UC DAVIS
CENTER FOR WATERSHED SCIENCES

CALVIN
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GitHub repo: https://github.com/msdogan/CALVIN-shortcourse

Hydroeconomic modeling

- Combines water resources systems & economics
- Allocates water among different users
- Water allocations are driven by economic value of water
- Economic costs & benefits are constrained by hydrology (water availability) & policies

Hydroeconomic modeling

Useful for

- Represents regional scale hydrologic, engineering and economic aspects
- Provide a framework for water resources systems
- Solution-oriented tools for discovering new strategies
- Investigates water management schemes and policy insights
- Useful for water resources planning & management decisions

Components

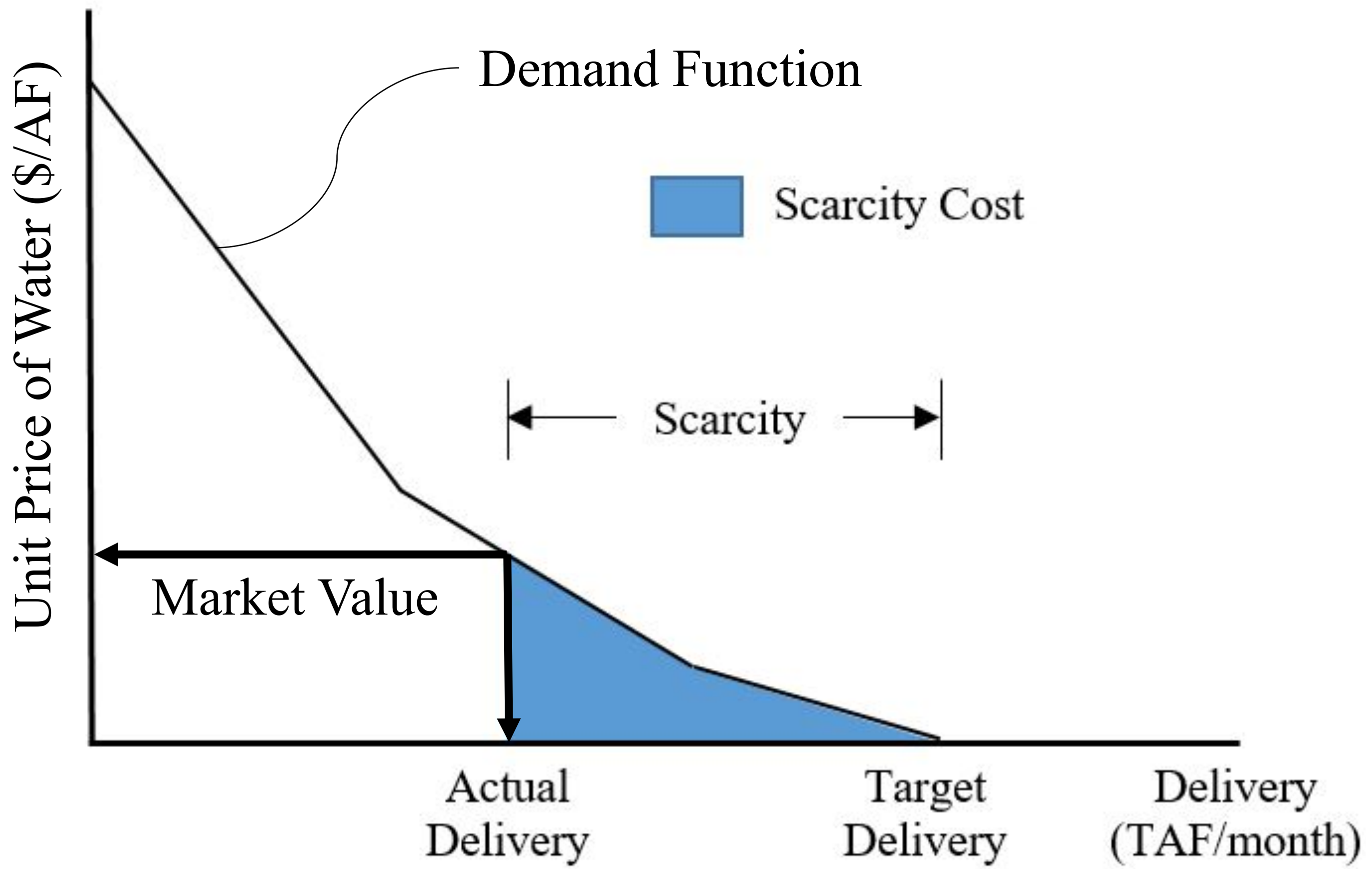
Hydro-economic models represent all major hydrologic and engineering parts of the system

- Water balance components
  - River flows, evaporation, groundwater recharge, and return flows
- Infrastructure components
  - Canals, reservoirs, treatment plants, surface and ground water pumping, and artificial recharge
- Water demands (agricultural, urban, and environmental), operating costs, and operating rules

Why an economical approach?

- Water is a scarce source
  - Should be managed and allocated efficiently
  - Economics offers methods to evaluate equity and efficiency
- Water has a value as a:
  - Commodity in various production processes
  - Diluter and transporter of waste
  - Recreational space
  - Ecological habitat

Economic Value of water



Formulation and design

- Hydro-economic models use simulation and optimization separately or together.
  - Simulation (What if?)
    - Simulate decisions on a time-step
    - Based on operating rules
  - Optimization (What is best?)
    - Objective function (minimize costs, maximize benefits)
    - Physical and management constraints

Applications

- Infrastructure planning and operation
- Capacity expansion
- Conjunctive use management (surface and ground water)
- Water allocation and market
- Adaptation (climate change)
- Collaboration for conflict resolution
- Design of institutional policies (water rights, flow requirements, no groundwater overdraft)

Limitations

- Simplification and aggregation of physical, economic and regulatory processes and data
- Deterministic approach (good future knowledge)
- Linearization of non-linear functions
- Ideal water market operations
- Mathematical representation of social, environmental and political objectives

Overall

Hydro-economic models:

- Represent engineered system, considering the economics of water demands and costs
- Provide a framework for planning and operation
- Increase system efficiency
- Help decision-makers better operate complex water systems

CALVIN model

- CALVIN = California Value Integrated Network
- Hydroeconomic optimization model
- Economics driven water allocation operations
- Optimizes deliveries to users (minimizing total operating and scarcity costs)
- Represents California's water infrastructure
- Historical monthly hydrology to represent hydrologic variability (Oct. 1921 to Sep. 2003)
- 2050 urban and agricultural demands

