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SMR.1307 - 2

Advanced Course:
CLIMATE CHANGE IN THE MEDITERRANEAN REGION
PART II: SOCIO-ECONOMIC ASPECTS AND IMPACTS
(12 - 16 November 2001)

"Vulnerability and Economic Impacts of Climate Change on Mediterranean Water Resources: Lessons from U.S. Studies"

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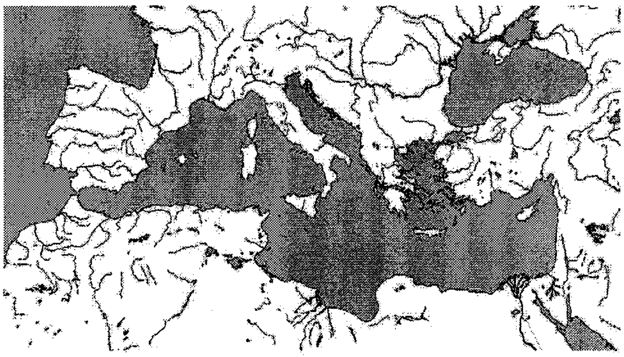
These are preliminary lecture notes, intended only for distribution to participants

Vulnerability and Economic Impacts of Climate Change on Mediterranean Water Resources: Lessons from U.S. Studies



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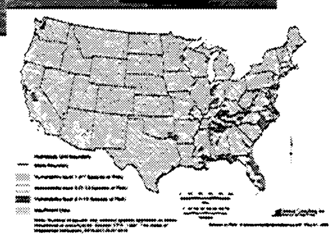
Abdus Salam International Centre for Theoretical Physics
Trieste, Italy
November 12-16, 2001

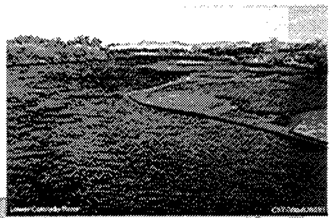
Course Objectives

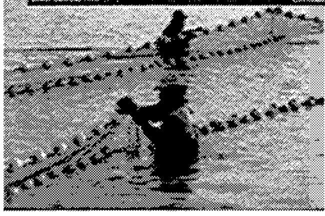
- Enhance understanding of water resource assessment methods
- Develop and organize water resource data and information
- Design indicators of water resource use and vulnerability
- Construct an economic model to examine watershed policies and economic impacts



Overview

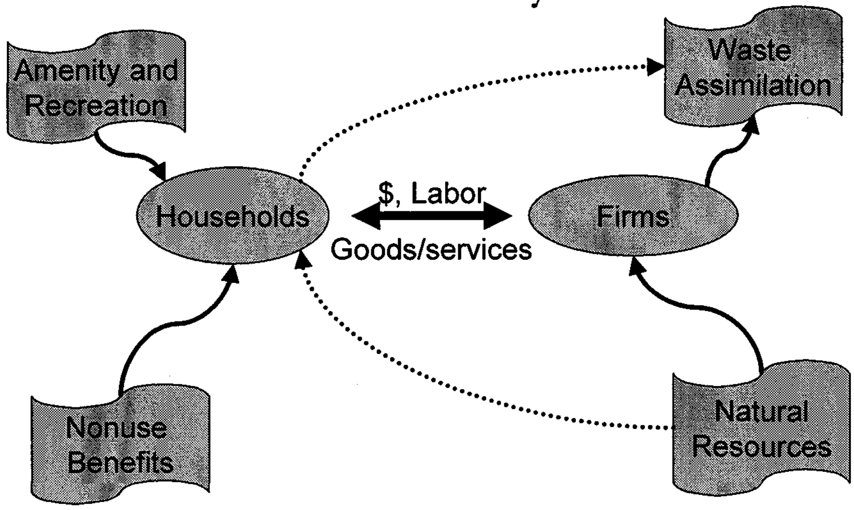
1. Water resources: define, identify, and characterize their condition and use
2. Competition for and conflict over WATER
3. Vulnerability of water resource services to multiple stressors:
   e.g., pollution, overuse, climate change
4. Strategies for coping with vulnerability and scarcity
5. Watershed planning: models that integrate concerns and help us look forward
6. What does the future hold?: Possible Climate Change





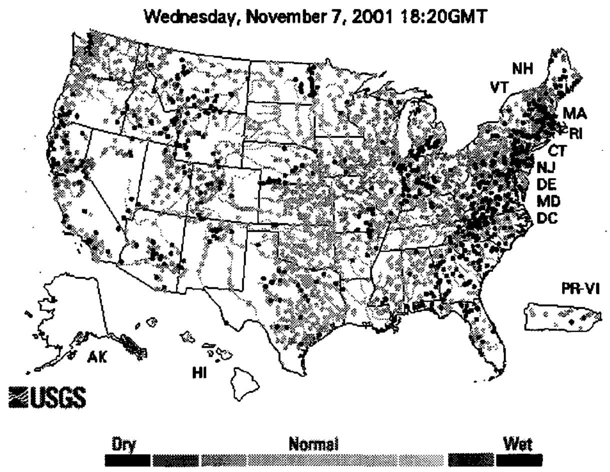
1.
Water resources: define, identify, and characterize their condition and use

Relationship between Economic and Environmental Systems

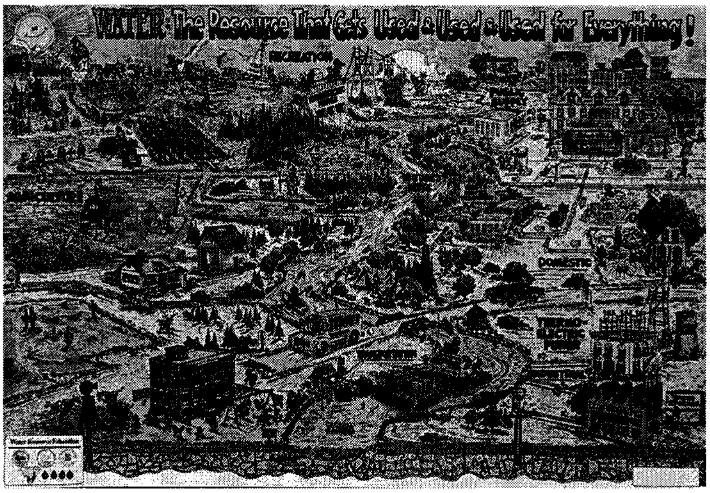


Surface-Water Resources: Streamflow Records

Map of real-time streamflow compared to historical streamflow for the day of the year



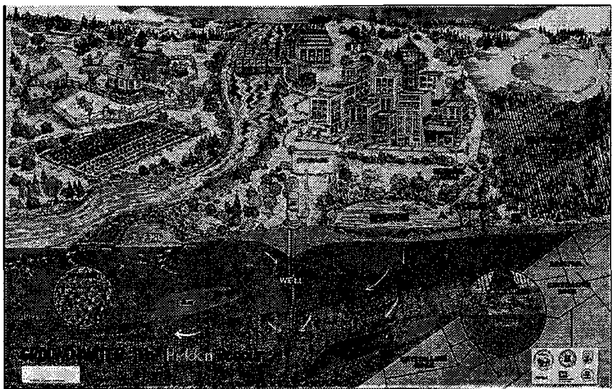
Surface Water

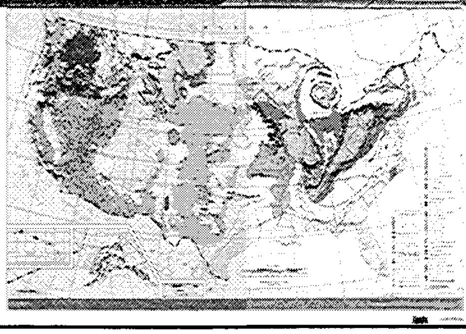


Multiple Uses

- Domestic
- Industrial
- Agriculture
- Navigation
- Recreation
- Electric Power
- Wetlands
- Pollution Control

Ground-Water Resources





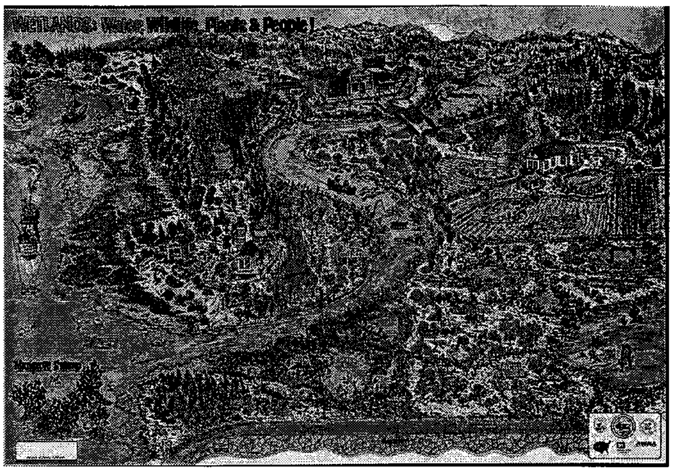
Key Characteristics

- Extent and location
- Depth and volume
- Quality
- Recharge Source and Rate

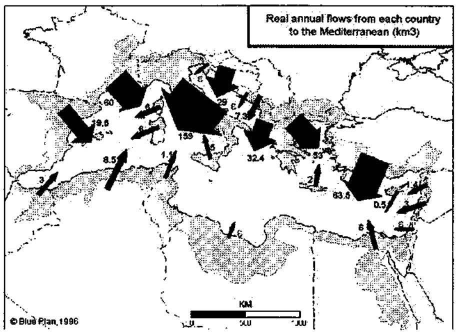
Wetlands, Habitat, Environment

Key Issues

- Pollution
  - Heavy metals
  - Pesticides
  - Nutrients
- Dissolved Oxygen
- Temperature
- Diurnal and Seasonal Streamflows



