History of Ground Water Models
Central Valley, California

Central Valley Ground-Water Modeling Workshop
July 11 and 12, 2008
Berkeley, California

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Outline

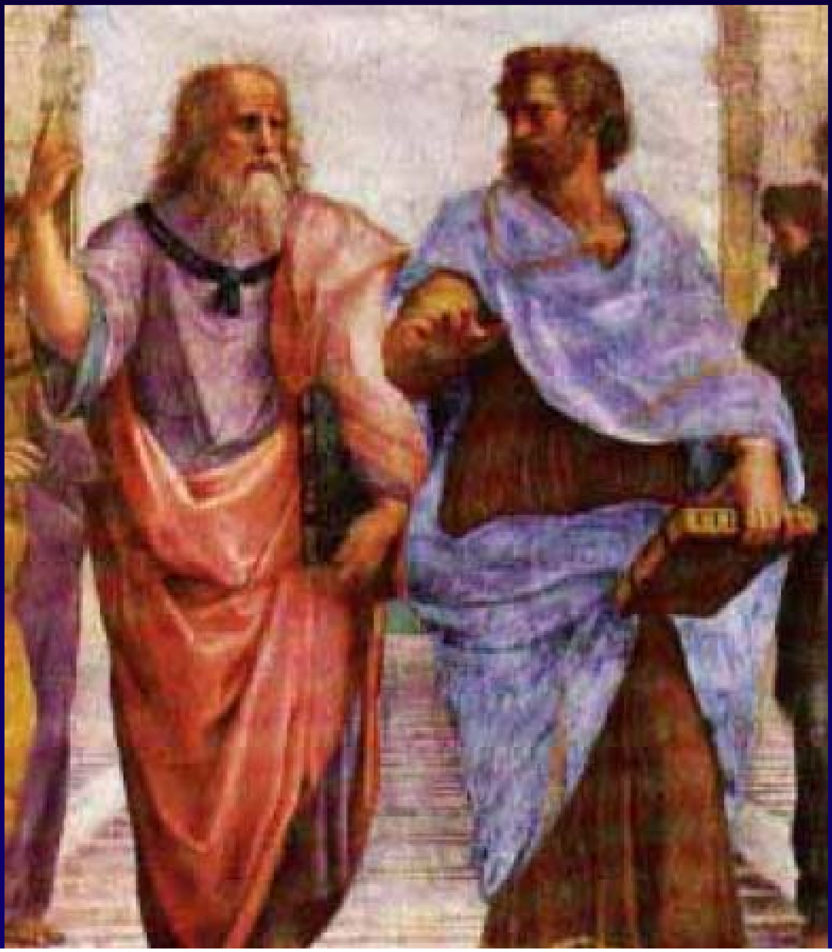
- Meaning of "ground-water models"
- Brief history on development of different types of models and understanding of ground-water flow
- History of ground-water studies (and development in the Central Valley)
- Evolution of numerical models of the Central Valley

What is a Model?

- A model is a representation of a process or object
- Types of models include
  - Conceptual
  - Physical
  - Mathematical

Conceptual models developed first

Pluto Aristotle—384-322 B.C.E.



- Aristotle, first European to describe the Hydrologic Cycle
- Earth science covered in his treatise "Meteorologica"

The same parts of the earth are not always moist or dry, but they change according as rivers come into existence and dry up.

Henri Darcy constructed an early physical model published in 1856

- Practical application for he needed to know how much sand was needed to filter a given volume of water for a water supply in Dijon, France
- Described in an appendix what is now known as Darcy's Law:

$$Q = KAdh / dl$$

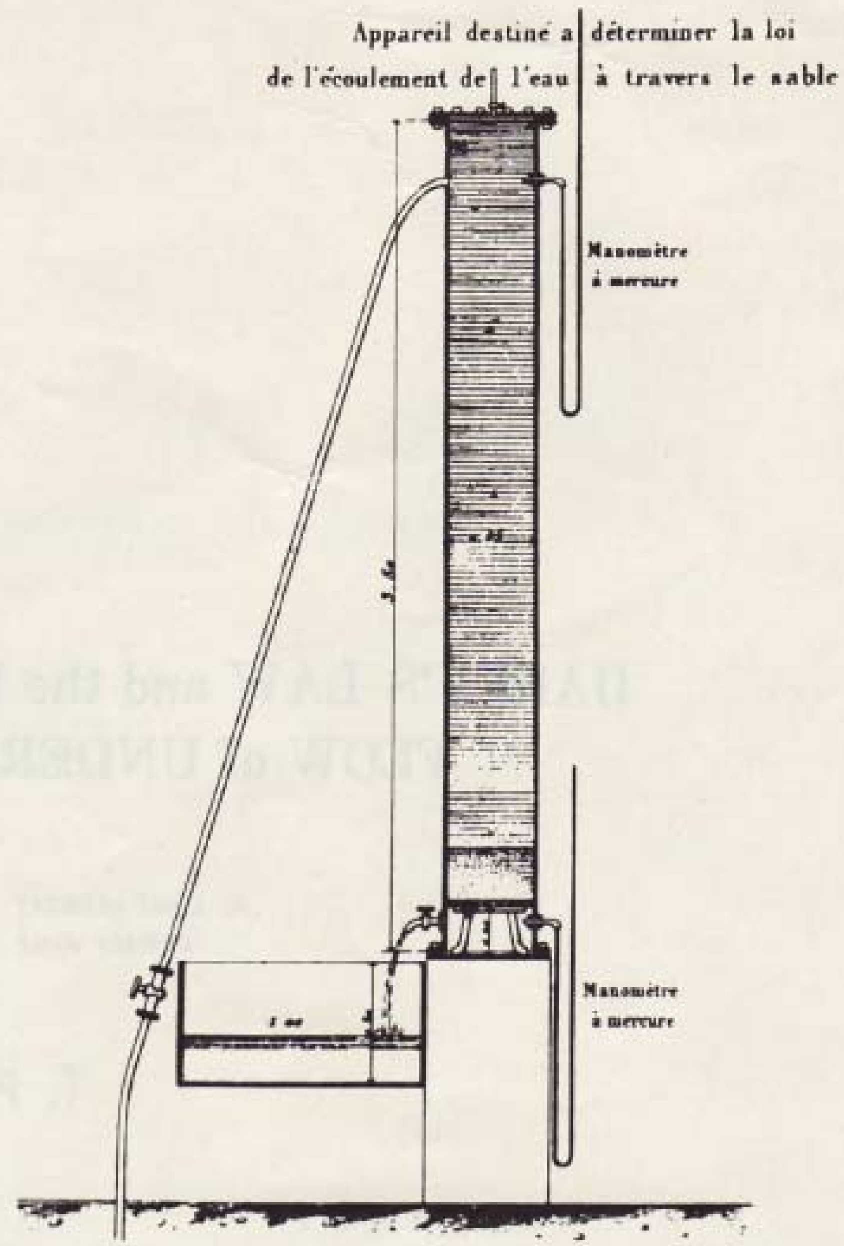


FIG. 1—FACSIMILE OF DARCY'S ILLUSTRATION OF HIS EXPERIMENTAL APPARATUS. (FROM *Les Fontaines Publiques de la Ville de Dijon, Atlas*, FIG. 3).

C.S. Slichter published "Theoretical Investigations on the Motion of Ground Waters", USGS 19th annual report, 1897-98

- Redid Darcy's experiment
- Experimentally determined range of porosity for different arrangements of packed spheres
- Expanded Darcy's Law and derived Laplace equation of steady ground water flow

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2} = 0$$

- Noted that steady flow of ground water analogous to steady flow of heat or electricity

Example from C.S. Slichter of flow into an artesian well

1. We shall first attempt to compute the flow into an artesian well which completely penetrates a level homogeneous water-bearing stratum,

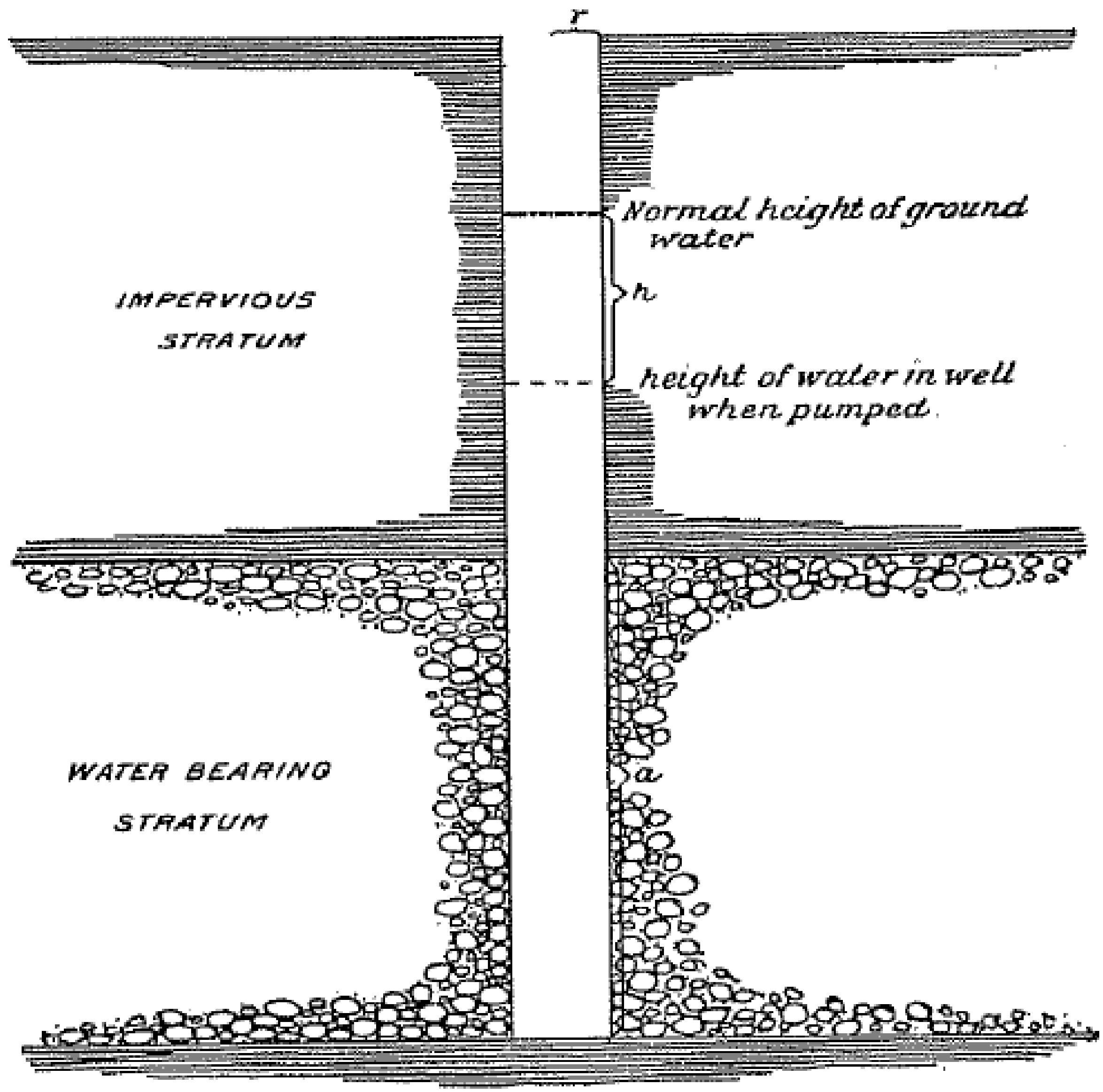


FIG. 81.—Section of a well which completely penetrates a water-bearing stratum.

Slichter's lines of flow into a well in a region in which ground water has a constant motion in a general direction

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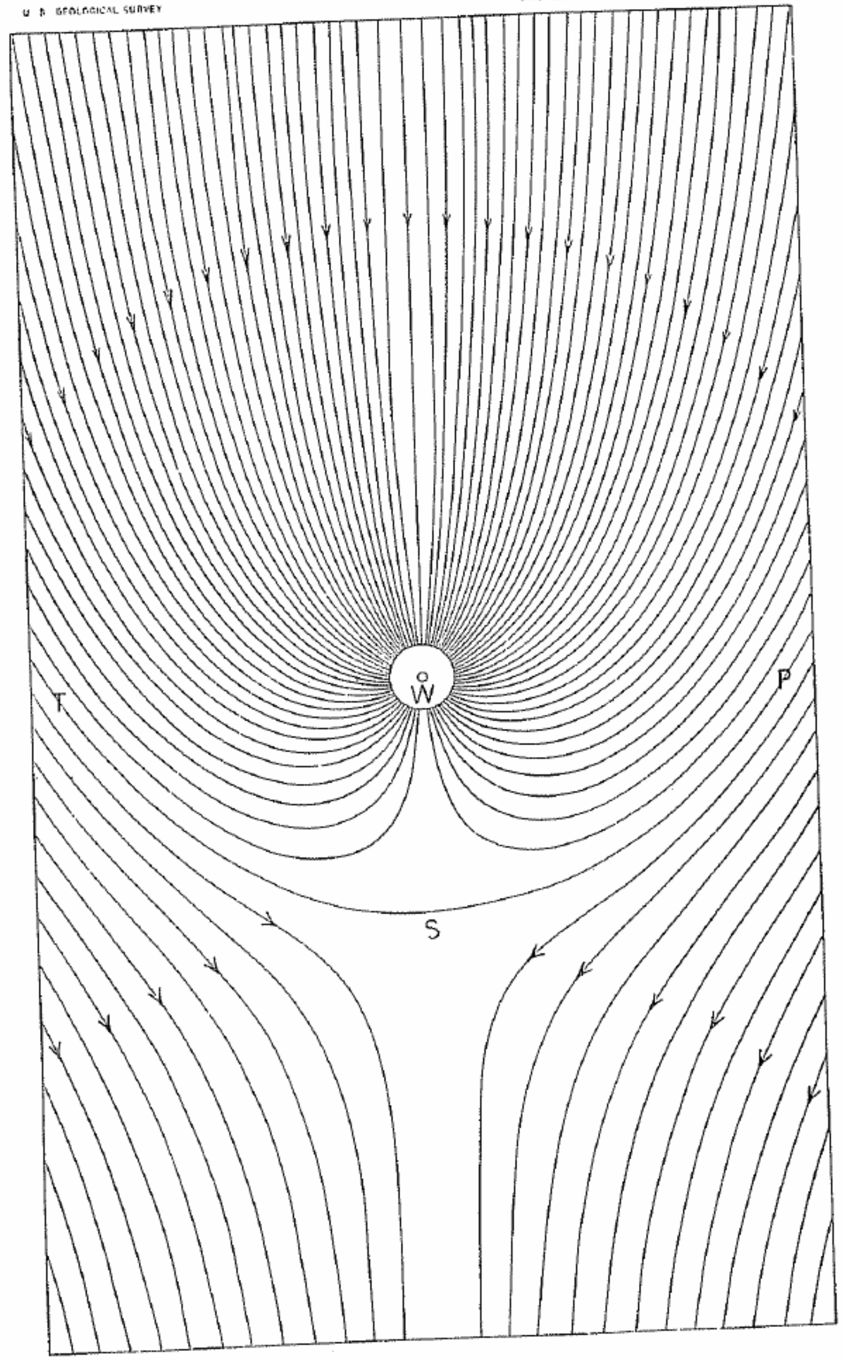


LINES OF FLOW INTO A WELL IN A REGION IN WHICH THE GROUND WATER HAS A CONSTANT MOTION IN A GENERAL DIRECTION

O.E. Meizner published a paper (1928) on the compressibility and elasticity of artesian aquifers

Meinzer stated “artesian aquifers are apparently all more or less compressible and elastic though they differ widely in degree and relative importance of these properties”

Prior to Meizner’s work, artesian aquifers were assumed incompressible and inelastic.