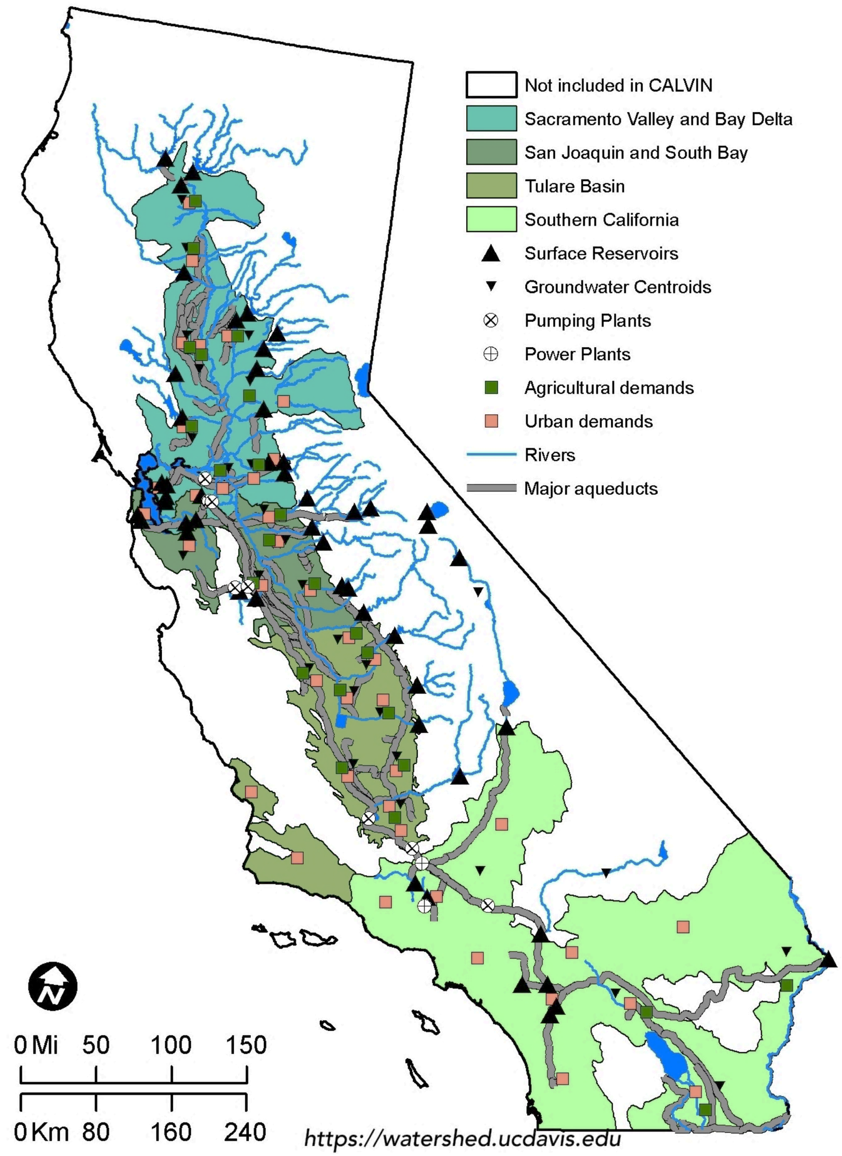
An integrated model

CALVIN is an integrated model

- Surface water & groundwater resources are used conjunctively
- Aggregated environmental, agricultural & urban demands are represented
- The physical system is connected via rivers, canals, aqueducts, & reservoirs
- Reservoirs carry water across time-steps (multi-period model)

Model coverage

- Most agricultural activities & urban population (~90%)
- 35 agricultural & 30 urban demand locations
- 9 wildlife refuge demands & 21 MIF requirements
- 33 groundwater basins, 53 surface reservoirs



Documentation

Appendix A	SWAP Model, Agricultural Water Values
Appendix B1	Urban Water Values I
Appendix B2	Urban Water Values II
Appendix C	HEC-PRM
Appendix F	Environmental Constraints
Appendix G	Operating Costs
Appendix H	Infrastructure
Appendix I	Surface Water Hydrology
Appendix J	Groundwater Hydrology
Appendix K	Irrigation Water Requirements

More information and documentation about CALVIN can be found at http://calvin.ucdavis.edu/

- Also theses, dissertations and publications

Motivation for CALVIN

- Interconnected water system
- Integrated water management tools
  - Reservoir operations
  - Groundwater and conjunctive use
  - Water conservation
  - Wastewater reuse
  - Water markets and transfers

Can we make better sense of this integrated system?

What is system's reaction to changes in facilities and policies?

How could system management be improved?

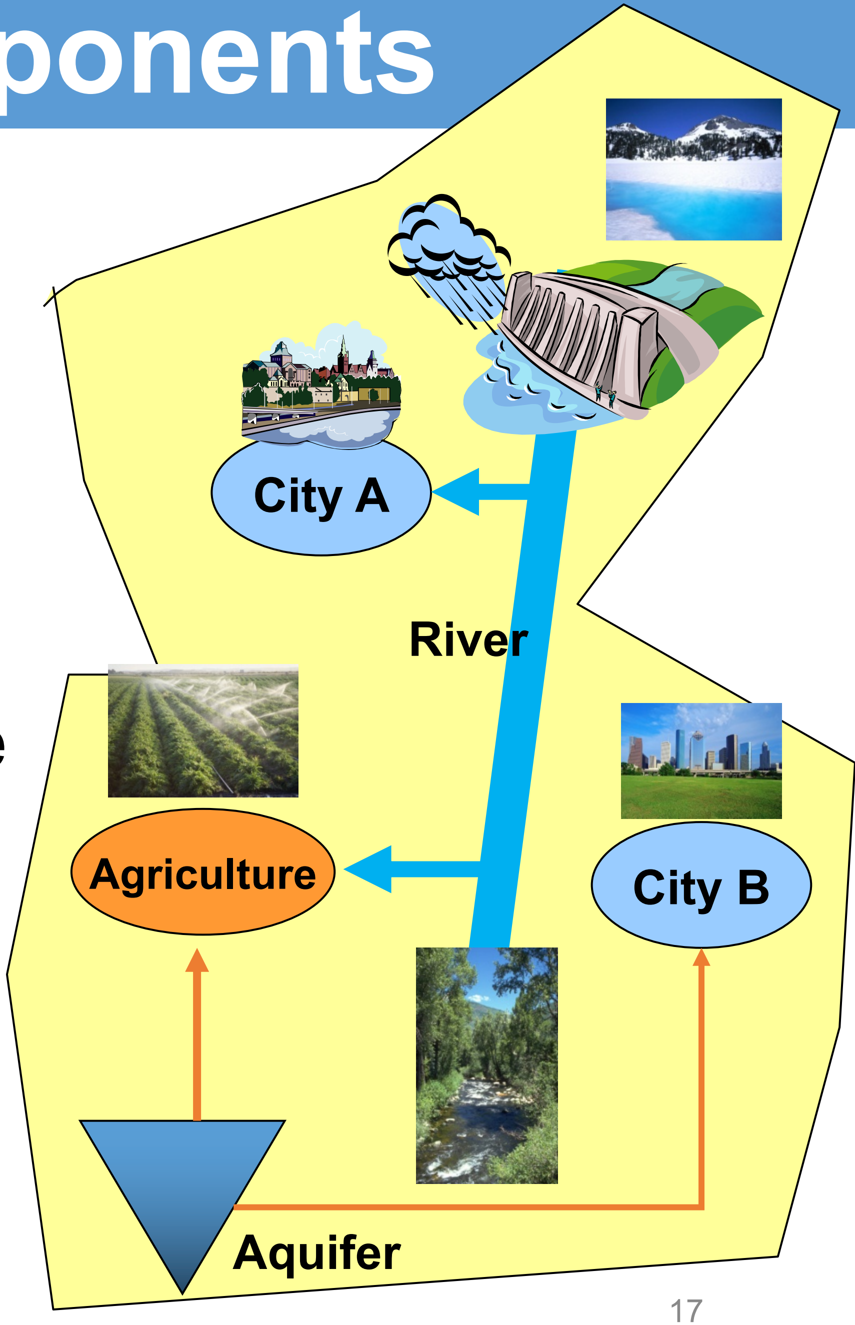
CALVIN studies

CALVIN has been used in numerous studies:

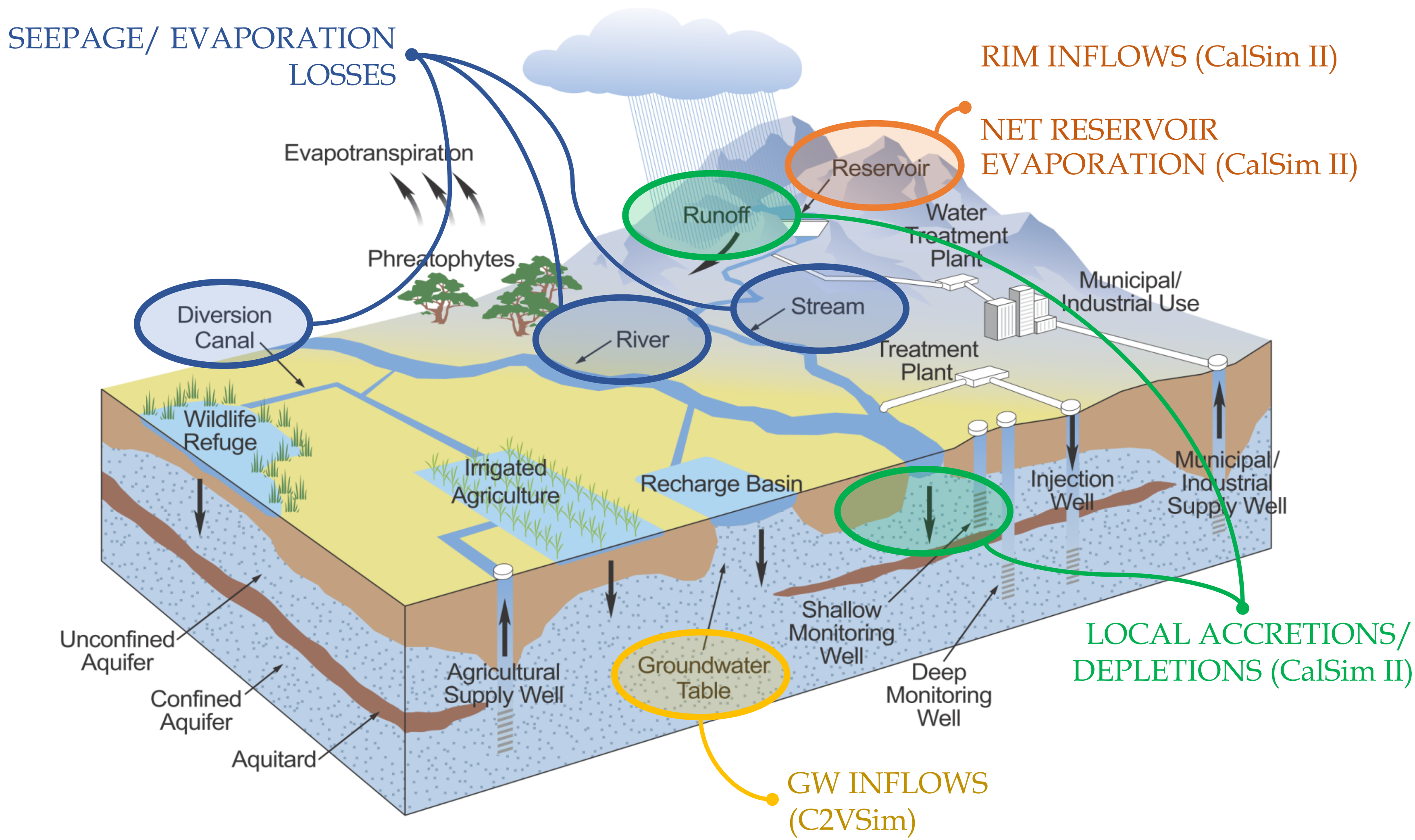
- Climate change & adaptation
- Groundwater overdraft
- Effects of removing a dam
- Marginal value of expanding storage
- Marginal value of adding/expanding infrastructure

Model Components

- Water sources
  - Rim inflows, groundwater inflows and local runoff
- Demand locations
  - Agricultural, urban, and wildlife refuge
- Conveyance infrastructure
  - Reservoirs, pumping facilities, and canals
- Capacity constraints
- Regulatory requirements
  - Minimum in-stream flow requirements



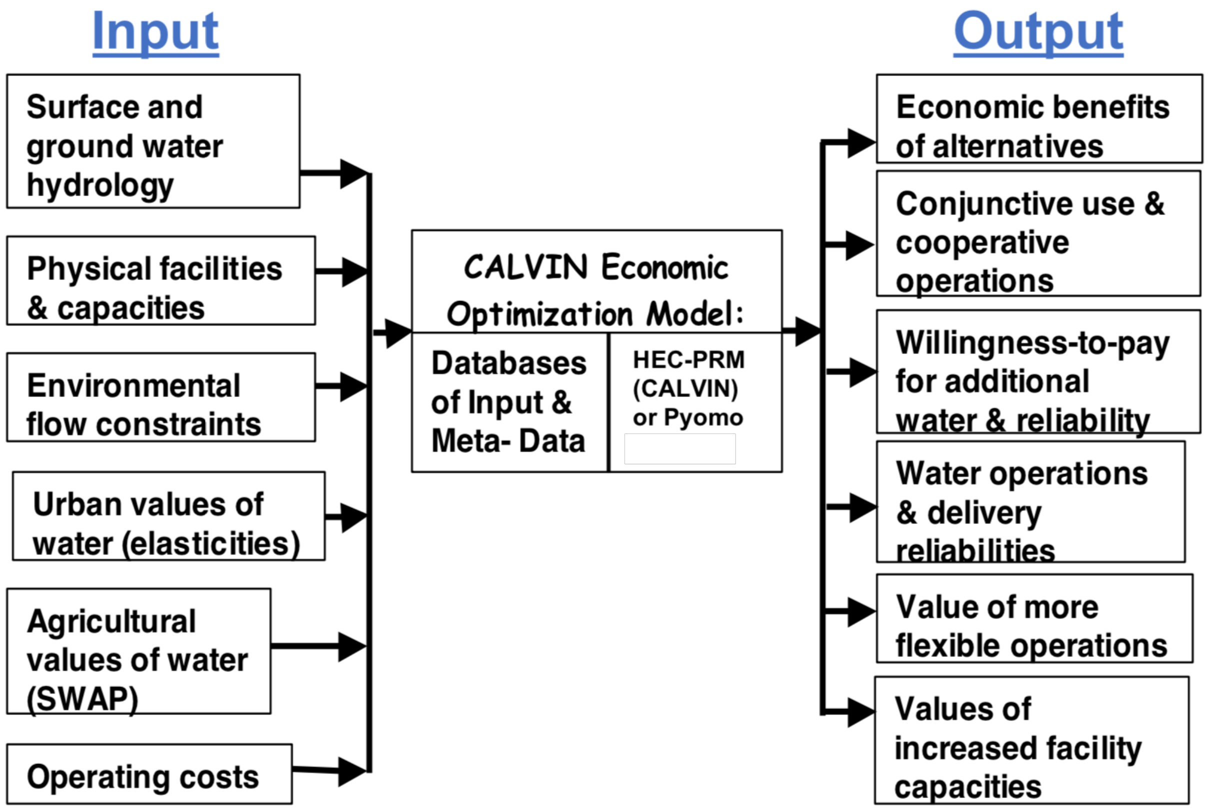
Hydrology



SEEPAGE/ EVAPORATION LOSSES
RIM INFLOWS (CalSim II)
NET RESERVOIR EVAPORATION (CalSim II)
Evapotranspiration
Phreatophytes
Reservoir
Runoff
Water Treatment Plant
Municipal/ Industrial Use
Diversion Canal
River
Stream
Treatment Plant
Wildlife Refuge
Irrigated Agriculture
Recharge Basin
Injection Well
Municipal/ Industrial Supply Well
Unconfined Aquifer
Confined Aquifer
Aquitard
Agricultural Supply Well
Groundwater Table
Shallow Monitoring Well
Deep Monitoring Well
LOCAL ACCRETIONS/ DEPLETIONS (CalSim II)
GW INFLOWS (C2VSim)

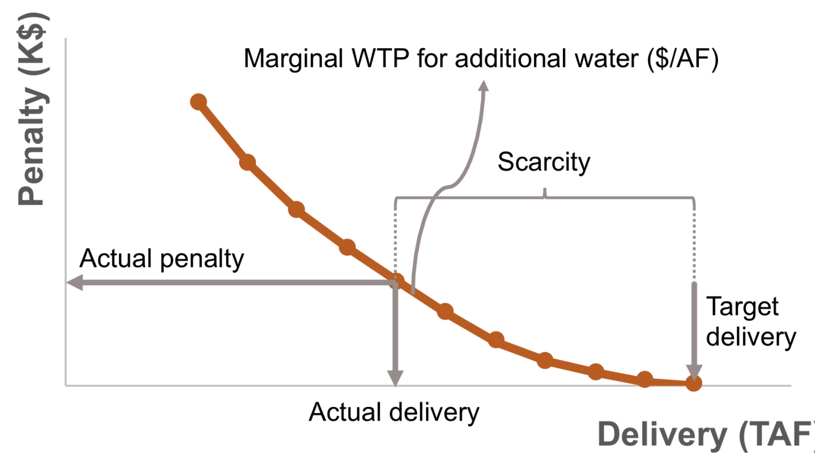
Data overflow

- Water operations are driven by economic value of water: Hydrologic data + economic data