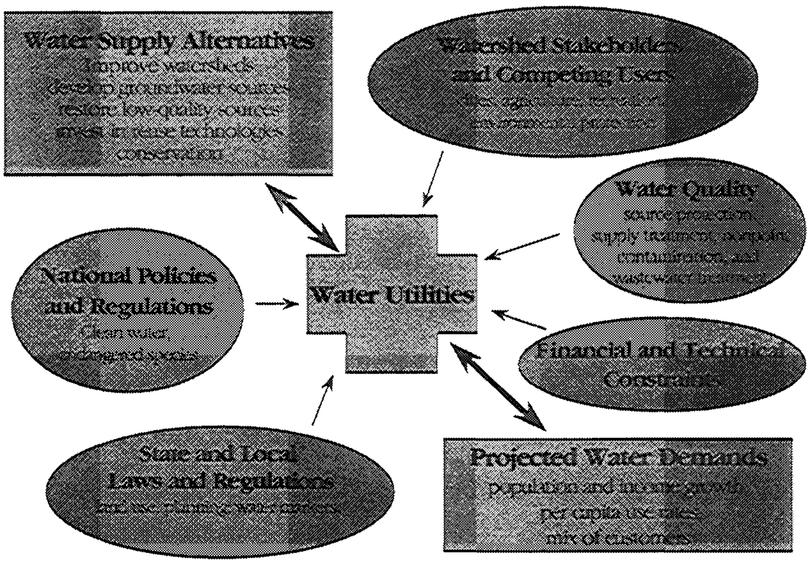
Possible Water Issues In the Mediterranean



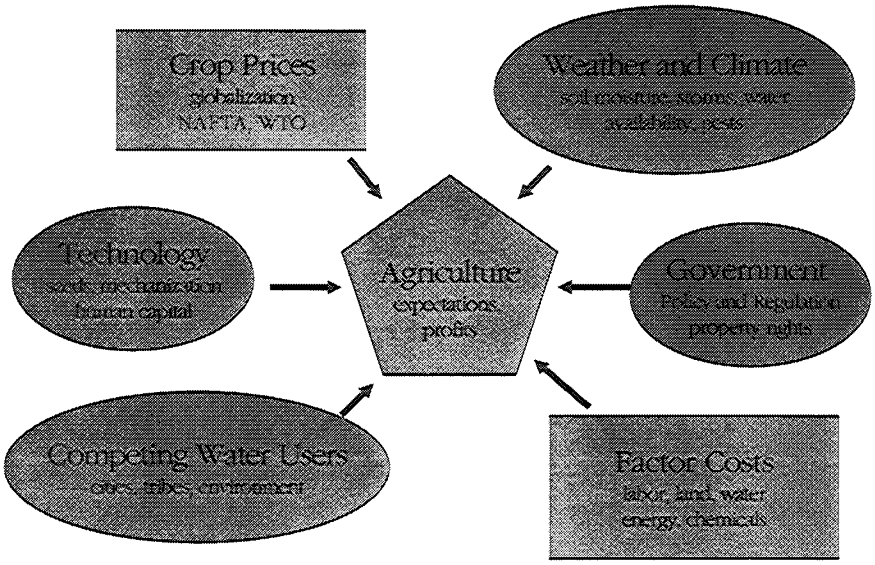
- Water supply to meet growing demands
  - storage/capital improvements
  - reallocation/transfers
  - rural drinking water
- Expanding environmental needs
  - maintaining/enhancing water quality
  - endangered species
- Managing existing supplies
  - flood planning response
- Legal and institutional challenges
  - inadequate/inappropriate government involvement
  - interstate/international conflicts/requirements
  - disputes among water users

2.
Competition for and conflict over WATER

Cities Under Pressure



Farms Under Pressure



3. Indicators of Vulnerability to Climate Change

Water Resource Stress:
A National Perspective

"Relative Regional Vulnerability of Water Resources to Climate Change"

Co-Authors: Neil Leary (IPCC formerly with USEPA)
Russel Jones (Stratus Consulting)
Joel Smith (Stratus Consulting)

Originally Published in: *Journal of the American Water Resources Association*. 1999. 35(6):1399-1410.

Republished in: Water Resources Journal, United Nations. 2000. n. 204(March):17-28.

and as a chapter in *Climate Change and Water Resources*, K Frederick (ed.), forthcoming, Edward Elgar.

Vulnerability Indicators

- Watershed Based <u>(204 USGS Watershed Classification)</u>
- 3-tiered classification of relative vulnerability
  - (1) low
  - (2) moderate
  - (3) high
- Vulnerability is based on relative distribution of numeric scores

Indicators for Supply and Consumptive Use

Level of Development
(share of annual streamflow withdrawn for use)

Natural Variability
(CV of annual streamflow)

Dryness Ratio
(share of precipitation evapotranspired)

Indicators for Supply and Consumptive Use (cont.)

Groundwater Depletion
(groundwater withdrawals to average baseflow)

Industrial Water-Use Flexibility
(share of withdrawals consumed)

Institutional Flexibility
(relative costs of water transfers)

Indicators for Instream Uses

Flood Risk
(population in 500 yr. floodplain)

Navigation
(average annual dredging costs)

Ecosystem Thermal Sensitivity
(number of extreme temperature days)

Indicators for Instream Uses (cont.)

Dissolved Oxygen
(% of observations <5mg/l)

Low Flow Sensitivity
(average baseflow cfs/mi^2)

Species at Risk
(number of aquatic/wetland species at risk)

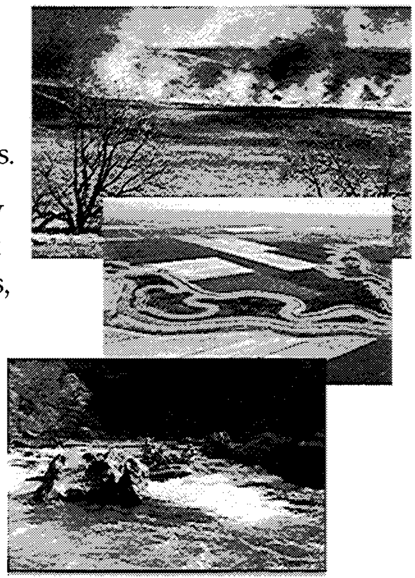
Vulnerability Summaries

Consumptive Use

Instream Use

Overall Index

Key Findings



- Vulnerability can vary significantly within large scale water resource areas.
- Supply and use vulnerability generally increases from east to west. Greatest in Southwest, California, Great Plains, and Texas.
- Instream use vulnerability (including flooding), generally increases from north to south. Greatest Southwest, Southern Plains, Mid-Atlantic, and Southeast.

4. Strategies for coping with vulnerability and scarcity

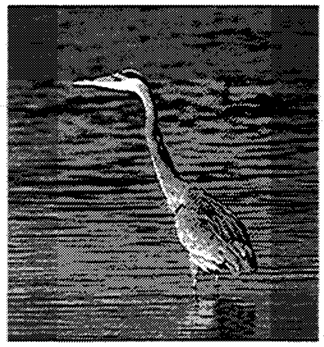
Ways We Can Better Cope

- Improve water management systems
  - develop models and approaches to evaluate institutional changes for more equitable and efficient prices and allocations
  - develop more complete and dissaggregated data on demographic trends and water use characteristics to improve demand forecasting
  - improve weather and climate forecasting capability and the accessability and use by irrigators
- Increase urban and agricultural water-use efficiency
  - develop water reuse and recycling infrastructure for new urban developments
  - increase the accessability of water-saving technologies for both urban and rural users

5.
Watershed planning: models that integrate concerns and help us look forward

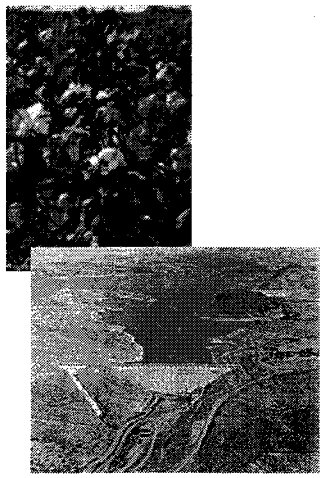
Objectives of Watershed Models

- Represent major spatial, physical, and economic characteristics of water supply and use
- Evaluate welfare, allocation, and implicit price changes associated with alternative hydrologic, management, and institutional conditions
- Identify opportunities to improve water management systems from a watershed perspective

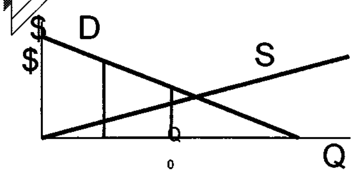


River Basin Model:

Economic Objectives Subject to Structural and Institutional Constraints



- Consumptive and nonconsumptive economic services
  - Agriculture, municipal and industrial, thermoelectric
  - Hydropower, navigation, flood damages, water quality
- Constrained by inflows, river characteristics, institutional provisions
- Outcomes indicate efficient water use, river flow, and storage
  - Across the mixture of users
  - Upstream and downstream services
  - Intertemporal allocation

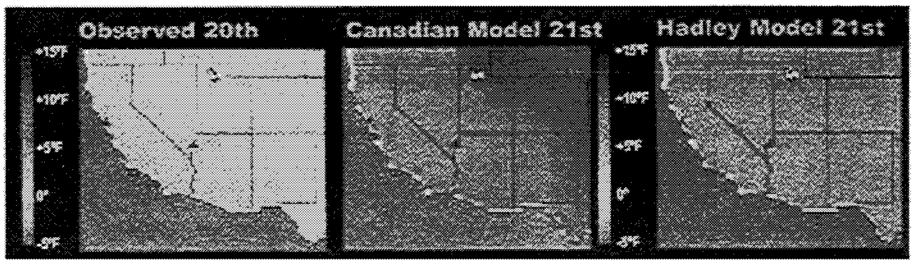


Economic Principles

- Allocative efficiency depends on water supply and demand
- Water supply is generated primarily from rainfall and tributary inflows – can be stored or used
- Water demand derives from the value of the services that water performs (economics and ecology)
- Lesson 1: Single Sector Market (undergraduate level)
- Lesson 2: Two Sector Market (graduate-level)

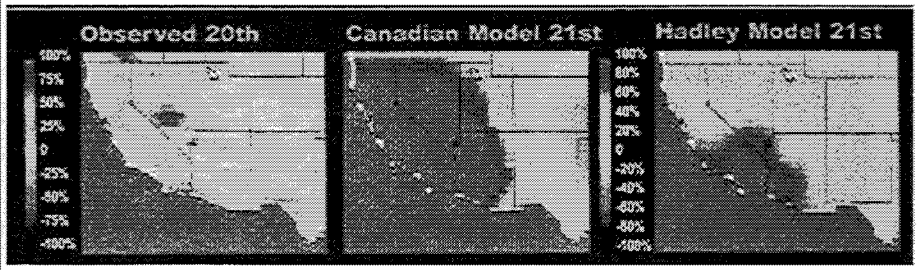
6.
What does the future hold?: Possible Climate Change

Possible Climate Futures for the American Southwest: Temperature



Source: The Potential Consequences of Climate Variability and Change (NAST 2000).

Possible Climate Futures for the American Southwest: Precipitation



Source: The Potential Consequences of Climate Variability and Change (NAST 2000).

Watershed Management: An Approach To Watershed Modeling

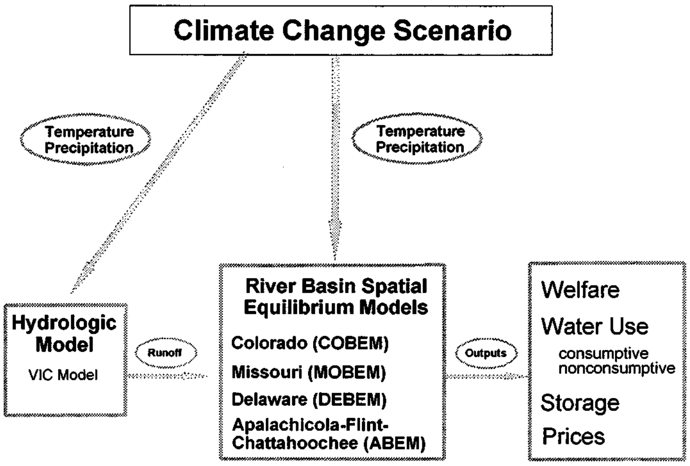
"Economic Effects of Climate Change on U.S. Water Resources,"

Co-Authors: Mac Callaway (RISOE, Denmark)
Joel Smith (Stratus Consulting)
Paul Kirshen (Tufts University)

Originally Published in: *The Impact of Climate Change on the United States Economy*, Robert Mendelsohn and James E. Neumann (eds.), Cambridge University Press, Cambridge.

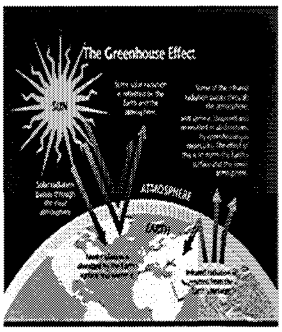
Republished in: *Water Resources and Climate Change*, Chapter 17, Ken Frederick (ed.), 2002, Edward Elgar Publishing.

Modeling Overview



Climate Scenarios in the U.S. Study

Simulations used incremental changes in temperature and precipitation



Baseline

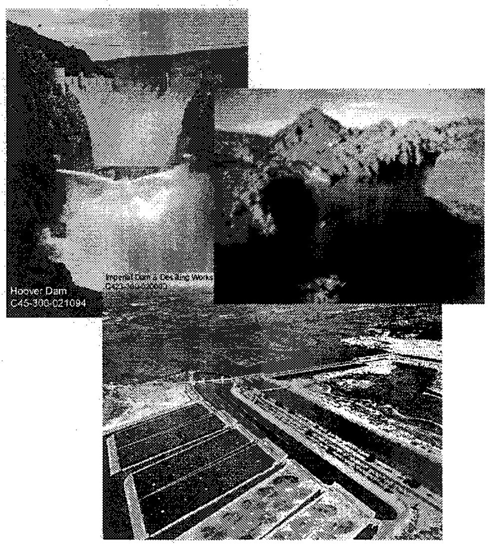
+2.5°C, +7%P	+5.0°C, -10%P
+5.0°C, +7%P	+5.0°C, +15%P
+1.5°C, +7%P	+1.5°C, +15%P
+2.5°C, -10%P	+1.5°C, -10%P
+2.5°C, +15%P	+5.0°C, +0%P

Model Basics

- Develop a schematic diagram of the watershed system
  - Describes physical structure (tributaries, inflows, and reservoirs
  - Identifies and locates watershed services
  - Show diversion points and instream uses
- Derive estimates for the model's objective function
  - Develop demand and supply curves for each service based on water diversion or instream flow
- Describe model constraints
  - Mass balance (upstream to downstream flow)
  - Intertemporal storage in reservoirs
  - Institutional flow restrictions

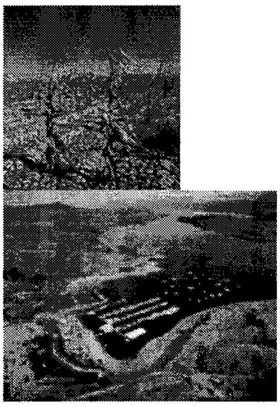
Outcomes: Colorado River Watershed

- Projected hydrologic and runoff changes
- Estimated changes in runoff and allocation in the Lower Colorado watershed
- Economic impacts across the watershed



Outcomes: Across Watersheds:

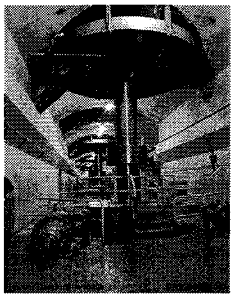
Colorado River, Missouri River, Delaware River, Appalachicola-Chattahoochee-Flint Rivers



Agriculture

Hydropower

Total Welfare



Major Inferences

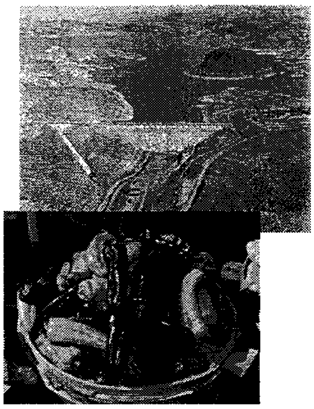
- Total welfare impacts are mitigated by market exchanges of between low and high valued users
- In periods of severe drought, the inflexibility of institional constraints, such as fixed volume provisions of Compacts in the western watersheds, exacerbates total welfare losses, particularly to upstream users.
- Hydrologic changes can have significant impacts on instream uses, which can exceed, in percentage terms, impacts to consumptive users.