Economic Geology, vol. 23, pp. 263-291

Idea of storage being important led C.V. Thesis (1935) in developing an equation that related the lowering of the potentiometric surface to the discharge of a pumping well and aquifer storage

$$s = \frac{Q}{4\pi T}\int_{r^2S/4Tt}^{\infty}\frac{e^{-u}}{u}\,du$$

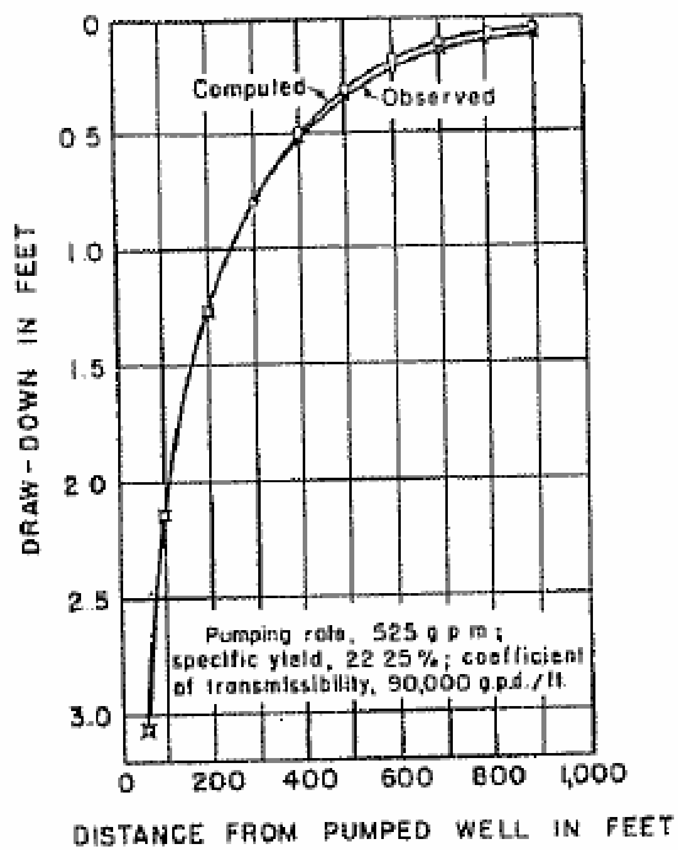


FIGURE 1.—OBSERVED AND COMPUTED DRAW-DOWNS IN VICINITY OF A WELL AFTER PUMPING 48 HOURS

Transactions of the America Geophysical Union of 1935, part 2

C.E. Jacob (1940) added to the understanding of storage when he published “On the Flow of Water in an Elastic Artesian Aquifer”

$$S = \rho g \theta m (1/E_w + b/\theta E_s + c/\theta E_c)$$

Identical to “Coefficient of Storage” of Theis

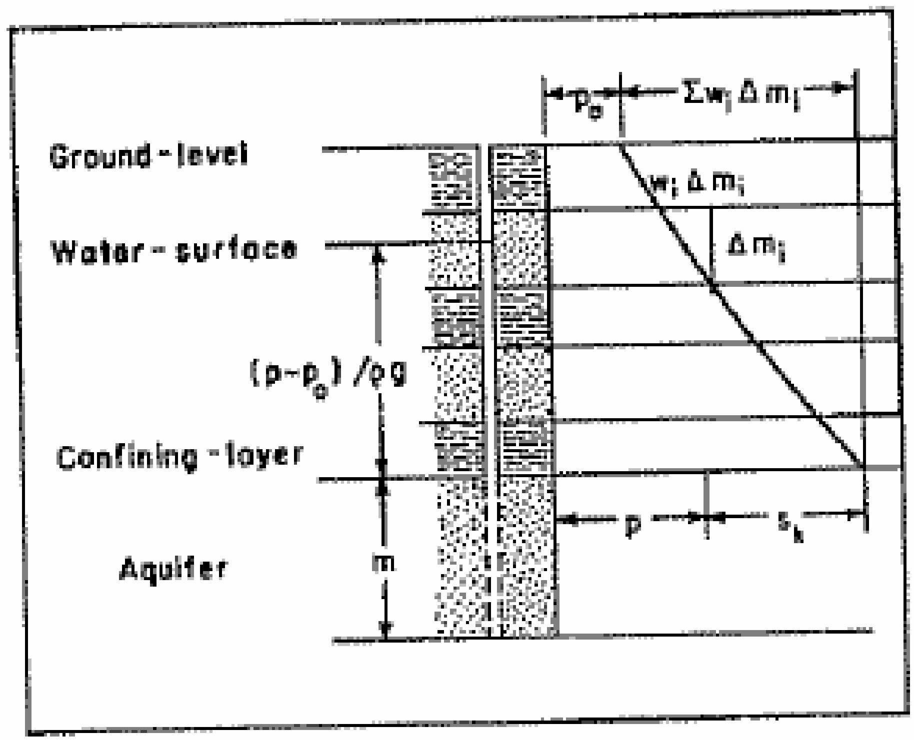
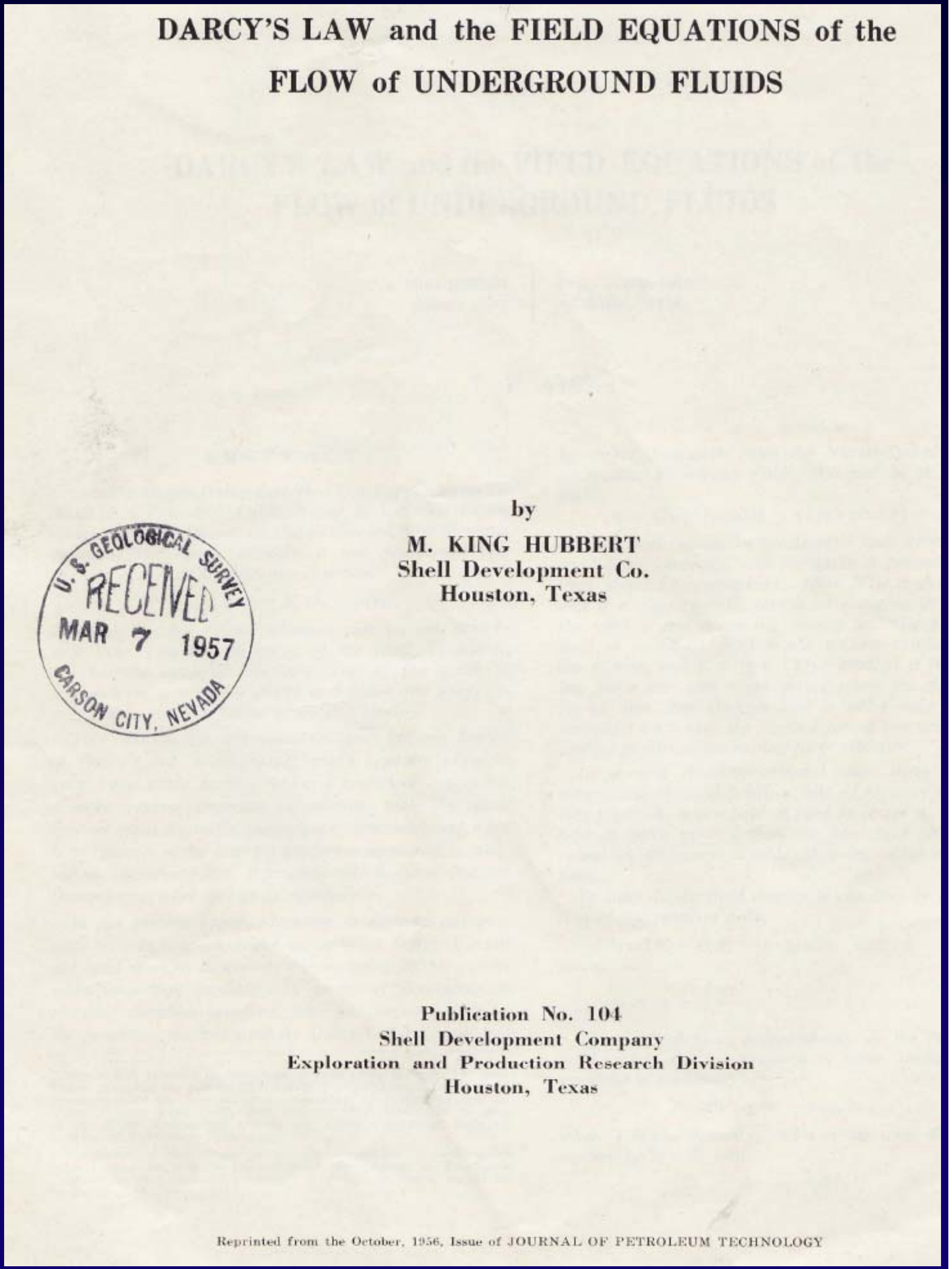


Fig. 1 Distribution of stress in artesian aquifer and overlying beds

Transactions of the America Geophysical Union of 1940, part 2

M. King Hubbert (1956) derived Darcy's Law from the fundamental equation of Navier and Stokes for motion of a viscous fluid and transformation from microscopic to macroscopic equations of motion



DARCY'S LAW and the FIELD EQUATIONS of the FLOW of UNDERGROUND FLUIDS

by

M. KING HUBBERT
Shell Development Co.
Houston, Texas

Publication No. 104
Shell Development Company
Exploration and Production Research Division
Houston, Texas

Reprinted from the October, 1956, Issue of JOURNAL OF PETROLEUM TECHNOLOGY

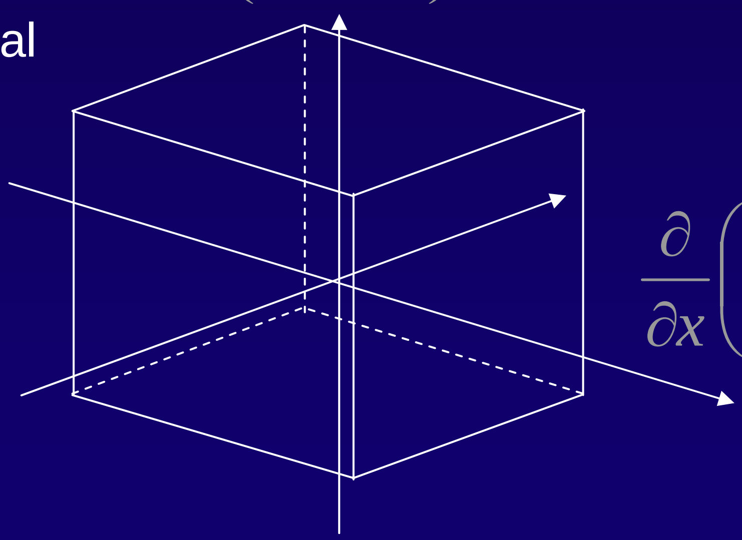
All this led to the ground-water flow equation in three dimensions

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

The equation is simply an expression of mass balance

$$\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)$$

Infinitesimal volume of aquifer



$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)$$

$$\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)$$

Darcy's Law:

$$q_x = K_{xx}\frac{\partial h}{\partial x}$$

$$q_y = K_{yy}\frac{\partial h}{\partial y}$$

$$q_z = K_{zz}\frac{\partial h}{\partial z}$$

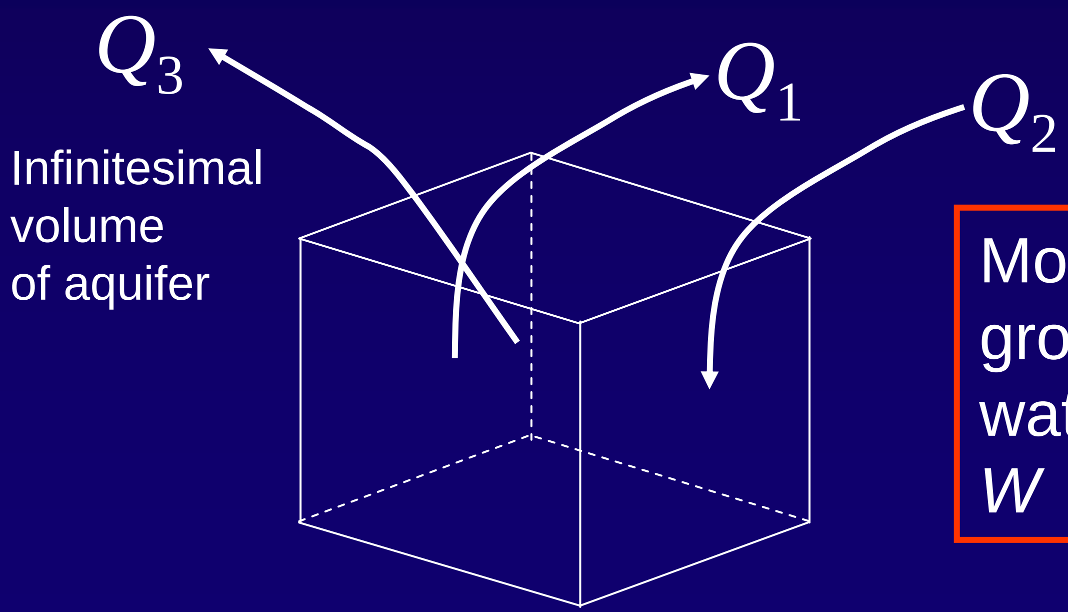
C.E. Jacob, 1950, Hydraulic

Ground-Water Flow Equation, "*W*" term

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-\underline{W}=S_s\frac{\partial h}{\partial t}$$