Economic value of water

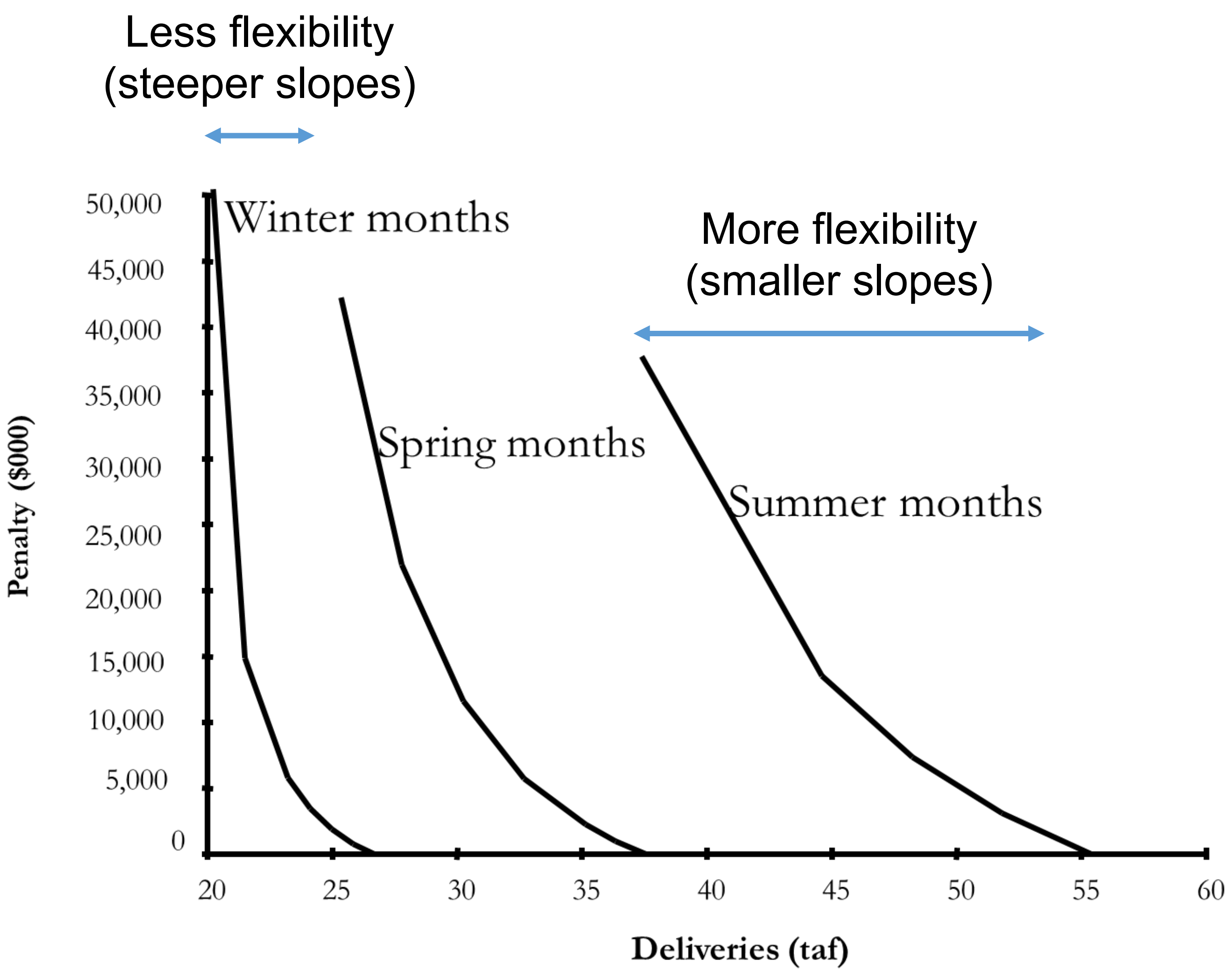
- Monthly varying total cost curves derive operations for agricultural & urban deliveries & hydropower
- Whenever a user's total demand (target delivery) is not met, scarcity occurs



- The difference between target & actual deliveries = scarcity
- The scarcity cost (penalty) is total loss due to lack of water related activities

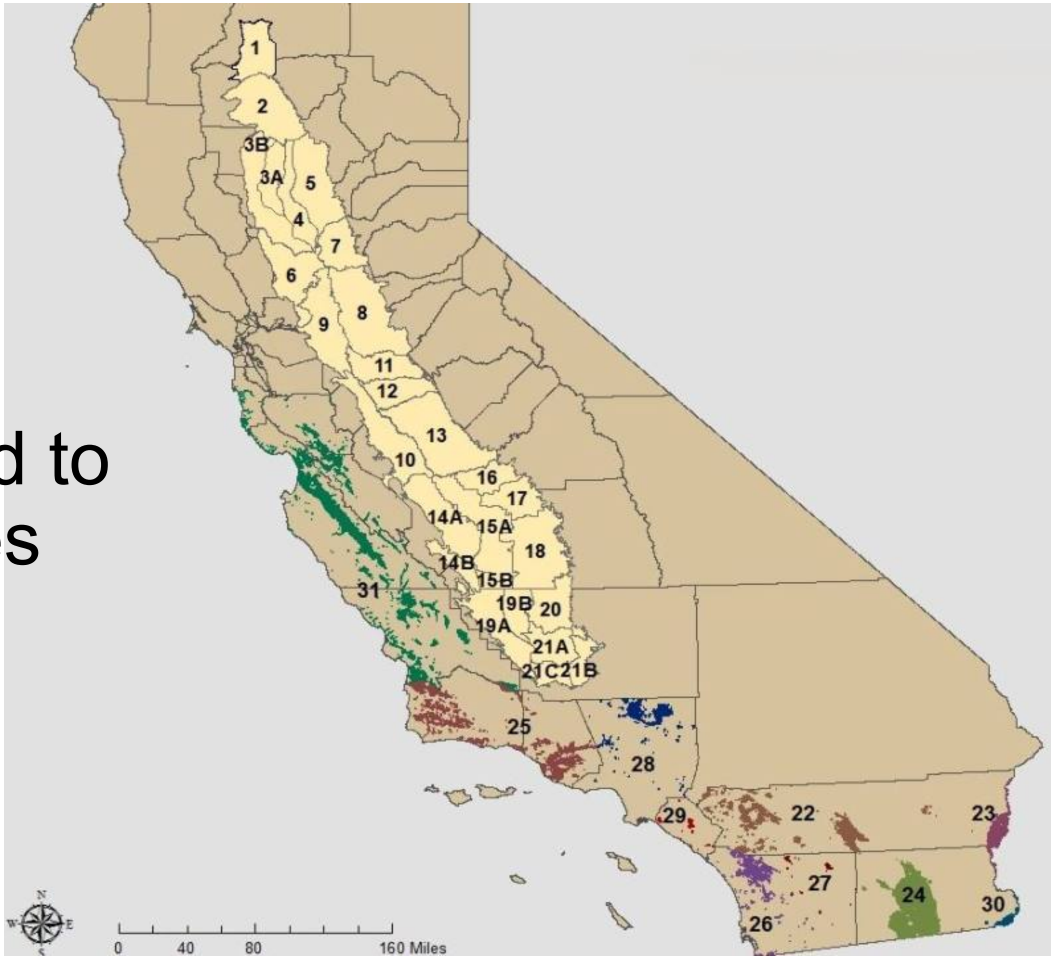
Demand curves

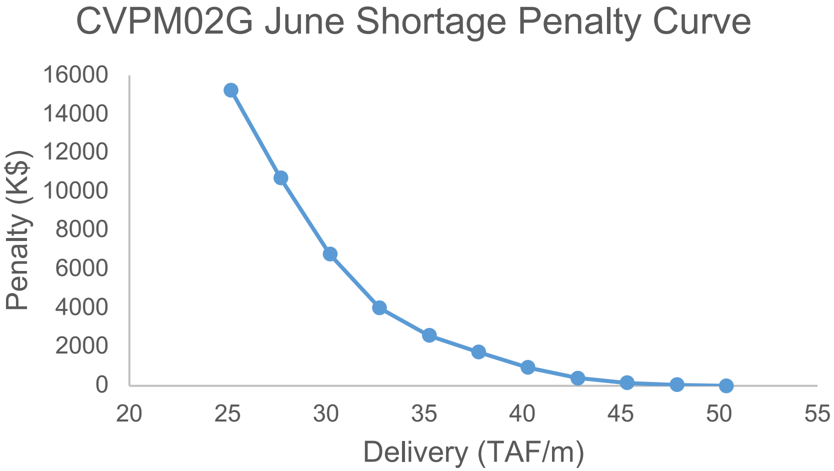
- Agricultural demand in different seasons



