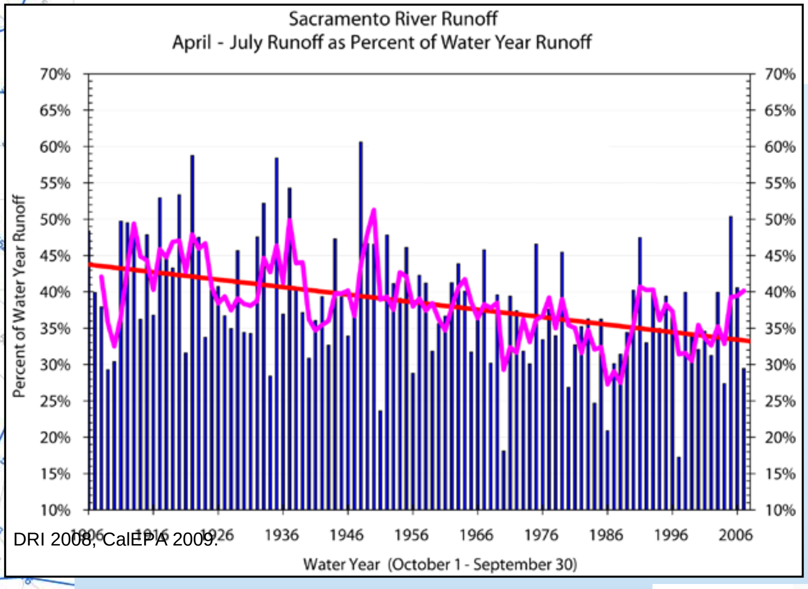
Nady and Larragueta. 1983. Development of Irrigation in the Central Valley. USGS Hydrologic Atlas 649, plate 2.

Surface Water System

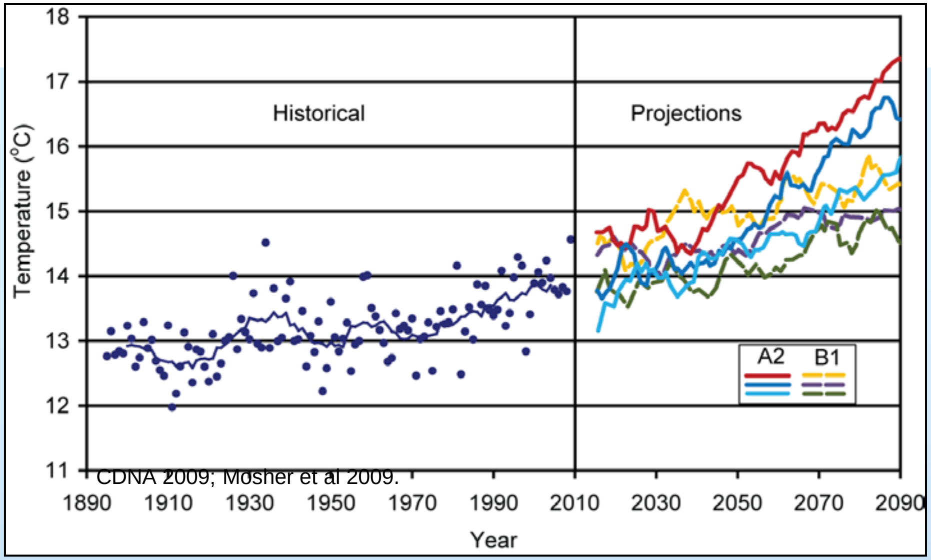




Climate Change



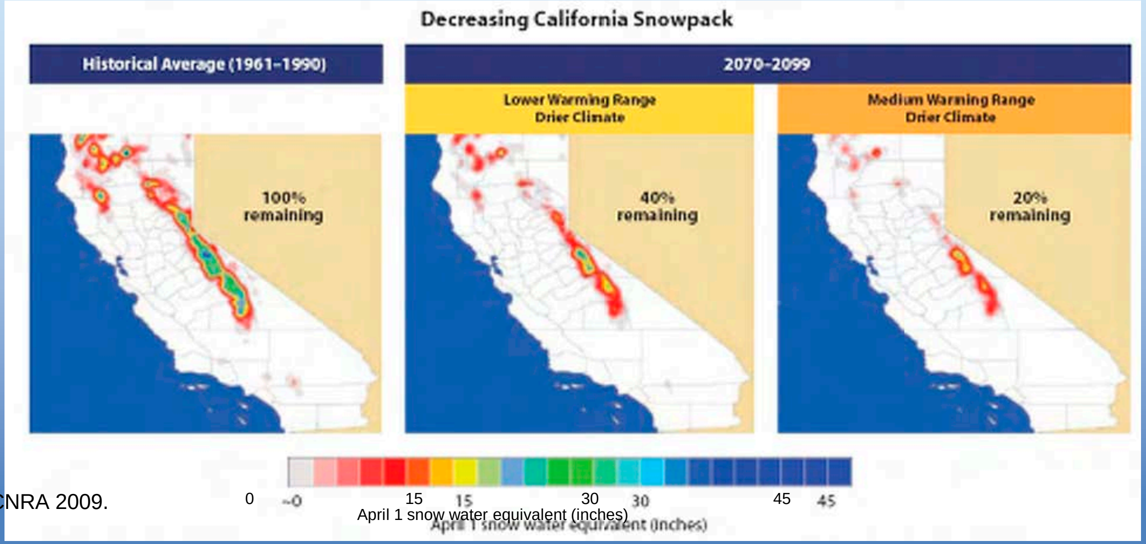
DRI 2008; CalEPA 2009.



CDNA 2009; Mosher et al 2009.

10% snowpack reduction 1960-2000.

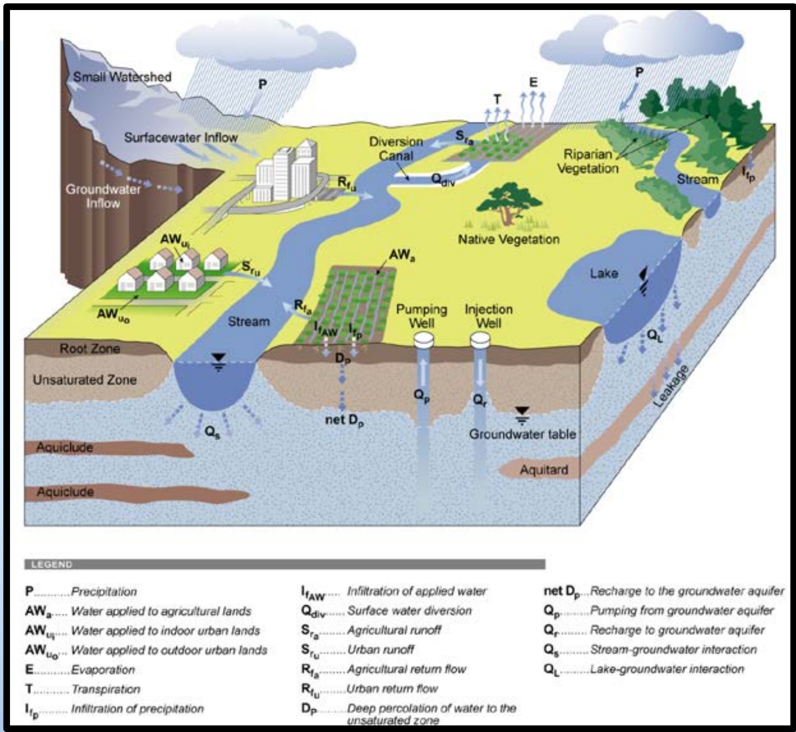
Continued warming could reduce snowpack volume by 25% by 2050



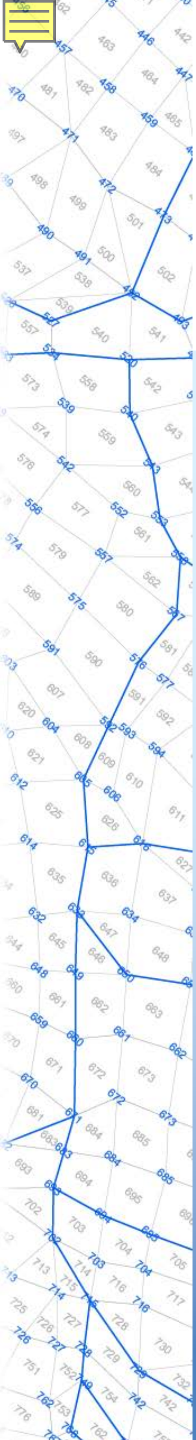
CNRA 2009.

Integrated Water Flow Model (IWFM)

- Open-source, regional-scale integrated hydrologic model
- Simulates land surface, groundwater, surface water, and surface-groundwater interactions
- Represent agricultural and urban water management practices, and their effects on the water system



- A planning and analysis tool that computes agricultural and urban water demands based on climatic, soil, land-use and agronomic parameters, then adjusts groundwater pumping and stream diversions to meet these demands



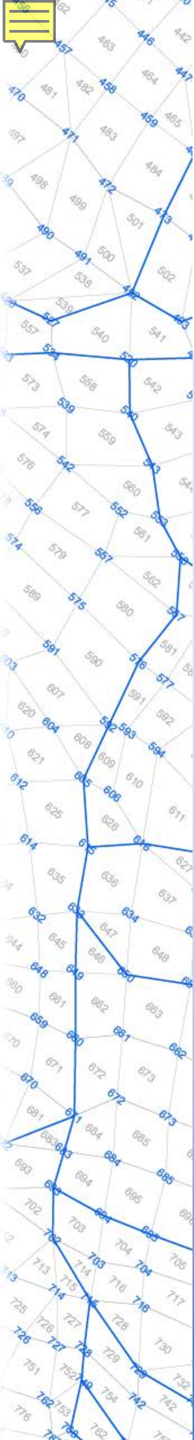
IWFM History

Derived from the Integrated Ground-Surface Water Model (IGSM)

- Originally developed by Young Yoon, UCLA (1976)
- Integrated model: Land Surface, Surface Water, Groundwater

Significant Models

- Central Valley Ground-Surface Water Model (CVGSM)
- Salinas Valley Groundwater Basin model
- Western San Joaquin Valley (WESTSIM)
- Friant Service Area
- Yolo County IGSM Model
- Sacramento County IGSM Model
- North American River Basin Model
- Kings Groundwater Basin Model



