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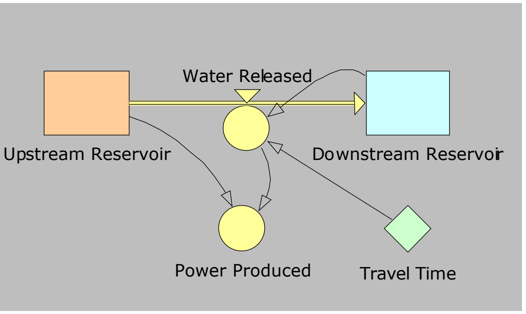

Water-Energy Systems Analysis Science

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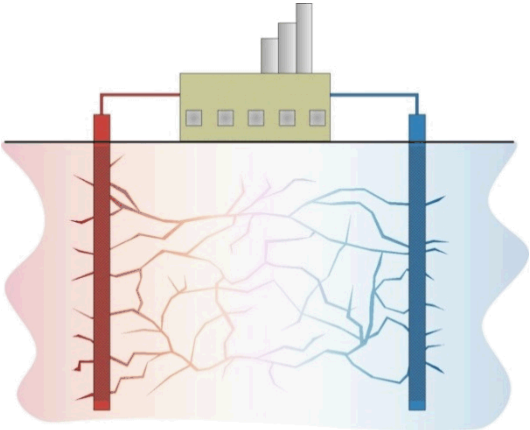
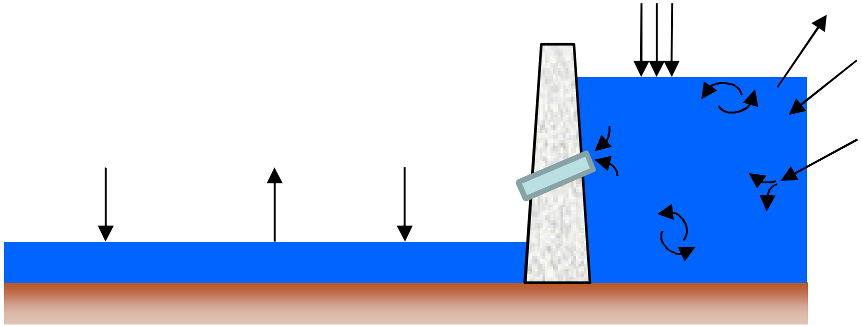
Water-Energy Systems Analysis

- Water-Energy: Problem Definition and Significance
- Systems Analysis
- Example Projects – Highlight Capabilities
  - GT-Mod: A simulation and analysis tool for geothermal performance assessment
  - HydroSCOPE: Reservoir operations model for optimizing power production and environmental performance



GT-Mod



HydroSCOPE

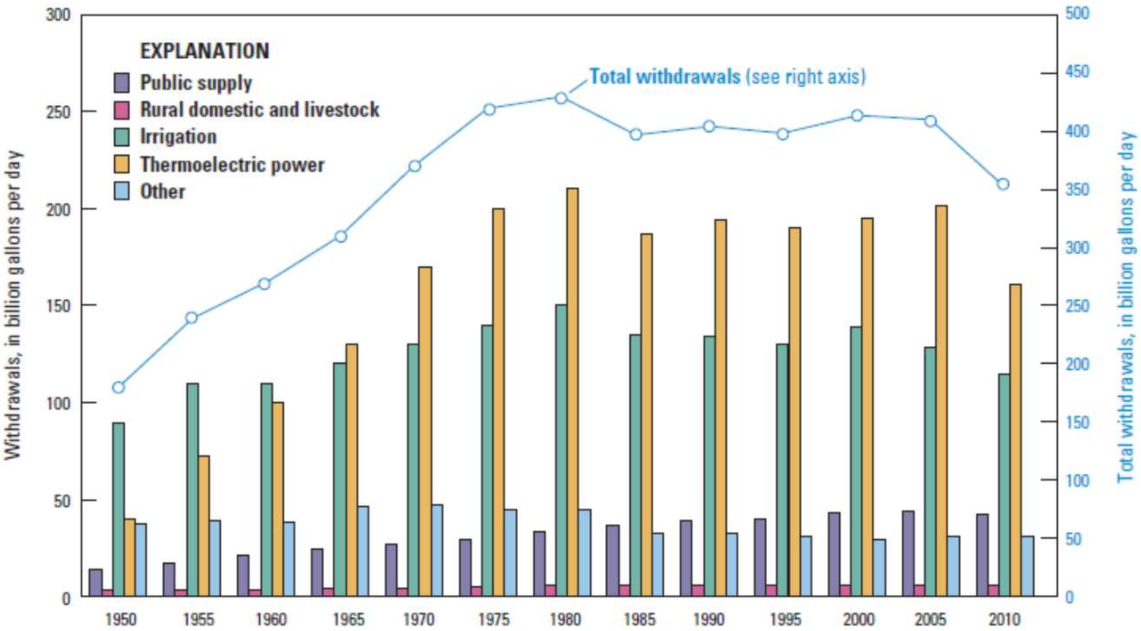
Water-Energy Systems

- Water for Energy
  - Cooling: ~89% of US Energy Production is Thermoelectric
  - Extraction (oil, gas, coal, uranium: mining, drilling, fracking)
  - Other (refining, slurry transport, cleaning)
- Energy for Water
  - Pumping, treatment and distribution, end uses (e.g., heating)
  - 4-13% of U.S. Electricity Generation
  - 30-40% of Municipality's Energy Bill
- Issues
  - Scarcity and sustainability
  - Quality (contamination and thermal)
  - Environmental
  - Human health

From: USGS, 2010, Estimated Use of Water in the United States in 2010, Circular 1405, http://pubs.usgs.gov/circ/1405/pdf/circ1405.pdf, 64 pp.

Water-Energy Systems

- Withdrawals vs Consumed



Withdrawals

Power Provider	Gallons Evaporated* per kWh
Western Interconnect	4.42
Eastern Interconnect	2.33
Texas Interconnect	0.43
U.S. Aggregate	2.00