Future Research

- Improve model calibration and validation
  - Baseline specifications to enhance model
  - Use 'positive mathematical programming' techniques to calibrate to baseline allocations
- Examine model properties, e.g., robustness of results to changes in modeling assumptions, spatial and temporal scale, and variability of runoff
- Develop ecosystem objectives/constraints and improve water quality modeling
- Enhance utility and policy relevance
- Develop models for additional regions

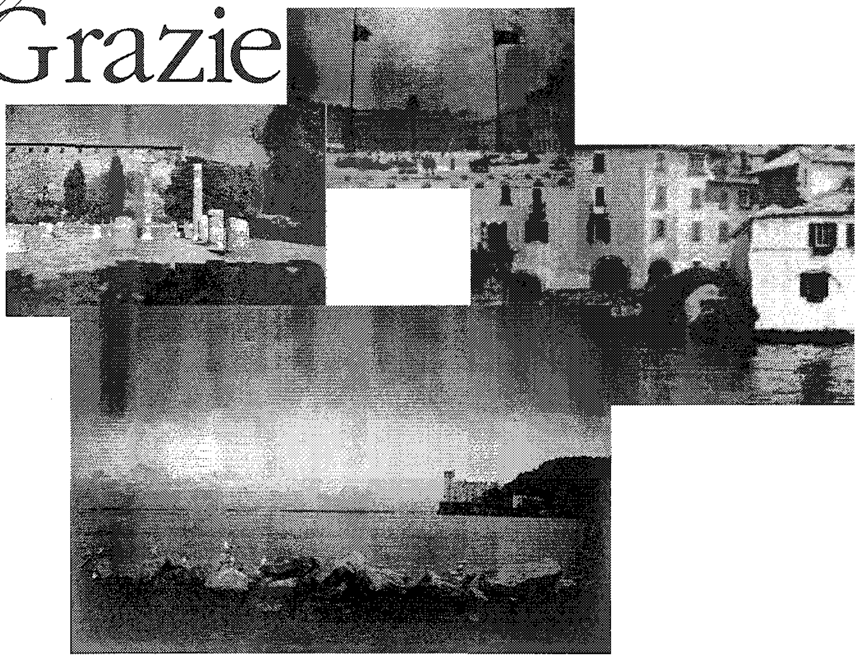
Water, Food, and Quality of Life:

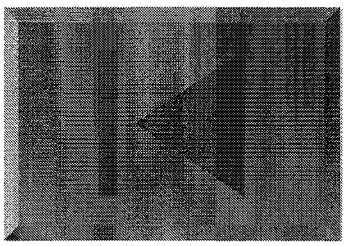
Take Home Messages



- Models are useful tools that can help plan and manage for a sustainable water future
- Consider market-based solutions: send the right messages to producers and consumers about water scarcity
- Encourage strategies that are flexible and that can adapt to changing conditions and uncertainties

Grazie





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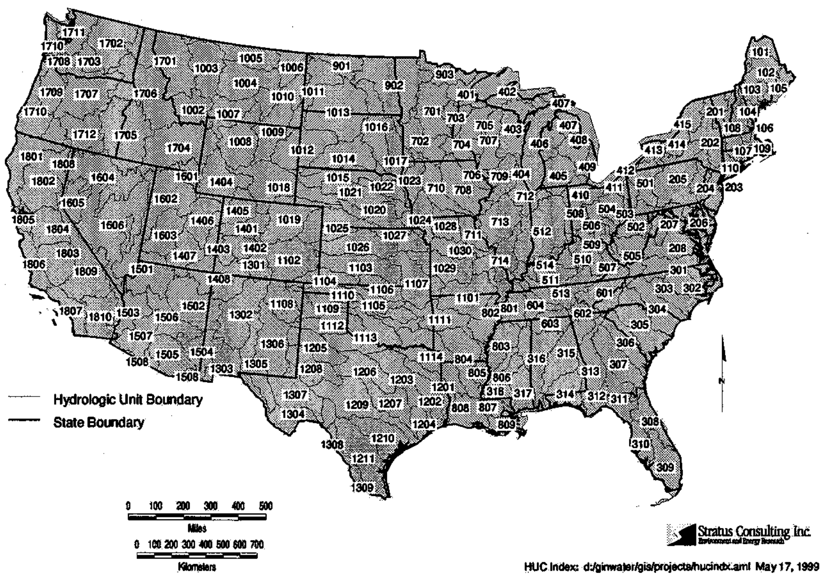
and as a chapter in *Climate Change and Water Resources*, K Frederick (ed.), forthcoming, Edward Elgar.

USGS Water Regions (4 digit)



Distribution and Supply

Table 3-1
Summary of Water Resource Vulnerability Indicators

Indicator	Description	Criteria Threshold[1] 1 = Low Vulnerability 2 = Medium Vulnerability 3 = High Vulnerability	Area of Concern: General Water Use	Area of Concern: Consumptive Demand	Area of Concern: Instream Use	Area of Concern: Ecosystem/ Water Quality
Distribution System and Supply Indicators						
Water Use to Storage Q_W/S	Ratio of total annual average surface and groundwater withdrawals in 1990 (Q_W) to total active basin storage (S).	Vulnerability class: 1 (<0.6), 2 (0.6-3), 3 (>3).	✝	✝		
Level of Development Q_W/Q_S	Ratio of total annual surface and groundwater withdrawals in 1990 (Q_W) to unregulated mean annual streamflow (Q_S).	Vulnerability class: 1 (<0.2), 2 (0.2-0.85), 3 (>0.85). This ratio reflects the extent to which a watershed's water resources are developed for consumptive uses.	✝	✝	✝	✝
Natural Variability σ_{Q_S}/Q_S	Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of annual streamflow (σ_{Q_S}) to the unregulated mean annual streamflow (Q_S).	Vulnerability class: 1 (<33%), 2 (33-67%), 3 (>67%). Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes.	✝	✝	✝	✝
Dryness Ratio $(P-Q_S)/P$	Share of total average annual precipitation (P) that is lost due to evapotranspiration (ET), where ET is defined as $P-Q_S$.	Vulnerability class: 1 (<63%), 2 (63-78%), 3 (>78%). Regions with the highest evapotranspiration losses are most vulnerable to relatively small changes in precipitation.	✝	✝		✝

Groundwater, Domestic, M&I

Table 3-1 (cont.)
Summary of Water Resource Vulnerability Indicators

Indicator	Description	Criteria Threshold[1] 1 = Low Vulnerability 2 = Medium Vulnerability 3 = High Vulnerability	Area of Concern: General Water Use	Area of Concern: Consumptive Demand	Area of Concern: Instream Use	Area of Concern: Ecosystem/ Water Quality
Consumptive Use and Institutional Flexibility Indicators						
Groundwater Reliance Q_{GW}/Q_W	Share of total annual withdrawals derived from groundwater in 1990.	Vulnerability class: 1 (<0.1), 2 (0.1-0.6), 3 (>0.6). Regions with relatively high groundwater reliance could be vulnerable to surface supply changes.		✝		
Groundwater Depletion Q_{GW}/Q_{Base}	Ratio of average groundwater withdrawals in 1990 to annual average baseflow, reflecting the extent that groundwater use rates may be exceeding recharge.	Vulnerability class: 1 (<8%), 2 (8-25%), 3 (>25%). Regions with high depletion rates are vulnerable to long-run changes in hydrology.	✝	✝		
Vulnerability of Domestic Water Uses 1. Q_S/pop. 2. (Q_S-Q_W)/pop.	Two measures estimating per capita water availability. The first measures per capita average annual streamflow (Q_S). The second nets withdrawals (Q_W) from streamflow.	Vulnerability class for streamflow per capita: 1 [>20 million gallons per person per year (Mgpy)], 2 (5-20 Mgpy), 3 (<5 Mgpy). Vulnerability class for net streamflow per capita: 1 (>10 Mgpy), 2 (3-10 Mgpy), 3 (<3 Mgpy).		✝		
M&I Water Use Share $Q_{Wm\&i}/Q_W$	Municipal and industrial sector share of total average annual withdrawals.	Vulnerability class: 1 (<10%), 2 (10-40%), 3 (>40%). Regions with high shares may have less flexibility in satisfying M&I water demands.		✝		

Agriculture, Flexibility

Table 3-1 (cont.)
Summary of Proposed Water Resource Vulnerability Indicators

Indicator	Description	Criteria Threshold[1] 1 = Low Vulnerability 2 = Medium Vulnerability 3 = High Vulnerability	Area of Concern: General Water Use	Consumptive Demand	Instream Use	Ecosystem/ Water Quality
Consumptive Use and Institutional Flexibility Indicators (cont.)						
Agricultural Water Use Share Q_{Wag}/Q_W	Agricultural sector withdrawals (Q_{Wag}) as a share of total average annual withdrawals.	Vulnerability class: 1 (>70%), 2 (20-70%), 3 (<20%). Because agriculture can serve as a source of water during periods of low supply, regions with relatively low shares of agricultural water use may have less flexibility in satisfying water demands.		✦		
Industrial Water Use Flexibility	Share of total annual average industrial water use that is consumed (i.e., not returned to the system).	Vulnerability class: 1 (<10%), 2 (10-40%), 3 (>40%). Greater rates of consumptive use by industry can indicate more intensive use of relatively expensive water-saving technologies, and, therefore, less flexibility in achieving further water savings in periods of low supply.		✦		
Institutional Flexibility	An integer-based flexibility score ranging from one to five is assigned to each state based on the relative degree of barriers to water trading.	Vulnerability class: 1 (flexibility score 0 or 1), 2 (flexibility score 2 or 3), 3 (flexibility score 4 or 5). States permitting water trading, such as most with prior appropriation, are more flexible in adapting to hydrologic changes.	✦	✦	✦	✦