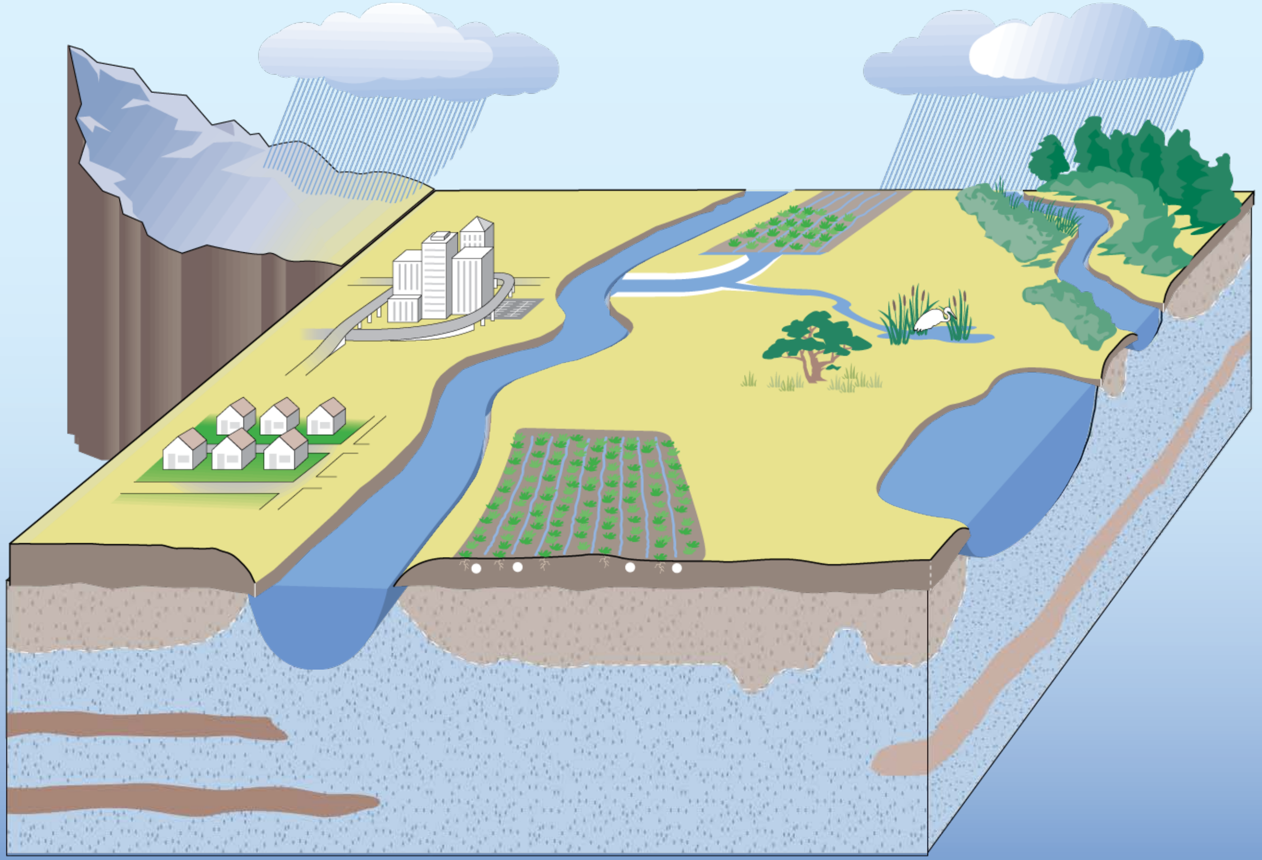
IWFM History

California Department of Water Resources

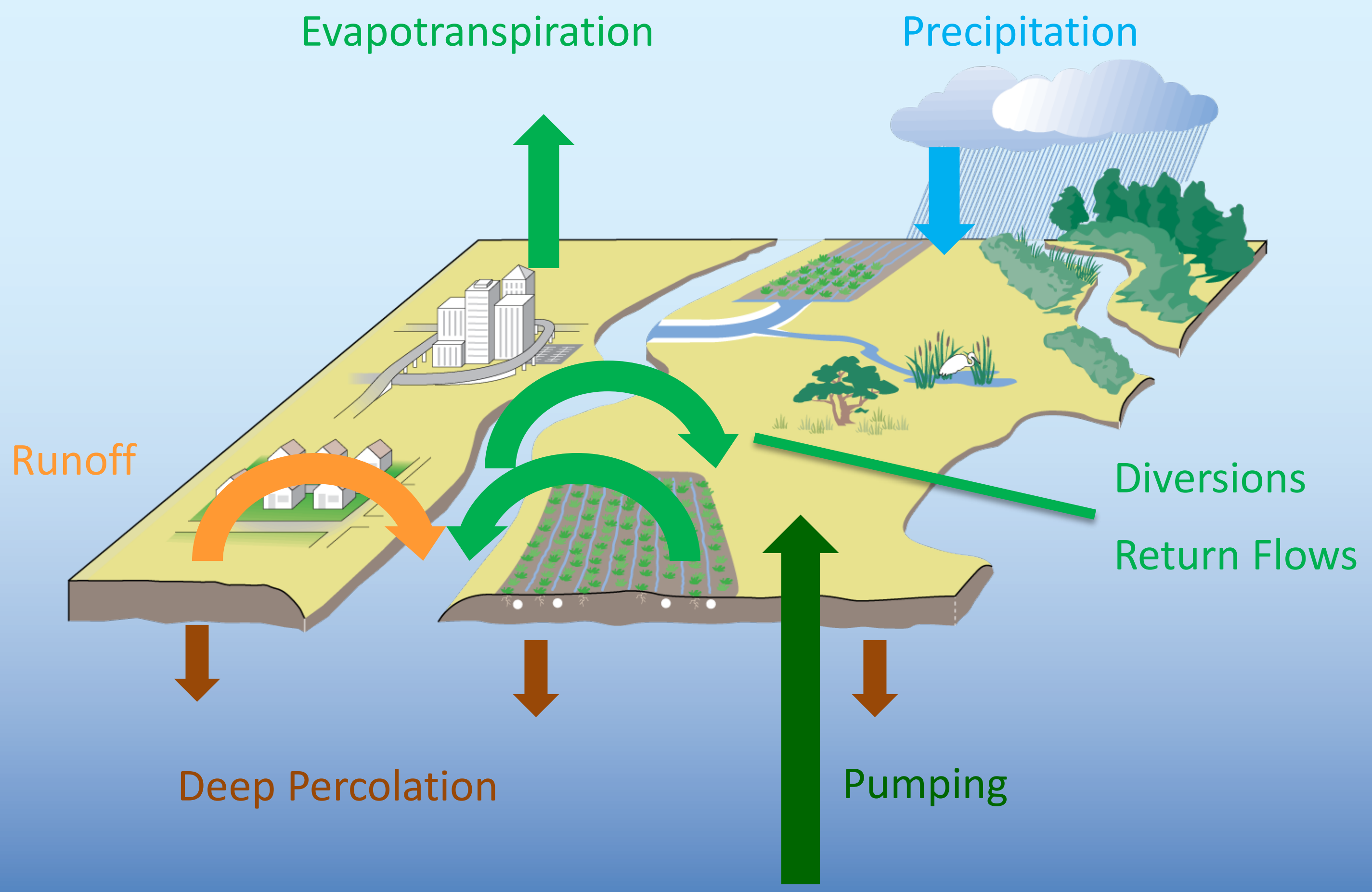
- Required a Central Valley Model for CalSim3 development
- Acquired IGSM source code
- Peer review to identify strengths and weaknesses
- Comprehensive update, port to Object Oriented FORTRAN
- Release as open-source software
- Continued development and improvement

Release

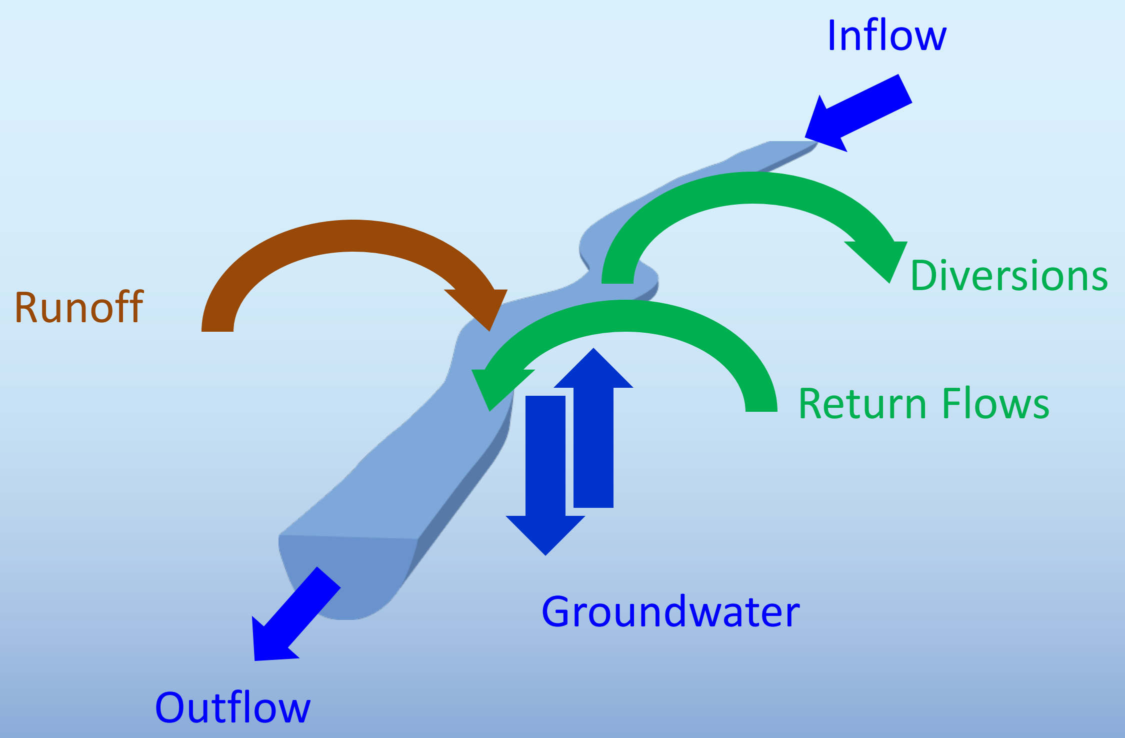
- Rename “Integrated Water Flow Model” in 2005
- Version 3.02 with subregional water budgets
- Version 4.0 with elemental water budgets