*Includes hydroelectric reservoir evaporation

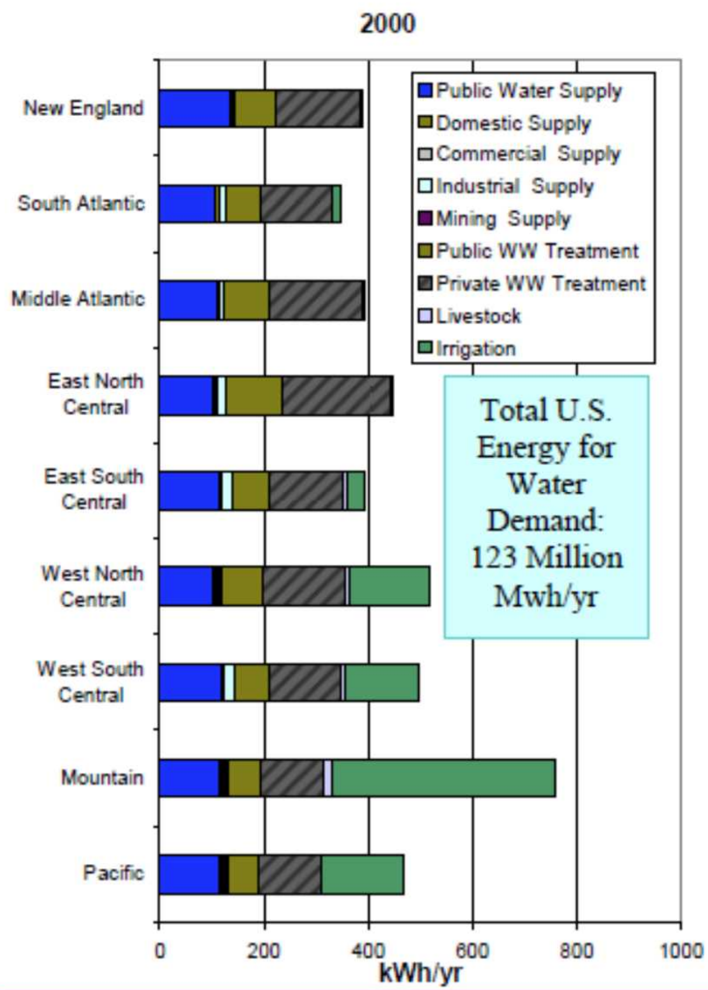
Consumed
(~116 bgd)

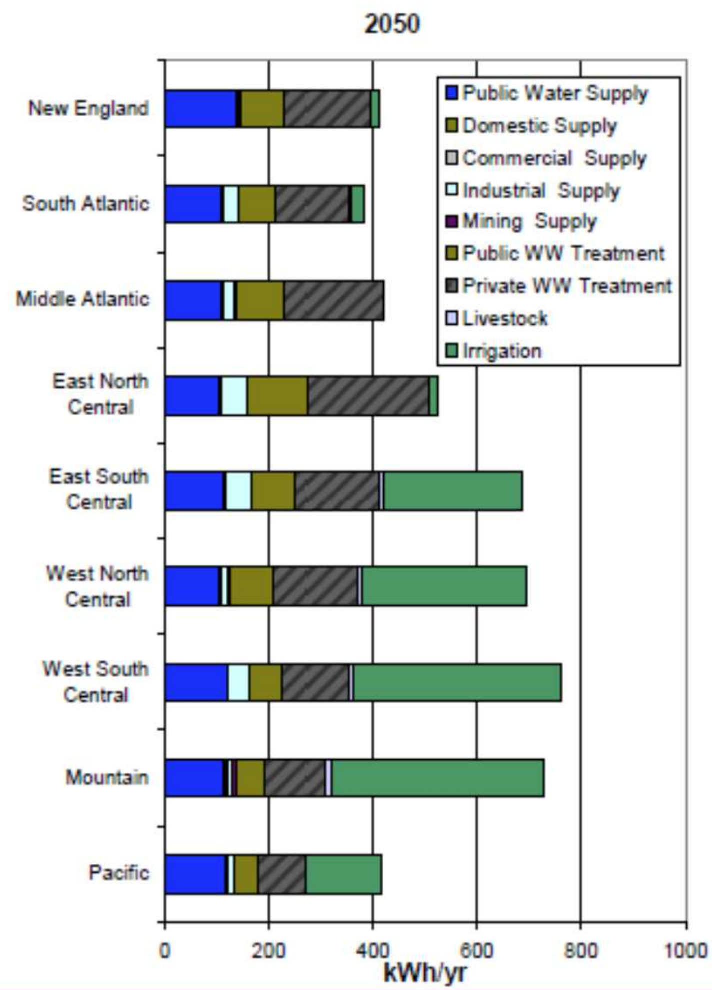
From: USGS, 2010, Estimated Use of Water in the United States in 2010, Circular 1405, http://pubs.usgs.gov/circ/1405/pdf/circ1405.pdf, 64 pp.

From: NREL, 2003, Consumptive Water Use for U.S. Power Production, NREL/TP-550-33905, http://www.nrel.gov/docs/fy04osti/33905.pdf, 18 pp.

Water-Energy Systems

- Energy for Water



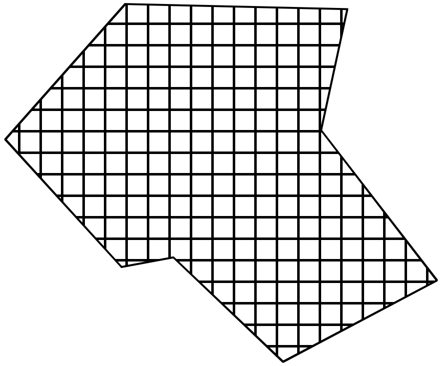


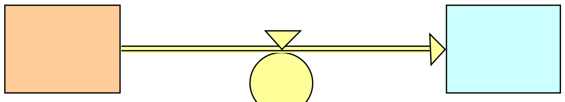
From: DOE, 2006, Energy Demands on Water Resources, Report to Congress On the Interdependency of Energy and Water, Circular 1405, http://pubs.usgs.gov/circ/1405/pdf/circ1405.pdf, 64 pp.

Systems Analysis

- System Dynamics (SD) Modeling
  - Finite difference modeling approach applied at a systems level
  - Solve a system of PDE’s using stocks and flows

Item	FD	SD
Systems	Single	Multiple
Domain	Grid	Non-grid
Flows	Gradient	Gradient or function
Emphasis	Internal spatial dynamics	External temporal dynamics
Commodities	Single	Multiple