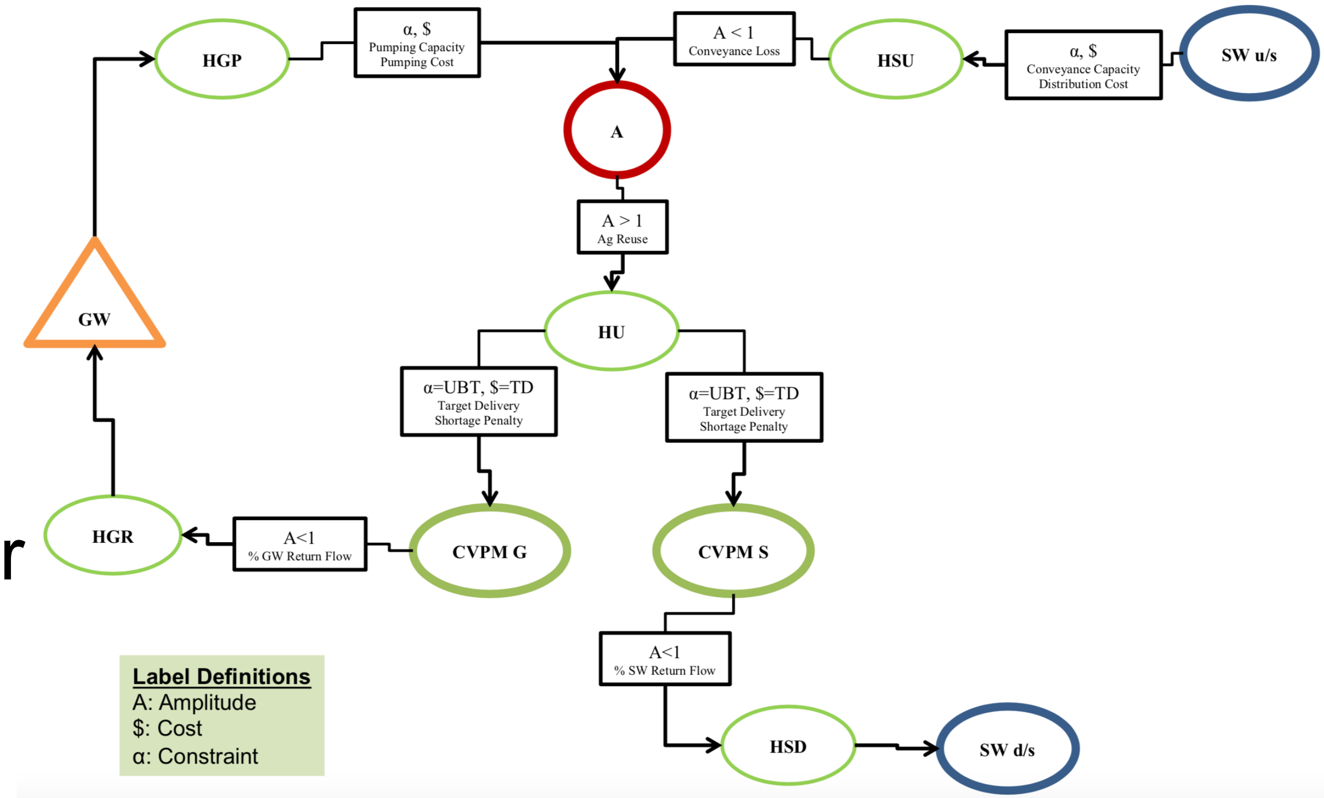
Agricultural demand

- CVPM 1-21 in the Central Valley
- Southern California demand locations
- SWAP model is used to create penalty curves





Agricultural demand

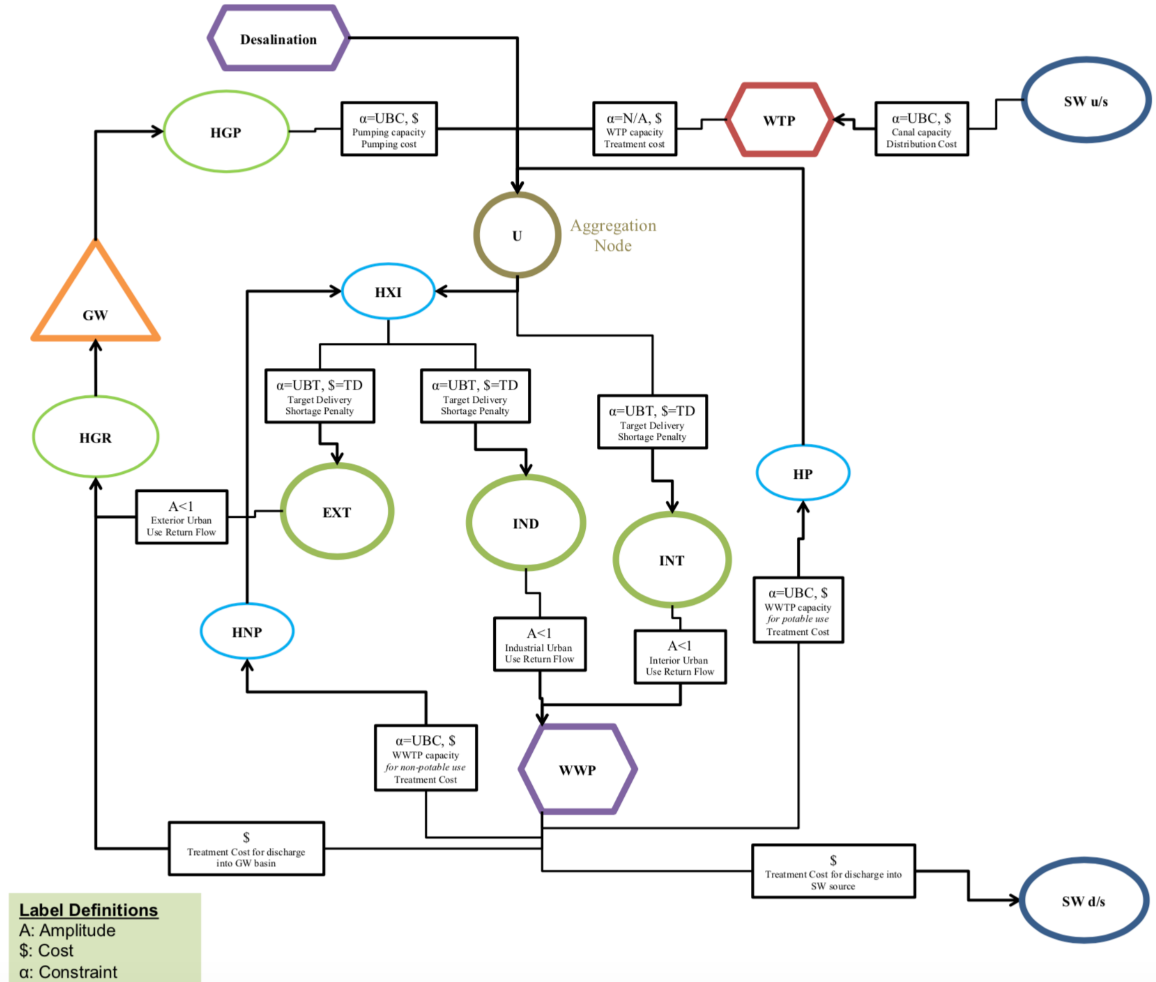


- Two supply sources: groundwater & surface

- Aggregated demand is divided into two parts based on return flow to groundwater or surface water

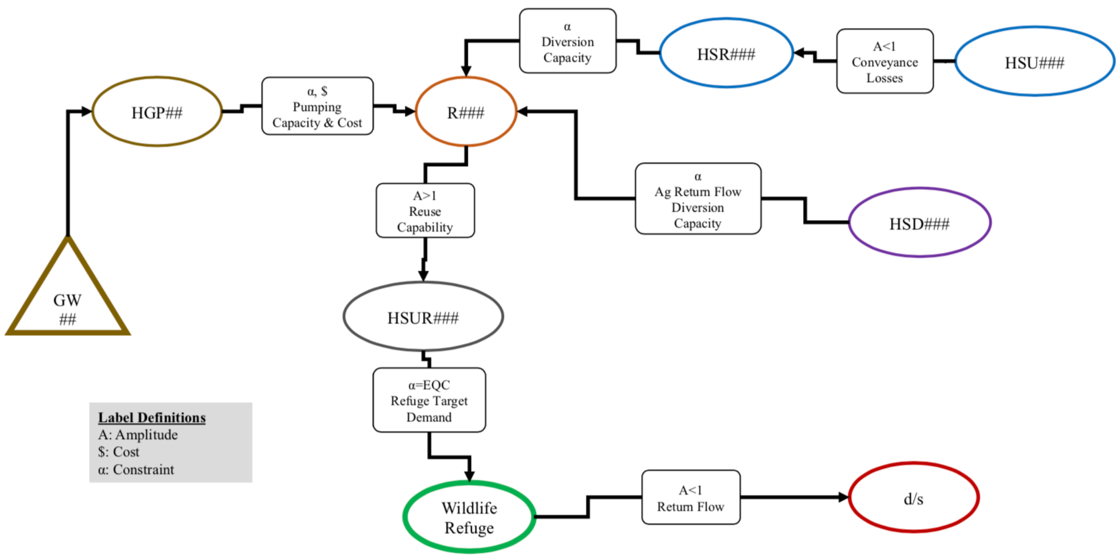
Urban demand

- Interior & exterior residential, & industrial demands
- Water sources:
  - Surface water
  - Groundwater
  - Desalination
  - Potable & non-potable recycled water