Hydropower, Flood, Navigation

Table 3-1 (cont.)
Summary of Water Resource Vulnerability Indicators

Indicator	Description	Criteria Threshold[1] 1 = Low Vulnerability 2 = Medium Vulnerability 3 = High Vulnerability	Area of Concern: General Water Use	Consumptive Demand	Instream Use	Ecosystem/ Water Quality
Instream Use Indicators						
Hydropower Capacity	Distribution of regional hydroelectric power capacity, in megawatts (MW).	Vulnerability class: 1 (<10 MW), 2 (10-500 MW), 3 (>500 MW). Identifies regions where hydroelectric producers as a whole are most at risk to losses from reduced streamflow.			✦	
Flood Risk	Population within the 500-year flood plain.	Vulnerability class: 1 (<20,000), 2 (20,000-200,000), 3 (>200,000).			✦	
Navigation	Average annual expenditures on dredging activities in navigable waterways.	Vulnerability class: 1 (<$2 million), 2 ($2-$20 million), 3 (>$20 million). Higher expenditures indicate relative importance of waterway and magnitude of existing efforts to clear waterway. Higher streamflows could result in greater deposition of sediment, while lower streamflows could require additional dredging to maintain navigable waterways.			✦	

Snow, Ecosystem (ice/heat)

Table 3-1 (cont.)
Summary of Proposed Water Resource Vulnerability Indicators

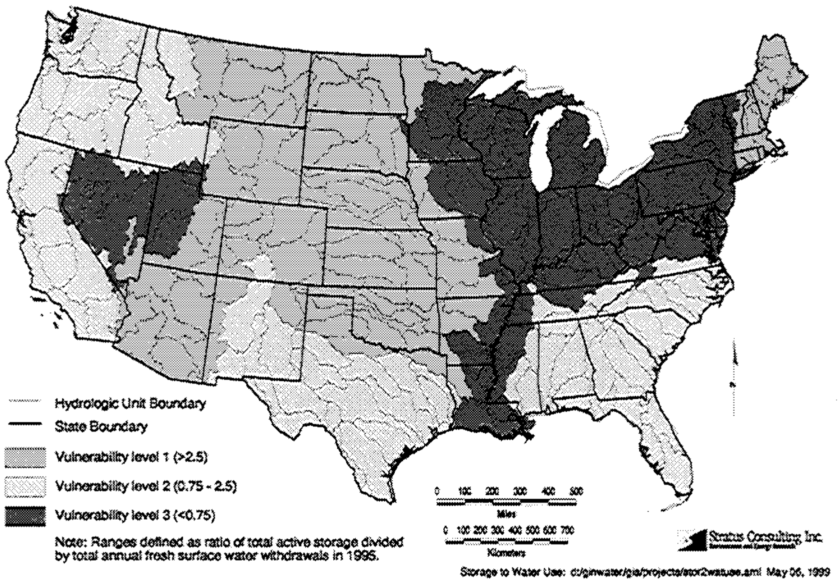
Indicator	Description	Criteria Threshold[1] 1 = Low Vulnerability 2 = Medium Vulnerability 3 = High Vulnerability	Area of Concern: General Water Use	Consump-tive Demand	Instream Use	Ecosystem/ Water Quality
Ecosystem/Water Quality Indicators						
Snow Influence	Share of average annual precipitation (P) that falls as snow (P_s) (i.e., snow water equivalent).	Vulnerability class: 1 (<12%), 2 (12-36%), 3 (>36%). Regions where snowmelt accounts for a significant share of available moisture are most vulnerable to shifts in seasonal precipitation.	✝			✝
Ecosystem Ice Cover Sensitivity	The average annual number of days with average temperatures below 0 °C.	Vulnerability class: 1 (<32 days), 2 (32-85 days), 3 (>85 days). Many ecosystems, particularly lakes and forests, have evolved with specific cold weather requirements.				✝
Ecosystem Heat Sensitivity	The average annual number of days with maximum temperatures exceeding 35 °C.	Vulnerability class: 1 (<15 days), 2 (15-40 days), 3 (>40 days). Extreme heat is a significant source of stress on ecosystems. Even regions adapted to relatively high temperatures may not easily tolerate even small increases in maximum temperatures.		✝		✝

Dissolved O2, Low Flow, Species

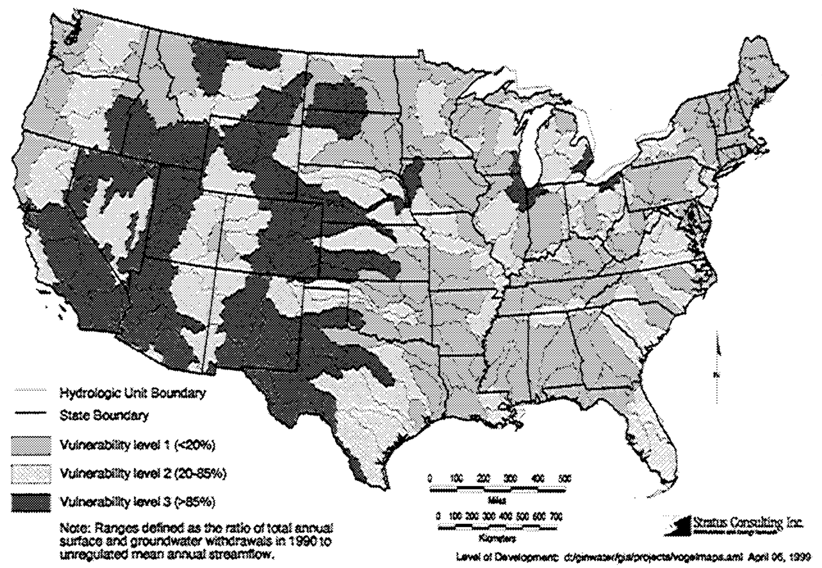
Table 3-1 (cont.)
Summary of Proposed Water Resource Vulnerability Indicators

Indicator	Description	Criteria Threshold[1] 1 = Low Vulnerability 2 = Medium Vulnerability 3 = High Vulnerability	Area of Concern: General Water Use	Consump-tive Demand	Instream Use	Ecosystem/ Water Quality
Ecosystem/Water Quality Indicators (cont.)						
Dissolved Oxygen	Percent of observations of ambient concentrations less than 5 mg/l.	Vulnerability class: 1 (<3%), 2 (3-15%), 3 (>15%). Dissolved oxygen levels in waterways decline with increasing temperatures, causing stress to aquatic wildlife.				✝
Low Flow Sensitivity	Unregulated mean baseflow in millions of gallons per day (Mgd), the amount of streamflow originating from groundwater outflow.	Vulnerability class: 1 (>4,800 Mgd), 2 (800-4,800 Mgd), 3 (<800 Mgd). Baseflow is a measure of the capacity of a watershed to sustain instream flows during low-flow periods. Aquatic ecosystems within watersheds with relatively low baseflows are most vulnerable to periods of severe and sustained drought.	✝			✝
Species at Risk	Number of aquatic/wetland species known to be at risk, either threatened or endangered.	Vulnerability class: 1 (<5 species), 2 (5-13 species), 3 (>13 species).				✝
1. Vulnerability classifications were generally determined after examination of the data distributions.						