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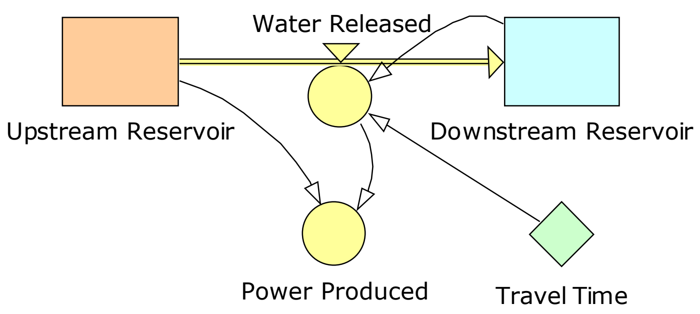
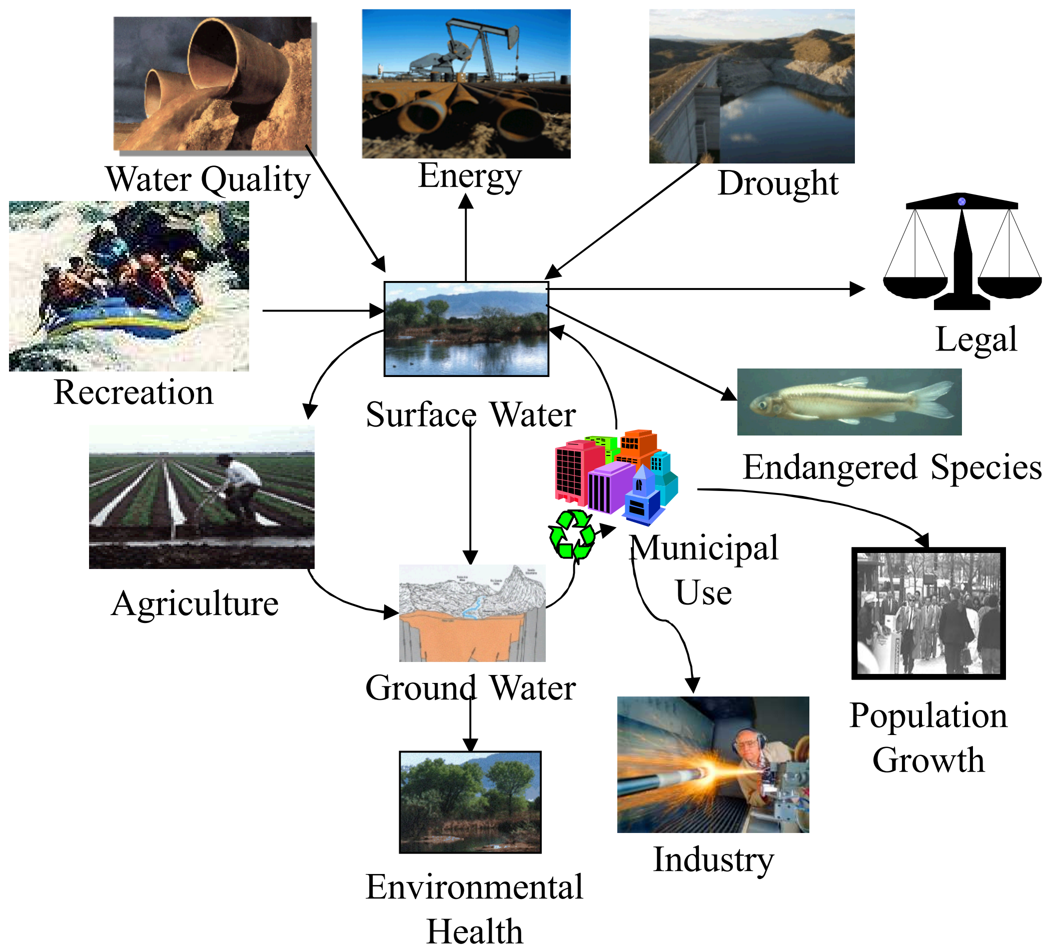


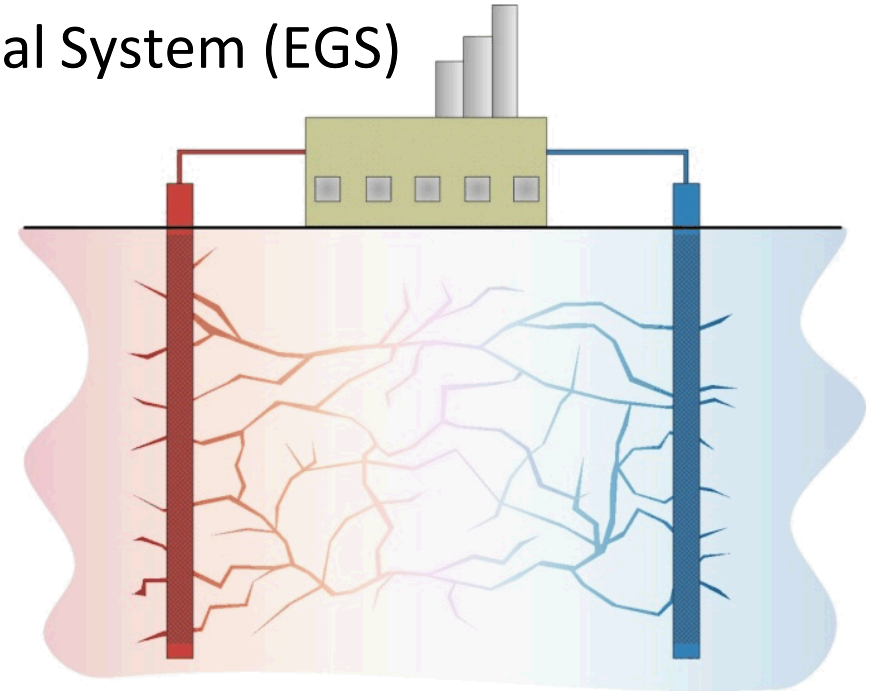
System Dynamics

- Provides a framework for integrating over a broad range of systems and factors
- Scalable to multiple spatial and temporal scales
- Fast execution
- Easily deployable

