Integrated Management of Surface Water and Groundwater – Approaches and Systems Tools

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Outline

- Systems Tools
- Simulation Models
- Optimization Models
- Multiobjective optimization
- Linking Simulation with Optimization
- Solvers
- Upper San Pedro River Basin Study
- Water Supply in Southern California
- Saltwater Barrier Projects in Southern California
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Systems Tools

- Simulation
- Optimization

Simulation Models

- Flow model (MODFLOW)
- Transport model (MT3DMS, FEMWATER, SUTRA, SEAWAT-2000)
- SEAWAT-2000 is based on MODFLOW-2000 and MT3DMS (USGS)

Optimization Models

Objective function and constraints

$$\min \; f(X)$$

subject to

$$g_i(x) \geq 0 \; , \; i = 1, 2, \ldots. m$$

$$\mathrm{x}_{\mathrm{j}} \geq 0 \; , \; j = 1, 2, \ldots. n$$

Multiobjective Optimization

- Vector optimization

$$\max Z(X) = [z_1(x), z_2(x), ..., z_p(x)]$$

subject to

$$g_i(x) \leq 0, \quad i = 1, 2, ...m$$

$$x_j \geq 0, \quad j = 1, 2, ...n$$

where

$p =$ objectives

$x = n -$ dim vestor of decision variables

$Z(X) =$ objective function

Multiobjective Optimization

- Pareto Optimality: A Pareto optimal alternative is one for which increasing the optimal level of satisfaction of one of the objectives can be done only at the expense of decreasing the optimum level of another objective

Multiobjective Optimization

Weighting method

$$\max \sum_{k=1}^{p} w_k z_k(x)$$

subject to $x \in X$

where $w_k \geq 0$ for all k and strictly positive for at least one objective

The noninferior set and the set of noninferior solutions can be generated by parametrically varying the weights in the objective function

Multiobjective Optimization

Constraint Method

$$\max z_r(x)$$

subject to

$$x \in X$$

$$z_k(x) \geq L_k \quad all\ k \neq r$$

Parametric variation of the L_k traces out the noninferior set.

Linking Simulation Model with Optimization

- Objective Function
- Constraint set (simulation model, upper and lower bounds, etc.)

- The embedding approach
- The response matrix approach
- Others

Embedding Approach

- A finite-difference or finite-element model is directly included as a part of the constraint set.
- For a linear model and linear objective function, the formulated problem can be solved by linear programming (LP)
- Quasilinearization can be used to linearize the nonlinear model, and iterate

Response Matrix Approach

- A simulation model is used to determine the influence of pumping/recharge at selected locations
- The influence coefficients form the response matrix
- The response matrix replaces the simulation model and is included in the constraint set of an optimization model

Response Matrix Approach

- Dimensionality is drastically reduced
- Response matrix is predicated on an initial policy
- For nonlinear problems, iteration is required for convergence

Others

- Differential dynamic programming
- Cutting plane

Linking Simulation with Optimization

Influence coefficient method (Becker and Yeh, 1972)

$$h_s\left(\mathbf{q}^1\right) = h_s\left(\mathbf{q}^0\right) + \sum_v \left.\frac{\delta h_s}{\delta q_v}\right|_{\mathbf{q}=\mathbf{q}^0} \left(q_v^1 - q_v^0\right)$$

- requires an initial policy $(\mathbf{q}^0)$
- nonlinear system: iteration is required

Gradient Calculation

- Parameter perturbation method (influence coefficient, finite-difference) - (L+1) simulation runs (L=no. of parameters)
- Sensitivity equation method - (L+1) simulation runs
- Adjoint state method - (N0+1) simulation runs (N0=no. of observation wells)

Gradient-Based Algorithms

- Linear programming (LP)
- Mixed integer LP (MILP)
- Quadratic programming
- Nonlinear programming (NLP)
- Mixed integer nonlinear programming (MINLP)
- Dynamic programming

