Optimising groundwater resources in California and England

Groundwater Asset Management Meeting
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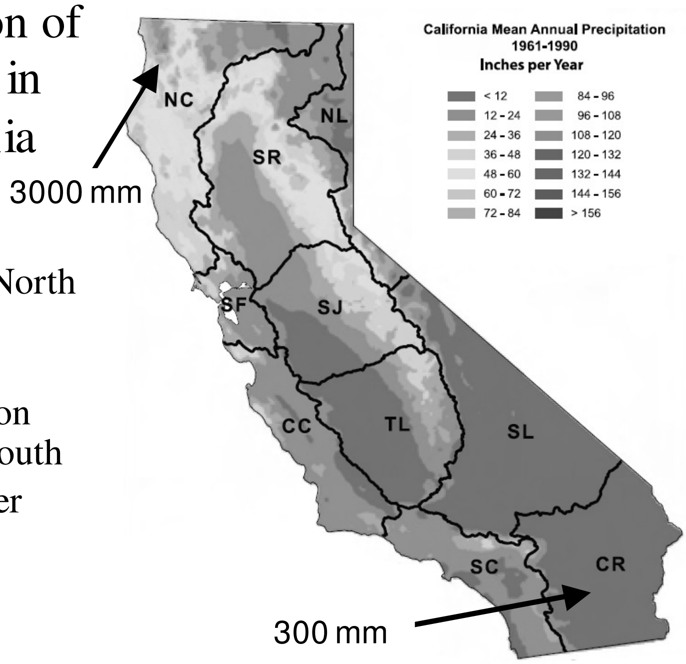
Outline

- California water management context
- Groundwater model formulations
- Integrated hydrological models
- Policy models, e.g. hydro-economic
- California – UK Discussion

Distribution of Rainfall in California



- Rainfall in North and near mountains
- Population on coast and South
- Result: water scarcity

Water Projects

Federal agencies:

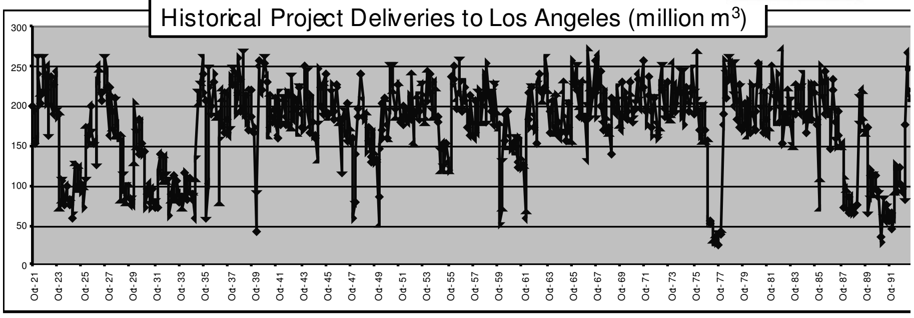
- US Bureau of Reclamation
- US Army Corps of Engineers

State:

- State Water Project

Water Management in California

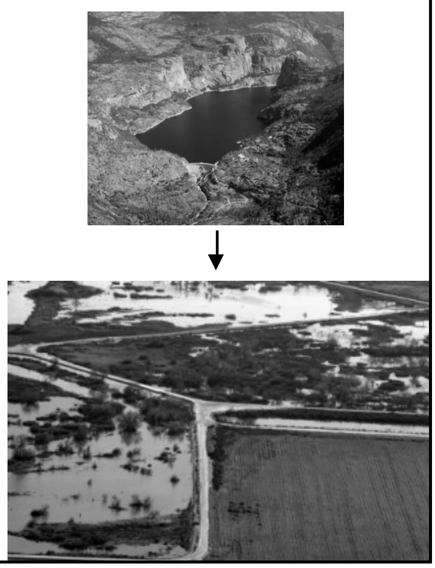
1960-80's : Large centralized water storage and conveyance projects made contracts with irrigation districts, municipal suppliers