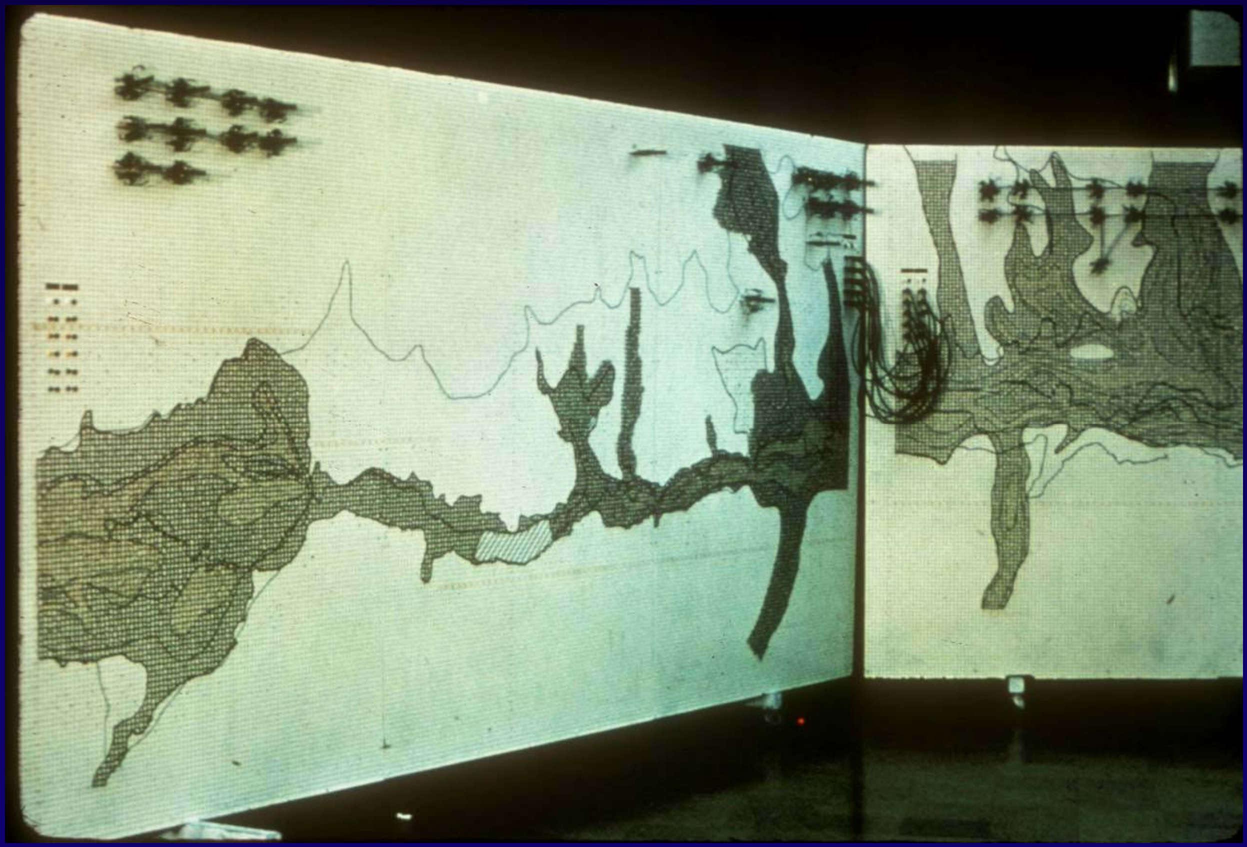
The "W" term is flow rate per unit volume of aquifer added to or taken from ground-water system.

$$W = Q_1 + Q_2 + Q_3 + \ldots Q_n$$



Most interaction between ground water and surface water is lumped into the *W* term

Before Computers, electric analog models were used to solve ground-water flow in regional aquifers



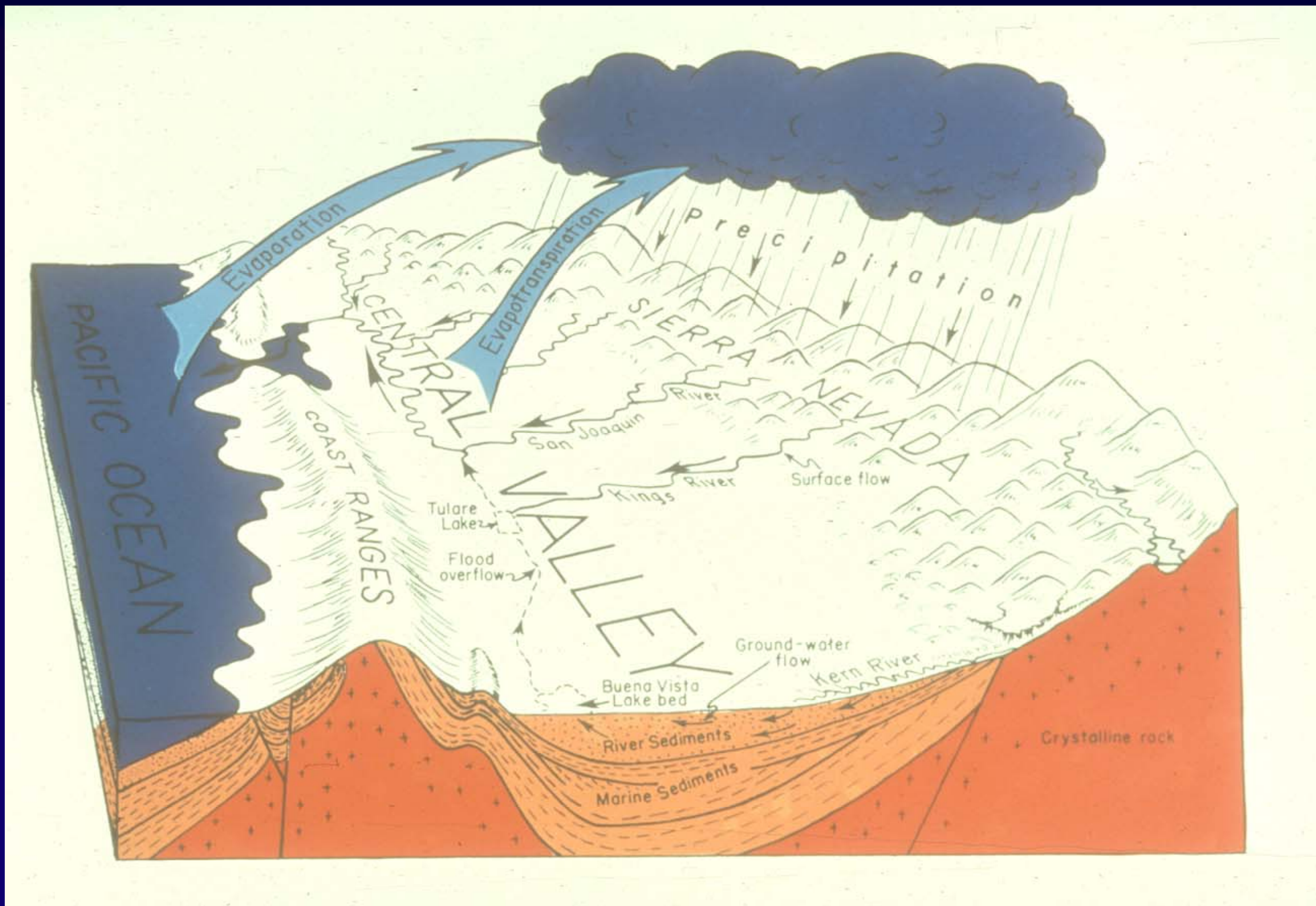
Before Computers, electric analog models were used to solve ground-water flow in regional aquifers

Computers replaced electric analog models

- Oil industry led development of computer programs using finite difference and finite element to approximate the ground-water flow equation
- 1960 and 70's rapid development of ground-water models
  - Pinder and Bredehoeft led the USGS in developing 2D finite-difference ground-water models
  - Trescott developed a 3D finite-difference model in 1975 that later became MODFLOW
  - Freeze developed a 3D saturated-unsaturated finite-difference flow model in 1973 that evolved into finite-element code FEMWATER by Yeh
  - Pricket and Lonquist at Illinois Geological Survey also developed a popular finite-difference code in early 70's
  - Recent codes provide more robust connection with surface water

Studies of the Central Valley mimicked development of methods

Hydrologic Cycle for the Central Valley

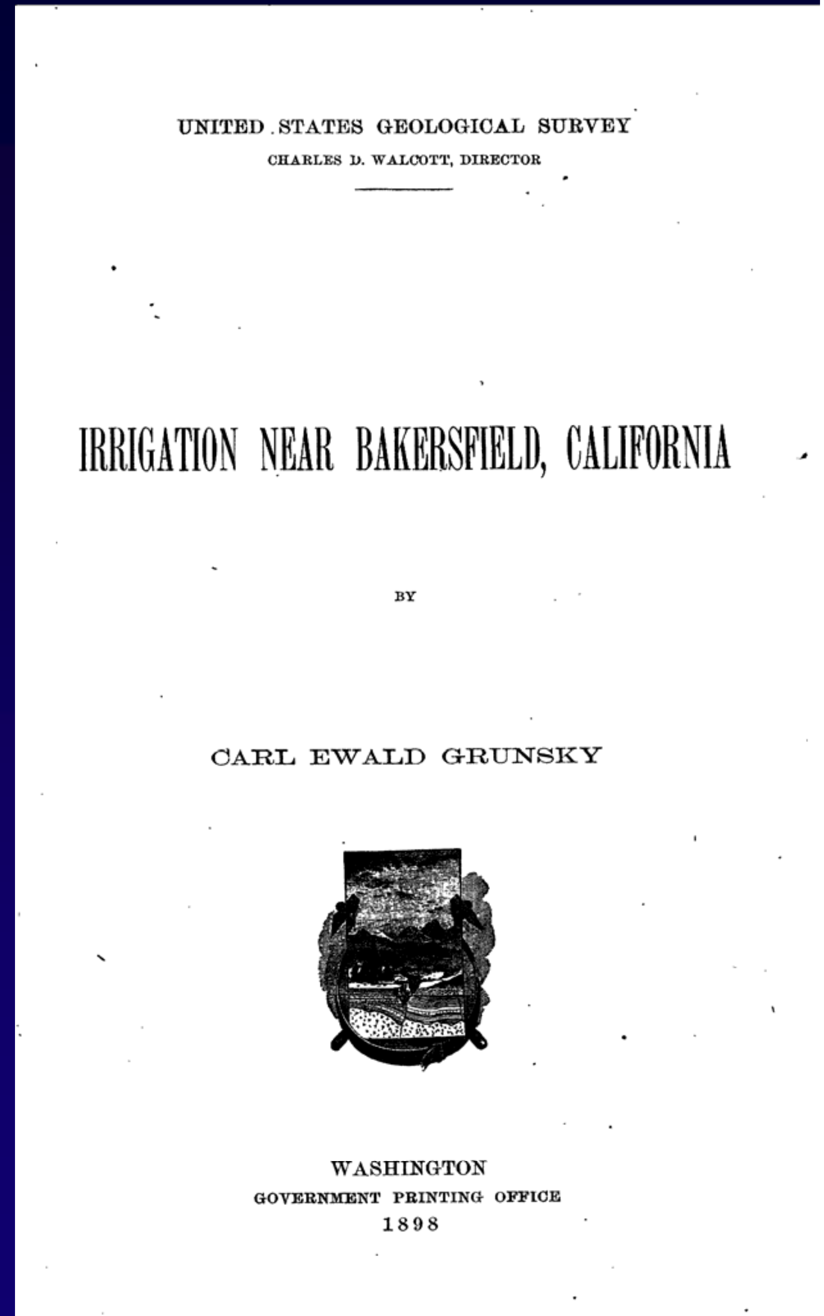


Early Studies focused on Irrigation

- Army Corps of Engineers published a report on Irrigation in California in 1874
- Early studies by Hall in 1886 and 1889 documented the area of artesian (flowing) wells in the Central Valley. The 1889 article was published in National Geographic (vol. 1, no. 4)

Early studies on irrigation

- USGS published two reports by C.E. Grunsky in 1898 on irrigation in Bakersfield and Fresno areas (USGS Water Supply and Irrigation Papers Nos. 17 & 18)
- A third report was by in 1899 on irrigation near Merced (USGS Water Supply and Irrigation Paper 19)


UNITED STATES GEOLOGICAL SURVEY
CHARLES D. WALCOTT, DIRECTOR

IRRIGATION NEAR BAKERSFIELD, CALIFORNIA

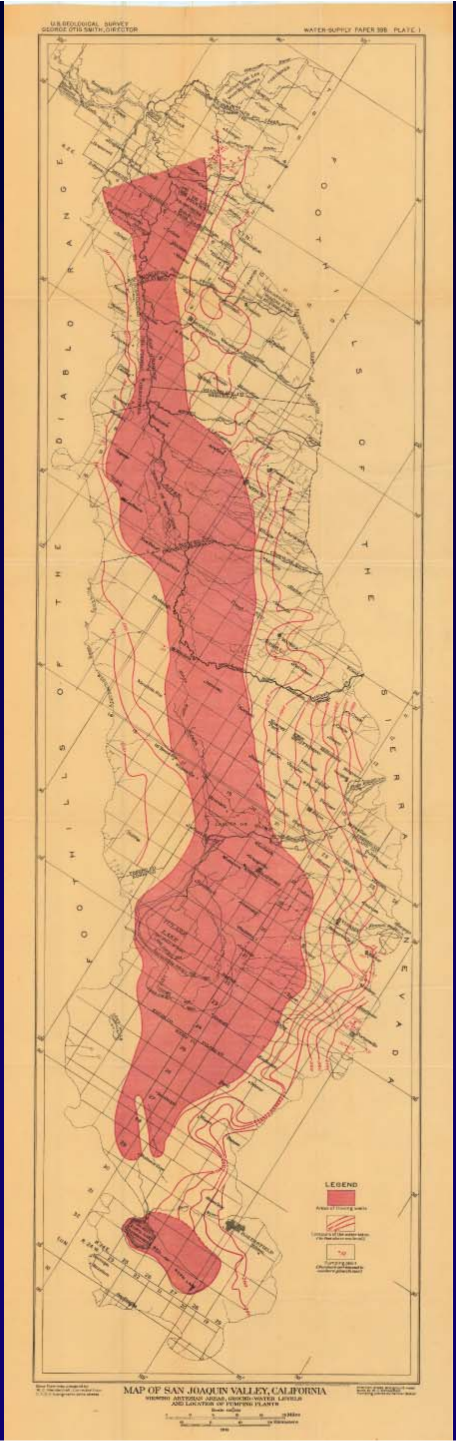
BY

CARL EWALD GRUNSKY

WASHINGTON
GOVERNMENT PRINTING OFFICE
1898

Early ground-water studies of the San Joaquin Valley

- USGS published a “preliminary report on ground waters of the San Joaquin Valley” by W. C. Mendenhall in 1906 (Water Supply Paper 222)
- A comprehensive ground-water study was of the San Joaquin Valley was done by Mendenhall, Dole, and Stabler in 1916 (USGS Water Supply Paper 398)