Table 1. Commercially Available Solvers

Solver	Web Site	Approach
CONOPT	www.conopt.com	From Arki Consulting. Uses GRG, SLP, and SQP.
CPLEX	www.ilog.com/products/cplex	ILOG's commercial solver. Uses proprietary primal and dual simplex; interior point; branch and bound.
DICOPT	egon.cheme.cmu.edu/Group/ResearchAreas.html	From Carnegie Mellon University. Uses outer approximation and equality relaxation techniques.
GRG2	www.solver.com	Frontline System's GRG routine, used in the Excel solver.
LINGO	www.lindo.com	LINDO Systems' commercial solver. Uses proprietary primal/dual simplex; interior point; branch & bound; GRG/SLP.
MINOS	www.sbsi-sol-optimize.com	From Stanford University. Uses primal simplex for LP and reduced gradient/quasi Newton for NLP.
OSL	www-3.ibm.com/software/data/bi/osl	IBM's commercial solver. Uses proprietary primal and dual simplex; interior point; branch and bound
PCx	www.softwareshop.anl.gov/pcx.html	Freeware LP solver from ANL using interior point predictor-corrector.
SNOPT	www.sbsi-sol-optimize.com	From Stanford University. Uses SQP with an augmented merit function.
XPRESS	www.dashoptimization.com	Dash's commercial solver. Uses primal and dual simplex; Newton barrier; branch and bound

Table 2. Solver Capability

Solver	LP	MILP	NLP	MINLP
CONOPT	✓		✓	
CPLEX	✓	✓		
DICOPT				✓
GRG2	✓		✓	
LINGO	✓	✓	✓	✓
MINOS	✓		✓	
OSL	✓	✓		
PCx	✓			
SNOPT	✓		✓	
XPRESS	✓	✓		

Global Search

- Genetic algorithm
- Simulated annealing
- Tabu search

- NSGA-II (nondominated sorting genetic algorithm)
  Deb, K. (2001), Multi-Objective Optimization Using Evolutionary Algorithms, 1st ed., xix, 497 p., John Wiley & Sons, Chichester; New York.

Global-Local Optimization

- Sequential global-local method
- Embedded global-local method

GA with Gauss-Newton

Upper San Pedro River Basin

- Multiobjective optimization
- Environmental objectives
- Sustainability - sustainable development involves taking care of the needs of the present without comprising the ability of future generation to meet their own needs
- Simulation and optimization

Upper San Pedro River Basin

- Located in the semiarid borderland of southeastern Arizona and the state of Sonora, Mexico

- San Pedro Riparian National Conservation Area (SPRNCA): first riparian reserve established by the US Congress in 1988 to preserve the rare riparian habitat (migratory birds, 82 species of mammals, 43 kinds of reptiles and amphibians, and populations of cottonwood-willow and mesquite trees) from damage due to increasing water demands in the surrounding areas.

Management Questions

- How to balance water needs for human consumption and conservation of riparian habitat?
- Options
  - forget about the trees...
  - stop development...
  - seek compromise

Management Model

- Multiobjective function (3 objectives)
  - Minimizing the net present value of groundwater depletion mitigation cost
  - Maximizing aquifer yield
  - Minimizing drawdown at selected locations
- Constraints
  - Network constraints (supply, demand, treatment and discharge nodes)
  - Groundwater head constraints

Water Supply in Southern California

- Imported water from the State Water Project by the California Aqueduct.
- Imported water from the Colorado River by the Colorado Aqueduct.
- Imported water from Mono Lake/Owens Valley by the Los Angeles Aqueduct.
- Local surface water
- Local groundwater (~40 %)
- Reclaimed water

The Metropolitan Water District of Southern California (MWD)

- Serving a population of 18 million
- Supplies 2.8 km3 (2.3 MAF) of water
- Service area: 13,462 m2 (5,200 sq mi)
- Six counties: San Diego, San Bernardino, Riverside, Orange, Los Angeles, Ventura)
- Two sources of imported water: State Water Project (SWP) and Colorado River Aqueduct (CRA)
- 1,246 km (775 mi) of pipelines
- 9 reservoirs
- 18 groundwater basins