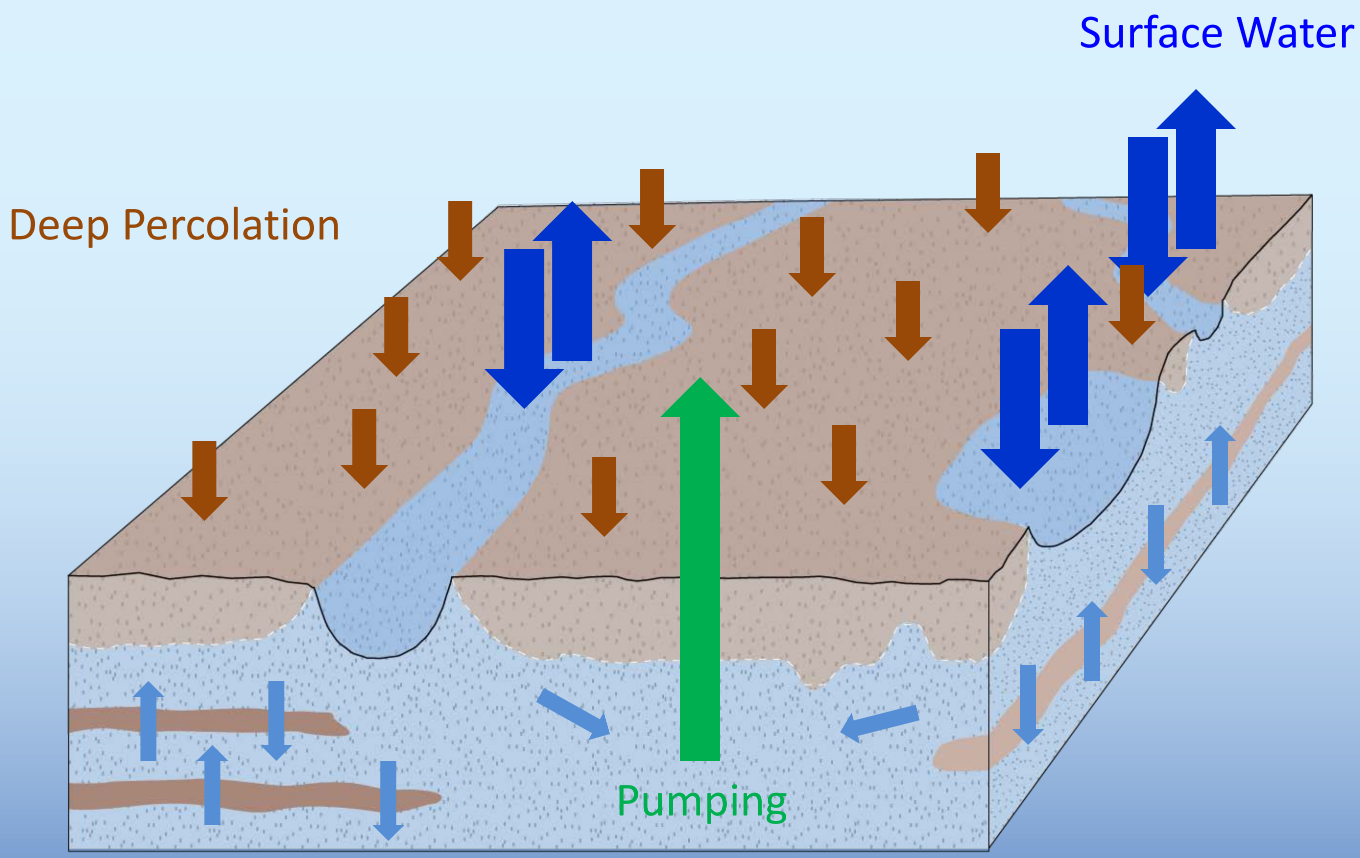
Land Surface Process



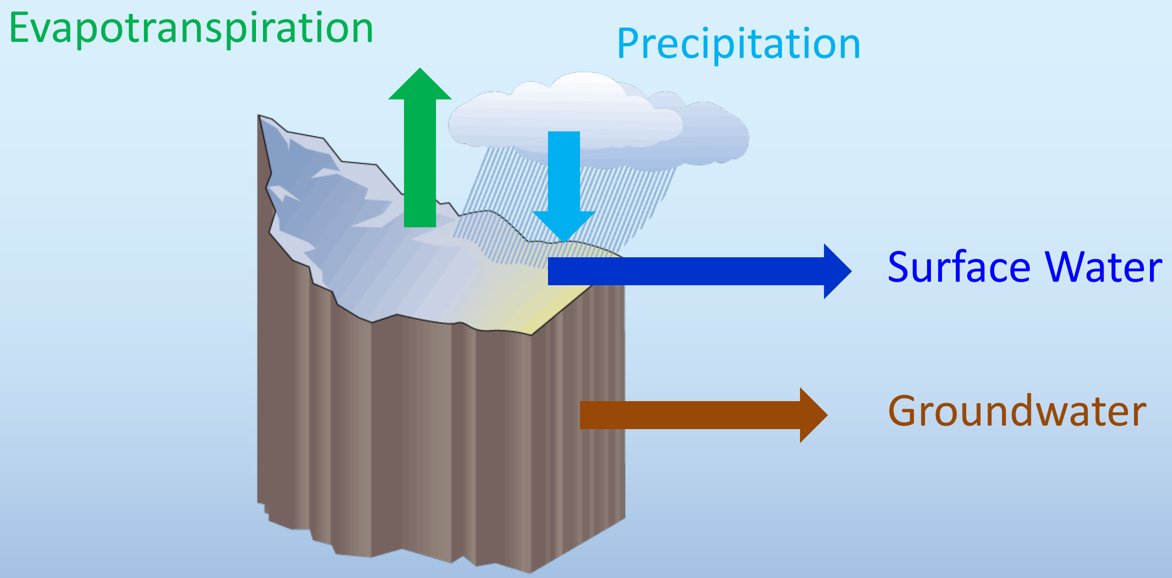
Surface Water Process



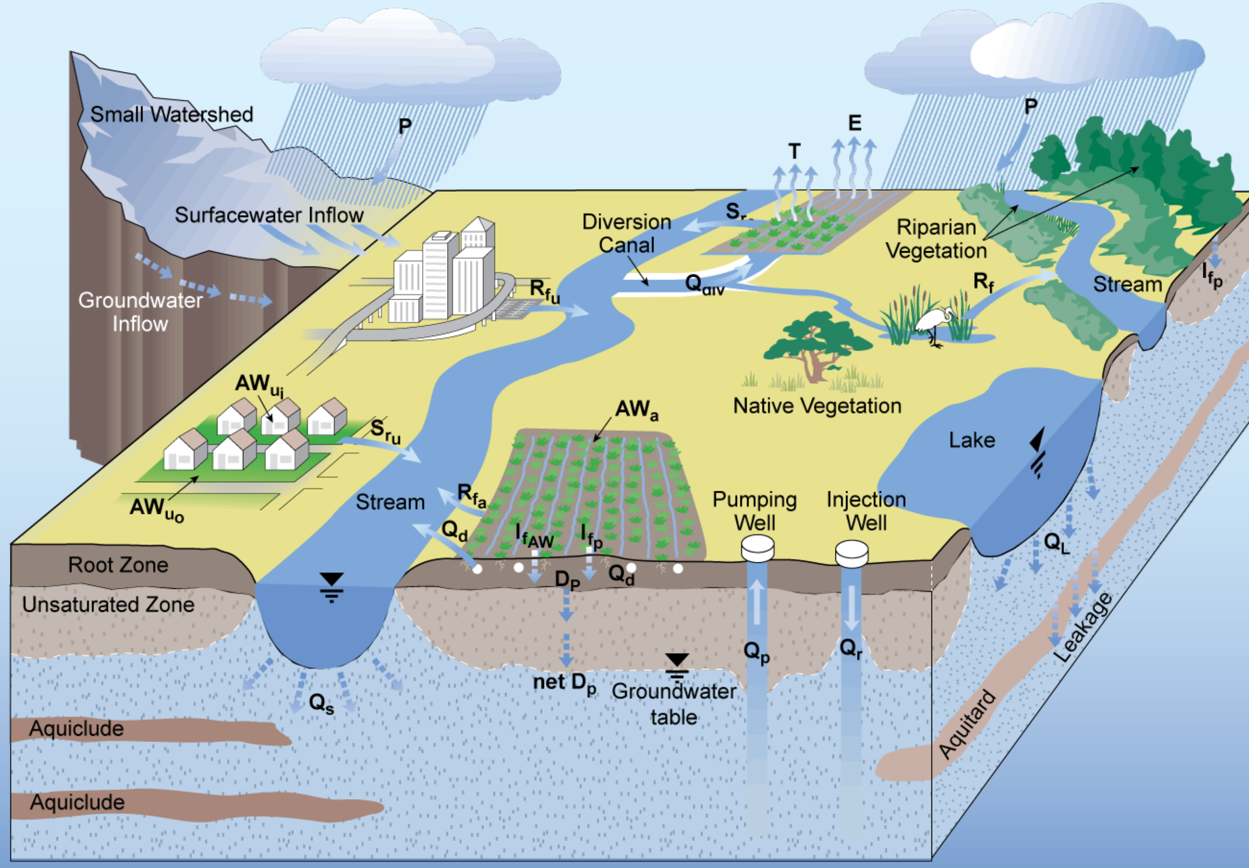
Groundwater Process



IWFM Small Watersheds

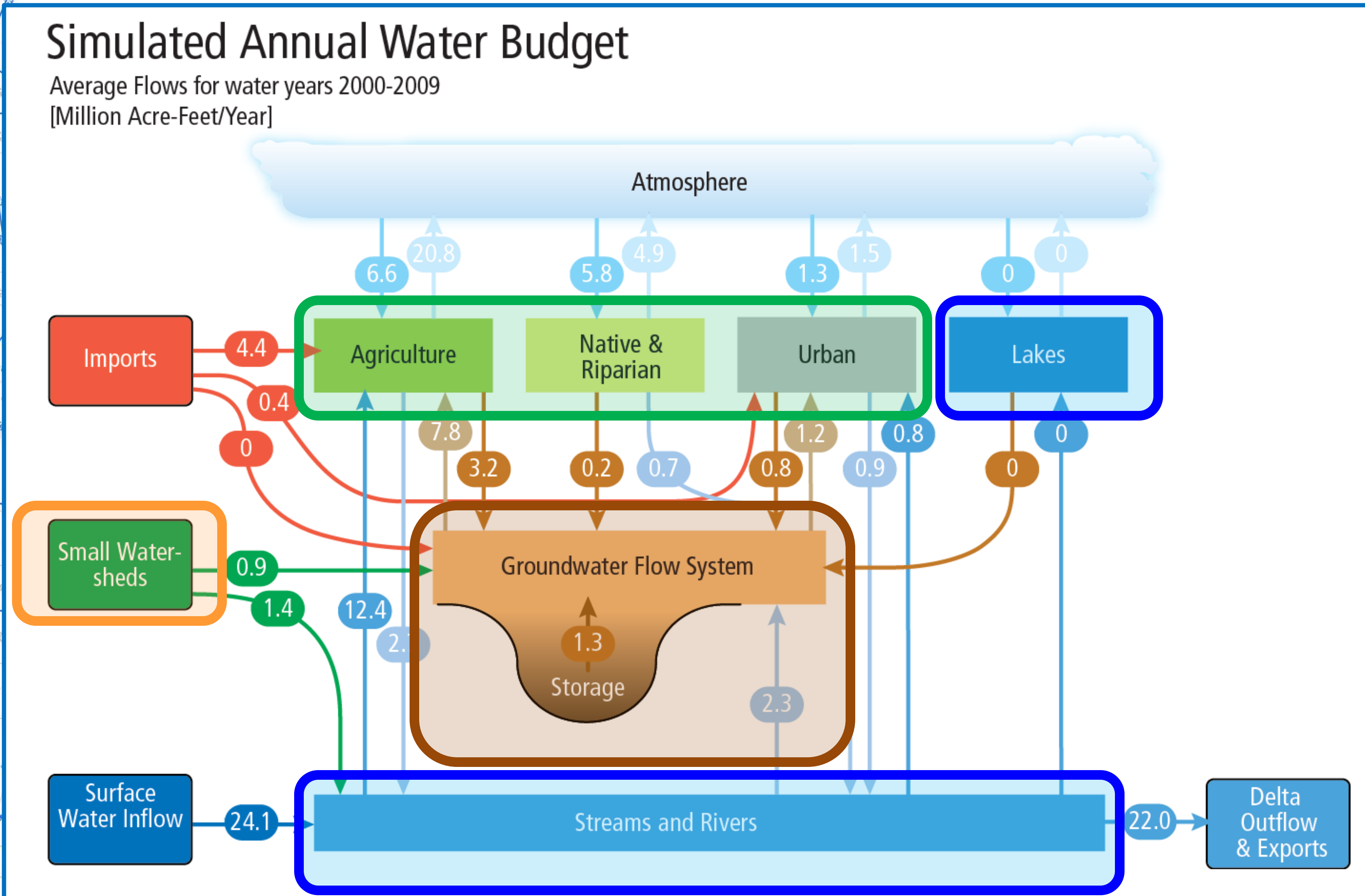


IWFM

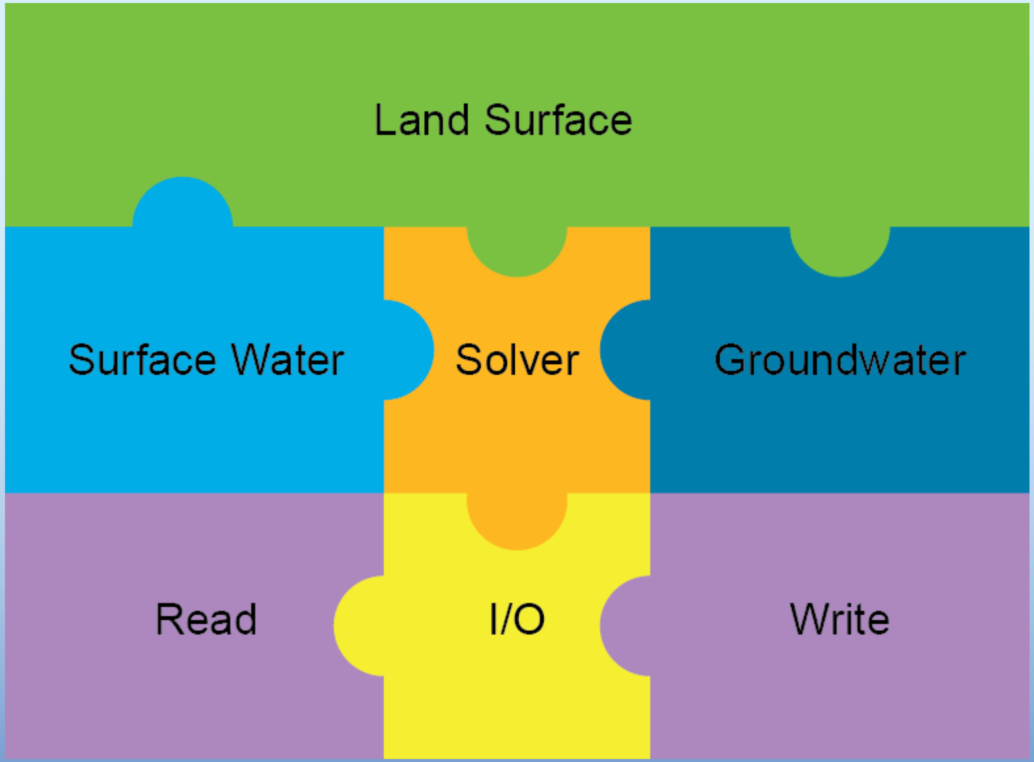


Small Watershed
P
Surfacewater Inflow
Groundwater Inflow
Diversion Canal
S_r
T
E
P
Riparian Vegetation
R_{f_u}
Q_{div}
R_f
Stream
I_{fp}
AW_{u_i}
S_{r_u}
AW_a
Native Vegetation
Lake
AW_{u_o}
Stream
R_{f_a}
Q_d
I_{fAW}
I_{fp}
Pumping Well
Injection Well
Q_L
Root Zone
D_p
Q_d
Unsaturated Zone
Q_p
Q_r
Leakage
net D_p
Groundwater table
Q_s
Aquiclude
Aquitard
Aquiclude