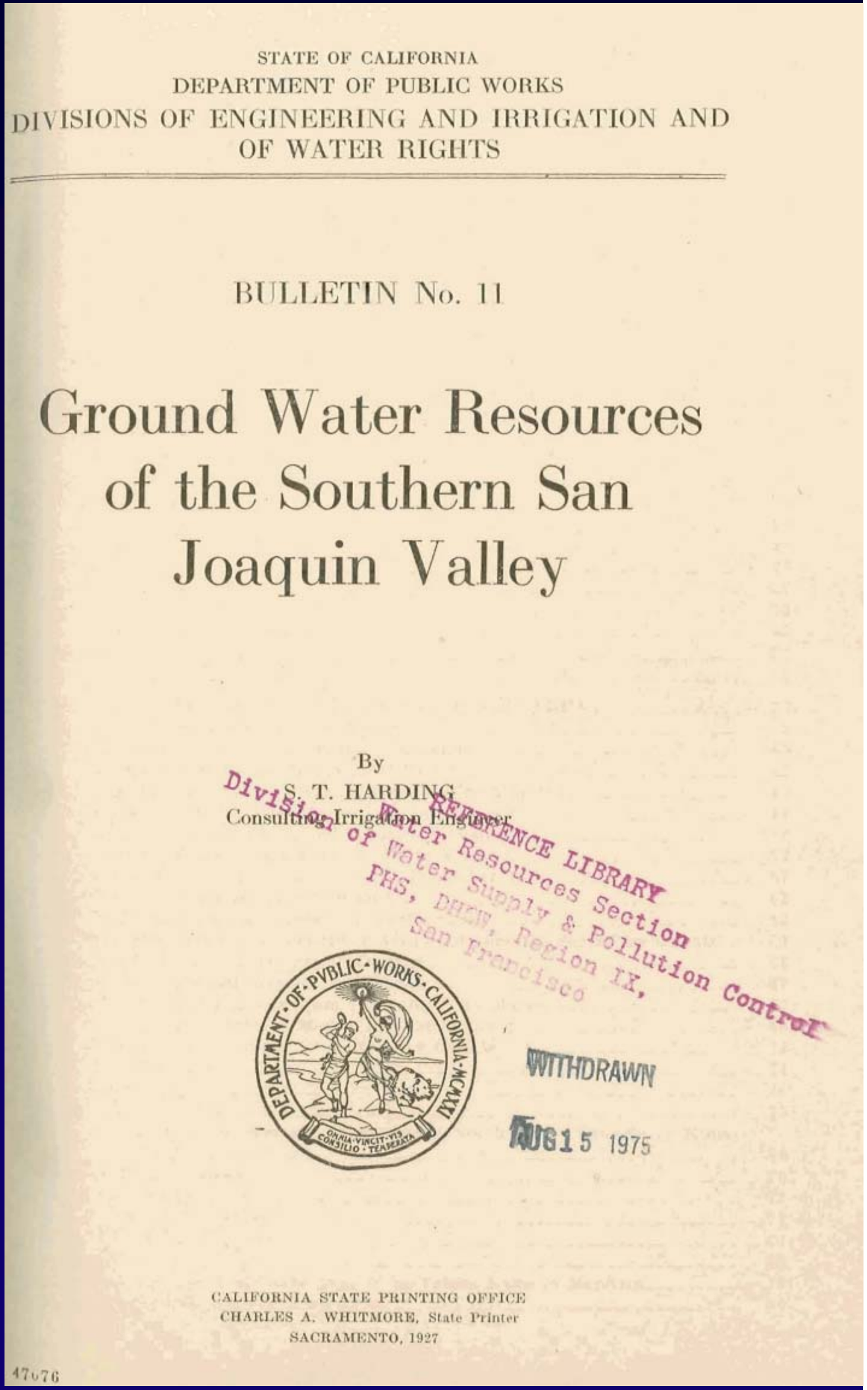


Ground-water studies of the Central Valley

- First ground water study for irrigation in the Sacramento Valley was by Kirk Bryan 1915 (Water Supply Paper 375-A)
- Followed by a more comprehensive study on the geology and ground-water resources by Kirk Bryan in 1923 (USGS Water Supply Paper 495)

Ground-water studies of the Central Valley

- California Department of Public Works, Divisions of Engineering and Irrigation and of Water Rights published a study in 1927 by S.T. Harding on Ground Water Resources in the southern San Joaquin Valley
- Published at the time when storage in artesian aquifers considered important


STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISIONS OF ENGINEERING AND IRRIGATION AND OF WATER RIGHTS

BULLETIN No. 11

Ground Water Resources of the Southern San Joaquin Valley

By
S. T. HARDING
Consulting Irrigation Engineer

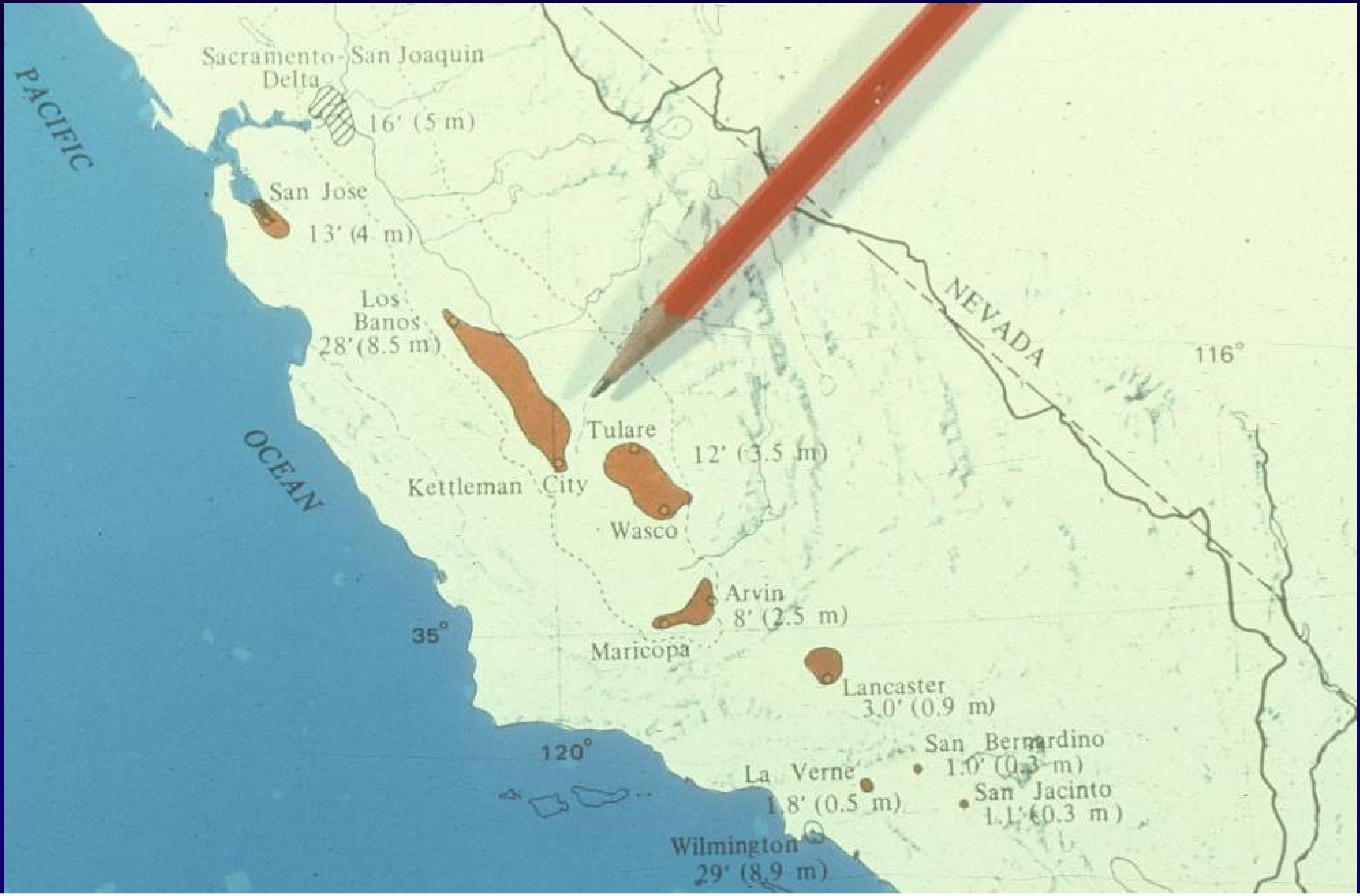
CALIFORNIA STATE PRINTING OFFICE
CHARLES A. WHITMORE, State Printer
SACRAMENTO, 1927

47076

Ground-water studies of the Central Valley

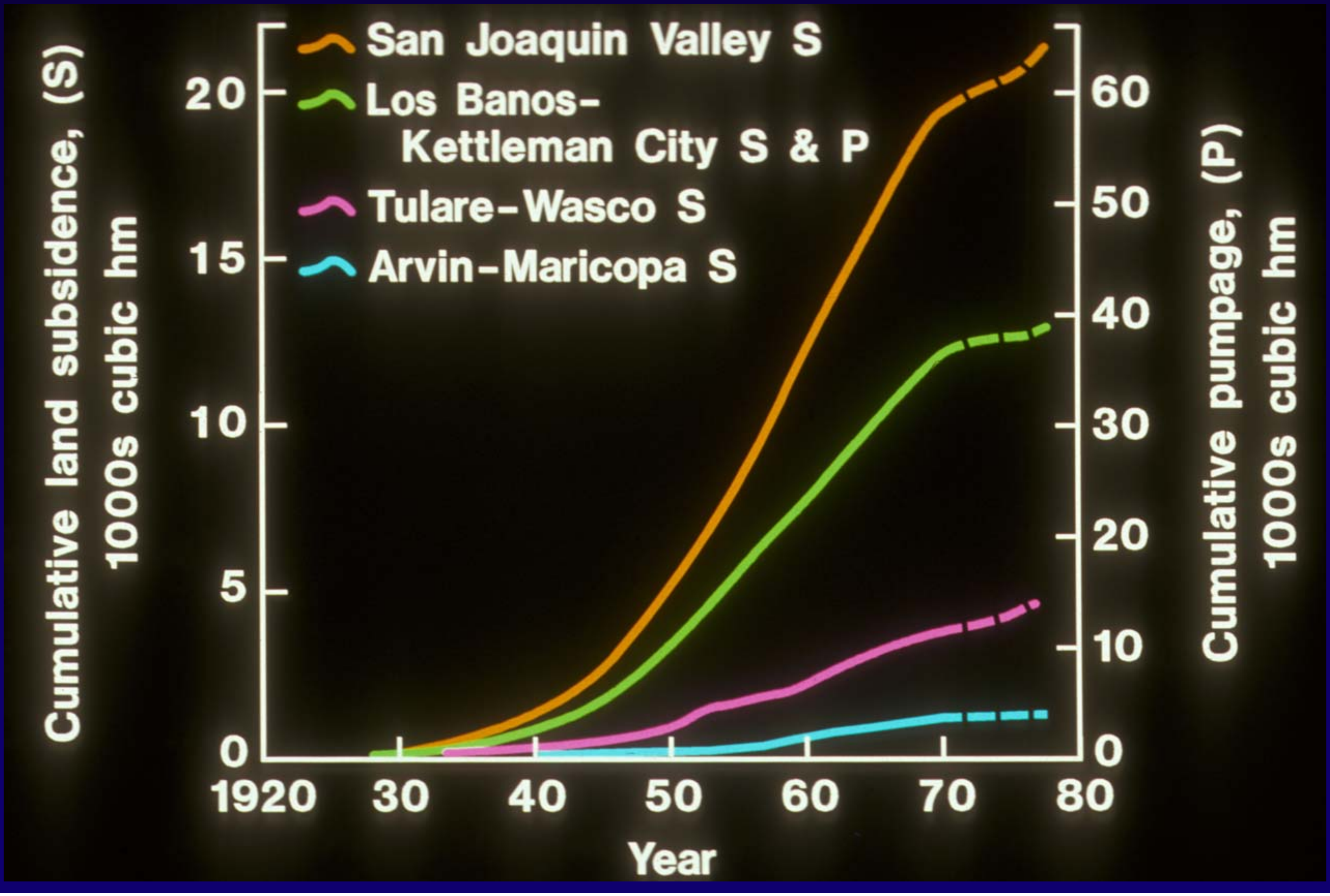
- Studies waned during the depression and World War II
- Following the war numerous studies began
- Most notable were research studies on land subsidence caused by fluid withdrawals led by Joseph Poland in cooperation with the California Department of Water Resources

Land subsidence from ground-water withdrawals affected many areas



Land Subsidence

- Studies led to understanding of inelastic compaction of clays in beds adjacent to and within to aquifers

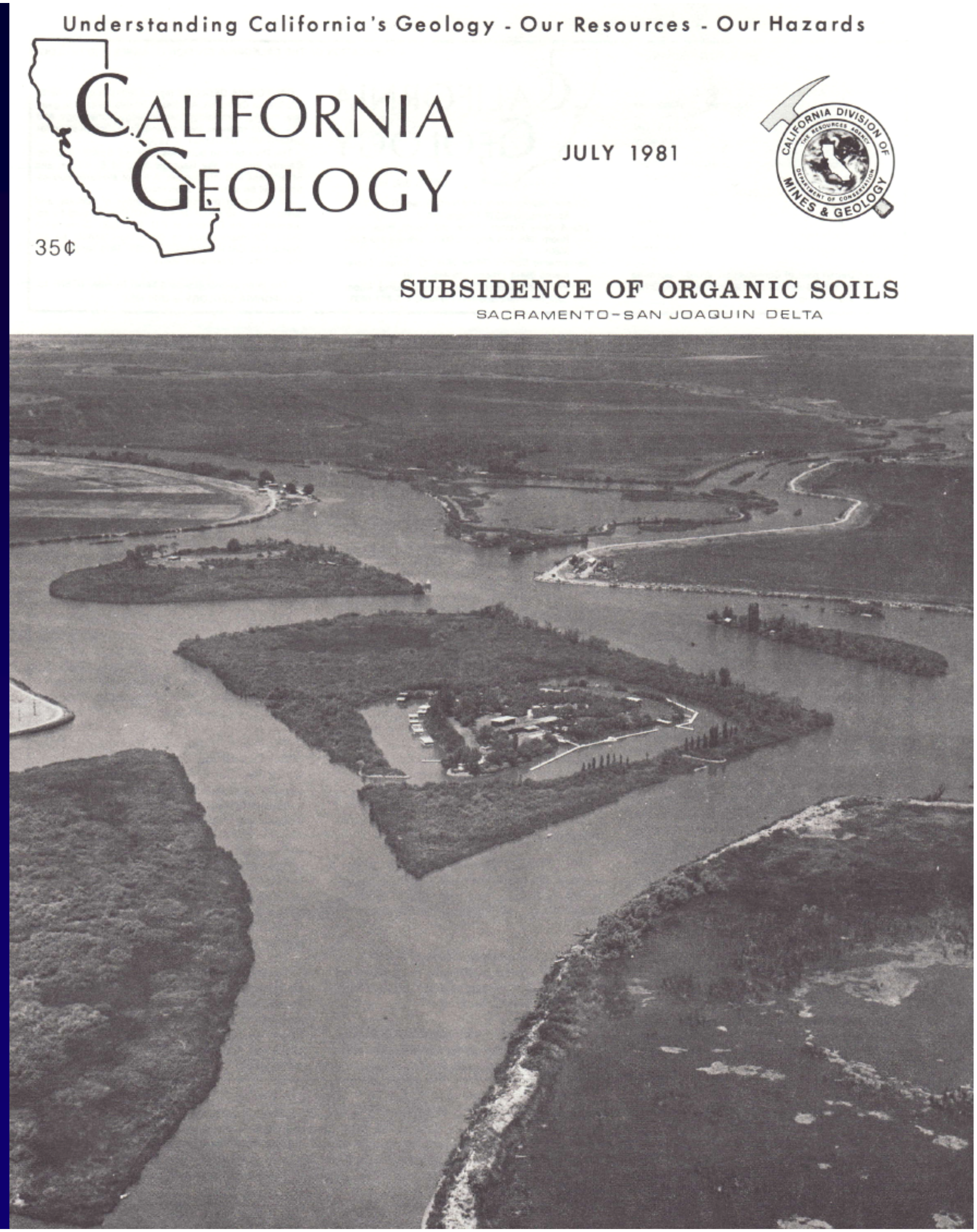


Oxidization of peat in Delta also caused land subsidence (Weir, 1950)

Fig. 10. The peat soil around this twenty-year-old house on Lower Jones Tract has subsided more than 4 feet. The pilings on which the house was built kept it from settling.