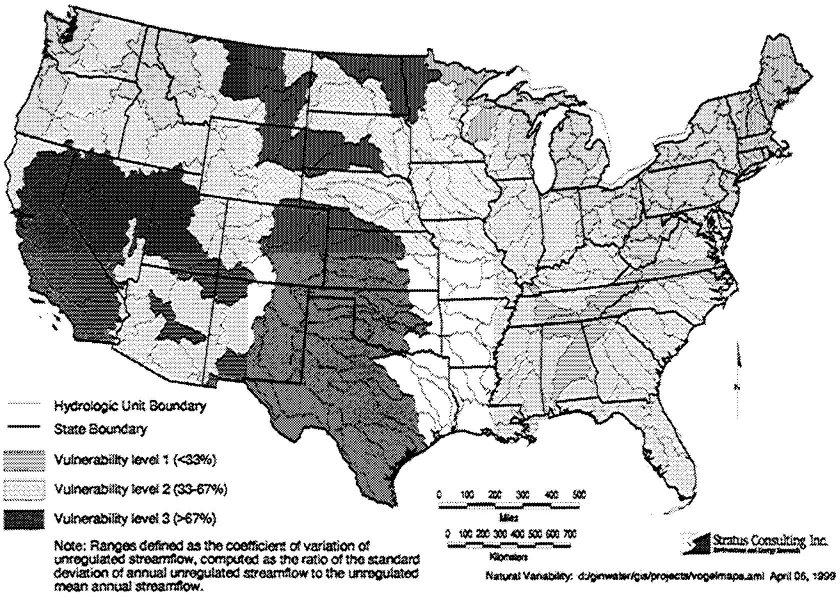
Water-Use to Storage



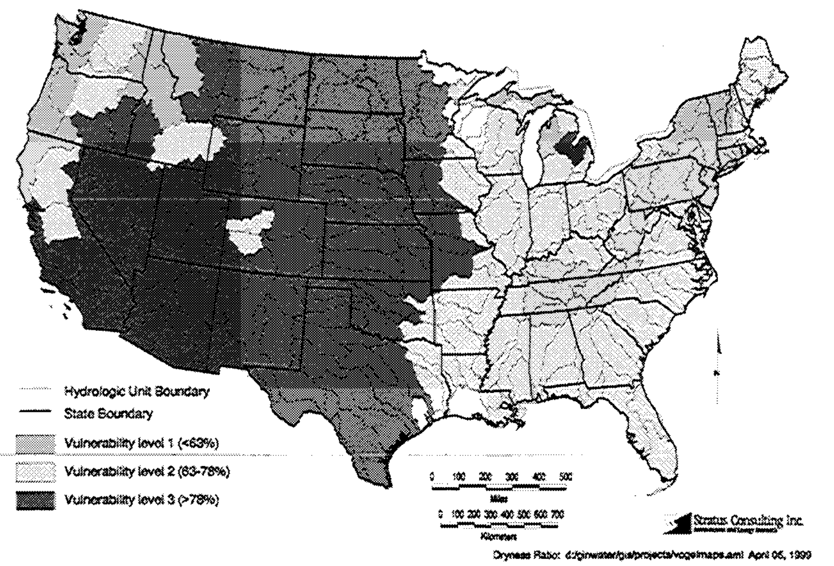
Level of Development



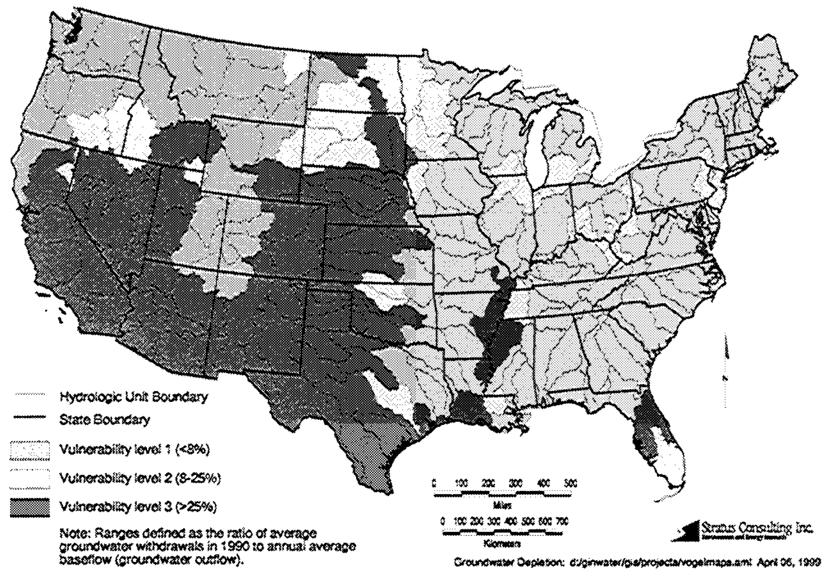
Natural Variability



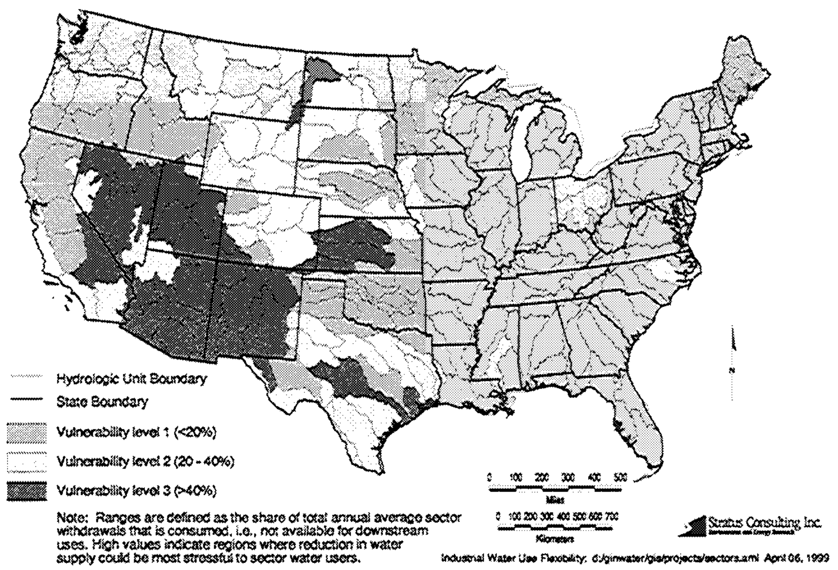
Dryness Ratio



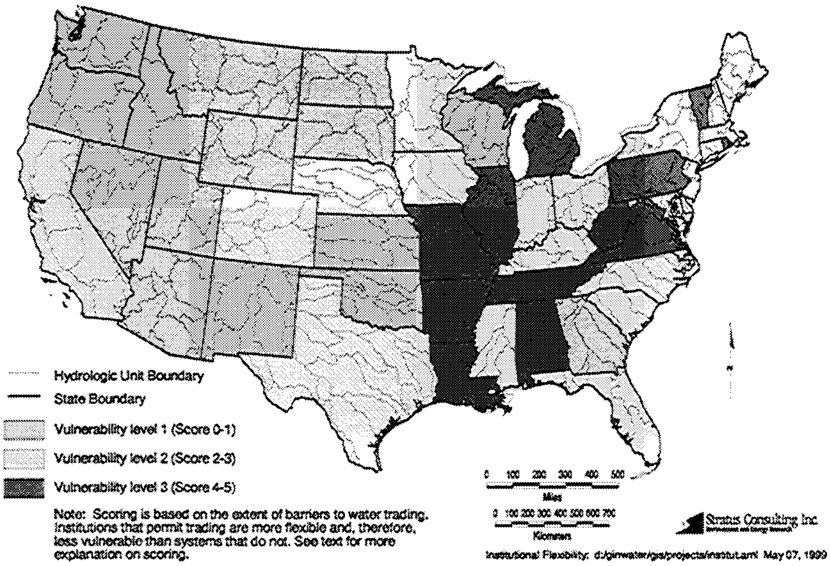
Groundwater Depletion



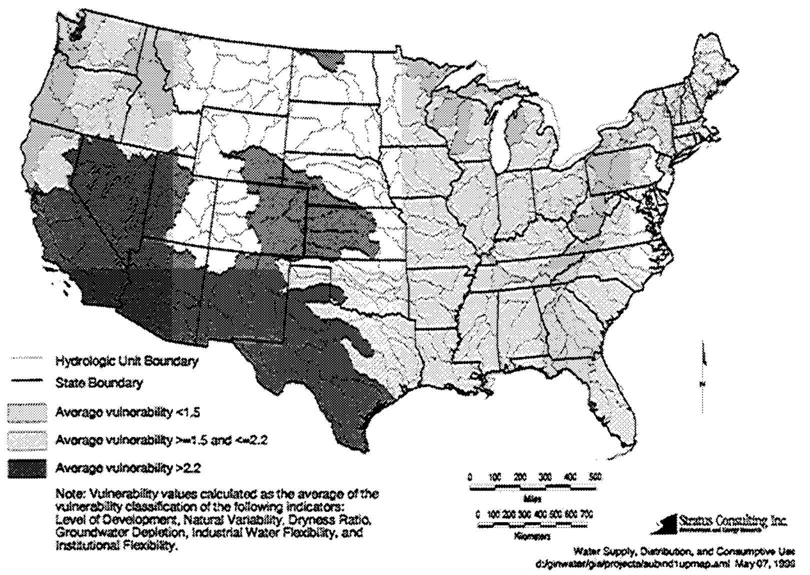
Water-Use Flexibility



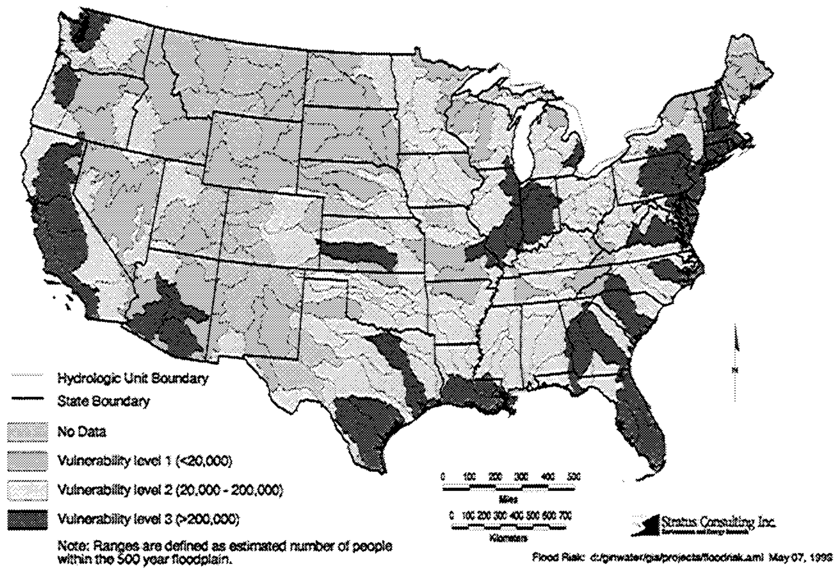
Institutional Flexibility



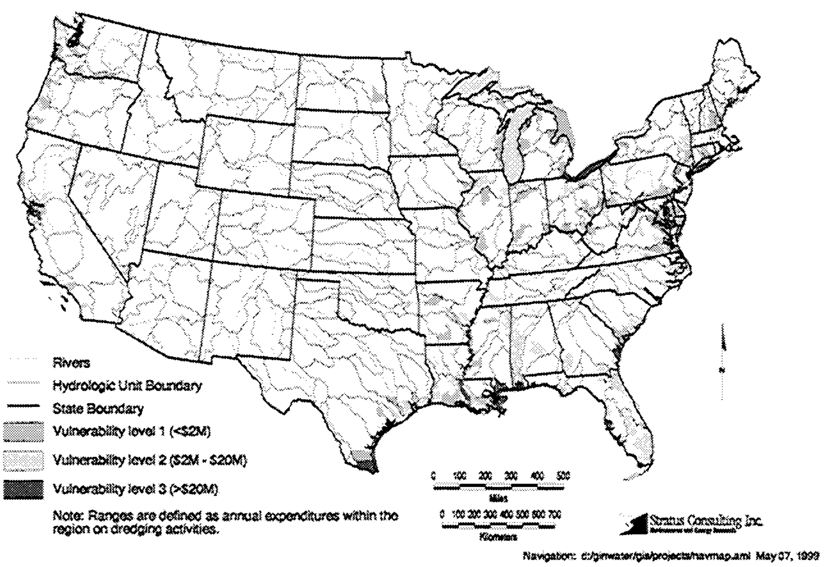
Subindex: Consumptive Use



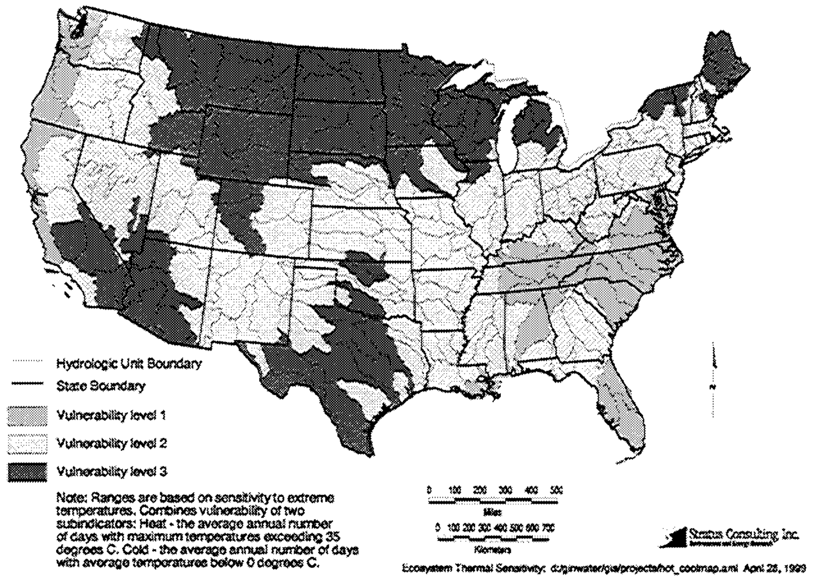
Flood Risk
Population in 500 year floodplain