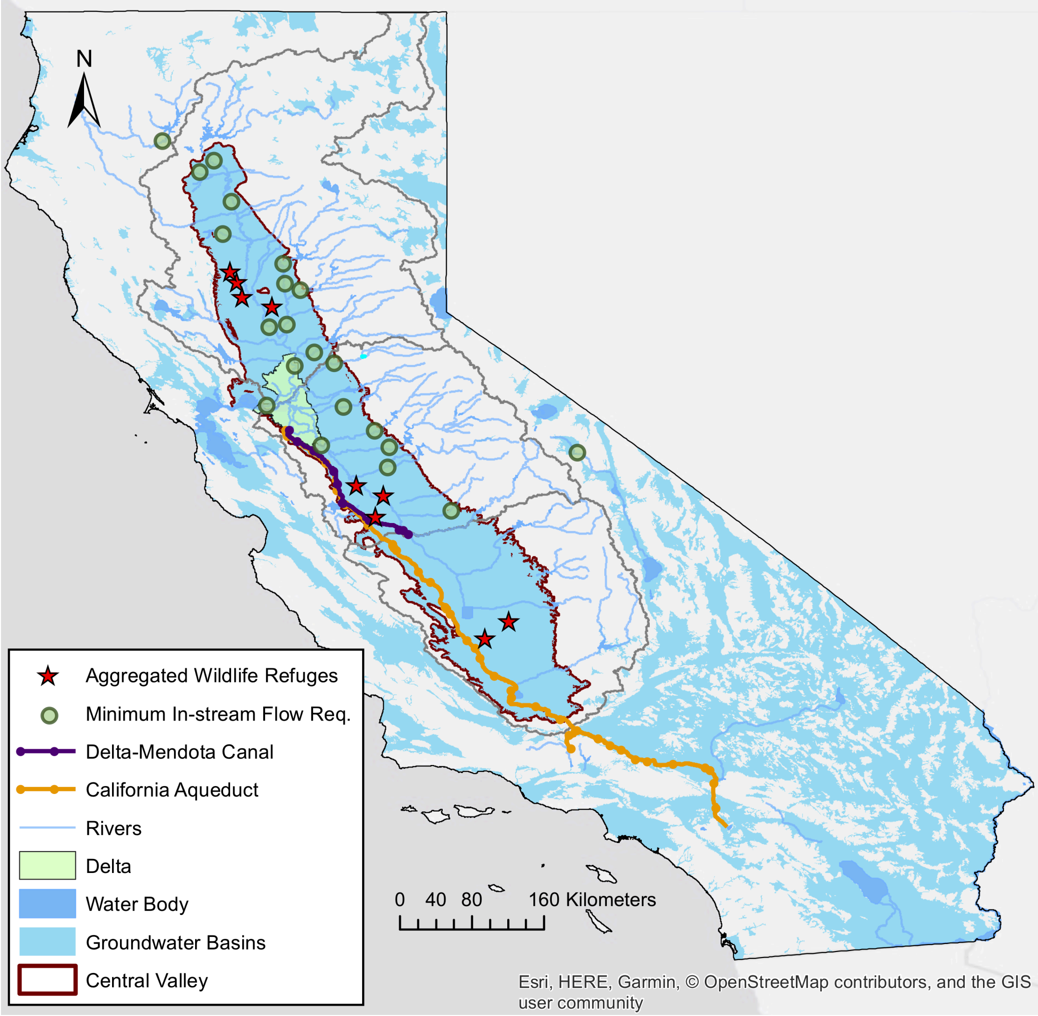
Wildlife refuge demand

- 9 wildlife refuge demand locations
- No economic representation
- Constrained water deliveries
- Supply sources:
  - Surface water
  - Groundwater
  - Agricultural return flow



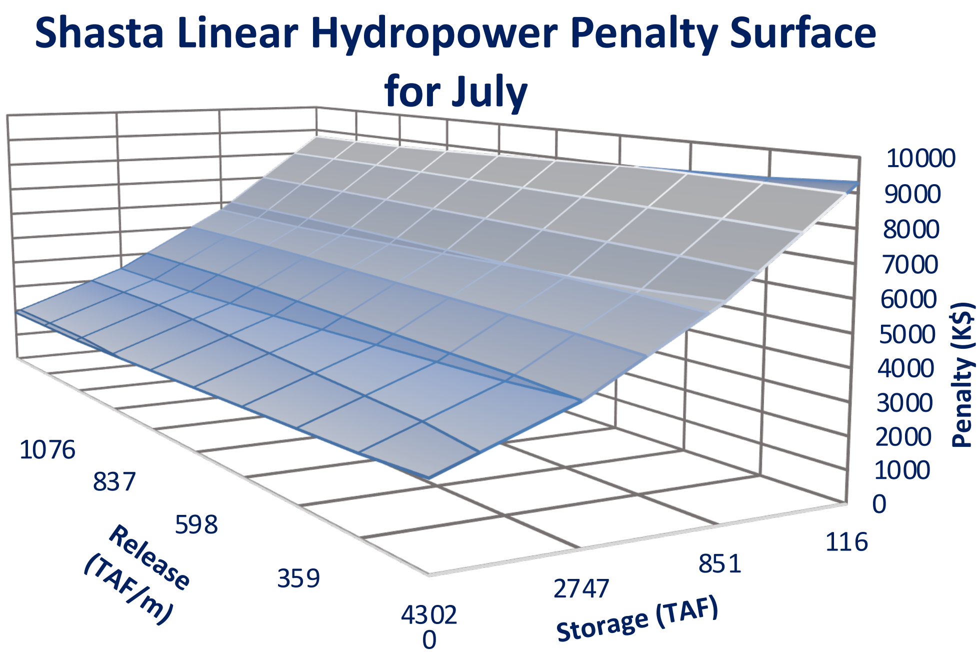
MIF Requirements

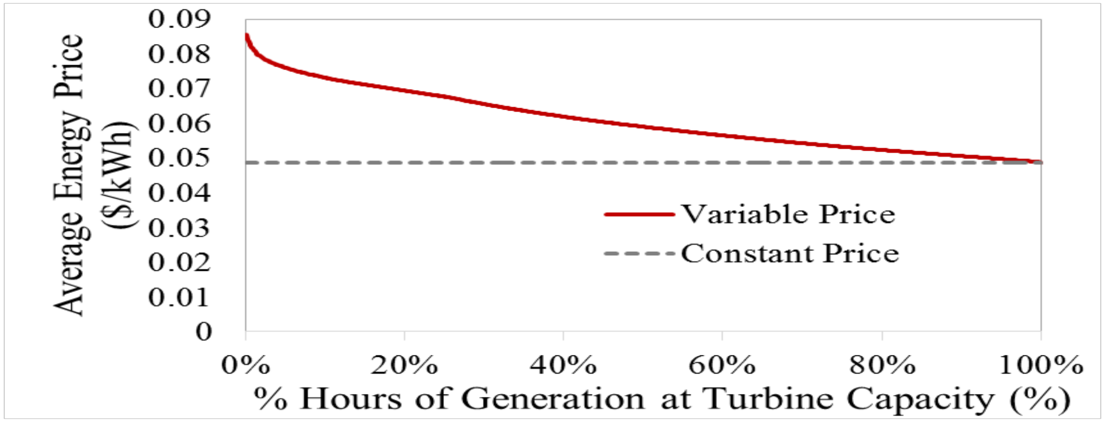
- Minimum in-stream flow requirements due to aquatic habitat needs
- Represented as lower bound constraints
- Mostly time-series obtained from CALSIM II model



Hydropower

- Monthly hydropower operations
- Penalty for not generating hydropower (reverse of a benefit curve)
- Represented on reservoir storage and release
- Hourly average energy prices