Hilgardia, v. 20, no. 3, p. 37-56

Subsidence of organic soils in Sacramento-San Joaquin Delta (Newmarch, 1981)



Subsidence also caused by applying water to previously dry soils—Process known as hydrocompaction

TYPICAL SUBSIDENCE ALONG ABANDONED IRRIGATION DITCH
(*Photograph by* California Department of Water Resources)

Ben Lofgren, Geological Society of America, Reviews in Engineering Geology, part II

Ground-water studies of the Central Valley

- A ground water study of the San Joaquin Valley was completed by George Davis and others in 1959 (U.S. Geological Survey Water Supply Paper 1469)
- A companion study of the Sacramento Valley was completed by Frank Olmstead and Davis in 1961 (U.S. Geological Survey Water Supply Paper 1497)

240 GEOLOGY OF NORTHERN CALIFORNIA Bull. 190

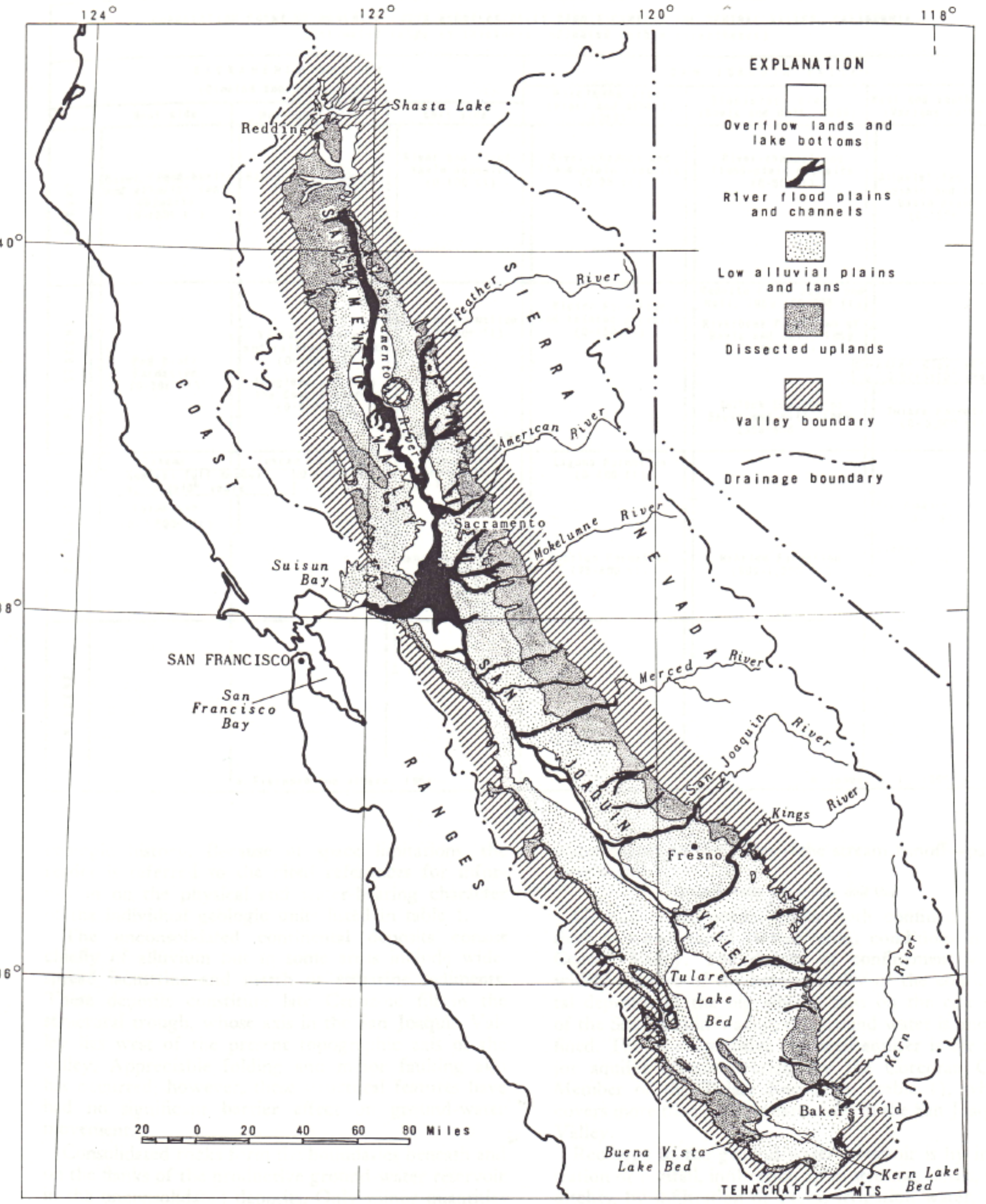
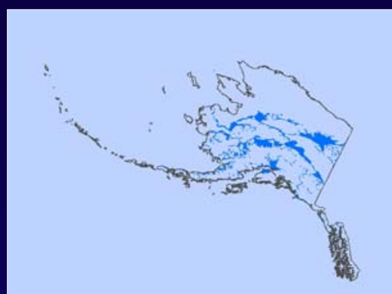
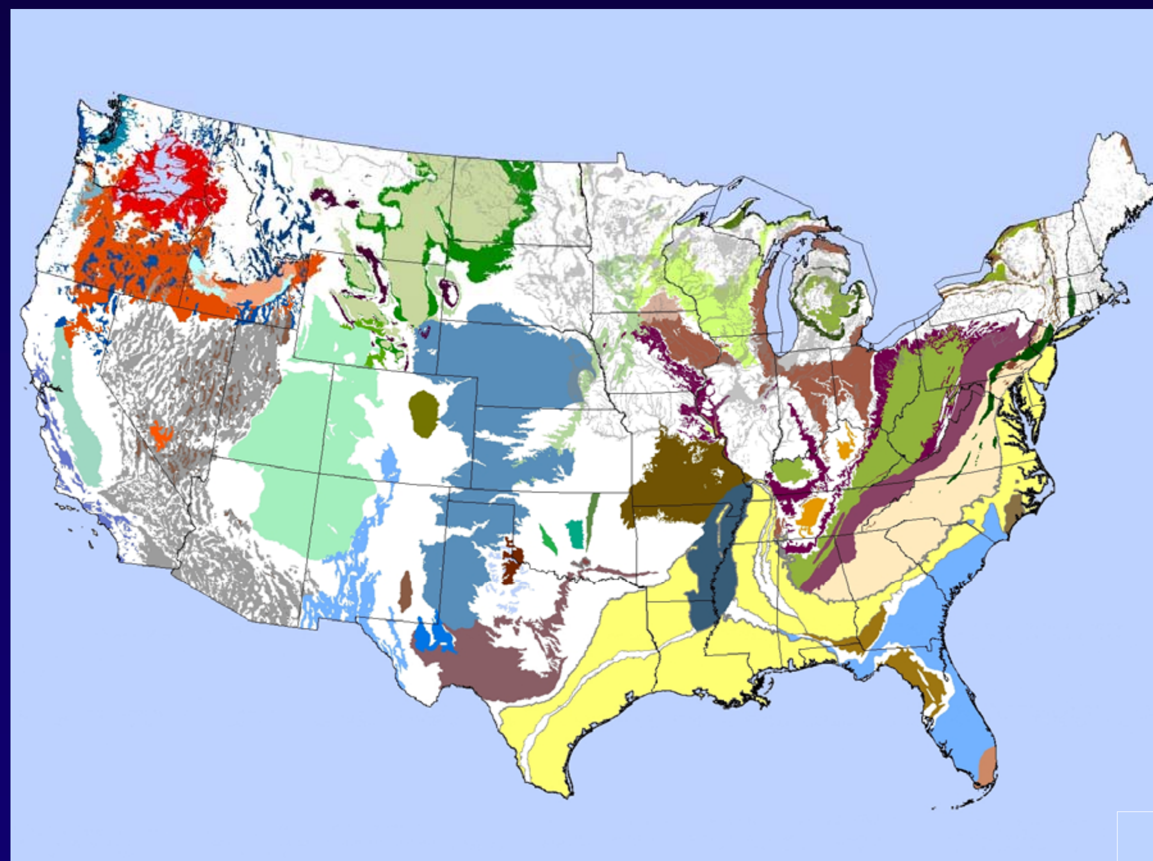


Figure 1. Geomorphic map of the Great Central Valley. Geomorphic units after Davis and others (1959, pl. 1) and Olmsted and Davis (1961, pl. 1).

Regional Aquifer System Analysis of the United States

- USGS began quantitative appraisals of the major ground-water systems of the United States in 1978

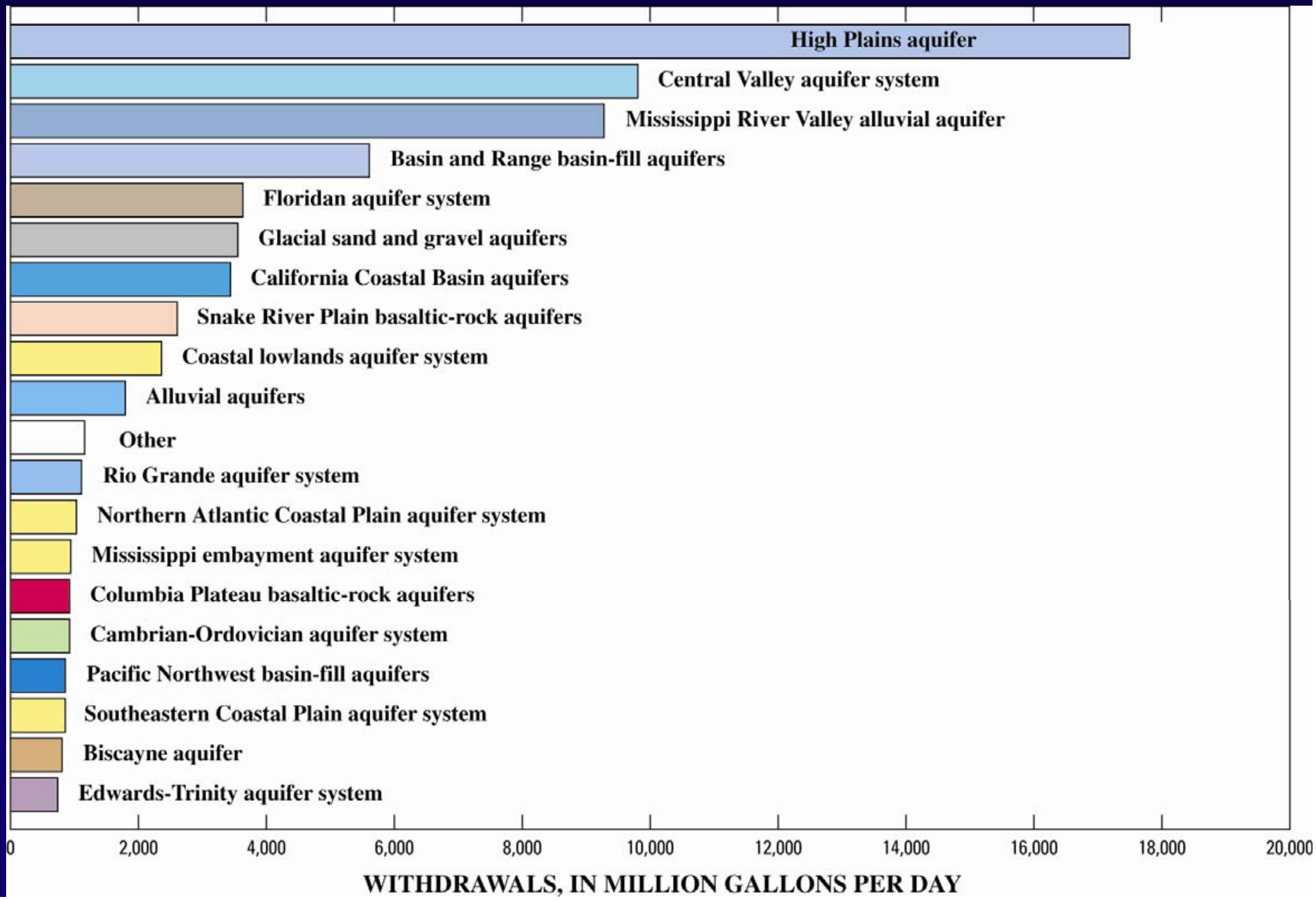




Source: U.S. Geological Survey National Atlas of the United States; http://nationalatlas.gov/atlasftp.html

Regional Aquifer System Analysis of the United States

- Central Valley was chosen because it had a long history of ground-water use and because of its economic importance



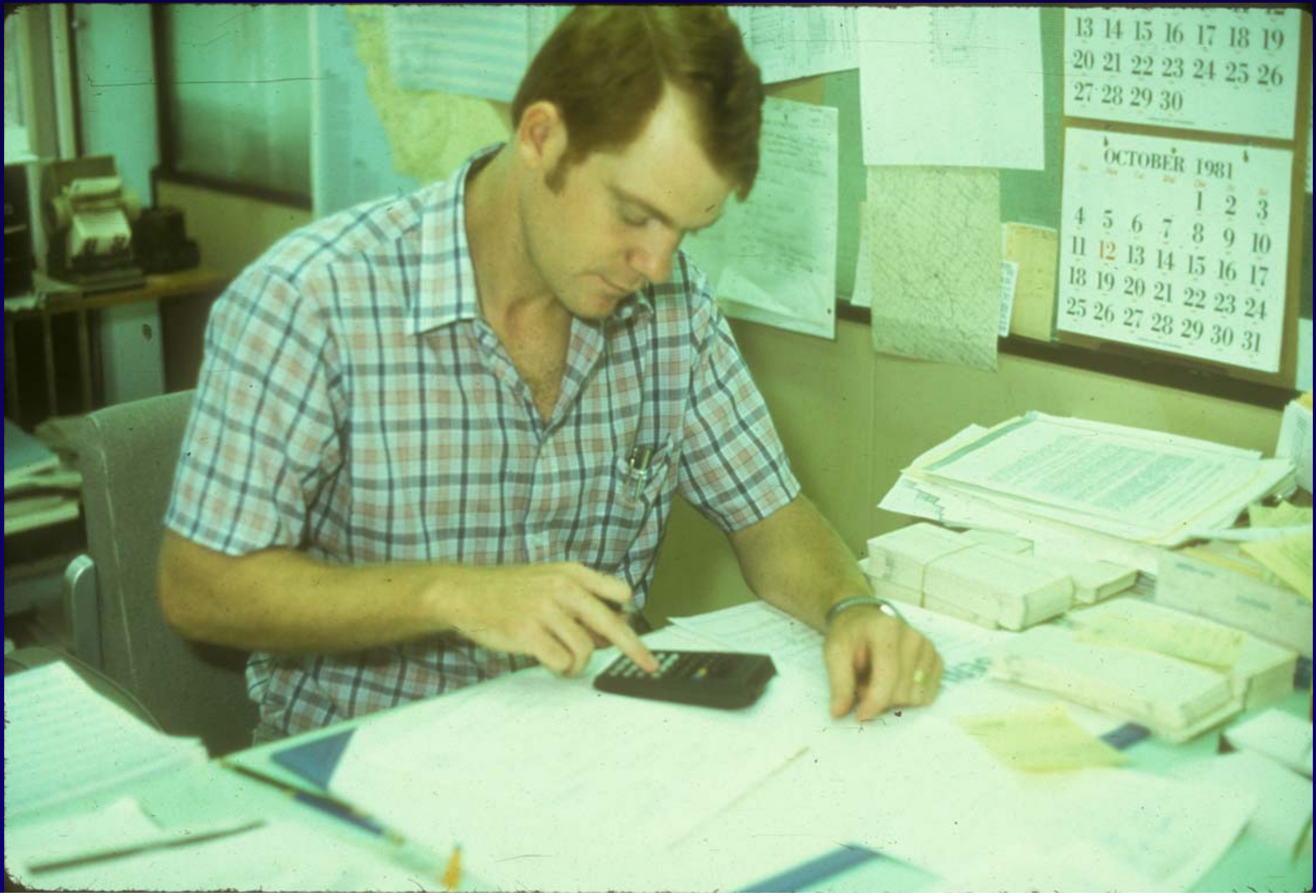
(Maupin and Barber, 2005)