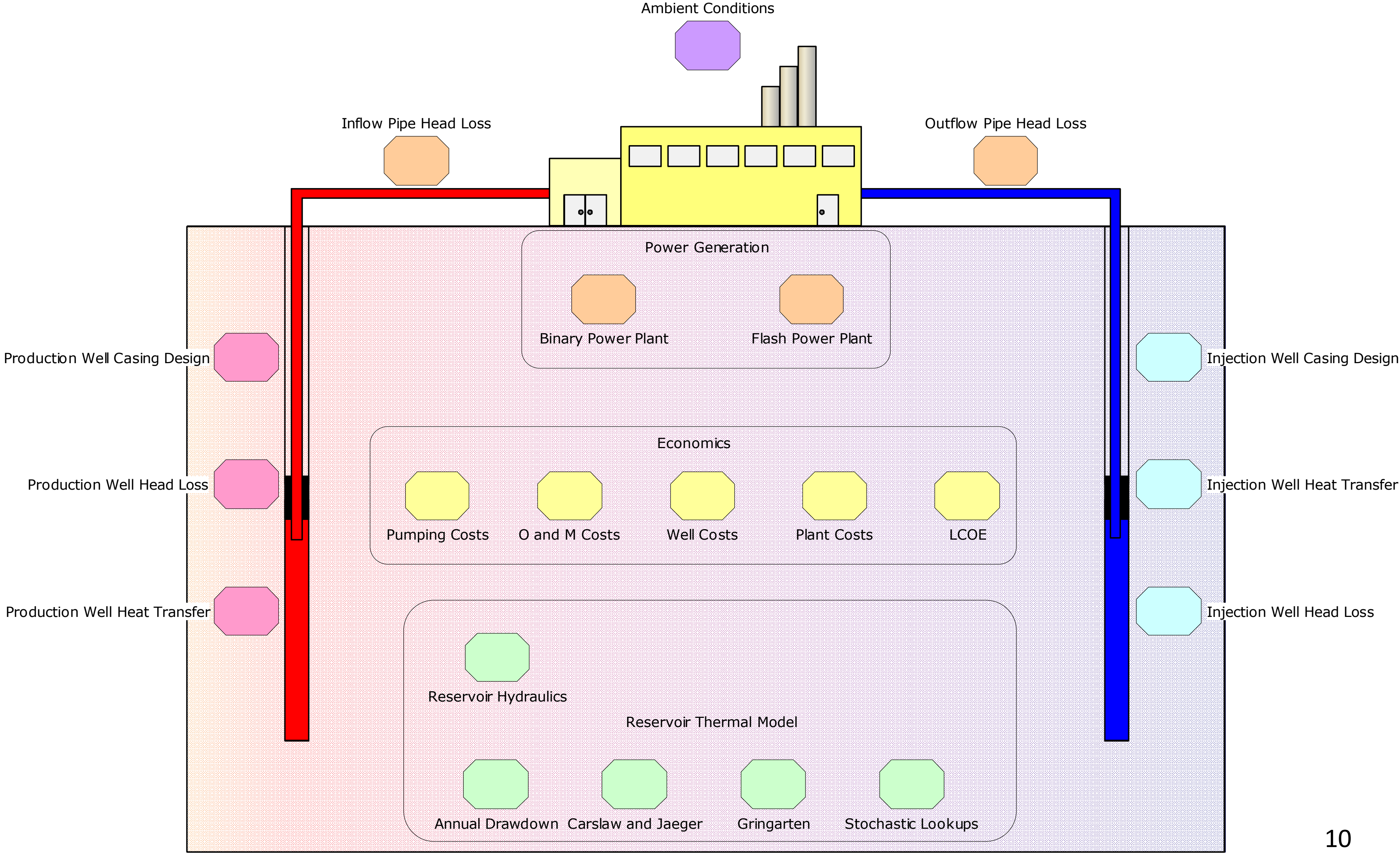


GT-Mod Example Project

- GT-Mod: A simulation and analysis tool for geothermal physical and economic performance assessment
- SD model of hydraulics, thermodynamics, power generation, and economics
- Example – Enhanced Geothermal System (EGS)
  - Probabilistic modeling
  - Quantitative risk assessment

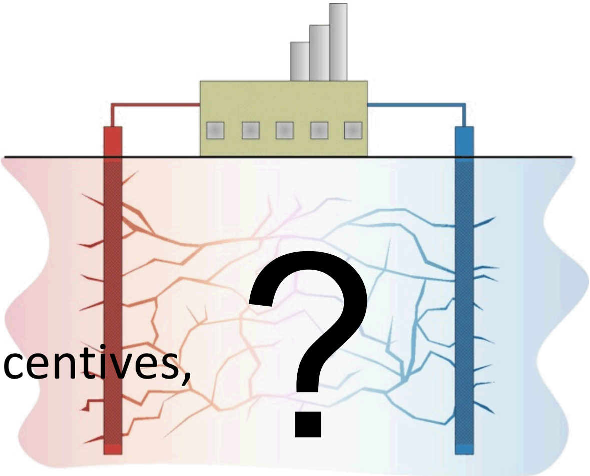


GT-Mod SD Model

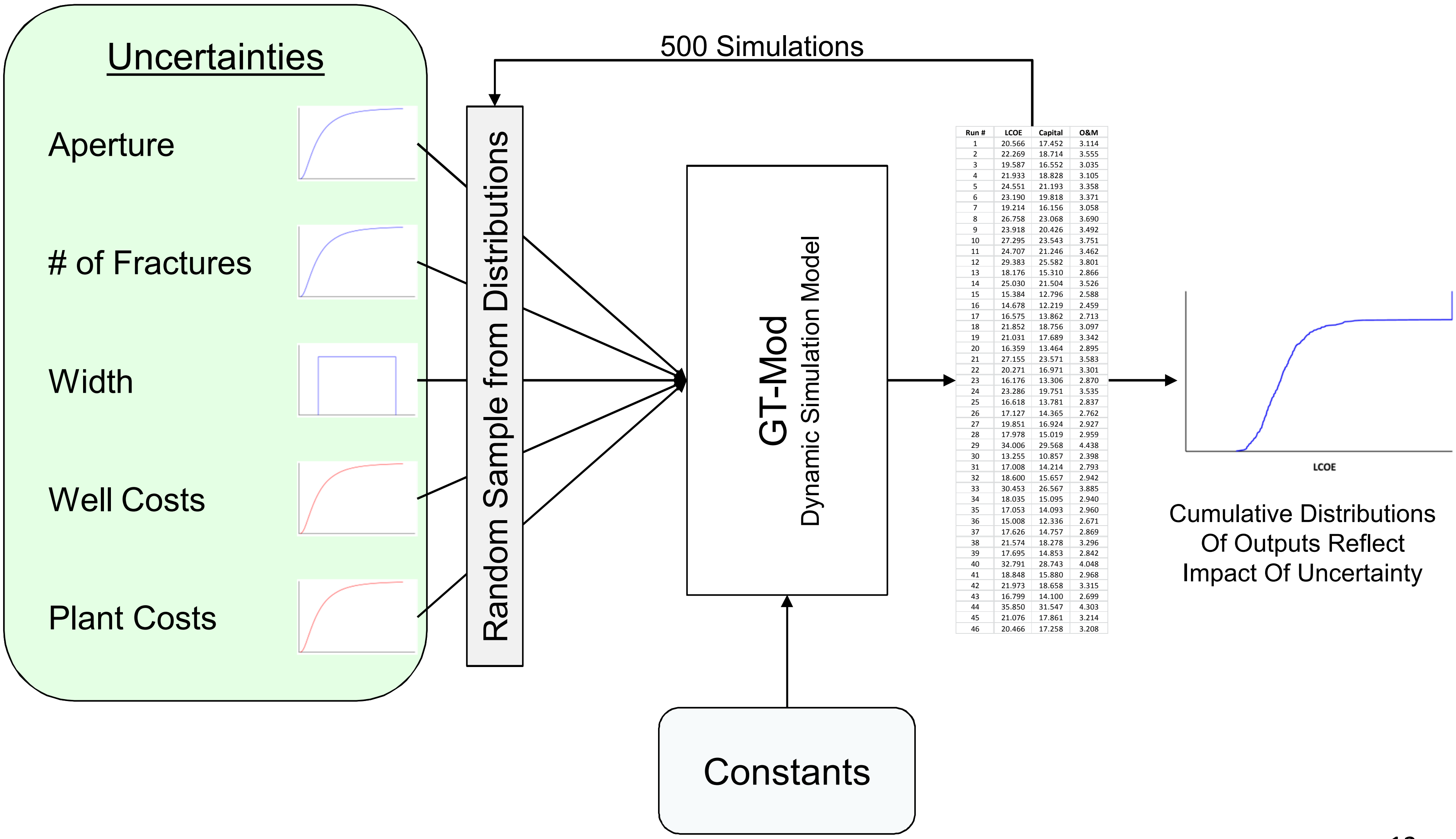


Uncertainties in Geothermal Energy

- Physical setting
  - Temperature at depth, rock type, stress field, etc.
  - Can be reduced through site exploration ($$)
- System performance
  - Hydraulic and thermal drawdown, water losses, pumping, etc.
  - Enhanced through stimulation, understood through exploration ($$)
- Plant performance
  - Conversion of heat to electricity
  - Most certain of the inputs
- Economic and regulatory future
  - Material & labor costs, discount rate, market incentives, environmental constraints, etc.
  - Cannot be reduced