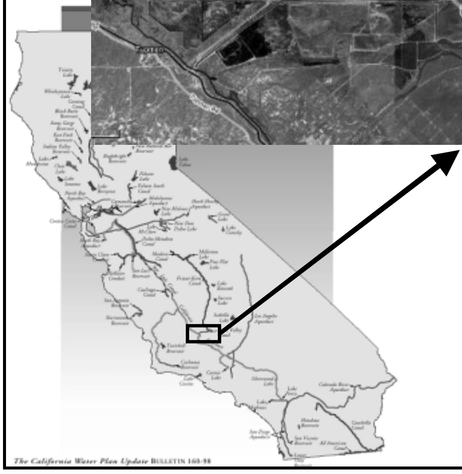


After the 1991 drought many contractors stopped relying on state and federal projects as a reliable unique external source

Water Management in California

- Larger buyers and newer irrigation districts (with junior water rights) have opted for a portfolio approach
  (conjunctive use, water trades, option contracts, conservation, waste-water reuse, desalination)
  rather than just rely on large projects
- After 1991 drought, political pressure led to increased flexibility of transfers among water right holders





Kern Alluvial Fan
Groundwater Bank

Conjunctive use of surface and groundwater requires integrated hydrological models

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Distributed Groundwater Modeling (Simulation & Optimisation)

1. Sequential time-marching (discretise space & time)
2. Eigenvalue method (discretise space, time-continuous)
3. Response functions or 'influence coefficients', 'discrete kernals'

Groundwater Flow Equation

Analytical groundwater flow equation

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)+Q = S_s \frac{\partial h}{\partial t}$$

F.D. or F.E. numerical scheme allows space discretization

$$[G]\{h\}+[D]\left\{\frac{\partial h}{\partial t}\right\} = \{Q\}$$

Sequential Time-marching (space, time discretised)

- Discretization occurs over space and time (most common, e.g. MODFLOW)
- Numerical approximations of groundwater flow equation are embedded into optimization model as equality constraints
- Simulation, optimisation solutions are identical in theory

Eigenvalue Method

- Space discretized, time continuous system of equations
- Uses matrix exponential, decomposition into eigenvalues and eigenvectors
  - → explicit solution for $\{h_t\}$ (t = management period of any length)
- Current aquifer state (incorporating past stresses) summarized into single state vector
  - → no need to account for past stresses
- Choose a reduced sets of *basic stresses* and *control variables*
  - → reduced set of equations

Response Functions

- Use a groundwater model to compile a database of responses at *control locations* caused by stresses at *management locations*
- Response matrix is used by simulation or optimization model, in lieu of running full numerical model

Response Functions Assumptions

- If relation between pumping and drawdown is linear – principle of superposition can be applied
  - multiplication of stress by a factor increases drawdown by same factor
  - Drawdown from multiple wells = sum of drawdowns induced by each well
- Relevant for confined aquifers or thick unconfined aquifers (drawdown negligibly affects transmissivity).

Distributed Groundwater Representations for Integrated Models

	Sequential time marching	Eigenvalue	Response function
Simulation	Many managed stresses, control pts.	Some managed stresses, control pts.	Few managed stresses, control pts.
Optimisation	Embedding method – beware instability	Embedding method – beware instability	Most widely used, software exists

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Two integrated hydrological models of California's Central Valley

Integrated = joint surface and groundwater simulation

- C2VSim (application of IWFM) - California Dept. of Water Resources
- CVRASA2 (application of MODFLOW) - USGS