Regional Aquifer System Analysis of the Central Valley

- Led by Gilbert Bertoldi
- Compilation of the hydrogeology was done by Ron Page (summarized in Professional Paper 1401-B)

Regional Aquifer System Analysis of the Central Valley

- Compilation of ground water data was done by Alex (aka Sandy) Williamson



Regional Aquifer System Analysis of the Central Valley

- Lindsay Swain was principal numerical hydrologist until his departure to Reston, VA (aka Mecca) in October, 1981

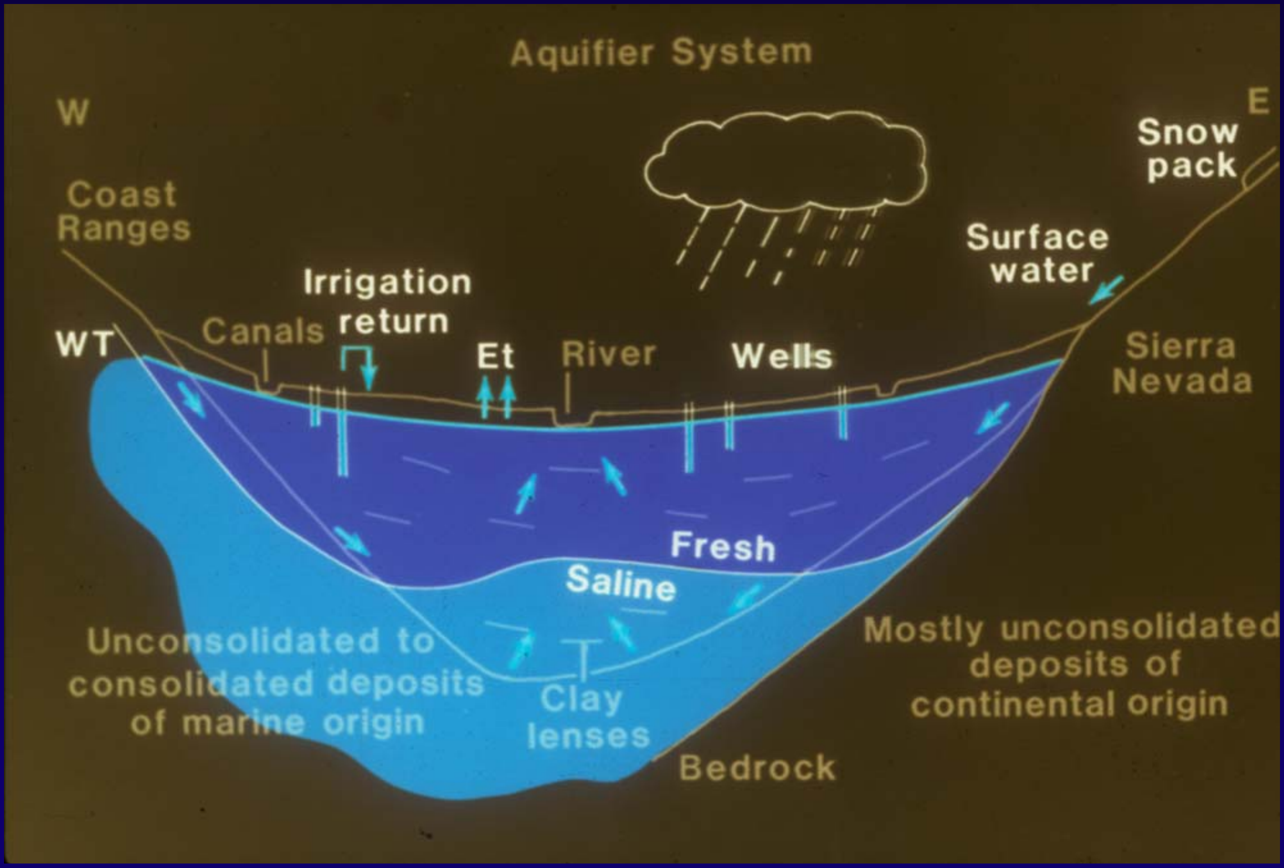
Regional Aquifer System Analysis of the Central Valley

- Gordon Bennett (leader of the national program) assigned me to work with Sandy for the duration

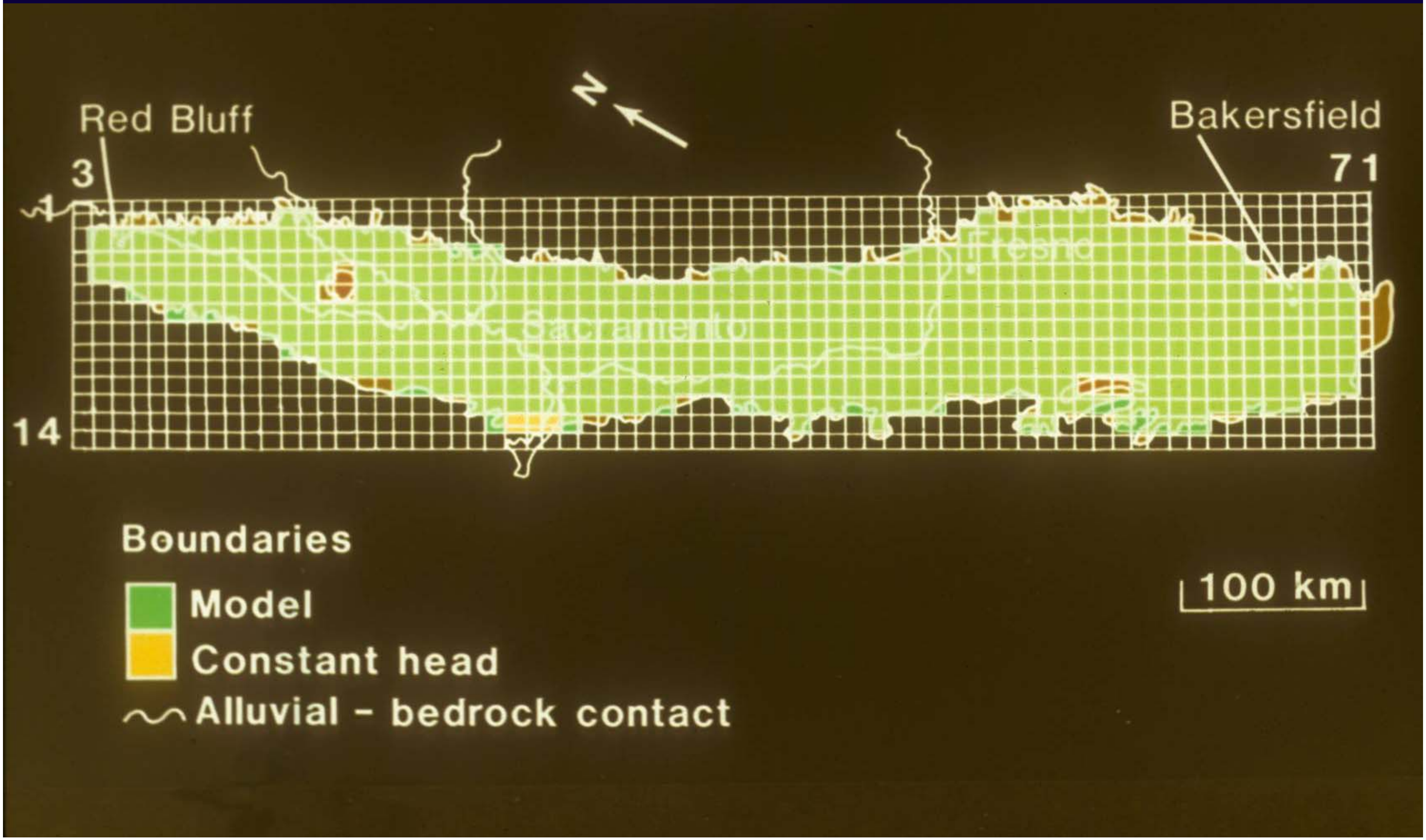
Central Valley Study summarized in four chapters of Professional Paper 1401

- Numerical model summarized in Chapter D

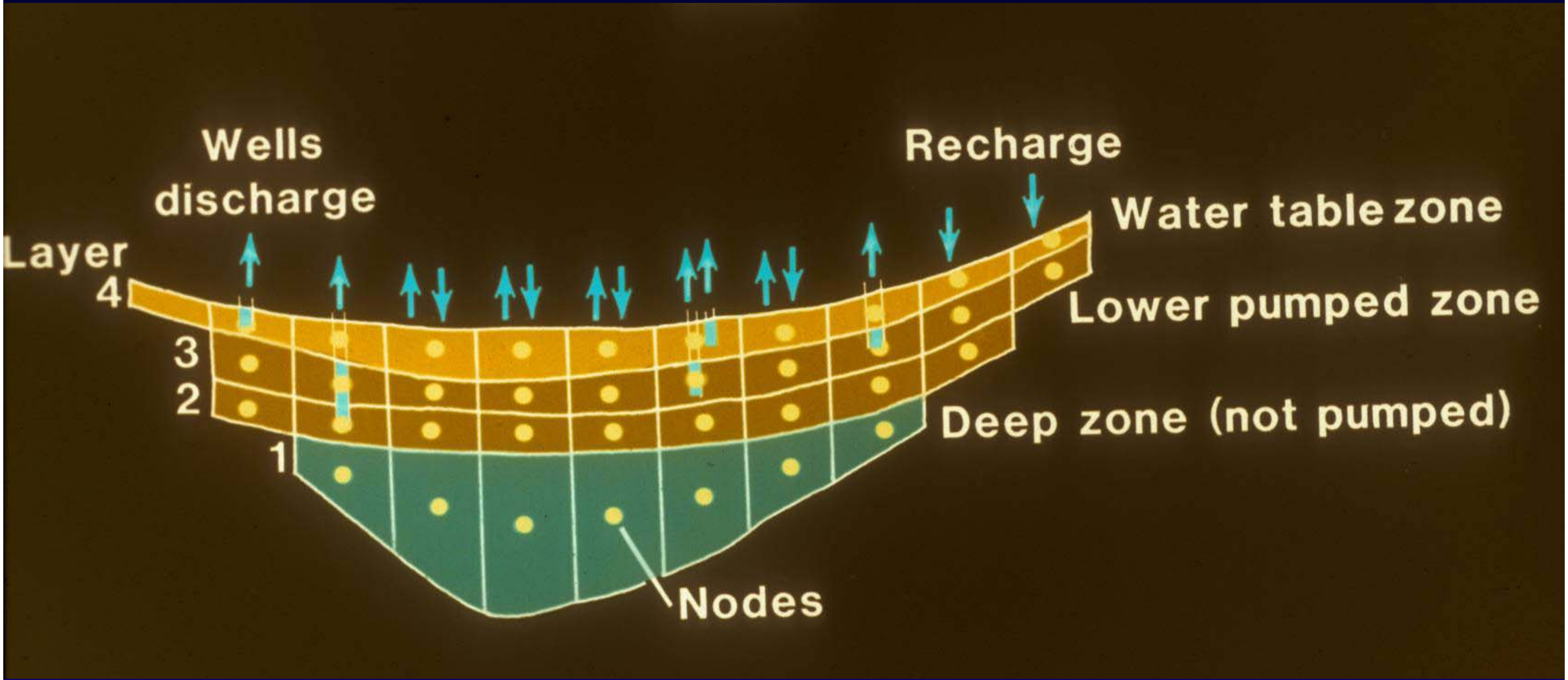
- Model included effects of inelastic compaction on aquifer storage but did not include interactions with surface water



Model Grid


Red Bluff
Bakersfield
3
1
71
14
Fresno
Sacramento
Boundaries
Model
Constant head
Alluvial - bedrock contact
100 km