Conjunctive Use

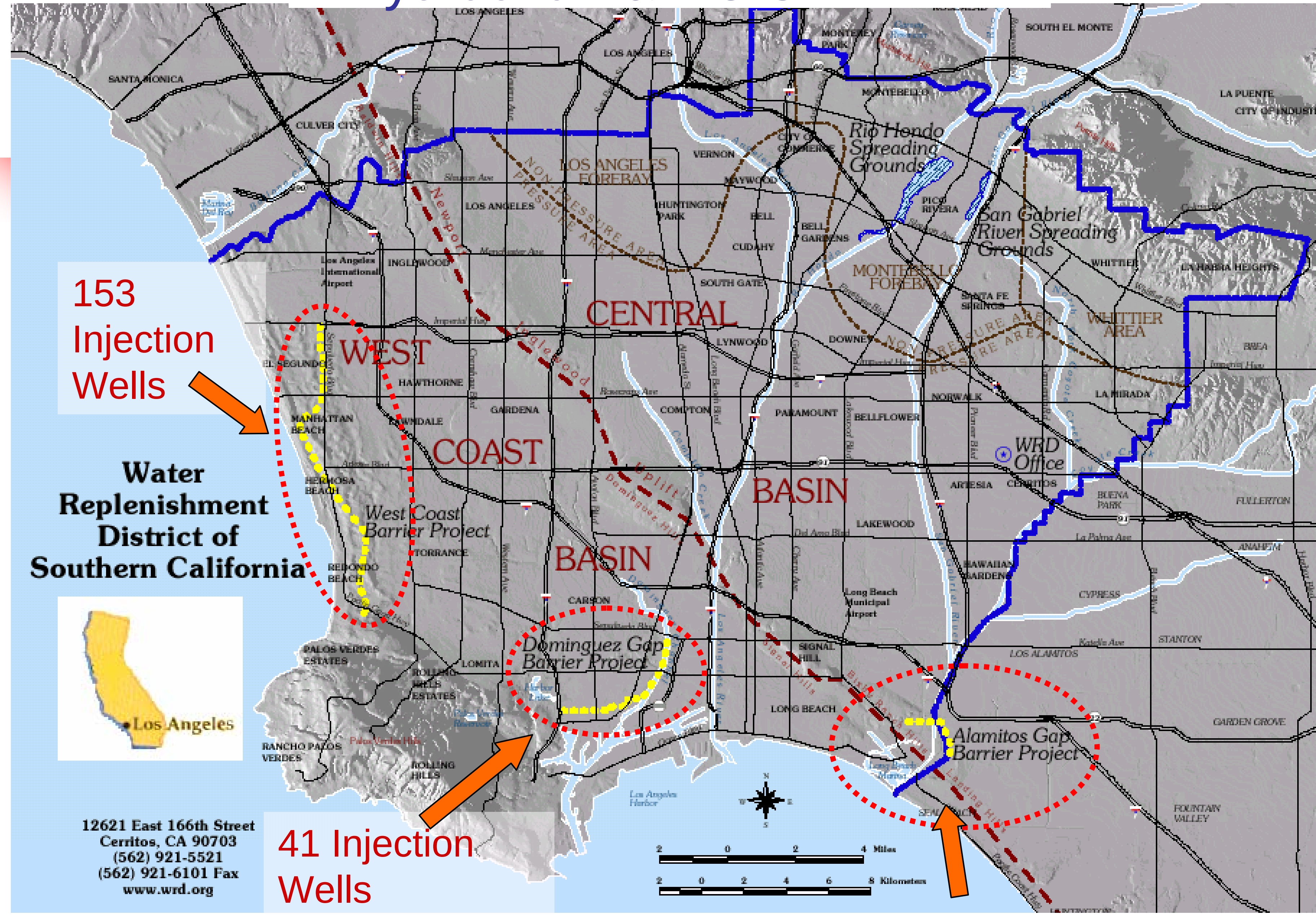
- Surplus surface water during period of abundance that would otherwise be lost to the ocean would be used to recharge local groundwater basins by direct or indirect means and remain in storage until needed during seasons of shortage or years of drought.

- By controlling the total water resources of a region, conjunctive use planning can increase the efficiency, reliability, and cost-effectiveness of water use, particularly in river basins with spatial or temporal imbalances in water demands and natural supplies.