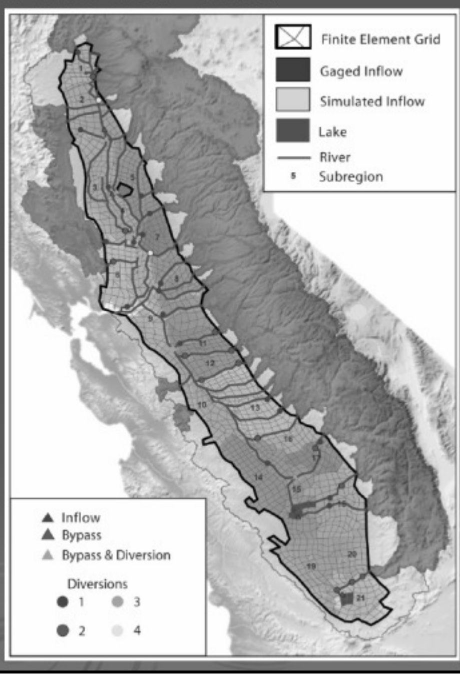
CA DWR

C2VSIM Model Grid

Finite Element Grid
- 3 layers
- 1393 nodes
- 1392 elements

Surface Water System
- 72 stream reaches
- 97 surface water diversion points
- 2 lakes
- 8 bypass canals

Land Use Process
- 21 subregions
- 4 Land Use Types
  - Agriculture
  - Urban
  - Native
  - Riparian

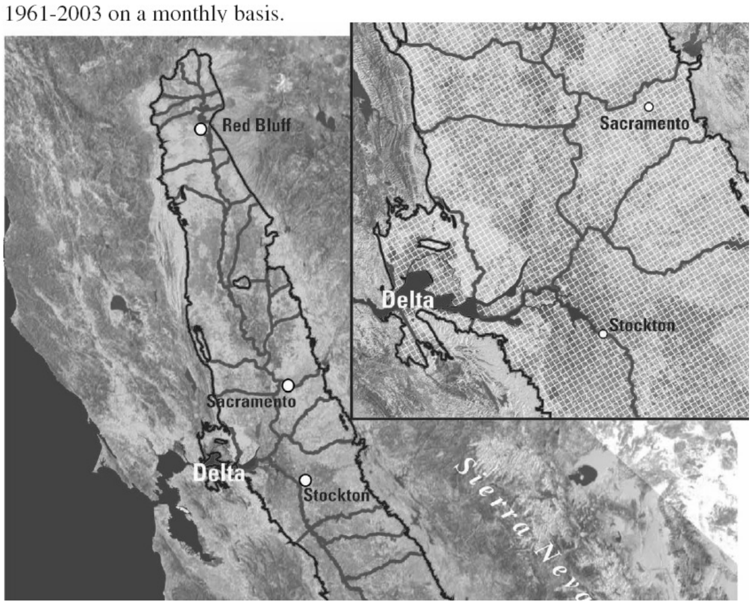


Charlie Brush, 2008

USGS

CVRASA2

An extensive update of the original USGS Central Valley Regional Aquifer Systems Analysis (CVRASA) is nearing completion. This new model, CVRASA2, includes the entire Central Valley aquifer system and covers the period from 1961-2003 on a monthly basis.



Distributed Groundwater Models within Systems Models

Model Suite	**Generic Groundwater model**	**Applications to Central Valley**	**Integration with surface hydrology**	**Storage & allocation simulation**	**Regional multi-period optimization**
CA DWR	IWFM	C2VSim	C2VSim	CALSIM-III & groundwater response functions	CALSIM-III with discrete kernels **?**
USGS	MODFLOW	CV-RASA2	Farm-process package		Groundwater Management process (GWM) **?**