CALVIN limitations

CALVIN has several limitations:

- Perfect hydrologic knowledge (limited in limited foresight model)
- Simplified groundwater representation (unit fixed pumping cost)
- Linearized cost curves (piecewise linear)
- Simplified hydropower representation due to linear programming (LP) framework

Lessons from CALVIN

CALVIN results show that

- Regional or statewide markets can reduce water scarcity costs
- Environmental flows have economic values for agricultural and urban and hydropower activities
- Economic values exist for expanded facilities
- Some scarcity is optimal
- Integrated local, regional, and statewide operation of water decreases competition with environmental uses (water trading)

CALVIN goals

The recent updates aims to

- Create a *cross-platform* model: MacOS, Windows
- Use *open data format*: `csv`, `JSON`
- Have *freely available*: data, code, modeling language & solvers are open-source or free of charge
- *Separate model & data*:
  - HOBBES is independent from any data
  - CALVIN's structure code is generalized (can solve any other network-flow problems)

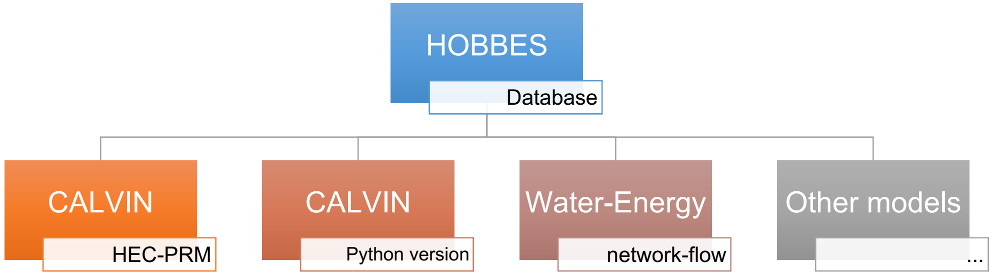
CALVIN improvements

- The original CALVIN uses HEC-PRM to solve its optimization problem
- With recent updates, CALVIN is moved to Python
- Pyomo library, a high level optimization modeling language in Python, is used
- Pyomo can connect to several freely available solvers
- Runtime is decreased from 2-5 days to 30min-1 hr, with parallelization in Pyomo.

HOBBES database

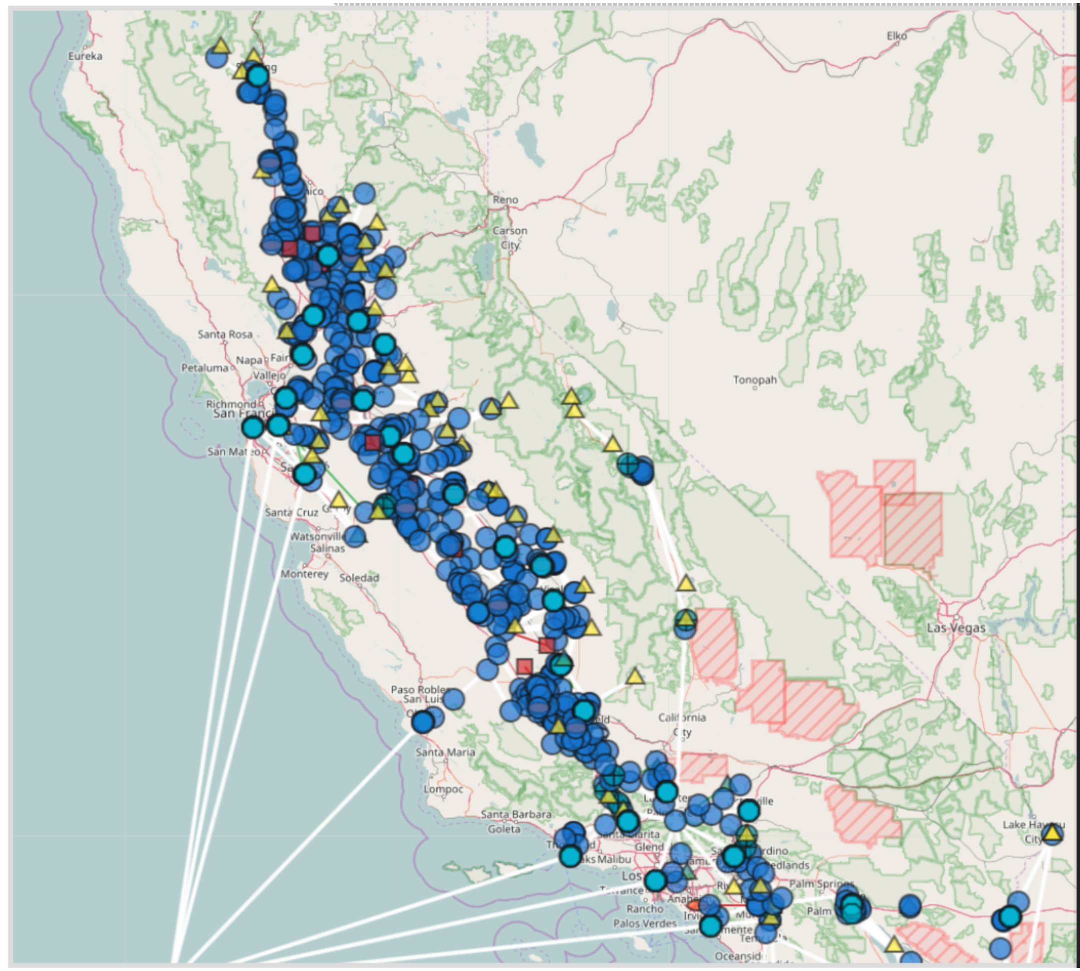
https://cwn.cws.ucdavis.edu

- A web-based open-source data storing and sharing platform
- Stores California's water network data
- Documentation and change tracking via GitHub
- Data visualization and animation
- Several models can be built around HOBBES, where built-in tools convert and export network data in the desired format



HOBBES visualization

- California water network
- Geocoded network elements
- Layered based on hydrologic regions and subregions
- Data visualization
- Animation tool



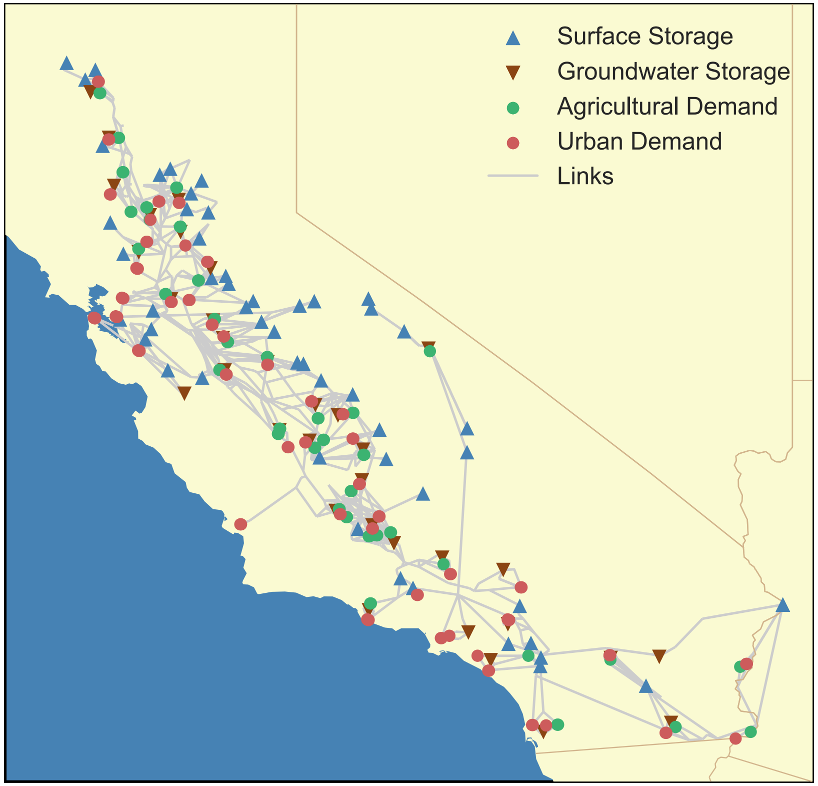
HOBBES for CALVIN (Python)