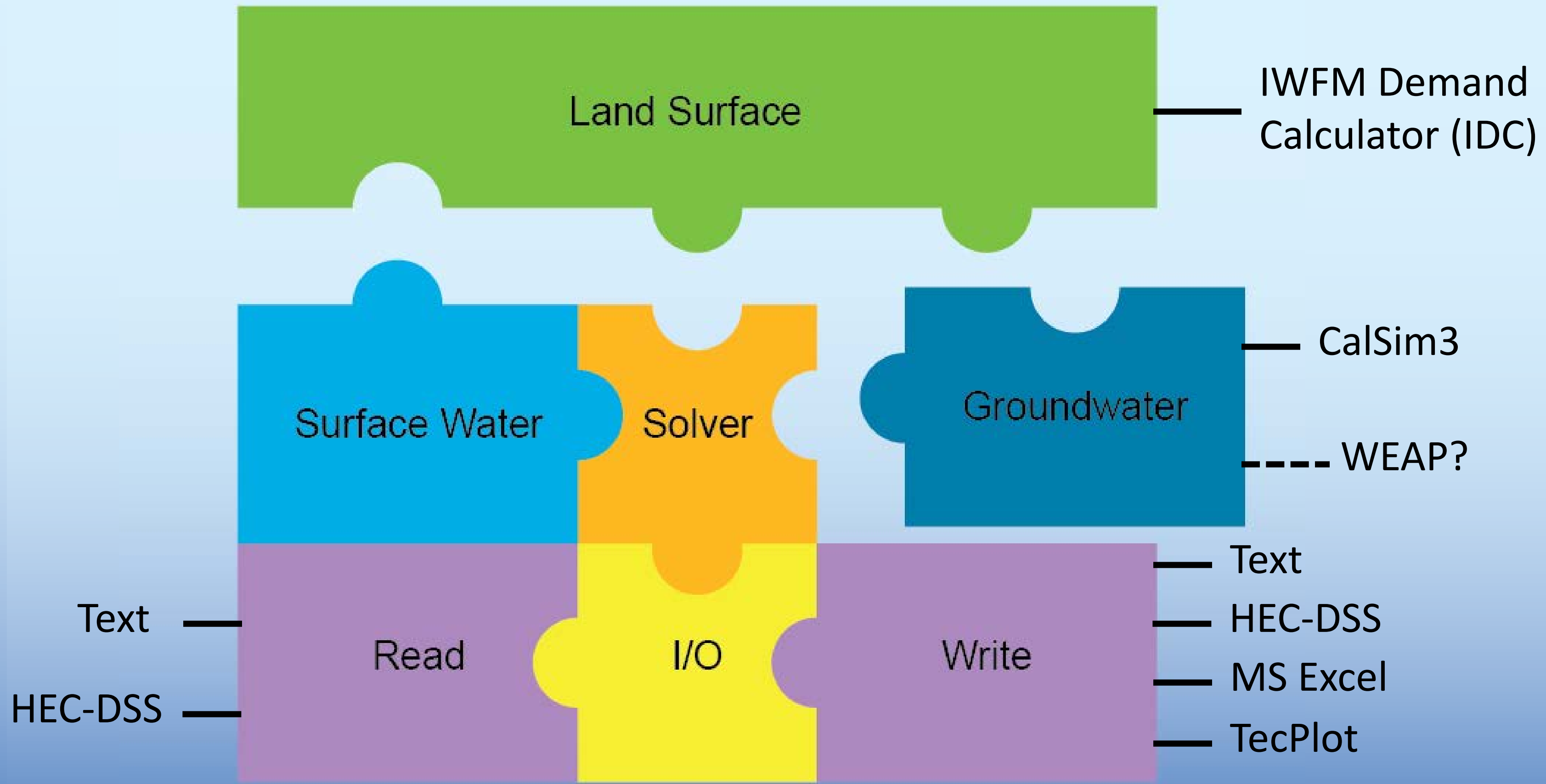
IWFM Water Balance Diagram



Object-Oriented Design

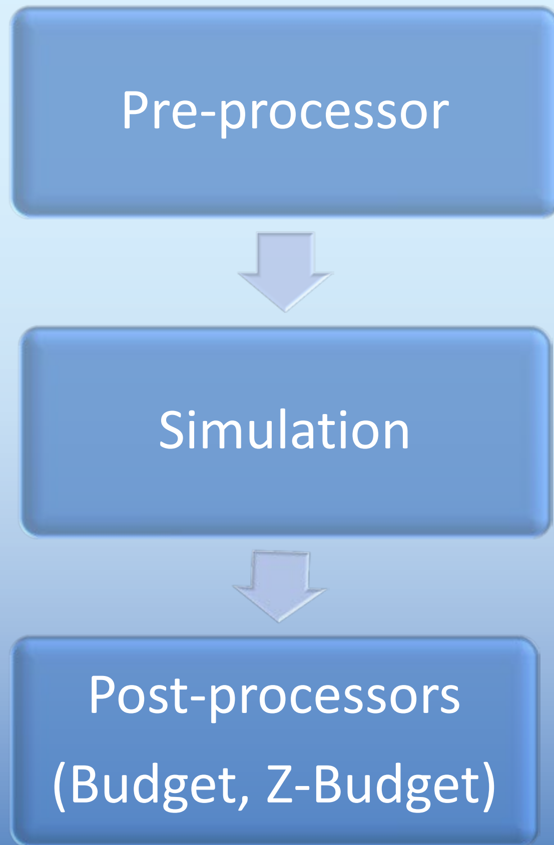


Link with Other Models



IWFM Application

IWFM consists four programs executed in sequence



IWFM Pre-Processor

Pre-processor

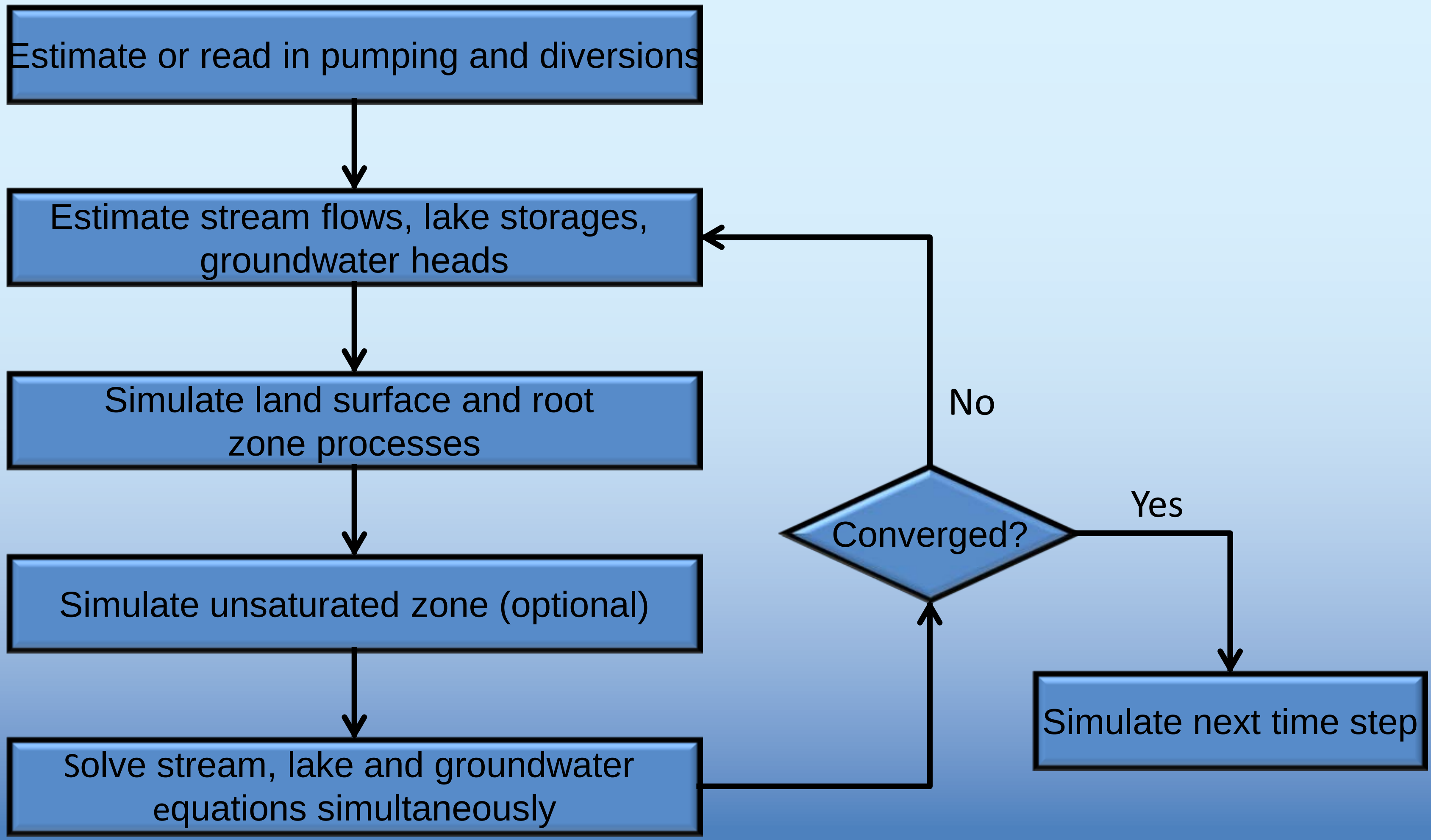
- Read nodal coordinates
- Link nodes to form elements
- Compile vertical aquifer stratigraphy at each node
- Link selected nodes to form river reaches
- Link river reaches into a flow network
- Compile profiles for river nodes
- Apply soil properties to elements
- Apply drainage patterns to elements
- Assign elements to subregions
- Link precipitation data to elements
- Compile specified pumping wells

IWFM Simulation

Simulation

- Read binary file produced by Preprocessor
- Calculate a balanced water budget for each model component for each time step
  - Precipitation, river inflow, diversions
  - Land use, crop acreage * ET, urban demands
  - Runoff and return flow
  - Deep percolation
  - Stream-groundwater flows
  - Calculate groundwater pumping
- Write out results for each time step to a series of files:
  - Budget and Z-Budget results to binary files
  - Groundwater and surface water hydrographs to text files
  - TecPlot movie data to text files

Simulation Scheme



IWFM Post-Processors

Post-processors
(Budget, Z-Budget)

- Read binary files produced by Simulation
- Budget tabulates a set of water budgets:
  - Land and Water Use
  - Root Zone
  - Groundwater
  - Stream Reaches
  - Small-Stream Watersheds
- Z-Budget compiles water budgets for user-specified aquifer zones of one to many elements. Example zones:
  - Subregions
  - Hydrologic Regions
  - Groundwater Basins

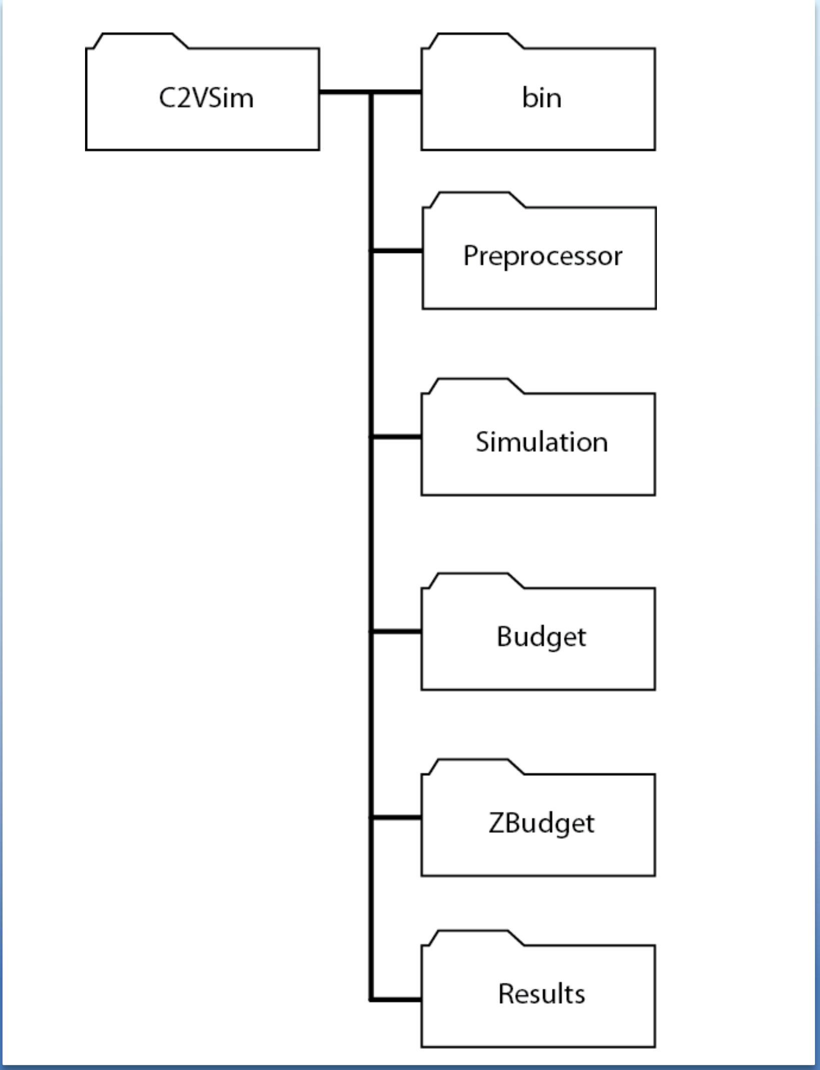
Input and Output Files

- Input files contain comment fields
- Tab-delimited for easy cut-and-paste with Excel
- Time-tracking simulations are aware of the date and time; input and output time-series data have a date and time stamp

```
C*******************************************************************************
C                         Rainfall Data Specifications
C
C   NRAIN ;  Number of rainfall stations (or pathnames if DSS files are used)
C             used in the model
C   FACTRN;  Conversion factor for rainfall rate
C             It is used to convert only the spatial component of the unit;
C             DO NOT include the conversion factor for time component of the unit.
C             * e.g. Unit of rainfall rate listed in this file = INCHES/MONTH
C                    Consistent unit used in simulation        = FEET/DAY
C                    Enter FACTRN (INCHES/MONTH -> FEET/MONTH) = 8.33333E-02
C                     (conversion of MONTH -> DAY is performed automatically)
C   NSPRN ;  Number of time steps to update the precipitation data
C             * Enter any number if time-tracking option is on
C   NFQRN ;  Repetition frequency of the precipitation data
C             * Enter 0 if full time series data is supplied
C             * Enter any number if time-tracking option is on
C   DSSFL ;  The name of the DSS file for data input (maximum 50 characters);
C             * Leave blank if DSS file is not used for data input
C
C-------------------------------------------------------------------------------
C         VALUE                                      DESCRIPTION
C-------------------------------------------------------------------------------
           1602                                      / NRAIN
           0.08333                                   / FACTRN  (in/month -> ft/month)
           1                                         / NSPRN
           0                                         / NFQRN
                                                     / DSSFL
C-------------------------------------------------------------------------------
C                             Rainfall Data
C                         (READ FROM THIS FILE)
C
C   List the rainfall rates for each of the rainfall station below, if it will
C   not be read from a DSS file (i.e. DSSFL is left blank above).
C
C   ITRN ;   Time
C   ARAIN;   Rainfall rate at the corresponding rainfall station; [L/T]
C
C-------------------------------------------------------------------------------
C ITRN    ARAIN(1)  ARAIN(2)  ARAIN(3) ...
C-------------------------------------------------------------------------------
```

Time	1	2	3	4	5	6	7	8
10/31/1921_24:00	1.34	1.34	1.32	1.27	1.34	1.31	1.30	1.34
11/30/1921_24:00	3.64	3.62	3.59	3.49	3.62	3.51	3.56	3.62
12/31/1921_24:00	8.15	8.14	7.86	7.49	8.08	7.43	8.01	7.97
01/31/1922_24:00	1.32	1.46	1.62	1.80	1.22	1.40	1.27	1.11
02/28/1922_24:00	7.61	7.95	7.98	8.02	7.25	7.23	7.09	6.63
03/31/1922_24:00	4.33	4.39	4.31	4.28	4.22	4.03	4.09	4.06
04/30/1922_24:00	0.94	0.91	0.92	0.91	0.94	0.93	0.93	0.94
05/31/1922_24:00	2.20	2.18	2.18	2.09	2.22	2.19	2.18	2.26
06/30/1922_24:00	0.71	0.72	0.67	0.62	0.76	0.58	0.74	0.82
07/31/1922_24:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
08/31/1922_24:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
09/30/1922_24:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10/31/1922_24:00	3.44	3.45	3.39	3.23	3.42	3.28	3.39	3.40
11/30/1922_24:00	3.54	3.64	3.74	3.79	3.47	3.51	3.41	3.22
12/31/1922_24:00	8.44	8.84	8.63	8.94	8.22	8.27	8.01	7.75
01/31/1923_24:00	4.06	4.09	4.02	3.90	4.05	3.95	3.99	4.01
02/28/1923_24:00	1.14	1.14	1.14	1.22	1.11	1.11	1.12	1.08