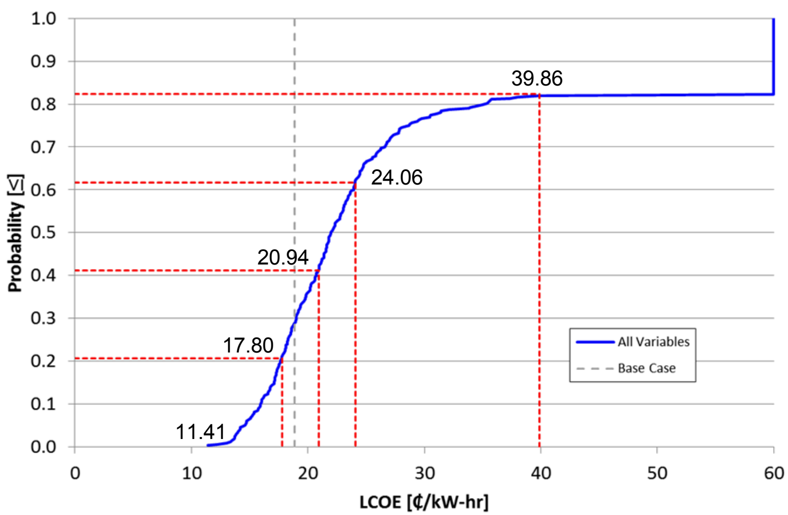
Probabilistic Modeling

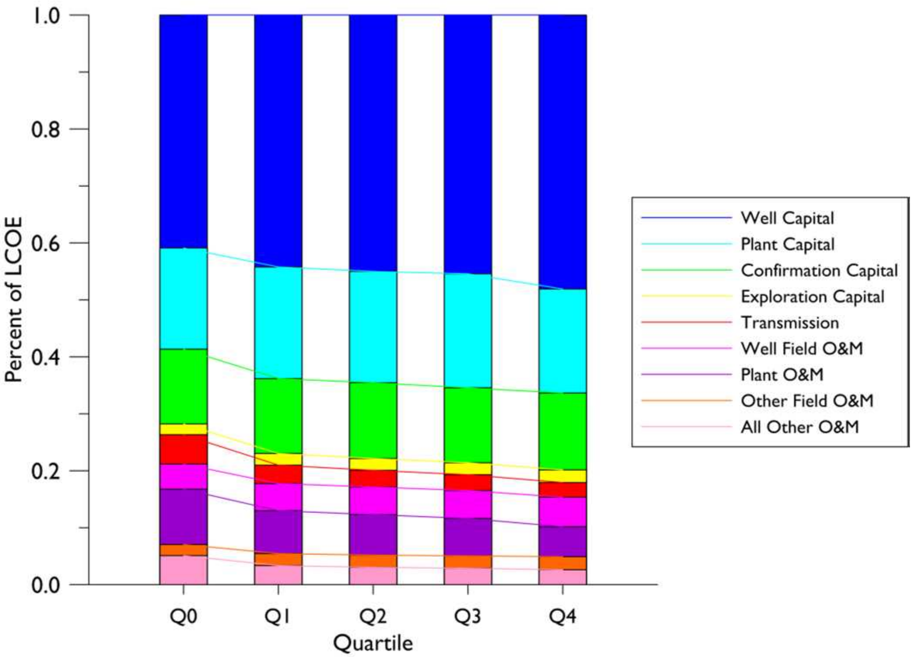


Run #	LCOE	Capital	O&M
1	20.566	17.452	3.114
2	22.269	18.714	3.555
3	19.587	16.552	3.035
4	21.933	18.828	3.105
5	24.551	21.193	3.358
6	23.190	19.818	3.371
7	19.214	16.156	3.058
8	26.758	23.068	3.690
9	23.918	20.426	3.492
10	27.295	23.543	3.751
11	24.707	21.246	3.462
12	29.383	25.582	3.801
13	18.176	15.310	2.866
14	25.030	21.504	3.526
15	15.384	12.796	2.588
16	14.678	12.219	2.459
17	16.575	13.862	2.713
18	21.852	18.756	3.097
19	21.031	17.689	3.342
20	16.359	13.464	2.895
21	27.155	23.571	3.583
22	20.271	16.971	3.301
23	16.176	13.306	2.870
24	23.286	19.751	3.535
25	16.618	13.781	2.837
26	17.127	14.365	2.762
27	19.851	16.924	2.927
28	17.978	15.019	2.959
29	34.006	29.568	4.438
30	13.255	10.857	2.398
31	17.008	14.214	2.793
32	18.600	15.657	2.942
33	30.453	26.567	3.885
34	18.035	15.095	2.940
35	17.053	14.093	2.960
36	15.008	12.336	2.671
37	17.626	14.757	2.869
38	21.574	18.278	3.296
39	17.695	14.853	2.842
40	32.791	28.743	4.048
41	18.848	15.880	2.968
42	21.973	18.658	3.315
43	16.799	14.100	2.699
44	35.850	31.547	4.303
45	21.076	17.861	3.214
46	20.466	17.258	3.208

GT-Mod Example Results

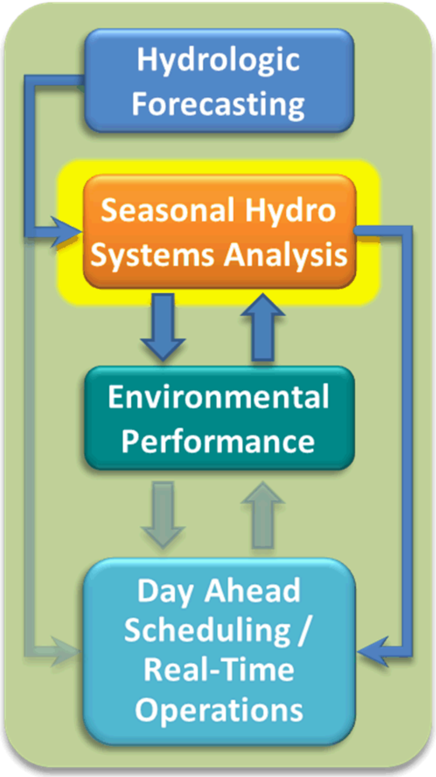
- 19% that ending production temperature < minimum
- 29 % LCOE < Base Case (default values, 18.831 ₵/kW-hr)
- Plant and well capital costs: 58% - 66% of LCOE