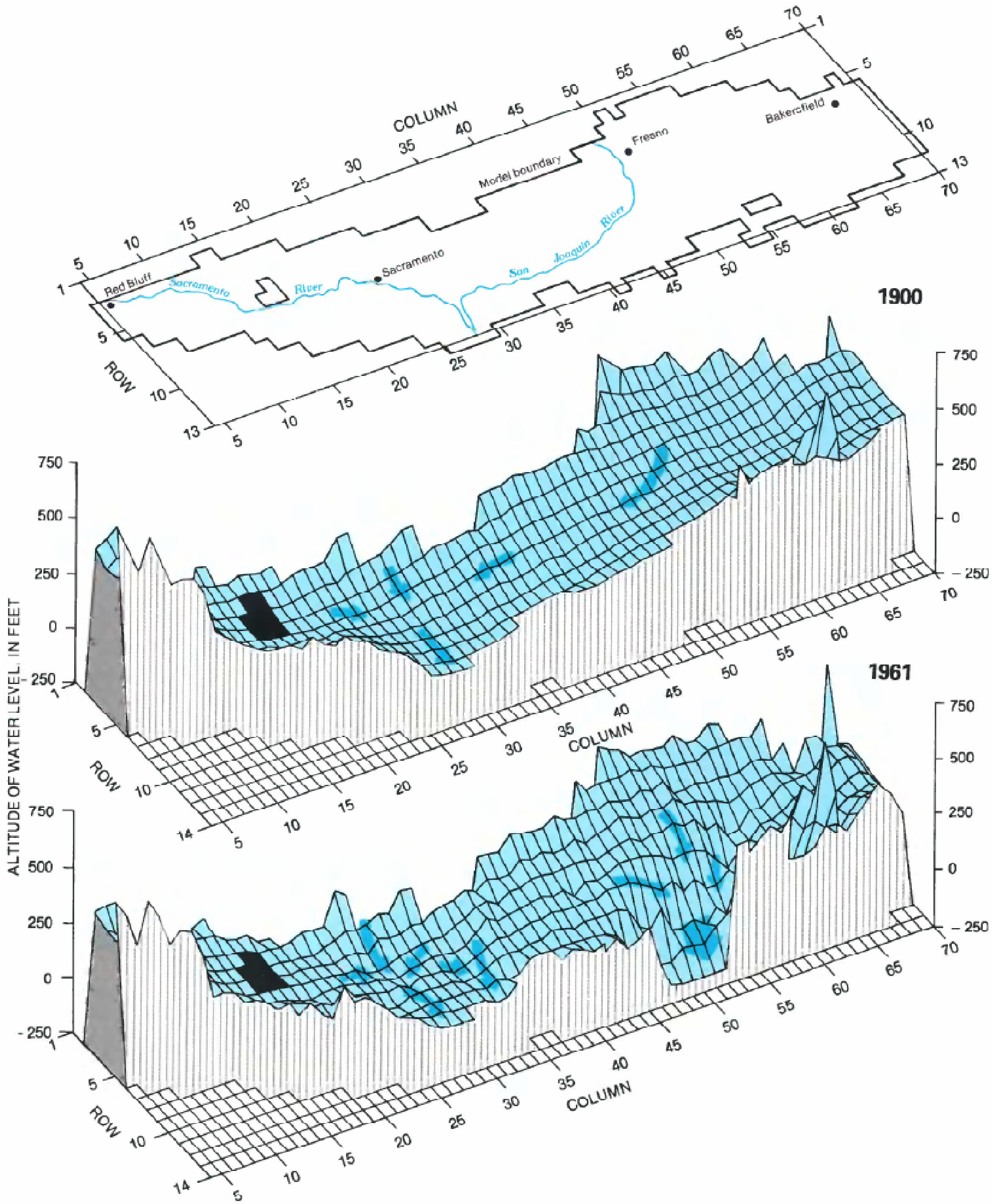
Model Layers



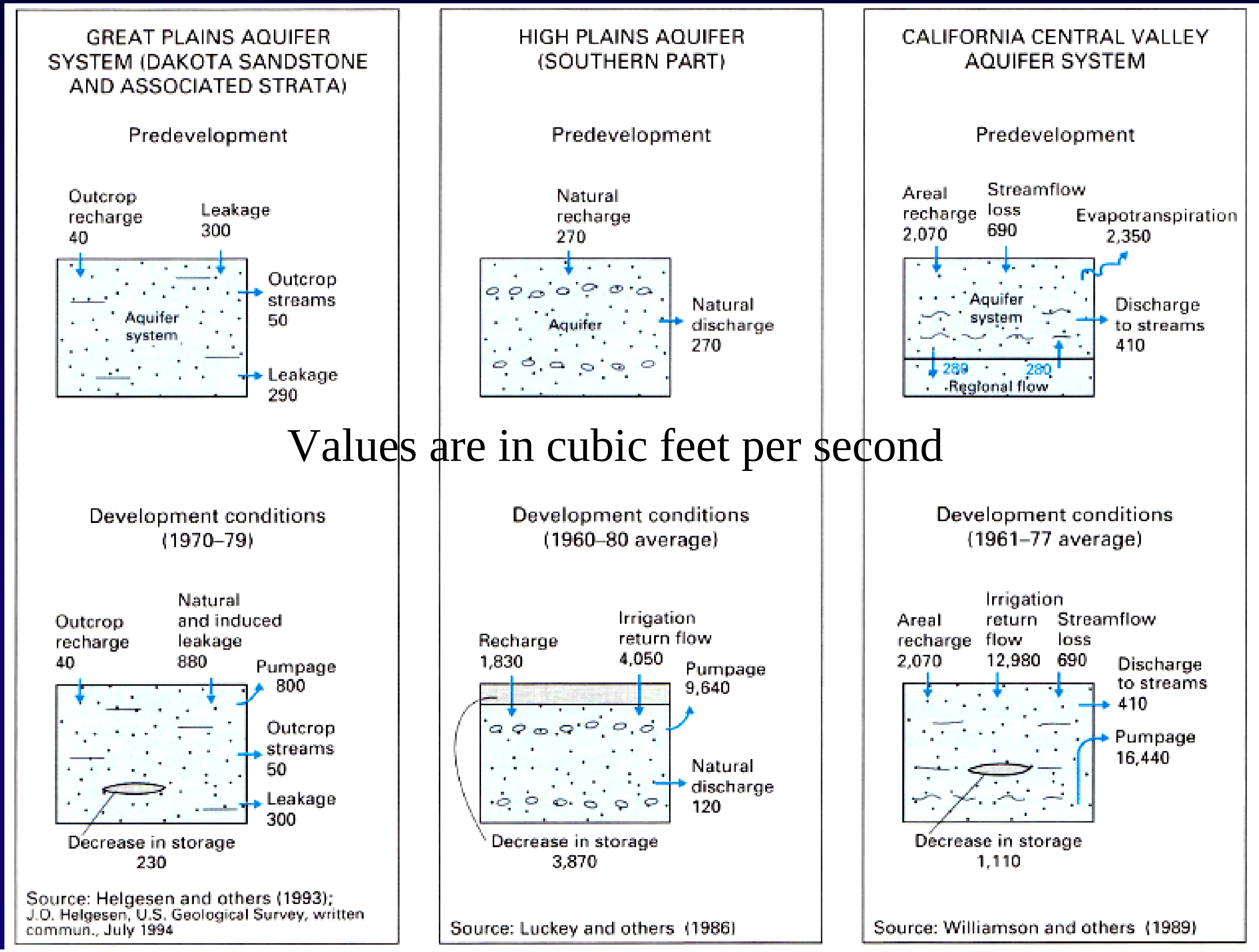
One transient simulation from 1961-77 with changes in recharge and pumping every 6 months took 1 hour and cost $200 on the USGS main frame (AMDAHL) but at least we didn't have to use card decks!

Ground-water pumping caused ground-water flow to change

Irrigation caused reduction in annual discharge to the Bay from about 24 to 15.7 million acre-feet



Comparison of changes in three regional aquifers (PP 1425)



Values are in cubic feet per second

Central Valley Ground-Surface Water Model (CVGSM) Calif. Depart. Of Water Resources (DWR)

Finite Element Grid for ground water

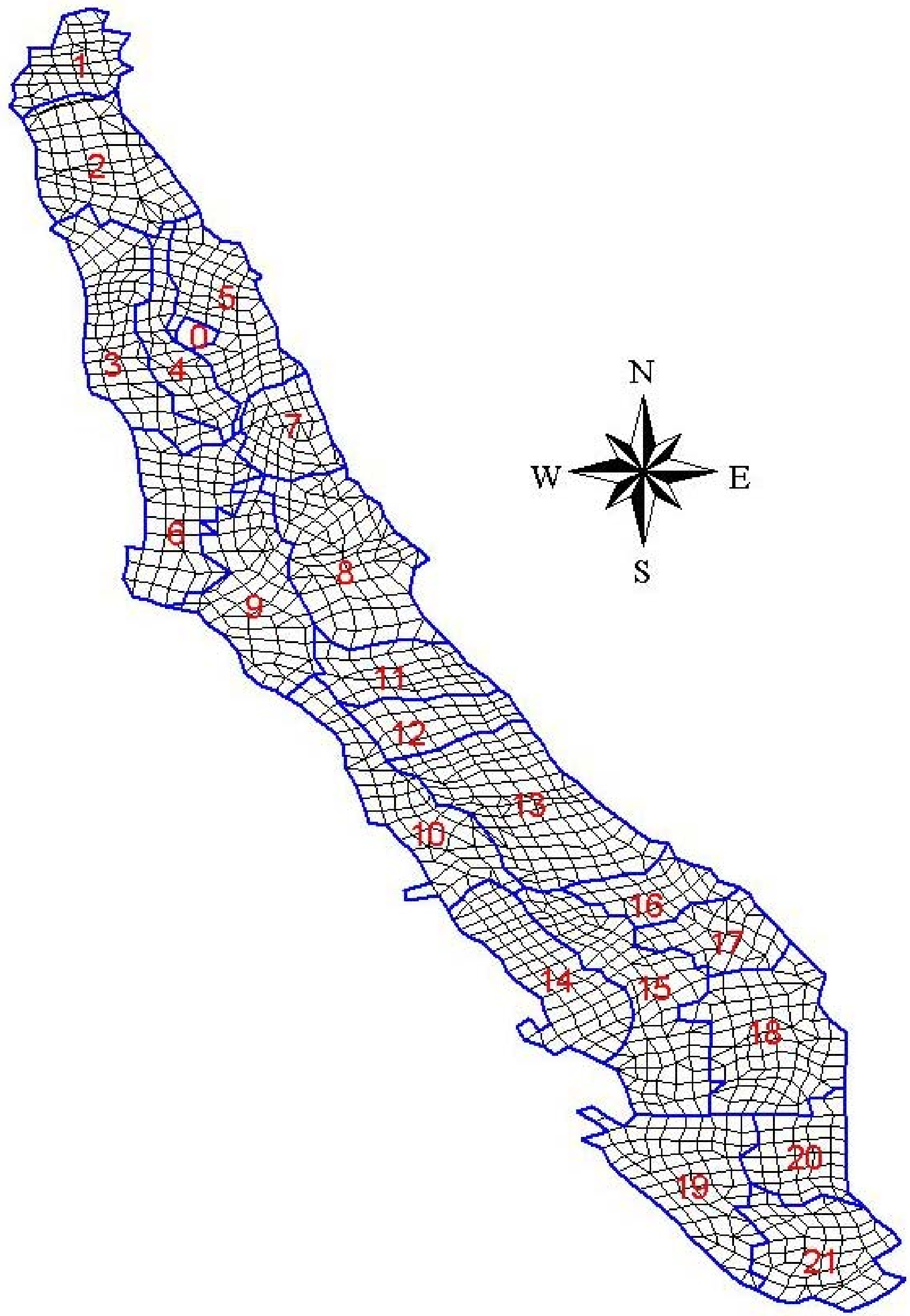
3 layers

1393 nodes

1392 elements

21 subregions

121 small watersheds



Central Valley Ground-Surface Water Model (CVGSM)

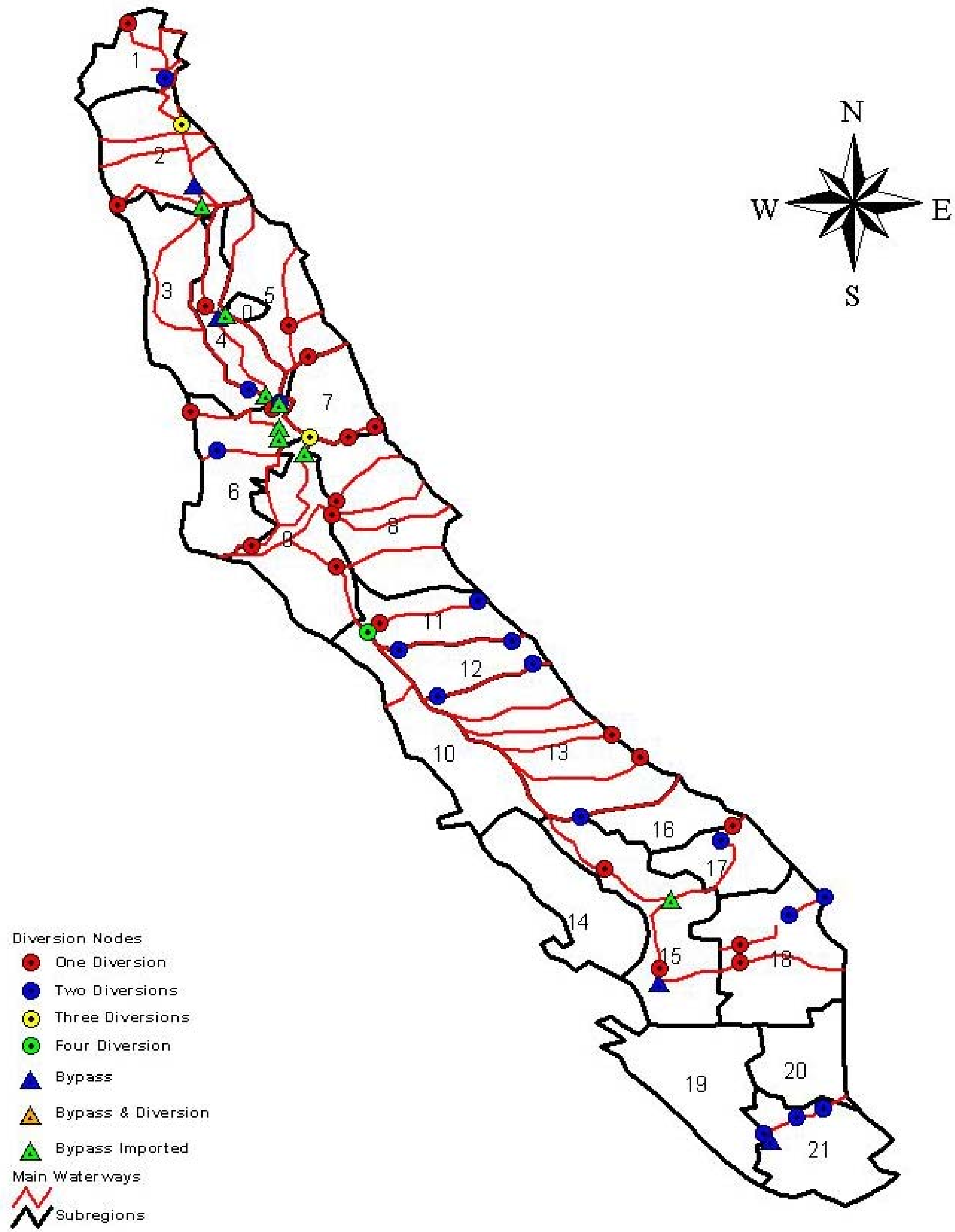
Surface water network

72 river reaches

97 surface water diversions

2 lakes

8 bypass canals



California Dept. of Water Resources CVSGM

- Monthly data 10/1921-9/1980
- Develop a comprehensive hydrologic database
- Adapt Calif. DWR and U.S. Bureau of Reclamation processes for estimating land-use-based demands
- Produce a common model that could be used by governments and agencies for studies
- Funded by DWR, USBR, SWRCB and CCWD
- Initial release in 1990
- Substantially revised in 2002

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Integrated Water Flow Model (IWFM) Application

For executables, documentation and source code, Google “IWFM”