Don't exist yet

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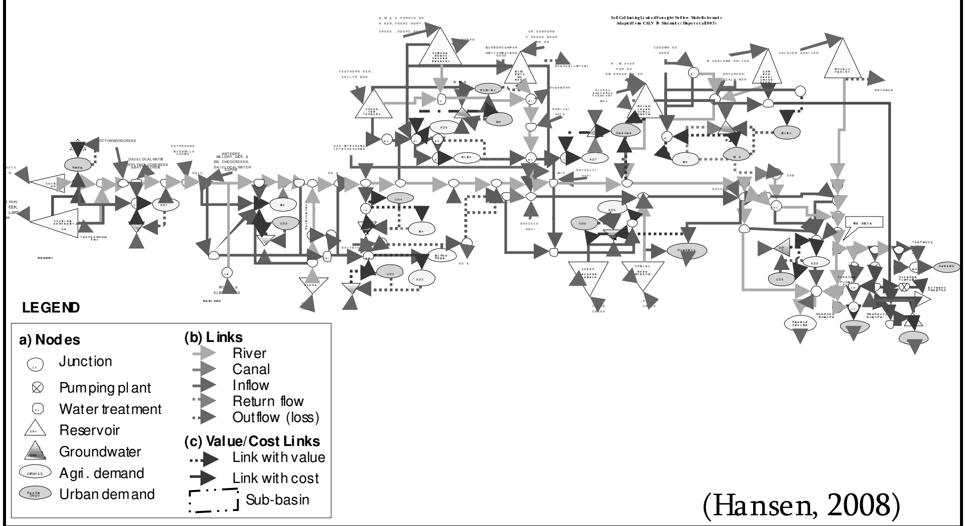
Hydro-economic Model Objectives

- Optimize groundwater with surface water network (→ identify promising conjunctive use opportunities)
- Maximize economic benefit (economic demands, operating costs)
- Investigate different groundwater optimisation formulations using upscaled 2D finite difference model

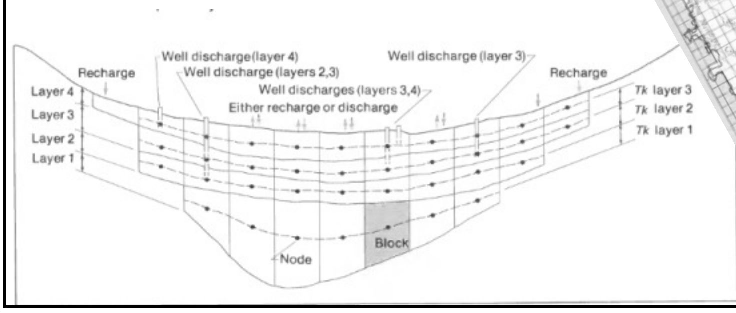
Hydro-economic model network schematic

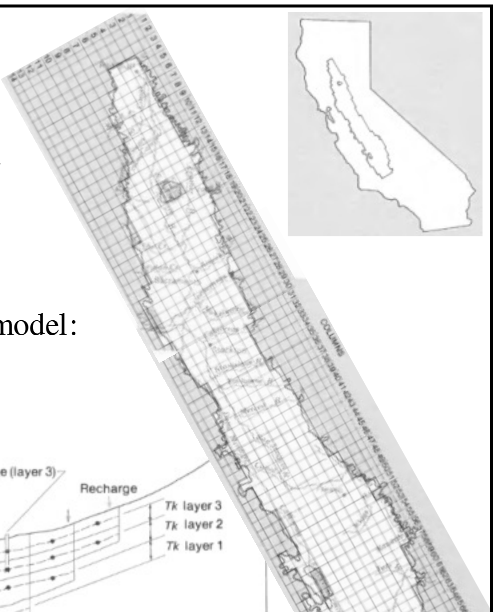


(Hansen, 2008)

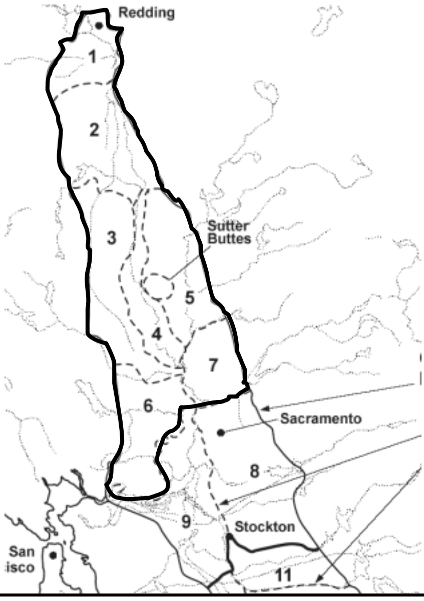
CV-RASA1 USGS Groundwater Model (1989)