Suggested File Hierarchy



Detailed Budget Tables

IWFM (v3.02.0036)
GROUND WATER BUDGET IN AC.FT. FOR SUBREGION 1 (DSA 58)
AREA: 328277.68 AC

Time	Deep Percolation	Beginning Storage (+)	Ending Storage (-)	Net Deep Percolation (+)	Gain from Stream (+)	Recharge (+)	Gain from Lake (+)	Boundary Inflow (+)	Subsidence (+)	Subsurface Irrigation (+)
10/31/1921_24:00	0.0	41093269.2	40825799.7	80152.5	-364317.1	867.7	0.0	5580.5	69.3	0.0
11/30/1921_24:00	0.0	40825799.7	40787589.3	46959.9	-102230.7	68.4	0.0	5526.1	41.7	0.0
12/31/1921_24:00	1774.9	40787589.3	40781748.8	32677.5	-55414.6	1.5	0.0	6173.2	27.5	0.0
01/31/1922_24:00	187.2	40781748.8	40770213.1	24643.6	-52693.1	1.4	0.0	6281.5	19.9	0.0
02/28/1922_24:00	969.5	40770213.1	40770676.2	19687.5	-37994.6	1.2	0.0	8451.2	10.2	0.0
03/31/1922_24:00	34.8	40770676.2	40763511.0	16261.0	-41925.0	1.4	0.0	8745.3	9.1	0.0
04/30/1922_24:00	2196.2	40763511.0	40755221.4	13895.3	-39956.6	837.8	0.0	8377.2	7.3	0.0
05/31/1922_24:00	8993.9	40755221.4	40740684.9	12612.7	-46117.7	1645.9	0.0	8295.0	6.2	0.0
06/30/1922_24:00	10397.7	40740684.9	40716832.4	12115.7	-55090.5	2113.2	0.0	8213.7	8.5	0.0
07/31/1922_24:00	12958.4	40716832.4	40696603.9	12348.8	-51668.9	2579.8	0.0	8013.1	6.3	0.0
08/31/1922_24:00	14326.9	40696603.9	40680795.6	12962.9	-47632.8	2563.0	0.0	7933.4	5.0	0.0
09/30/1922_24:00	9271.8	40680795.6	40665417.5	12704.3	-45693.6	1776.9	0.0	7854.4	4.9	0.0
10/31/1922_24:00	5154.1	40665417.5	40650780.5	11835.0	-43101.2	829.1	0.0	7896.2	10.5	0.0
11/30/1922_24:00	478.3	40650780.5	40636197.5	10724.0	-40814.8	1.3	0.0	7819.7	14.7	0.0
12/31/1922_24:00	1856.0	40636197.5	40631348.0	9674.8	-31697.4	1.5	0.0	9430.8	10.7	0.0
01/31/1923_24:00	1198.6	40631348.0	40621470.3	8846.1	-36887.5	1.4	0.0	10470.0	11.3	0.0
02/28/1923_24:00	0.0	40621470.3	40604148.5	8079.5	-43167.9	1.2	0.0	10158.4	12.0	0.0
03/31/1923_24:00	0.0	40604148.5	40588048.2	7412.7	-40767.2	44.8	0.0	10058.5	11.6	0.0
04/30/1923_24:00	1834.1	40588048.2	40580201.5	6917.9	-32751.9	700.1	0.0	10333.0	9.2	0.0
05/31/1923_24:00	8555.3	40580201.5	40556339.0	6935.8	-49348.2	1703.0	0.0	9949.2	13.9	0.0
06/30/1923_24:00	10818.1	40556339.0	40534626.4	7422.6	-47830.2	2070.6	0.0	9851.4	13.8	0.0
07/31/1923_24:00	12950.8	40534626.4	40515163.6	8459.6	-46713.9	2579.4	0.0	9634.6	12.5	0.0
08/31/1923_24:00	14467.1	40515163.6	40499071.0	9894.0	-44624.1	2559.9	0.0	9538.8	14.2	0.0
09/30/1923_24:00	10163.2	40499071.0	40484602.6	10552.6	-42589.2	1666.5	0.0	9563.9	19.0	0.0
10/31/1923_24:00	0.0	40484602.6	40468059.3	9538.2	-41652.2	64.4	0.0	9469.9	19.6	0.0
11/30/1923_24:00	0.0	40468059.3	40450811.5	8501.7	-40492.9	53.9	0.0	9376.9	19.8	0.0
12/31/1923_24:00	0.0	40450811.5	40436600.4	7669.7	-37125.4	1.5	0.0	9284.8	17.8	0.0
01/31/1924_24:00	603.7	40436600.4	40422598.1	6936.0	-36112.1	1.4	0.0	9264.8	16.8	0.0
02/29/1924_24:00	421.4	40422598.1	40411736.8	6346.5	-33109.2	1.2	0.0	9932.6	15.6	0.0
03/31/1924_24:00	0.0	40411736.8	40392170.2	5843.6	-40672.7	18.9	0.0	9636.3	18.3	0.0
04/30/1924_24:00	4172.5	40392170.2	40372684.1	5580.2	-39141.0	1115.8	0.0	9460.1	19.8	0.0
05/31/1924_24:00	5908.3	40372684.1	40355592.5	5555.1	-38876.5	1469.5	0.0	9324.2	16.9	0.0
06/30/1924_24:00	7155.9	40355592.5	40338481.8	5723.5	-39233.5	1811.4	0.0	9231.4	17.1	0.0
07/31/1924_24:00	8853.1	40338481.8	40322659.5	6144.1	-38418.7	2109.8	0.0	9139.6	16.6	0.0
08/31/1924_24:00	9954.3	40322659.5	40308146.4	6804.5	-37605.7	2030.9	0.0	9053.6	16.0	0.0
09/30/1924_24:00	10544.7	40308146.4	40294384.2	7623.4	-37206.8	1921.5	0.0	8958.7	15.6	0.0
10/31/1924_24:00	5726.2	40294384.2	40286744.8	7853.9	-30520.4	829.1	0.0	9234.7	13.0	0.0
11/30/1924_24:00	811.0	40286744.8	40280979.5	7421.2	-27505.9	1.4	0.0	9341.1	11.6	0.0
12/31/1924_24:00	1522.4	40280979.5	40277307.1	6906.2	-26190.0	1.6	0.0	10544.1	10.0	0.0
01/31/1925_24:00	875.5	40277307.1	40272288.2	6382.9	-27490.1	1.4	0.0	11054.7	9.9	0.0
02/28/1925_24:00	1493.3	40272288.2	40296453.2	5939.7	-1284.8	1.2	0.0	13899.1	0.3	0.0
03/31/1925_24:00	33.9	40296453.2	40276792.9	5487.1	-44426.3	1.4	0.0	14054.1	13.3	0.0
04/30/1925_24:00	1228.9	40276792.9	40272302.1	5129.9	-26339.4	174.3	0.0	14141.7	11.2	0.0
05/31/1925_24:00	7670.2	40272302.1	40256625.0	5139.2	-41007.7	1434.7	0.0	13782.1	11.8	0.0
06/30/1925_24:00	10936.7	40256625.0	40238249.9	5803.6	-44772.6	2097.3	0.0	13575.9	14.2	0.0
07/31/1925_24:00	13349.6	40238249.9	40223940.3	6609.8	-41601.2	2567.0	0.0	13322.1	13.4	0.0
08/31/1925_24:00	14753.1	40223940.3	40214408.3	8070.7	-38148.7	2548.5	0.0	13189.6	11.9	0.0
09/30/1925_24:00	14694.2	40214408.3	40207991.2	9669.7	-36047.1	2225.4	0.0	13178.5	10.8	0.0
10/31/1925_24:00	962.5	40207991.2	40200886.0	9171.5	-34263.7	523.0	0.0	12954.8	10.5	0.0
11/30/1925_24:00	498.5	40200886.0	40195273.0	8218.6	-31269.7	14.1	0.0	12920.1	9.5	0.0
12/31/1925_24:00	757.6	40195273.0	40192688.0	7332.0	-27186.4	1.6	0.0	12797.0	7.9	0.0
01/31/1926_24:00	1661.6	40192688.0	40192766.0	6636.1	-25291.9	1.4	0.0	14167.1	6.5	0.0
02/28/1926_24:00	1101.5	40192766.0	40207715.7	6055.1	-12240.3	1.2	0.0	16132.0	1.5	0.0

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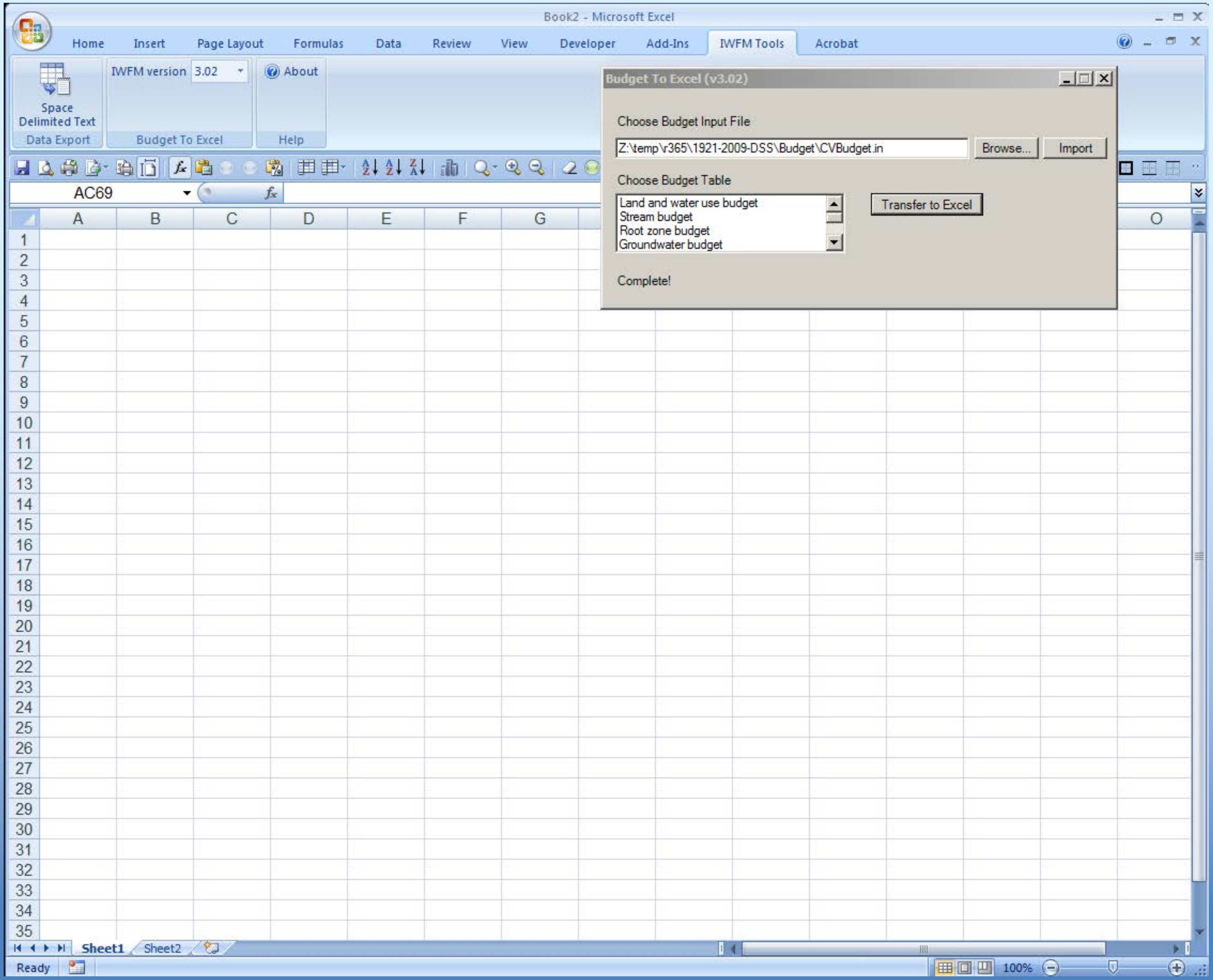