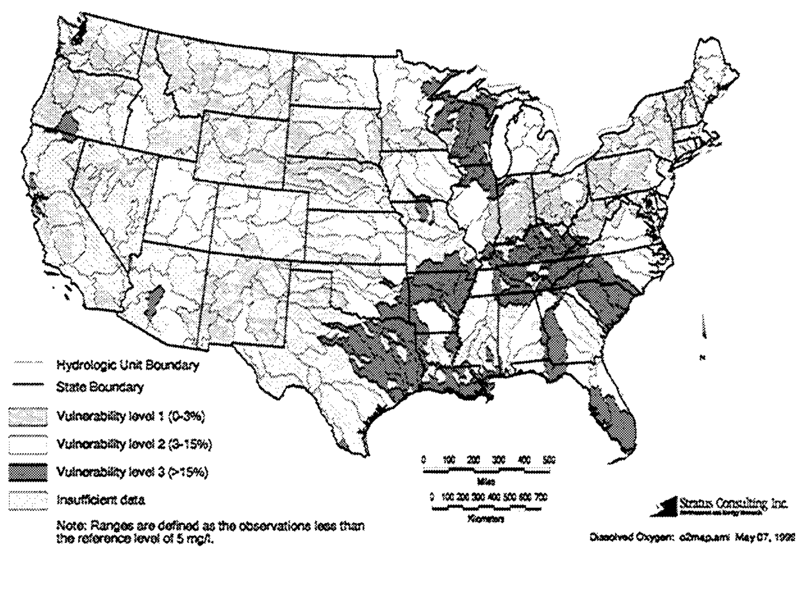
Navigation

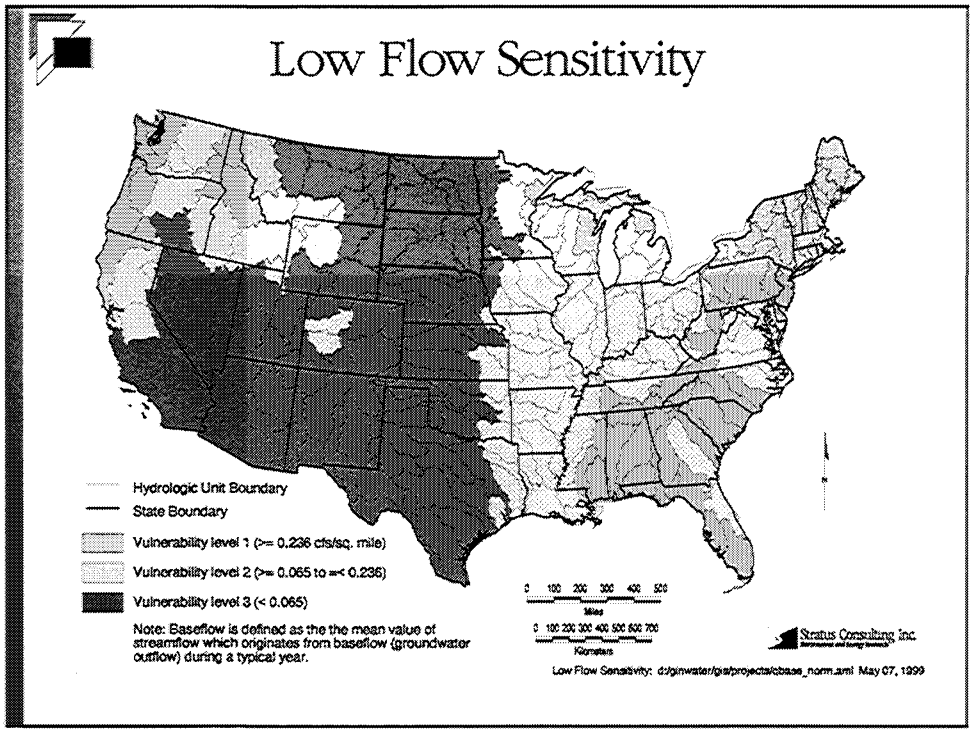


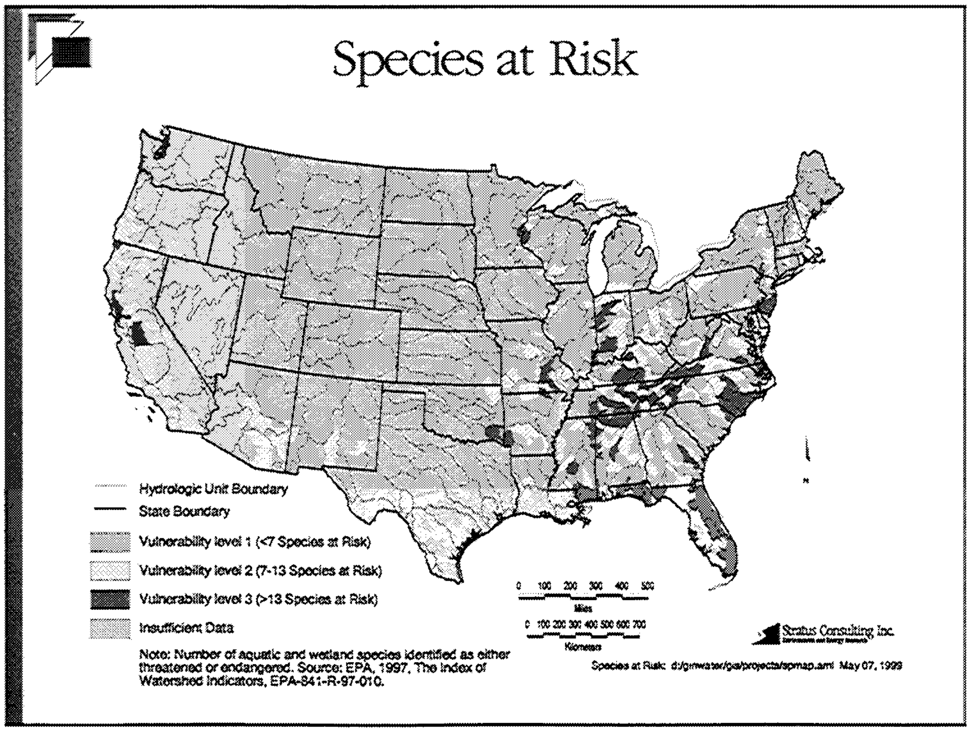
Ecosystem Thermal Sensitivity



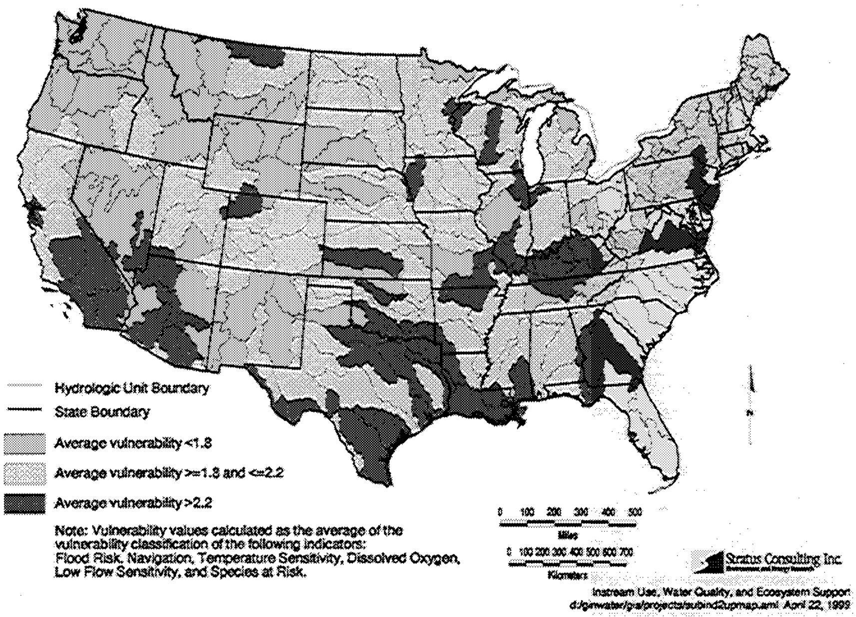
Water Quality: Dissolved Oxygen



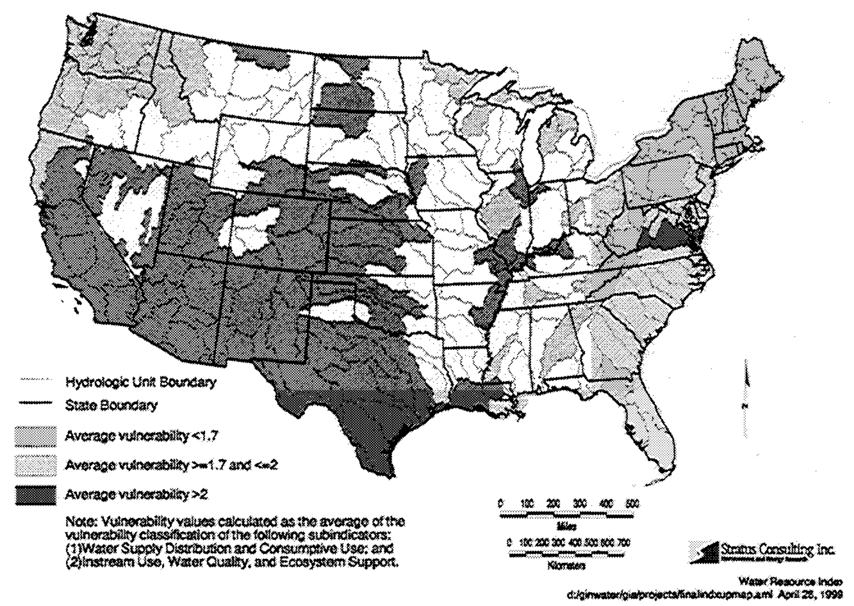

Low Flow Sensitivity
Hydrologic Unit Boundary
State Boundary
Vulnerability level 1 (>= 0.236 cfs/sq. mile)
Vulnerability level 2 (>= 0.065 to =< 0.236)
Vulnerability level 3 (< 0.065)
Note: Baseflow is defined as the the mean value of streamflow which originates from baseflow (groundwater outflow) during a typical year.
0 100 200 300 400 500
Miles
0 100 200 300 400 500 600 700
Kilometers
Stratus Consulting Inc.
Low Flow Sensitivity: d:/ginwater/gis/projects/cbase_norm.aml May 07, 1999