- CALVIN Python version uses matrices for all parameters: *c*, *a*, *l*, *u*
- Calvin-network-tool in HOBBES converts input data into a network matrix
- The network matrix is input to CALVIN (Python)
- Each of network matrix lines correspond to a link – decision var. (full size model has 6 millions)

i	*j*	*k*	*c*	*a*	*l*	*u*

Network-flow model

- CALVIN represents the physical system with nodes and links
- Nodes represent reservoirs, demand locations, power and pumping plants and junctions



- Links only connect nodes to each other
- All network parameters are applied to links: amplitude (loss factor) *a*, unit cost *c*, lower bound *l*, & upper bound *u*

Linear Programming model

- As an network-flow LP model, CALVIN minimizes statewide water scarcity and operating costs within constraints

$$\min_X z = \sum_i \sum_j \sum_k c_{ijk} X_{ijk}$$

Objective Function

$$X_{ijk} \geq l_{ijk}, \forall (i,j,k) \in A$$

Lower bound constraint

$$X_{ijk} \leq u_{ijk}, \forall (i,j,k) \in A$$

Upper bound constraint

$$\sum_i \sum_k X_{jik} - \sum_i \sum_k a_{ijk} X_{ijk} = 0\,, \forall j \in N$$

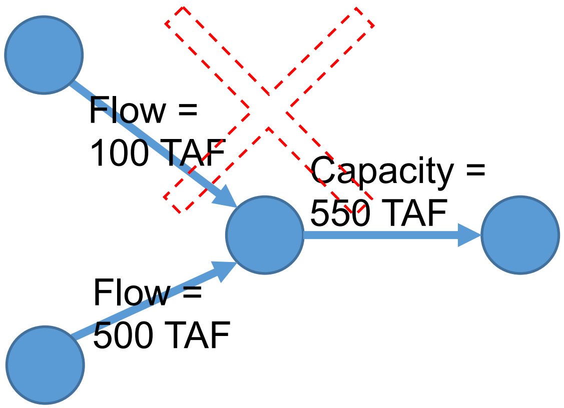
Mass balance constraint

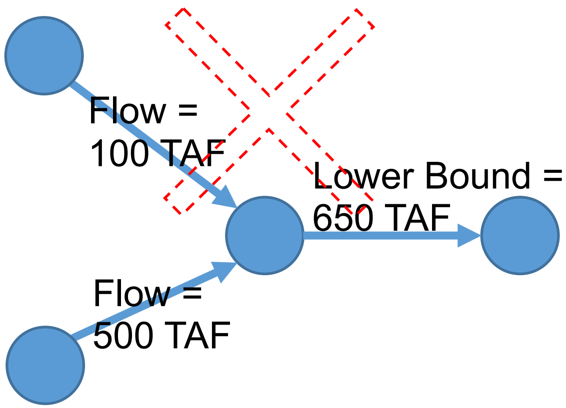
where *X* is flow (decision variable); *c* is unit cost; *l* is lower bound; *u* is upper bound; *a* is amplitude

index *i* represents origin node; *j* is terminal node; *k* is a piecewise component

Resolving infeasibilities

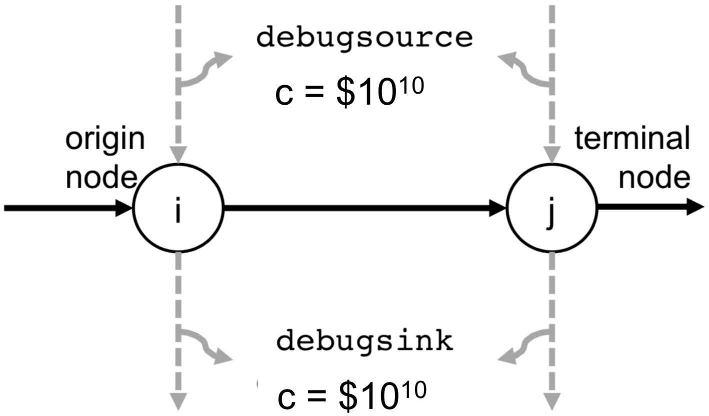
- When a mass-balance constraint at any location is not met, the model results in infeasible solution
- Due to size of the model, in case of infeasibility, you never know where the problem is





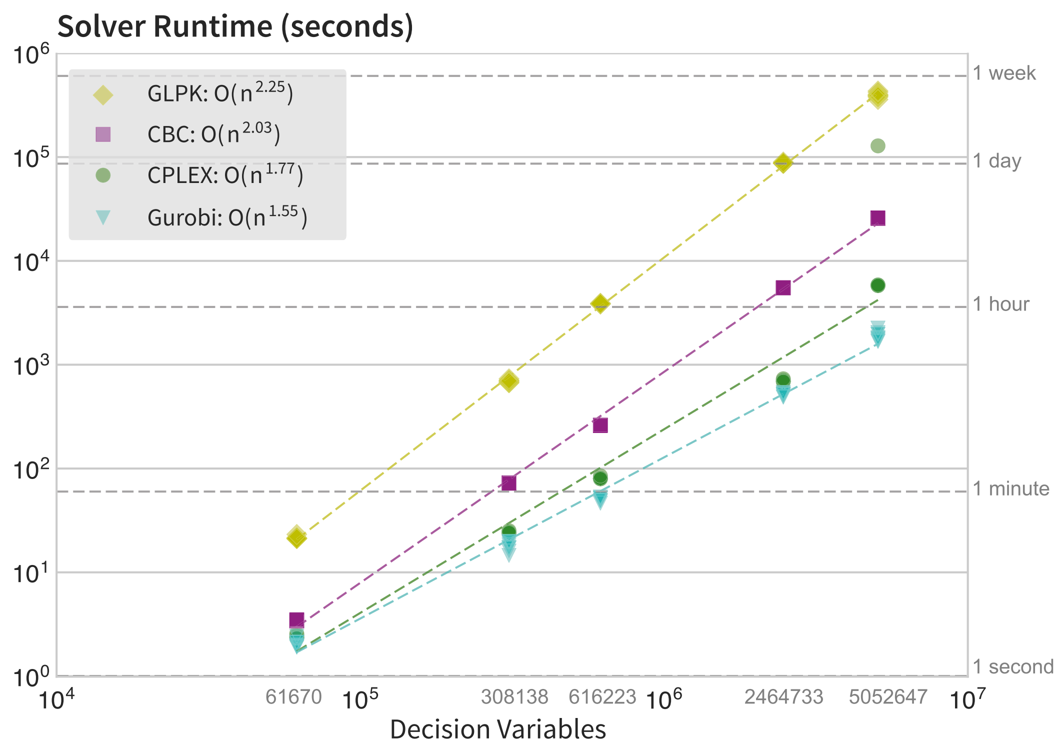
Debug mode

- When network is modified (climate change, adding a new requirement or element etc.), first run in debug mode
- Debug mode adds two links (debug source & debug sink) at very high cost ($\sim 10^{10}$)
- The debug cost is much higher than any other cost in CALVIN to make sure it is not used unless there is infeasibility
- Then postprocess to eliminate debug flow



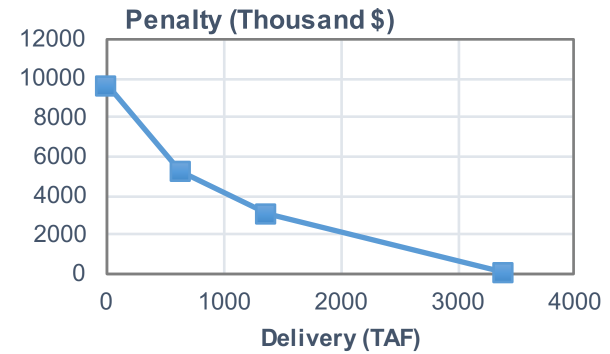
CALVIN runtime

- Solver wall clock runtime for different model sizes
- Installed solvers:
  - GLPK
  - CBC
  - Gurobi
  - CPLEX
- Log-log scale: exponential increase of runtime



A small network example

- Modeling of a reservoir with following properties
- Two time-steps

Initial storage (TAF)	3686.84
Ending period storage (TAF)	2923.297
Reservoir inflow 1983-10-31 (TAF/m)	301.765
Reservoir inflow 1983-11-30 (TAF/m)	650.408
Evaporation loss factor	0.99716
Penalty curve (due to (lost) hydropower benefits)	
Reservoir storage capacity (TAF)	3400 (less due to flood storage)
Reservoir release capacity	None (assumed for simplicity)

Network-flow form