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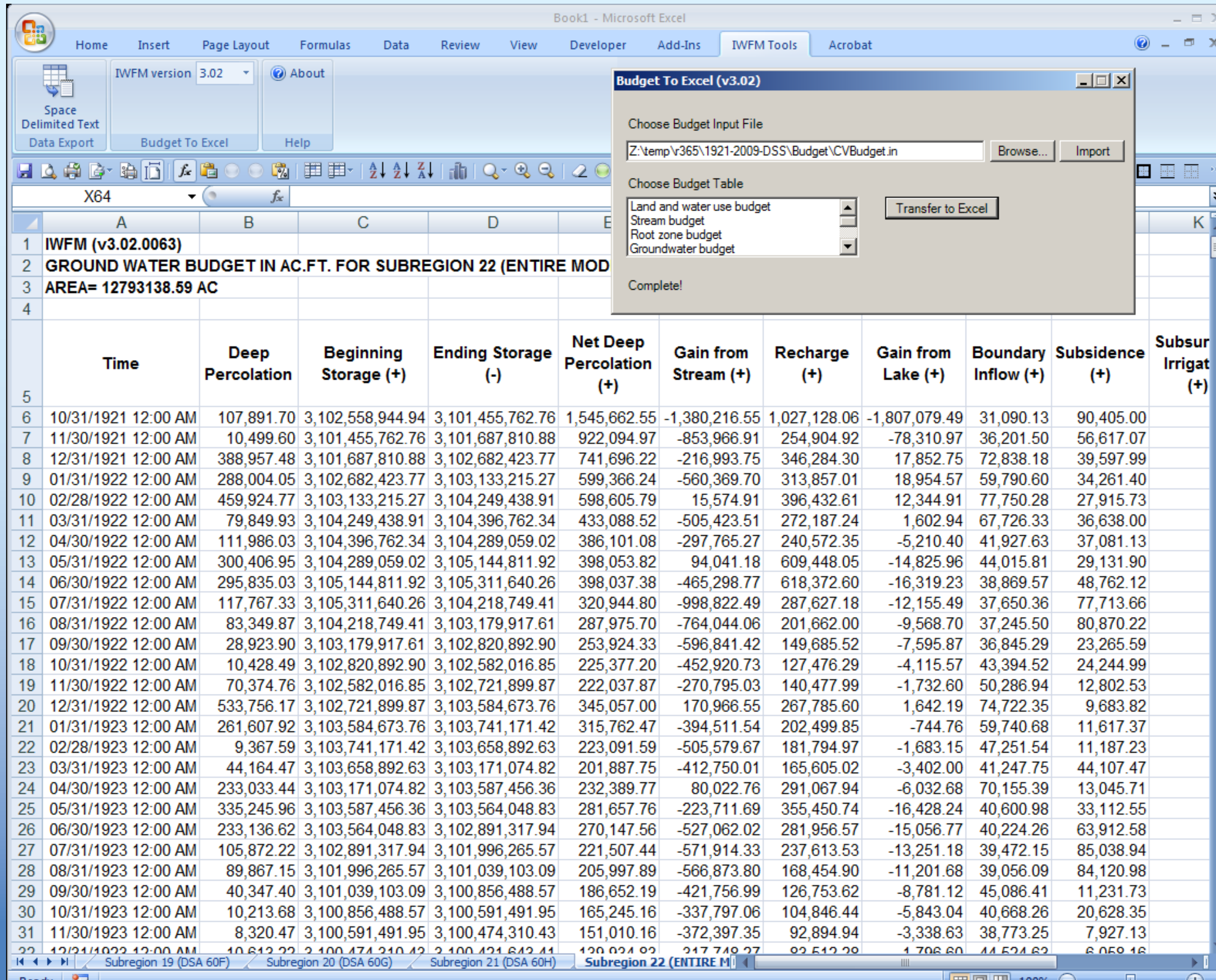


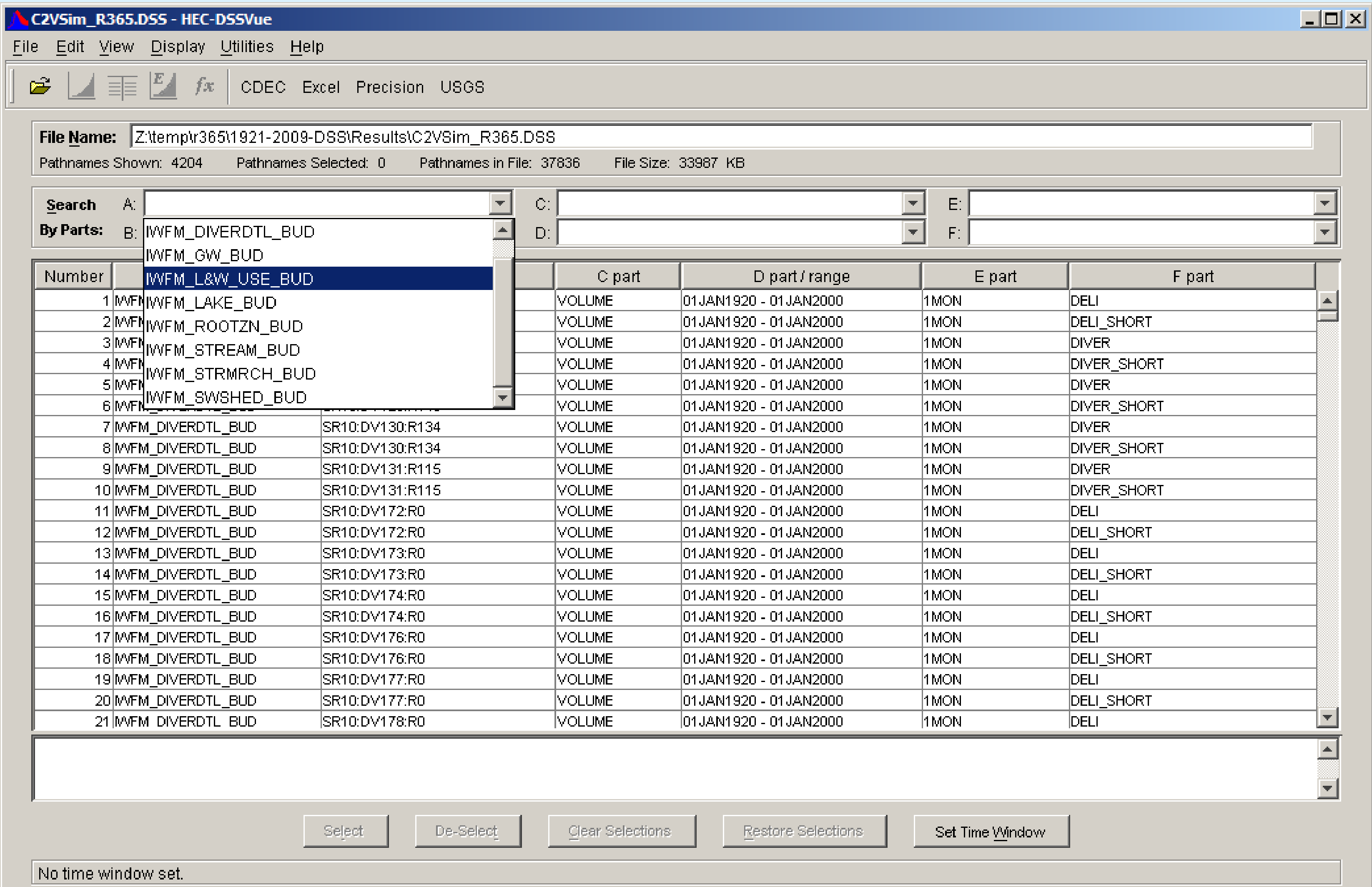
IWFM (v3.02.0063)

GROUND WATER BUDGET IN AC.FT. FOR SUBREGION 22 (ENTIRE MOD

AREA= 12793138.59 AC

Time	Deep Percolation	Beginning Storage (+)	Ending Storage (-)	Net Deep Percolation (+)	Gain from Stream (+)	Recharge (+)	Gain from Lake (+)	Boundary Inflow (+)	Subsidence (+)	Subsur Irrigat (+)
10/31/1921 12:00 AM	107,891.70	3,102,558,944.94	3,101,455,762.76	1,545,662.55	-1,380,216.55	1,027,128.06	-1,807,079.49	31,090.13	90,405.00	
11/30/1921 12:00 AM	10,499.60	3,101,455,762.76	3,101,687,810.88	922,094.97	-853,966.91	254,904.92	-78,310.97	36,201.50	56,617.07	
12/31/1921 12:00 AM	388,957.48	3,101,687,810.88	3,102,682,423.77	741,696.22	-216,993.75	346,284.30	17,852.75	72,838.18	39,597.99	
01/31/1922 12:00 AM	288,004.05	3,102,682,423.77	3,103,133,215.27	599,366.24	-560,369.70	313,857.01	18,954.57	59,790.60	34,261.40	
02/28/1922 12:00 AM	459,924.77	3,103,133,215.27	3,104,249,438.91	598,605.79	15,574.91	396,432.61	12,344.91	77,750.28	27,915.73	
03/31/1922 12:00 AM	79,849.93	3,104,249,438.91	3,104,396,762.34	433,088.52	-505,423.51	272,187.24	1,602.94	67,726.33	36,638.00	
04/30/1922 12:00 AM	111,986.03	3,104,396,762.34	3,104,289,059.02	386,101.08	-297,765.27	240,572.35	-5,210.40	41,927.63	37,081.13	
05/31/1922 12:00 AM	300,406.95	3,104,289,059.02	3,105,144,811.92	398,053.82	94,041.18	609,448.05	-14,825.96	44,015.81	29,131.90	
06/30/1922 12:00 AM	295,835.03	3,105,144,811.92	3,105,311,640.26	398,037.38	-465,298.77	618,372.60	-16,319.23	38,869.57	48,762.12	
07/31/1922 12:00 AM	117,767.33	3,105,311,640.26	3,104,218,749.41	320,944.80	-998,822.49	287,627.18	-12,155.49	37,650.36	77,713.66	
08/31/1922 12:00 AM	83,349.87	3,104,218,749.41	3,103,179,917.61	287,975.70	-764,044.06	201,662.00	-9,568.70	37,245.50	80,870.22	
09/30/1922 12:00 AM	28,923.90	3,103,179,917.61	3,102,820,892.90	253,924.33	-596,841.42	149,685.52	-7,595.87	36,845.29	23,265.59	
10/31/1922 12:00 AM	10,428.49	3,102,820,892.90	3,102,582,016.85	225,377.20	-452,920.73	127,476.29	-4,115.57	43,394.52	24,244.99	
11/30/1922 12:00 AM	70,374.76	3,102,582,016.85	3,102,721,899.87	222,037.87	-270,795.03	140,477.99	-1,732.60	50,286.94	12,802.53	
12/31/1922 12:00 AM	533,756.17	3,102,721,899.87	3,103,584,673.76	345,057.00	170,966.55	267,785.60	1,642.19	74,722.35	9,683.82	
01/31/1923 12:00 AM	261,607.92	3,103,584,673.76	3,103,741,171.42	315,762.47	-394,511.54	202,499.85	-744.76	59,740.68	11,617.37	
02/28/1923 12:00 AM	9,367.59	3,103,741,171.42	3,103,658,892.63	223,091.59	-505,579.67	181,794.97	-1,683.15	47,251.54	11,187.23	
03/31/1923 12:00 AM	44,164.47	3,103,658,892.63	3,103,171,074.82	201,887.75	-412,750.01	165,605.02	-3,402.00	41,247.75	44,107.47	
04/30/1923 12:00 AM	233,033.44	3,103,171,074.82	3,103,587,456.36	232,389.77	80,022.76	291,067.94	-6,032.68	70,155.39	13,045.71	
05/31/1923 12:00 AM	335,245.96	3,103,587,456.36	3,103,564,048.83	281,657.76	-223,711.69	355,450.74	-16,428.24	40,600.98	33,112.55	
06/30/1923 12:00 AM	233,136.62	3,103,564,048.83	3,102,891,317.94	270,147.56	-527,062.02	281,956.57	-15,056.77	40,224.26	63,912.58	
07/31/1923 12:00 AM	105,872.22	3,102,891,317.94	3,101,996,265.57	221,507.44	-571,914.33	237,613.53	-13,251.18	39,472.15	85,038.94	
08/31/1923 12:00 AM	89,867.15	3,101,996,265.57	3,101,039,103.09	205,997.89	-566,873.80	168,454.90	-11,201.68	39,056.09	84,120.98	
09/30/1923 12:00 AM	40,347.40	3,101,039,103.09	3,100,856,488.57	186,652.19	-421,756.99	126,753.62	-8,781.12	45,086.41	11,231.73	
10/31/1923 12:00 AM	10,213.68	3,100,856,488.57	3,100,591,491.95	165,245.16	-337,797.06	104,846.44	-5,843.04	40,668.26	20,628.35	
11/30/1923 12:00 AM	8,320.47	3,100,591,491.95	3,100,474,310.43	151,010.16	-372,397.35	92,894.94	-3,338.63	38,773.25	7,927.13	