Saltwater Barrier Projects in Southern California

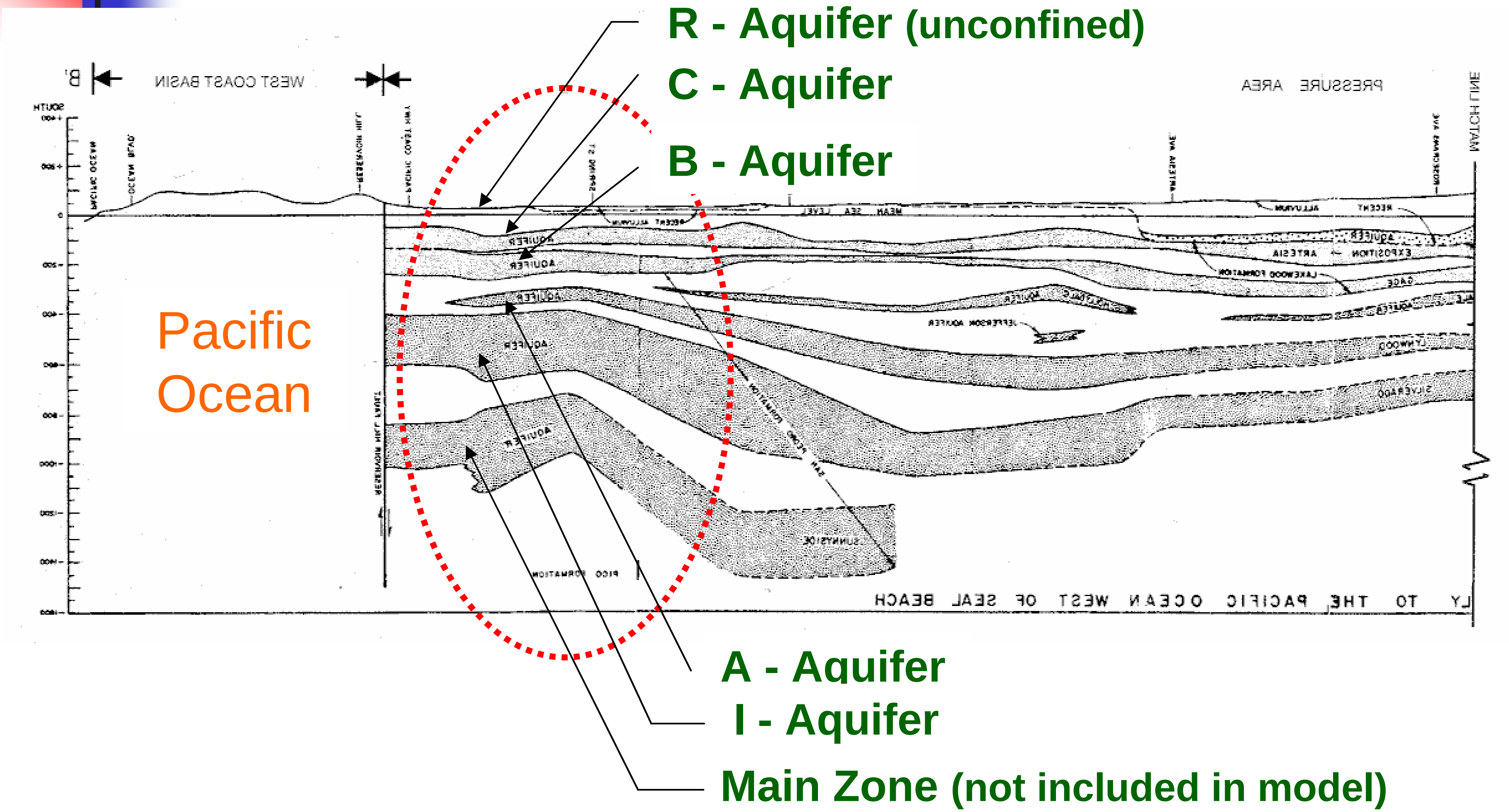
- An array of injection wells, parallel & in close proximity to the coastline
- Since 1959, three saltwater barrier projects have been implemented: West Coast Basin, Dominquez Gap, Alamitos
- Protect a 20.3 MAF of groundwater reserve in the Los Angeles County

Hydraulic Barriers



35 Injection Wells

Los Alamitos Geologic Cross Section



Conclusions

- Systems analysis provides a complete documentation and understanding of how and why the system works
- Small improvements in operations of existing systems translate into large benefits

Conclusions

- Simulation and optimization models provide the decision-makers with a set of tools to analyze the behavior of a water resources system
- Drastic improvement in computational technology, the availability of solvers, together with user-friendly interactive interfaces make systems analysis much more practical

Thank You