HydroSCOPE Example Project

- HydroSCOPE: Reservoir operations model for optimizing power production and environmental performance
- Multi-laboratory effort (ANL, PNNL, SNL)
- Reservoir and river routing SD model
- Multi-objective optimization w/ DAKOTA
- Example
  - Use of ensemble forecasts
  - Minimizing ‘regret’



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- Multi-laboratory effort (ANL, PNNL, SNL)
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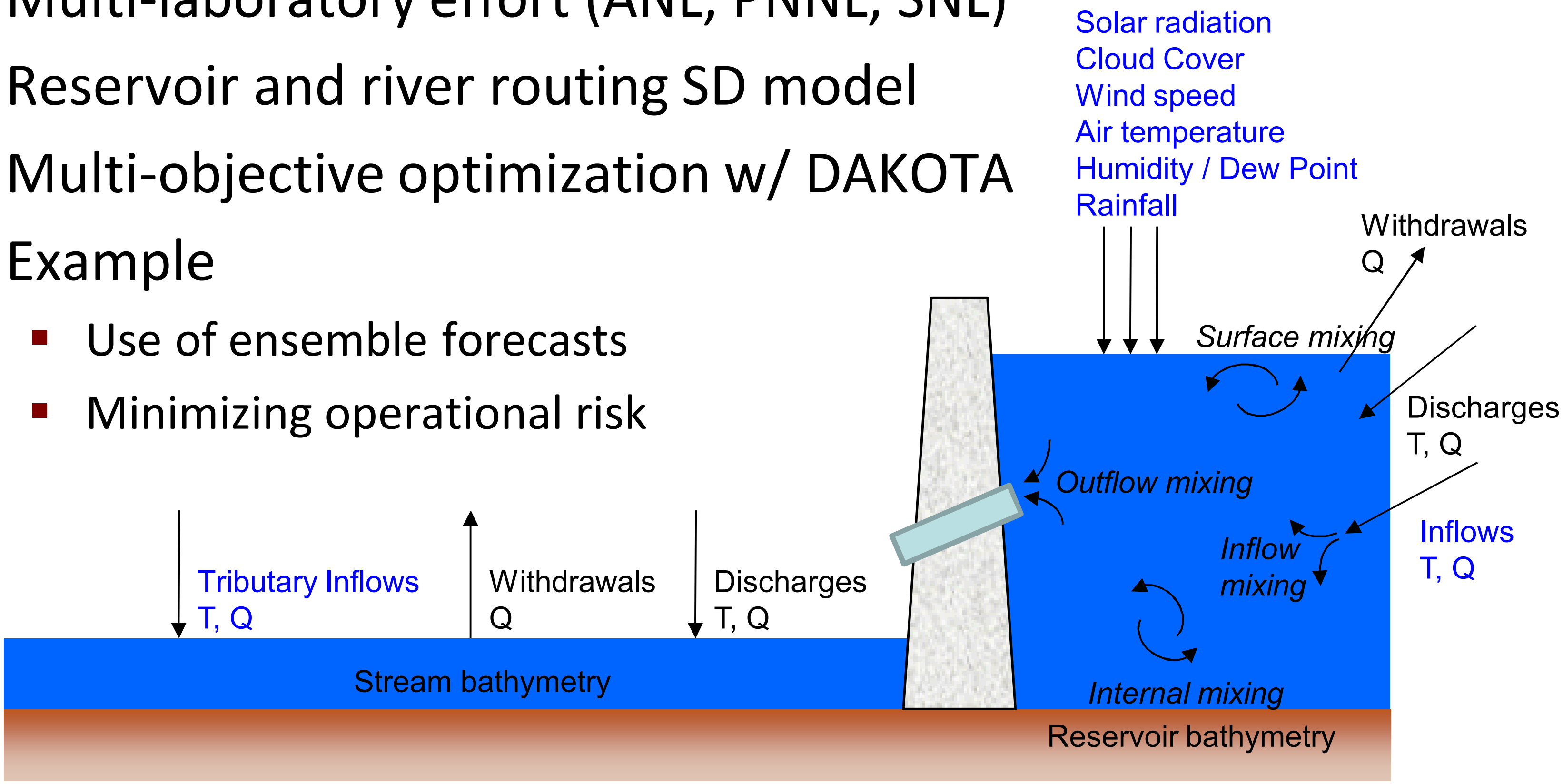
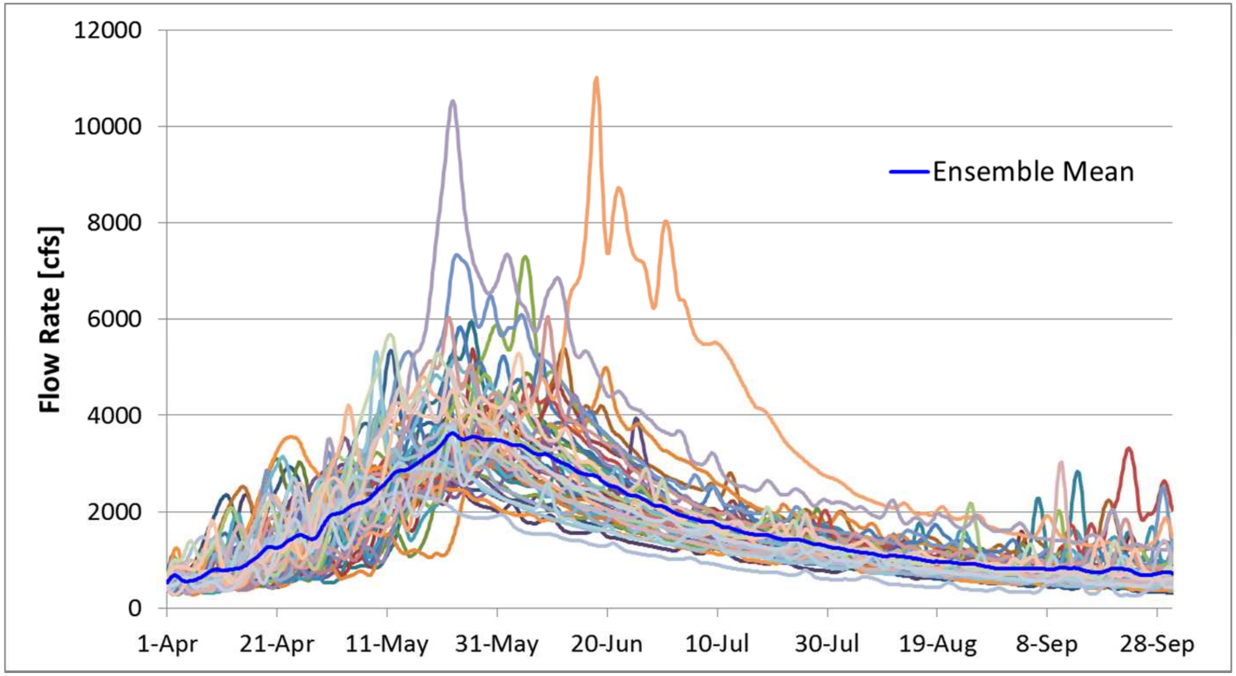
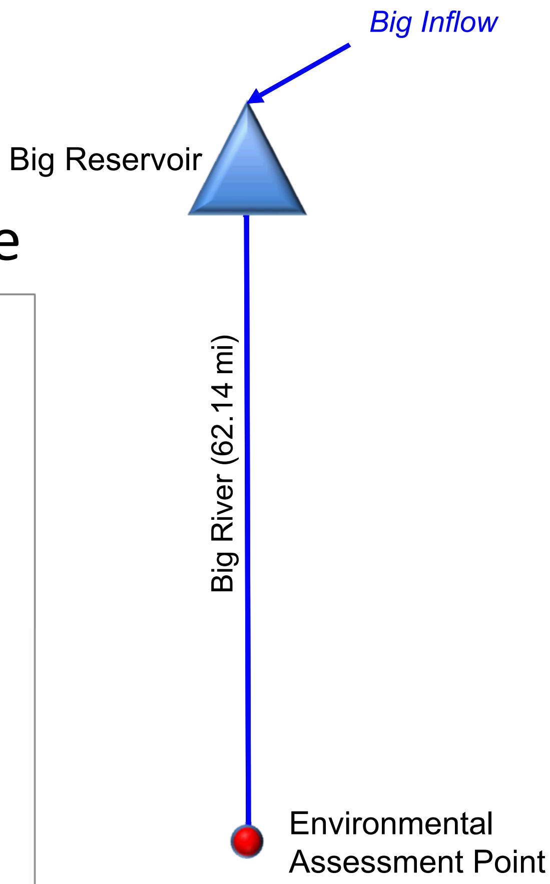
- Multi-objective optimization w/ DAKOTA
- Example
  - Use of ensemble forecasts
  - Minimizing operational risk