HEC-DSS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IWFM_GW_BUD
IWFM_L&W_USE_BUD
IWFM_LAKE_BUD
IWFM_ROOTZN_BUD
IWFM_STREAM_BUD
IWFM_STRMRCH_BUD
IWFM_SWSHED_BUD
Number | C part | D part / range | E part | F part
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2 IWFM | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI_SHORT
3 IWFM | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DIVER
4 IWFM | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DIVER_SHORT
5 IWFM | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DIVER
6 IWFM | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DIVER_SHORT
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8 IWFM_DIVERDTL_BUD | SR10:DV130:R134 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DIVER_SHORT
9 IWFM_DIVERDTL_BUD | SR10:DV131:R115 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DIVER
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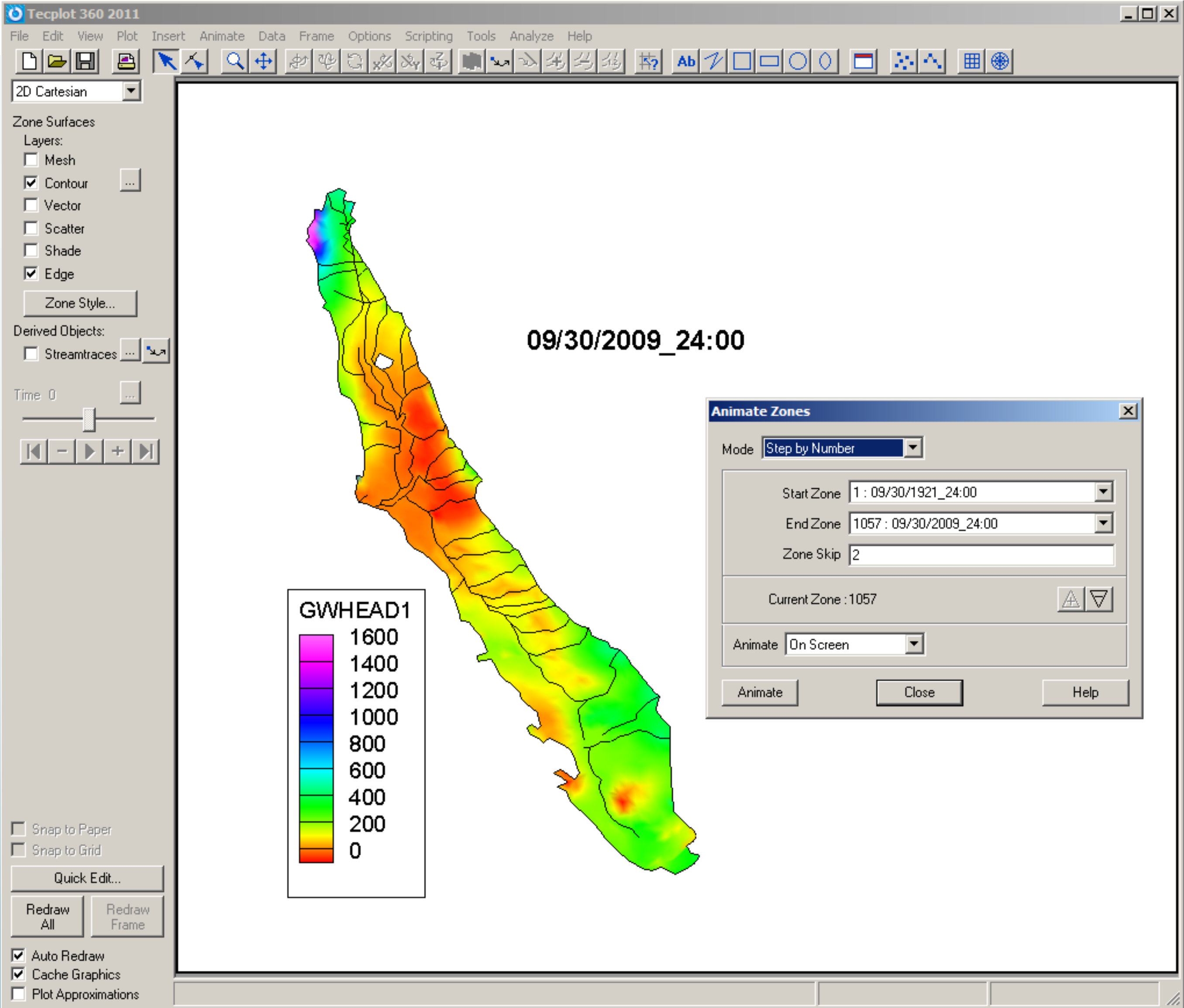
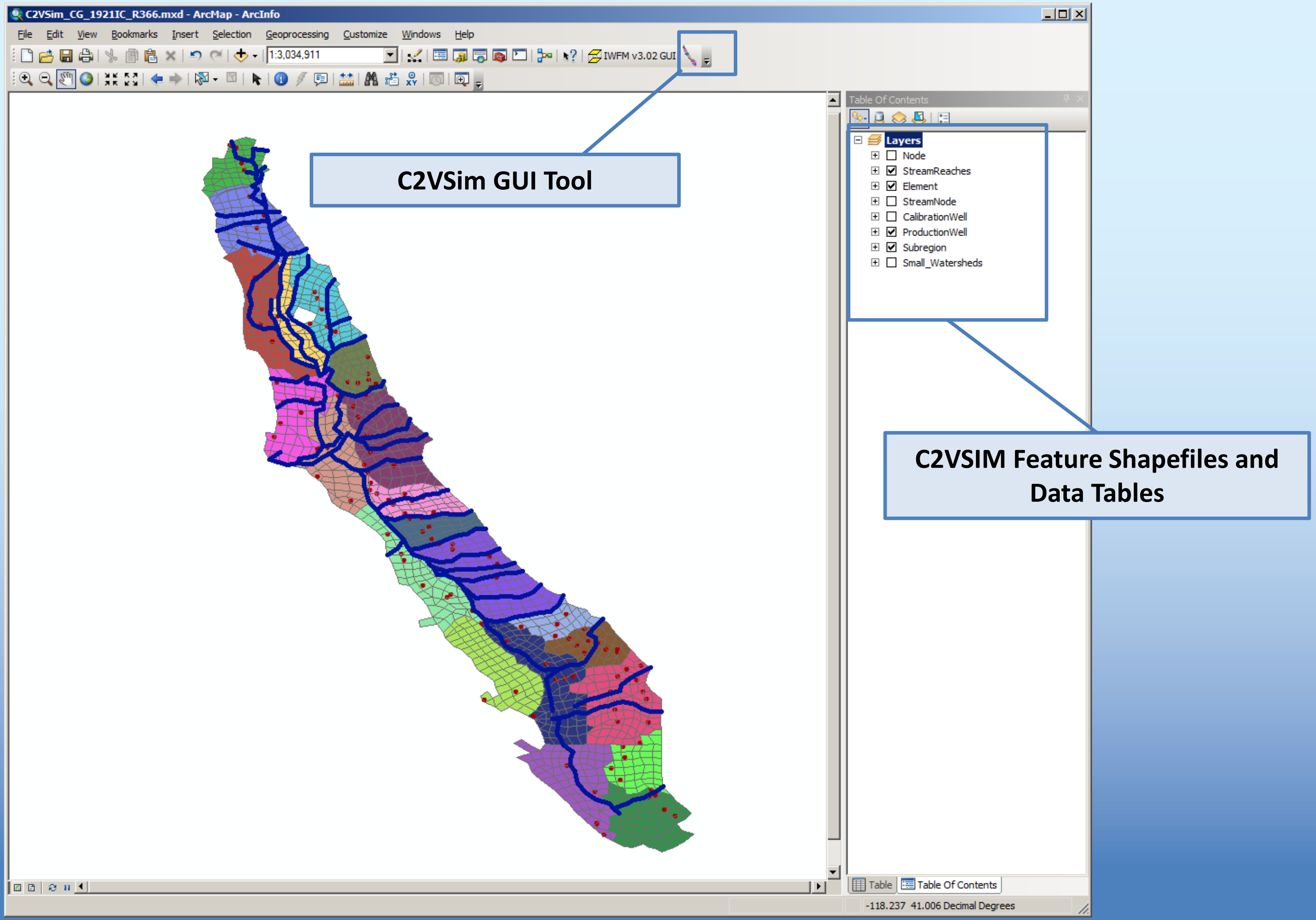
11 IWFM_DIVERDTL_BUD | SR10:DV172:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI
12 IWFM_DIVERDTL_BUD | SR10:DV172:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI_SHORT
13 IWFM_DIVERDTL_BUD | SR10:DV173:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI
14 IWFM_DIVERDTL_BUD | SR10:DV173:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI_SHORT
15 IWFM_DIVERDTL_BUD | SR10:DV174:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI
16 IWFM_DIVERDTL_BUD | SR10:DV174:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI_SHORT
17 IWFM_DIVERDTL_BUD | SR10:DV176:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI
18 IWFM_DIVERDTL_BUD | SR10:DV176:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI_SHORT
19 IWFM_DIVERDTL_BUD | SR10:DV177:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI
20 IWFM_DIVERDTL_BUD | SR10:DV177:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI_SHORT
21 IWFM_DIVERDTL_BUD | SR10:DV178:R0 | VOLUME | 01JAN1920 - 01JAN2000 | 1MON | DELI
Select De-Select Clear Selections Restore Selections Set Time Window
No time window set.