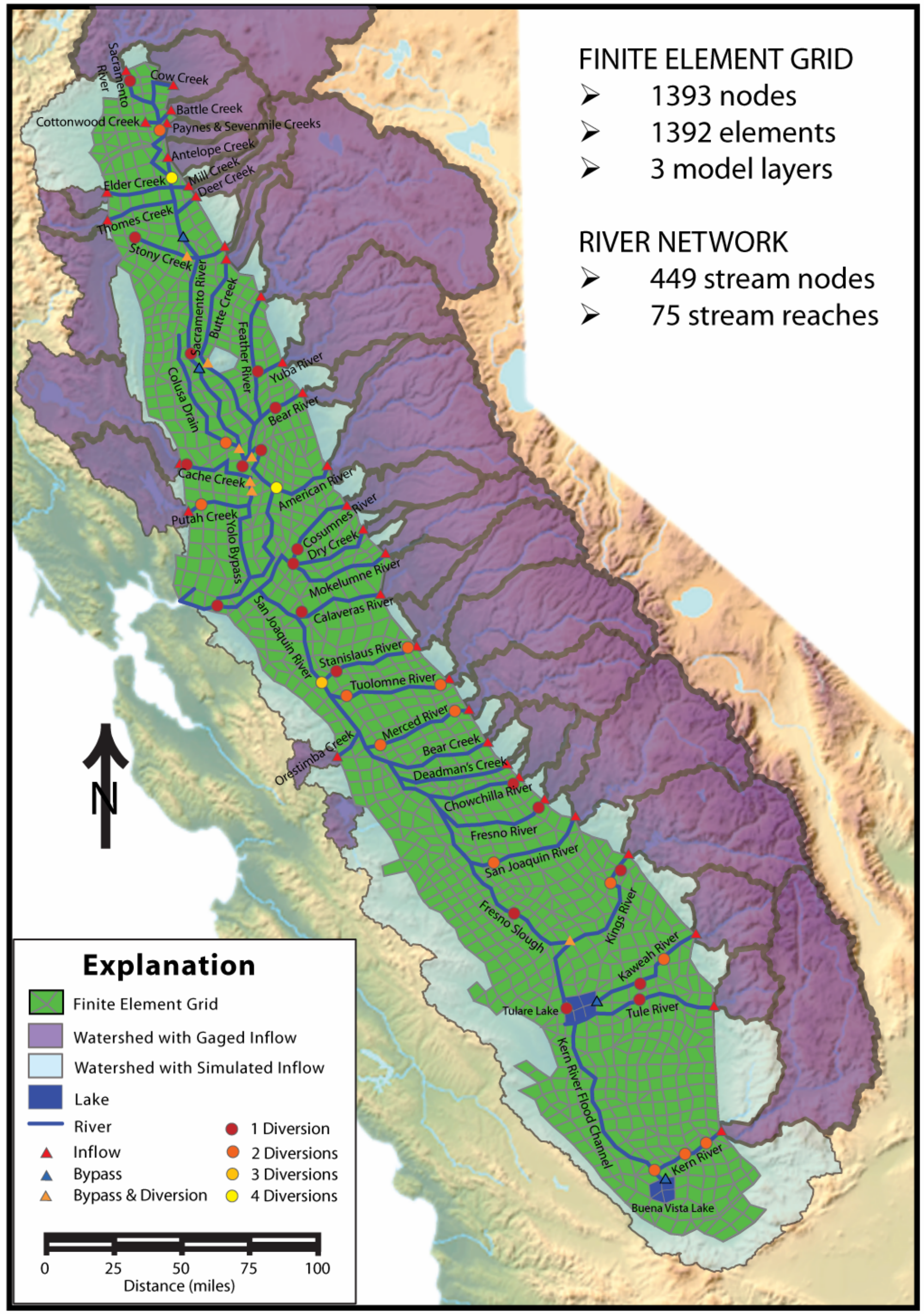
C2VSIM Model Grid

Finite element grid
- 3 layers
- 1393 nodes
- 210 small watersheds

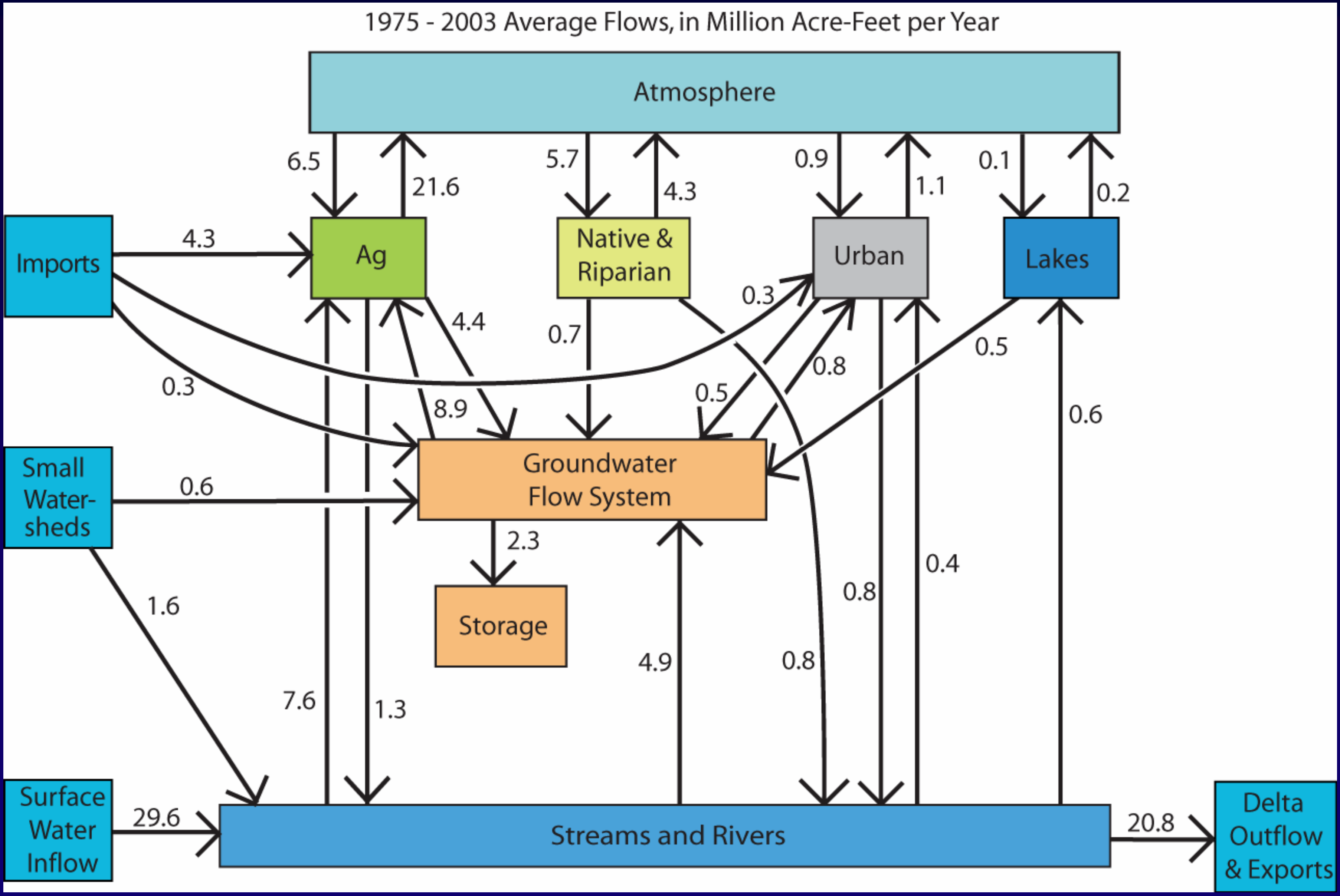
Surface water system
- 75 river reaches
- 2 lakes
- 97 diversion points
- 6 bypasses

Land use process
- 21 subregions
- 4 Land Use Types
  - Agriculture
  - Urban
  - Native
  - Riparian

simulation period
- 10/1921-9/2003



Water Budget Example

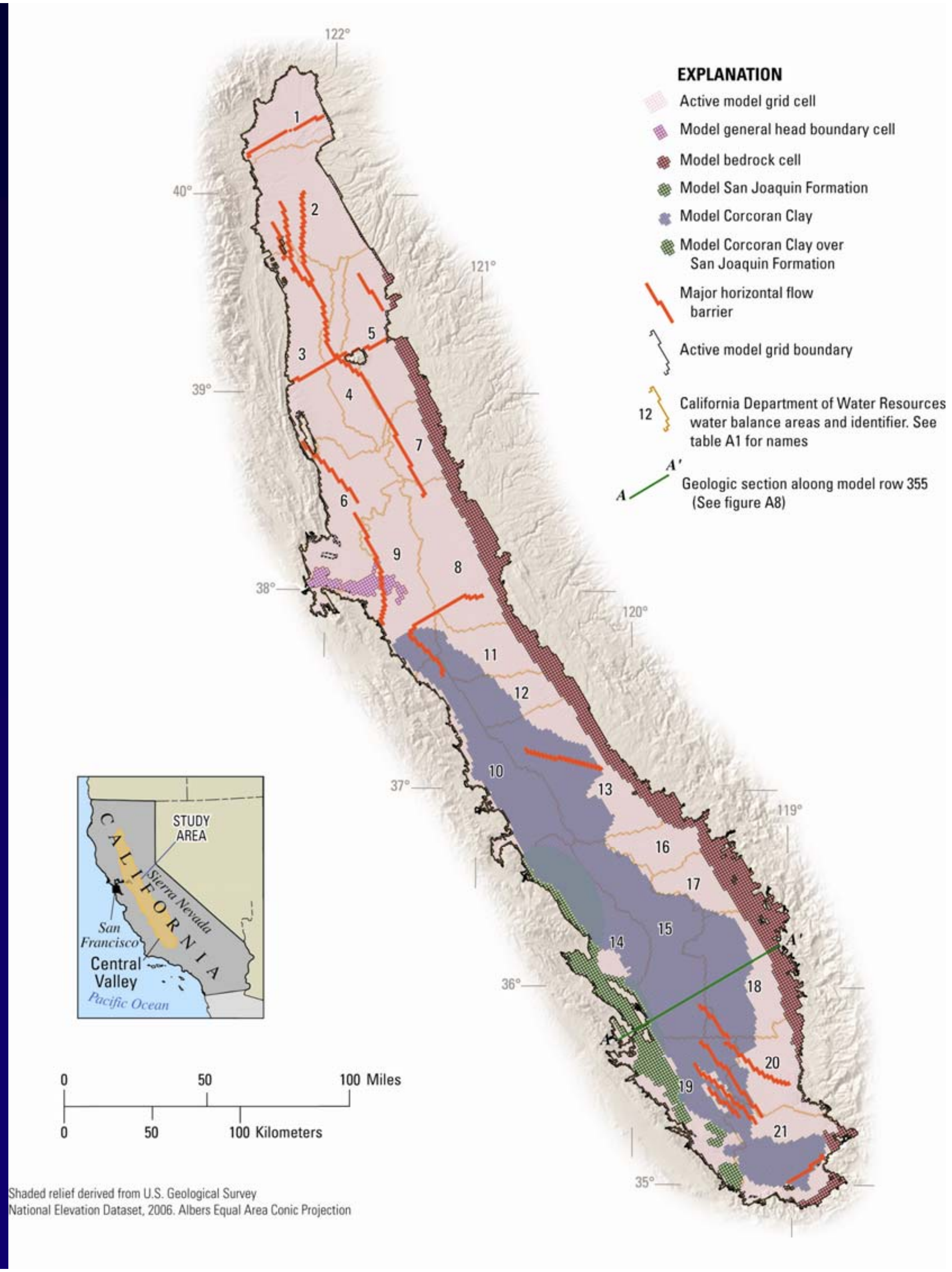


USGS National Water Resources Program

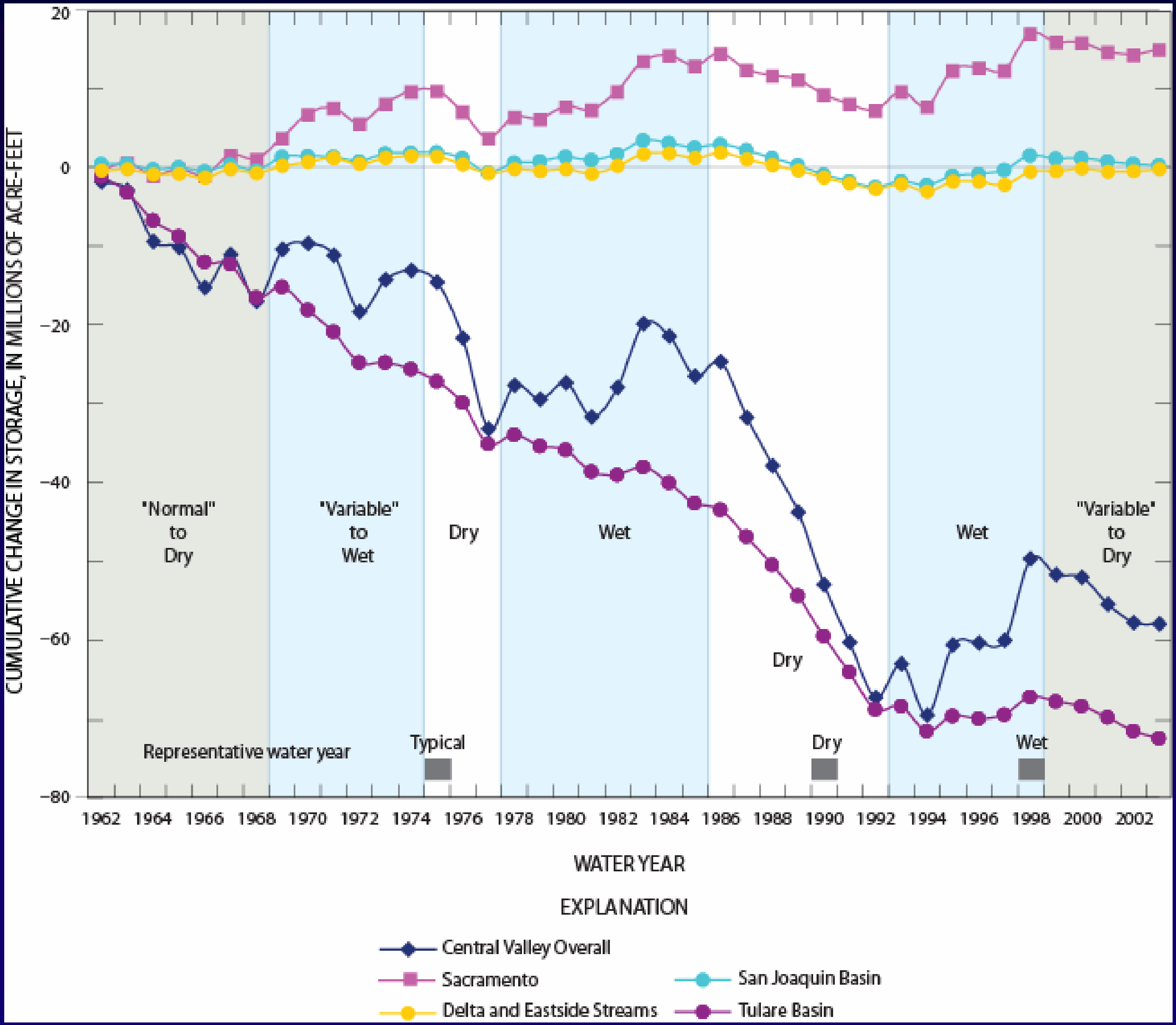
- Water Science Center of USGS recently began an analysis of the Central Valley using the new Farm Process in MODFLOW as part of regional studies for the National
- Study being done by Claudia Faunt, Randy Hanson and Kenneth Belitz at the USGS office in San Diego, and Wolfgang Schmidt at the University of Arizona (author of the Farm Process)
- Model includes better methods for simulating inelastic compaction, surface-water interactions, and effects of farm requirements

Model overview

- **Uniform one sq. mile cells**
- **1961 – 2003**
  (monthly time steps)
- **Packages\Processes**
  - **Farm (water budget)**
  - **Stream flow routing (SFR)**
  - **Wells (MNW) (municipal/ farm)**
  - **Subsidence (SUB)**
  - **Flow barriers (HFB)**
- **Sensitivity Analysis and Calibration with Parameter Estimation (UCODE)**



Change in ground water storage through time



USGS

Summary

- Studies of ground water flow in the Central Valley have mirrored the development of methods to analyze and evaluate flow and storage in aquifers
- Undoubtedly, this trend will continue into the future because of the importance of water to the economy of the Central Valley