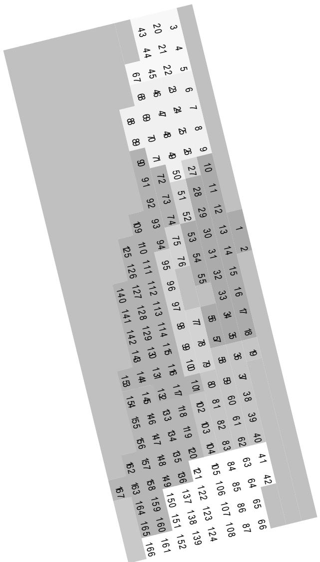
Finite-Difference Groundwater model:
(529 6 x 6 mile cells, 4 layers)





Economic Demands





Hydro-Economic Optimisation

$$Z = \sum_t agBenefits^t + \sum_t urbBenefits^t - \sum_t c_{ij} X_{ij}^t - \sum_t C_{gj} X_{gj}^t - \sum_t INFEAS_i^t \quad \forall i, g, j$$

Maximize economic benefits - costs

$$S_i^{t+1} - S_i^t = \inf_i^t + \sum_j X_{ji}^t - \sum_j e_{ij} X_{ij}^t + INFEAS_i^t \quad \forall\, i, t$$

S.T. Mass balance at network nodes: ΔS = In - Out

$$C_{gj}^t = unitc * (elev_g - H_g^t) \quad \forall\, g, d, t$$

Groundwater pumping costs

$$H_i^t = f(H_i^{t-1}, NETX_i^t, \ldots) \quad \forall\, i \in GHN, \quad t$$

Groundwater heads

$$NETX_i^t = i_i^t + \sum_j X_{ji}^t - \sum_j X_{ij}^t \quad \forall i \in GHN, \quad t$$

Net recharge to groundwater subbasins

$$\min x_{ij} \le X_{ij}^t \le \max\ x_{ij} \quad \forall\, i, j, t$$

$$\min s_i \le S_i^t \le \max s_i \quad \forall i, t$$

$$\min h_i \le H_i^t \le \max h_i \quad \forall i, t$$

Capacity constraints: flow, storage, groundwater head

Groundwater representations

Lumped groundwater sub-basin:

$$H_i^t = H_i^{t-1} + \frac{NETX_i^t}{storcoef_i * area_i} \qquad \forall i \in GHN, \quad t$$

Sequential time-marching FD:

$$H_n^t = \left(\sum_m^N D_{nm} * H_n^{t-1} + \left(rhs_n^{t-1} + NETX_n^{t-1} \right) * \Delta t \right) * \left(\sum_m^N \Delta t * \left(G_{nm} + D_{nm} \right) \right)^{-1} \qquad \forall n \in GWMC, \quad t$$

Eigenvalue:

$$H_i^t = \sum_{n=1}^N ared_{in} * \left(e_n * L_n^{t-1} + \sum_i f_{ni} * NETX_i^t \right) \qquad \forall \quad i \in GHN, \quad t$$

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UK – CA discussion

- Are tools, lessons transferable?
- Similarities:
  - Increasing water scarcity
  - Benefits from conjunctive use
  - Stream-aquifer interaction modelling is key
- Differences:
  - CA: Uncontrolled groundwater use is associated to land right (no metering); management is a local initiative
  - UK: Groundwater extraction licensing system

Conclusions

- Several methods available to model groundwater flow within integrated models
- Choice should depend on
  - ratio of management locations / total model cells
  - linearity of hydrogeology, spatial resolution of results
- Choice affects model size, speed and accuracy
- Integrated surface and ground water models improve conjunctive use
- Some value of shared UK-CA tools and methods

Thank you

Reference:

Harou J., Lund J., (*in press*), Representing Groundwater in Water Management Models - Applications to California, PIER Report: California Energy Commission

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