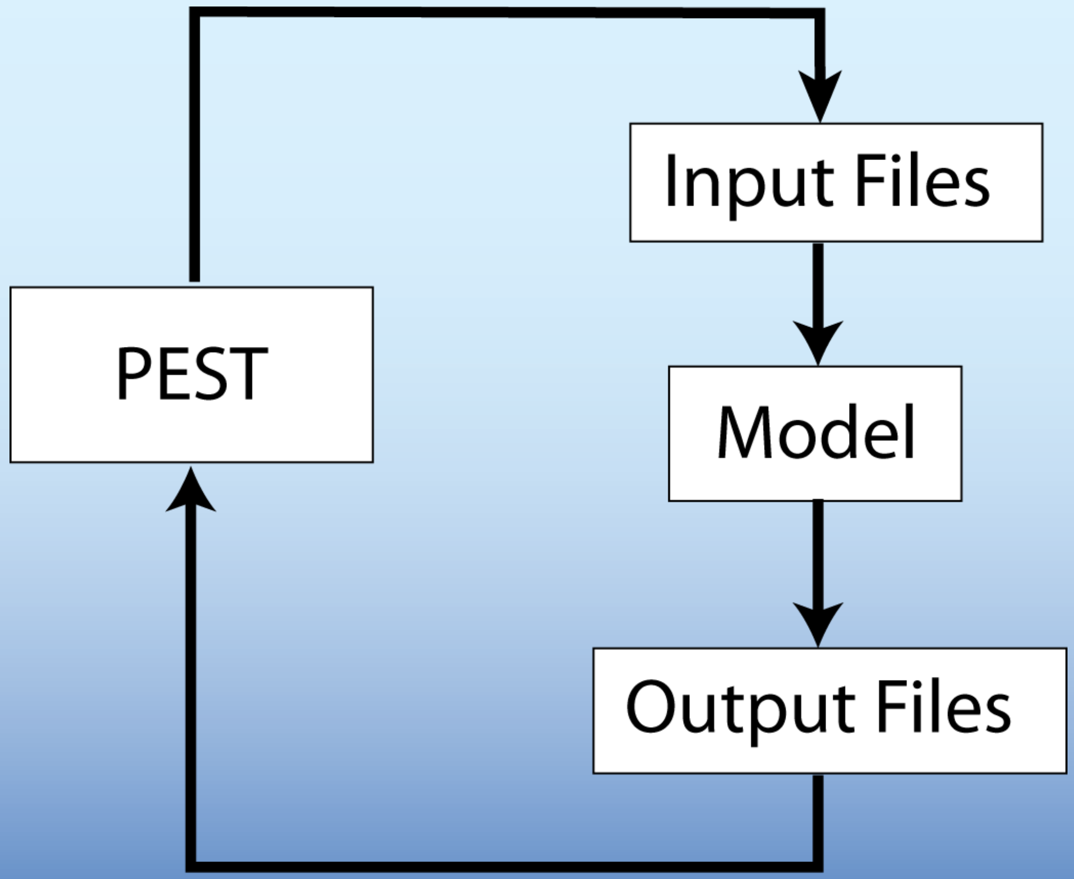
TecPlot-Ready Output



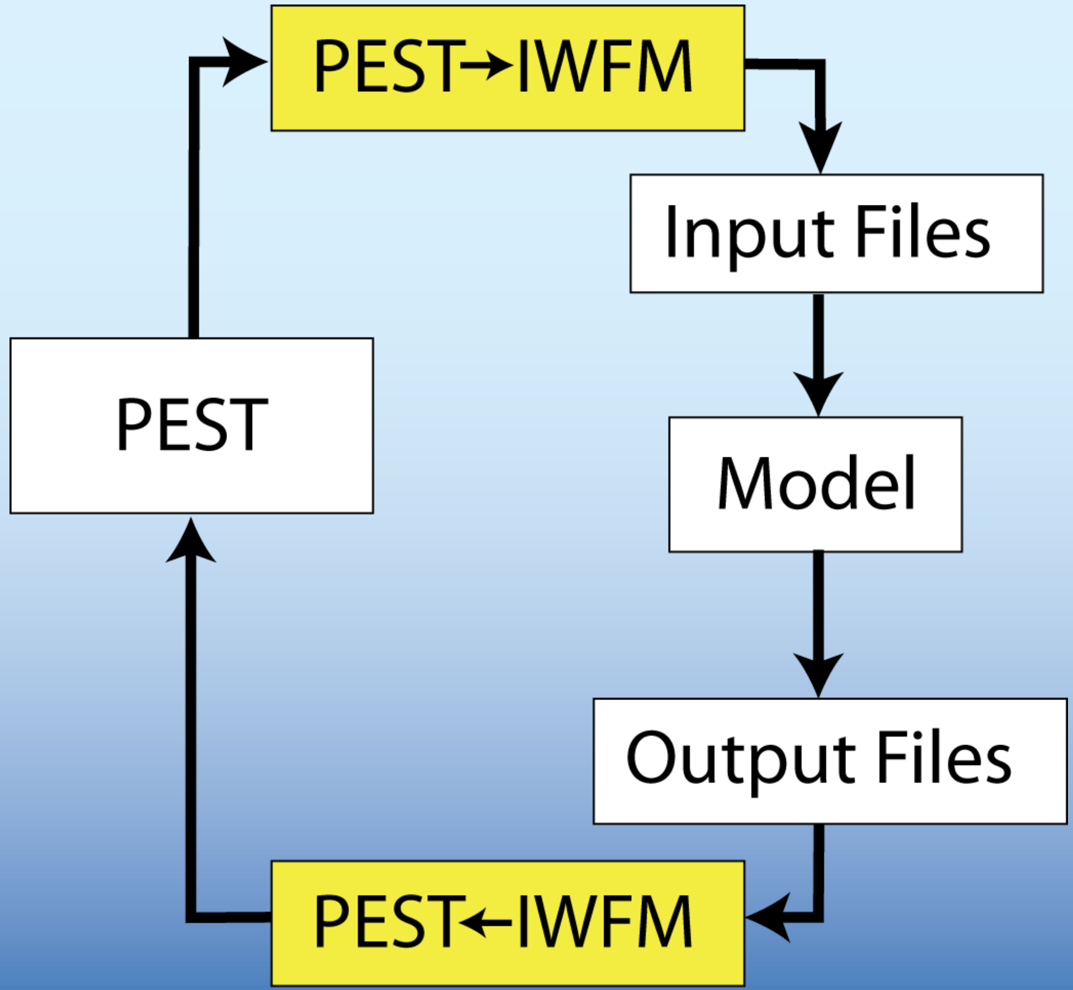
C2VSim ArcGIS Tool



Calibration Tools



PEST-IWFM Tools

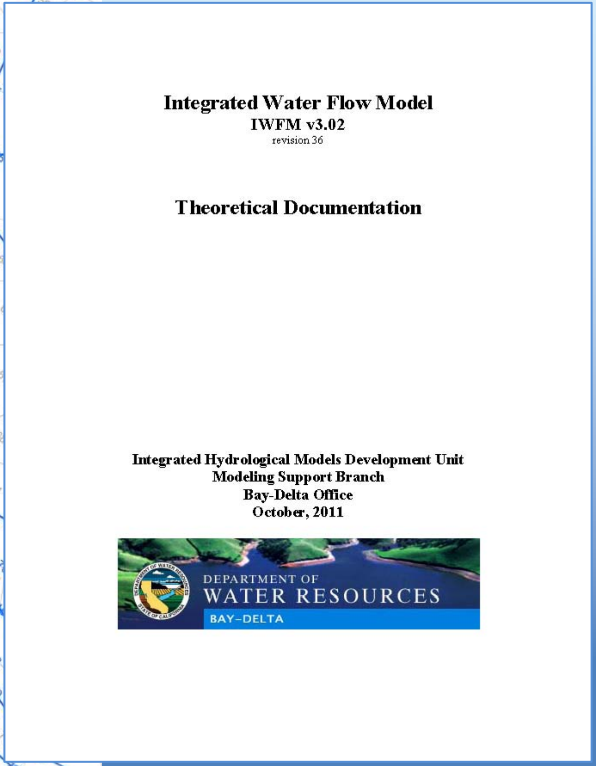


PEST-IWFM Tools

- Translate parameters from pilot points to IWFM
  - CVoverwrite.dat file
  - FAC2REALI program
- Convert IWFM hydrographs to SMP format
  - IWFM2OBS program
- Calculate vertical head differences to SMP format
  - IWFM2OBS program
- Stream-groundwater flows to SMP format
  - STACDEP2OBS program
- Log-transform surface water hydrographs
  - LOG_TRAN_SMP program

Documentation and User Support

- Theoretical documentation, user's manual, reports, technical memorandums, previous presentations and posters, user's group presentations, and published articles in peer reviewed journals are available at the IWFM web site (google "IWFM")
- Technical support by DWR staff



Integrated Water Flow Model
IWFM v3.02
revision 36

Theoretical Documentation

Integrated Hydrological Models Development Unit
Modeling Support Branch
Bay-Delta Office
October, 2011

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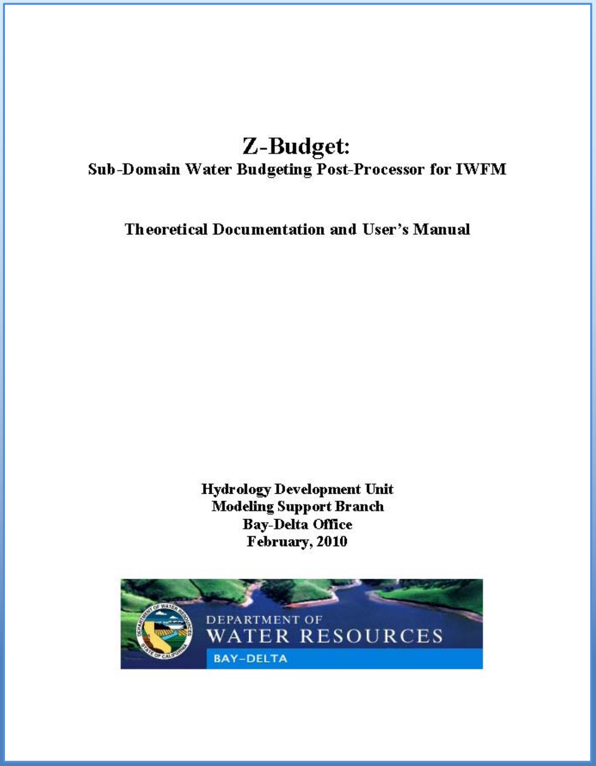
Integrated Water Flow Model
IWFM v3.02
revision 36

User's Manual

Integrated Hydrological Models Development Unit
Modeling Support Branch
Bay-Delta Office
October, 2011

DEPARTMENT OF WATER RESOURCES BAY-DELTA



Z-Budget:
Sub-Domain Water Budgeting Post-Processor for IWFM

Theoretical Documentation and User's Manual

Hydrology Development Unit
Modeling Support Branch
Bay-Delta Office
February, 2010

DEPARTMENT OF WATER RESOURCES BAY-DELTA

Validation and Verification

Eleven verification runs; report available at IWFM web site (Ercan, 2006)

VERIFICATION PROBLEMS FOR IWFM

This report is prepared under the direction of

Emin C. Dogrul, PhD, P.E.,
Tariq N. Kadir, P.E.

By

Ali Ercan

Department of Water Resources
Bay-Delta Office
Modeling Support Branch
Hydrology and Operations Section

July 2006

	Test										
	1.a	1.b	1.c	1.d	2.a	2.b	3	4	5	6a	6b
Hydrological processes											
Groundwater flow											
Confined aquifer					*	*			*		
Semi-confined aquifer							*				
Unconfined aquifer	*	*	*	*			*	*		*	*
Recharge/pumping wells											
Pumping					*	*	*		*		*
Recharge									*		*
Partially penetrating											
Multiple wells						*					
Tile drainage and subsurface irrigation											
Land subsidence									*		
Stream flows										*	*
Lakes											
Surface flows											
Soil moisture in the root zone and unsaturated zone											
Small watersheds											
Flow characteristics											
Steady state flow	*	*	*	*							
Transient flow					*	*	*	*	*	*	*
Boundary conditions											
Zero flow (impermeable barrier)	*	*	*	*	*	*	*	*	*	*	*
Specified flux		*									
Specified head	*				*	*	*	*		*	*
Rating table				*							
General head			*								
Dimensions											
1D	*	*	*	*				*			
2D					*	*	*		*	*	*
Quasi 3D											

Table 1.1 Functionality table of tests performed.

Validation of Z-Budget Post-processor

Z-Budget:

Sub-Domain Water Budgeting Post-Processor for IWFM

Theoretical Documentation and User's Manual

Hydrology Development Unit
Modeling Support Branch
Bay-Delta Office
February, 2010

DEPARTMENT OF WATER RESOURCES
BAY-DELTA

Flow Computation and Mass Balance in Galerkin Finite-Element Groundwater Models

Emin C. Dogrul, P.E.[1]; and Tariq N. Kadir, P.E.[2]

Abstract: In most groundwater modeling studies, quantification of the flow rates at domain and subdomain boundaries is as important as the computation of the groundwater heads. The computation of these flow rates is not a trivial task when a finite-element method is chosen to solve the groundwater equation. Generally, it is believed that finite-element methods do not conserve mass locally. In this paper, a postprocessing technique is developed to compute mass-conserving flow rates at element faces. It postprocesses the groundwater head field obtained by the Galerkin finite-element method, and the calculated flow rates conserve mass locally and globally. The only requirement for the postprocessor to be applicable is the irrotationality of the flow field, i.e., the curl of the Darcy flux should be zero. The accuracy and the mass conservation properties of the new postprocessor are demonstrated using several test problems that include one-, two-, and three-dimensional flow systems in both homogeneous and heterogeneous aquifer conditions.

DOI: 10.1061/(ASCE)0733-9429(2006)132:11(1206)

CE Database subject headings: Finite element method; Mass; Ground-water flow; Computer analysis; Computation; Hydrologic models.

Introduction

Finite-element methods, particularly the Galerkin finite-element method (GFEM), are commonly utilized in groundwater modeling studies because complex boundaries can be represented more closely. Generally, the momentum equation, i.e., Darcy equation, is substituted into the equation of mass conservation, and the resulting equation is solved for the groundwater head. In most groundwater modeling studies, quantification of flow rates is as important as the simulation of the groundwater heads. One reason for this is that most groundwater basins are divided into political subdomains such as water districts, counties, or states with differing strategies of managing their groundwater resources. Simulation of groundwater flow rates between adjacent subdomains caused by varying management strategies is sometimes the ultimate goal of a modeling study. Another reason is the need to examine the detailed inflow/outflow components at a subdomain level during calibration and verification stages of a modeling study.

When the flow rates are required, the conventional approach is to postprocess the groundwater head field, computed using GFEM, by substituting it into the Darcy equation and obtaining the flux field. Then, the normal component of the Darcy flux is integrated over the domain or subdomain boundary to obtain the flow rates. However, this postprocessing approach has been shown to generate flow rates that violate local as well as global mass balances. Yeh (1981) reported global mass balance errors of up to 30% when the conventional postprocessing method is used. He suggested that the finite-element approach that is used to simulate the groundwater head field also be applied to Darcy equation with the fluxes as the state variables. Although his method produced better results, test problems still showed mass balance errors of 2–9% (Yeh 1981). Commenting on Yeh's work, Lynch (1984) showed that precise global mass balance can be achieved in GFEM by proper treatment of the Dirichlet boundary conditions. He pointed out that the common practice of discarding Galerkin equations—the discrete version of the conservation equation—along Dirichlet boundaries violates the mass balance by requiring that these fluxes be approximated by the conventional postprocessing method. He showed that retaining the Galerkin equation at Dirichlet boundaries as the equation for the flux resulted in precise global mass balance. Similar observations have been made by other researchers (Carey 1982; Carey et al. 1985; Hughes et al. 2000; Berger and Howington 2002; Carey 2002). In fact, the same idea can be used to compute the internal fluxes, i.e., once the groundwater head at an internal node is computed with GFEM, that node can be treated as a Dirichlet boundary and the Galerkin equation at the node can be solved for the flux (Hughes et al. 2000; Carey 2002). Cordes and Kinzelbach (1992) used an alternative postprocessing method where the elements were subdivided into patches and individual fluxes for each patch were computed by assuming that the flow field was irrotational. In their method, triangular and quadrilateral elements were treated separately.

The aim of this paper is to develop and test a postprocessor that uses the groundwater heads computed by GFEM to obtain flow rates across finite-element faces, i.e., normal flux integrated along each of the element faces, that do not violate local and global mass balances. Once flow rates through each of the ele-

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Note. Discussion open until April 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on March 15, 2005; approved on December 29, 2005. This paper is part of the *Journal of Hydraulic Engineering*, Vol. 132, No. 11, November 1, 2006. ©ASCE, ISSN 0733-9429/2006/11-1206–1214/$25.00.

Key Limitations

- Time step and stream routing: Stream flow must travel from upstream to downstream within the length of time step for the zero-storage assumption to be valid
- Time step and rainfall runoff: Re-calibrate curve numbers for different time steps (for C2VSim, the input data time step is itself a limitation)
- Spatial scale of demand and supply: Demand and supply computations are performed at the subregion level
- Vertical distribution of pumping: Static distribution limits the ability to simulate changes in the pumping depth during simulation period
- Aquifer and root zone thickness: Aquifer thickness should be large compared to root zone thickness to minimize error in case groundwater table is close to ground surface; likely to occur in native and riparian vegetation areas

IWFM Development

- Version 3.02:
  - Subregion water budgets
- Version 4
  - Element water budgets

New Features of IWFM v4

- Improved root zone module (a.k.a. IDC v4)
  - Root zone flow processes and agricultural water demands are computed at each cell for each land-use type
  - Agricultural water demands are computed using methods from irrigation scheduling models
  - Explicit simulation of rice and refuge operations
  - Simulation of re-use of agricultural tail water at different spatial resolutions
  - Simulation of regulated deficit irrigation
  - Ability to specify water demands (i.e. contractual demands) instead of computing them dynamically
  - Explicit representation of effective precipitation and ETAW
  - Detailed budget output for each land-use type

New Features of IWFM v4

- Ability to run the root zone module (IDC) by itself or as linked to IWFM with the same input data files
- Reduced size of Z-Budget binary output file for run-time efficiency
- Water budget output at user-selected stream nodes
- Ability to generate water budget tables accumulated to time steps larger than the simulation time step

Future IWFM Developments

- Improved simulation of riparian vegetation
- Improved simulation of rainfall-runoff and overland flow
- Improved hydraulic routing of stream flows that account for change in storage
- Continue developing ArcGIS based GUI
- Simulation of water quality
- Emulate an agricultural economics model in IWFM
- Parallel processing

IWFM Applications

- California Central Valley Groundwater-Surface Water Model
- Butte County Groundwater Model (Heywood, CDM)
- Walla Walla River Basin Model (Petrides, OSU)
- Yolo County Integrated Model (DWR, UCD)
- Kings River Model (HydroMetrics)
- Merced Area (MAGPI, RMC)

END