Ensemble Forecasts

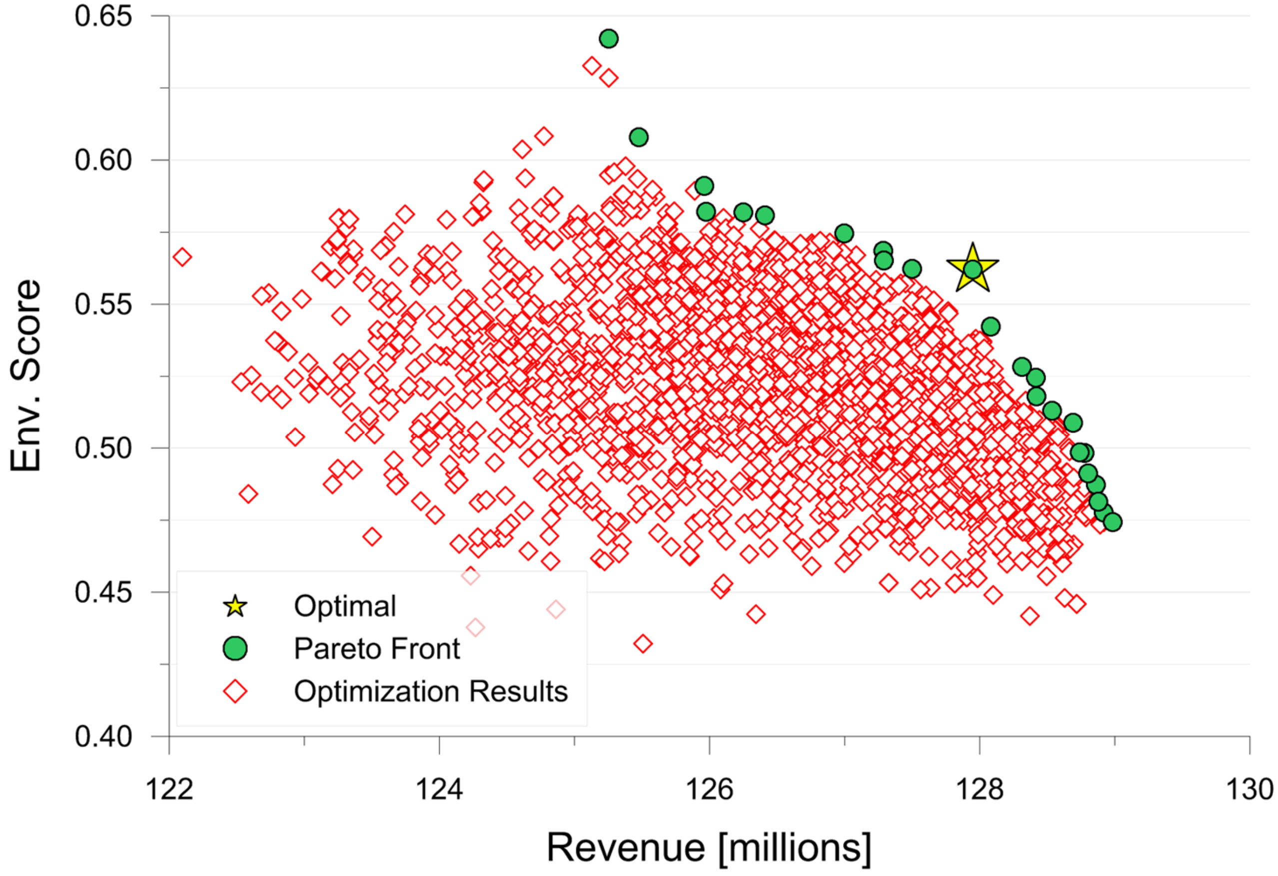
- One reservoir and river reach system
- One environmental assessment point
- 50, 6-month forecasts
- Maximize revenue and environmental score





Ensemble Mean

- Typical approach optimizes on the ensemble mean
- Pareto front defines line of tradeoff (2500 simulations)

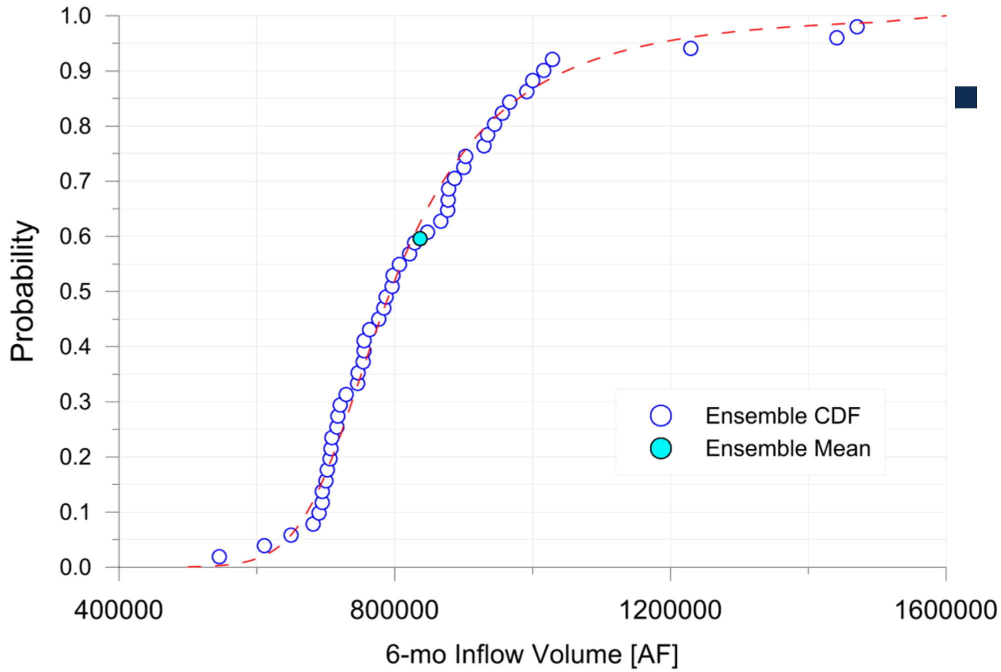


Minimizing Regret

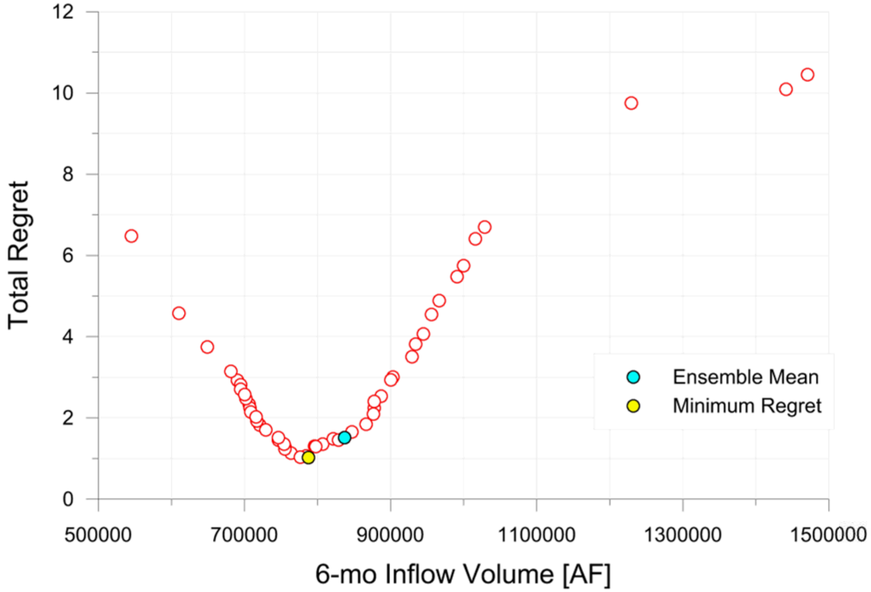
- Is the ensemble mean the ‘best’ forecast to use?
- Any forecast we use will be wrong so we want to minimize the consequence of being wrong (i.e., minimize regret)
  - Given an ensemble of ‘n’ forecasts, what is the risk of assuming forecast ‘j’ and realizing forecast ‘i’?
- Similar to the classic definition of risk (R = P*C) but the consequence is expressed as missed opportunity

Minimizing Regret

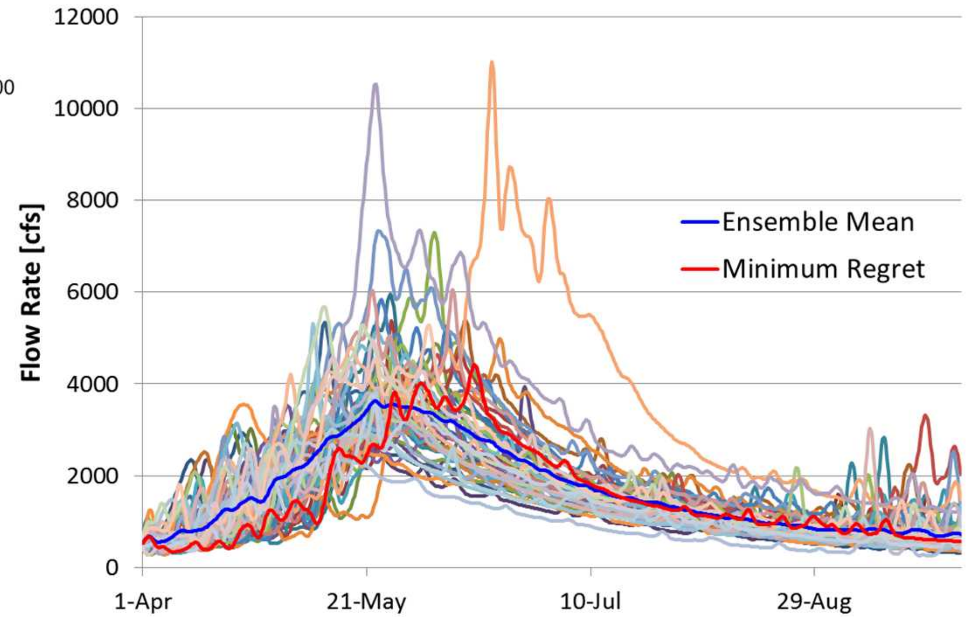
- Convert forecasts to inflow volumes
- Optimize each forecast and choose optimum
- Compare the performance of each optimum operation schedule to the other 49 and calculate regret
- Sum regret scores



HydroSCOPE Ensemble Results



<u>6-mo Inflow Volume [AF]</u>
Ensemble Mean = 836790
Minimum Regret = 787475



Summary

- Water-Energy Systems Analysis Science
  - Examines the intersection between water and energy to try and understand the complex dynamics that control the reliability and sustainability of each
  - Supports decision making and risk management approaches
  - Provides insight into future needs and priorities
- System Dynamics Capabilities
  - Model complex systems of systems with multiple stakeholders and objectives
  - Scalable
  - Fast execution
  - Stochastic modeling for uncertainty and risk assessment
  - Data analysis