Species at Risk
Hydrologic Unit Boundary
State Boundary
Vulnerability level 1 (<7 Species at Risk)
Vulnerability level 2 (7-13 Species at Risk)
Vulnerability level 3 (>13 Species at Risk)
Insufficient Data
Note: Number of aquatic and wetland species identified as either threatened or endangered. Source: EPA, 1997, The Index of Watershed Indicators, EPA-841-R-97-010.
0 100 200 300 400 500
Miles
0 100 200 300 400 500 600 700
Kilometers
Stratus Consulting Inc.
Species at Risk: d:/ginwater/gis/projects/spmap.aml May 07, 1999

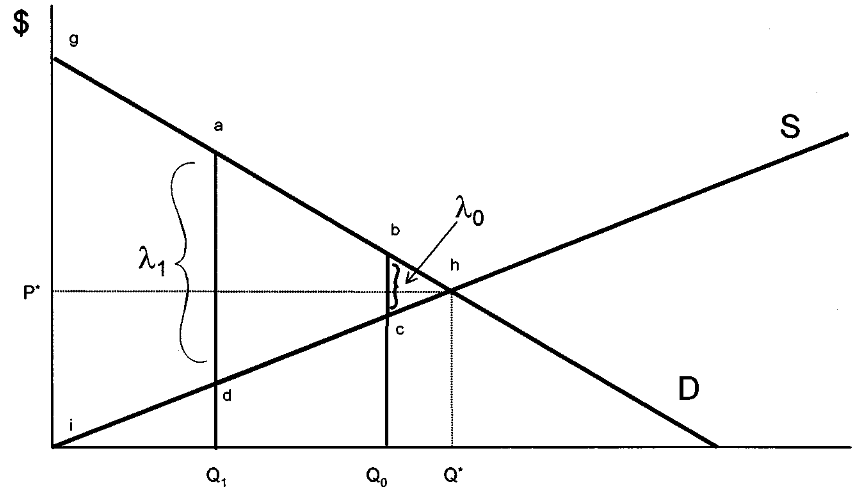
Subindex: Instream Use



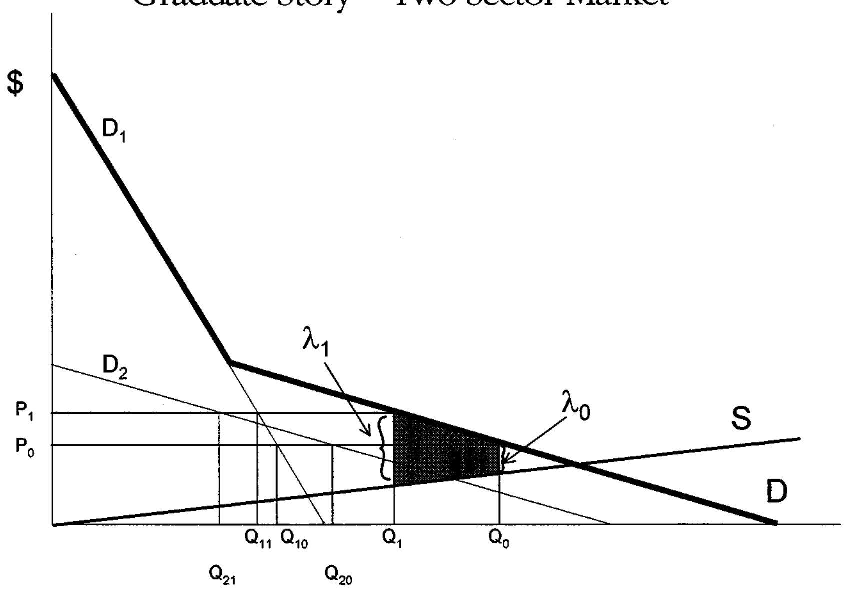
Overall Index



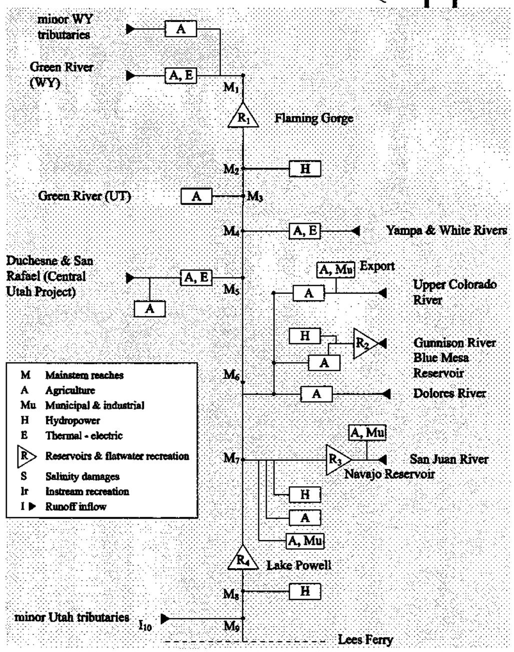
Economic Efficiency:
Undergraduate Story – Single Sector Market



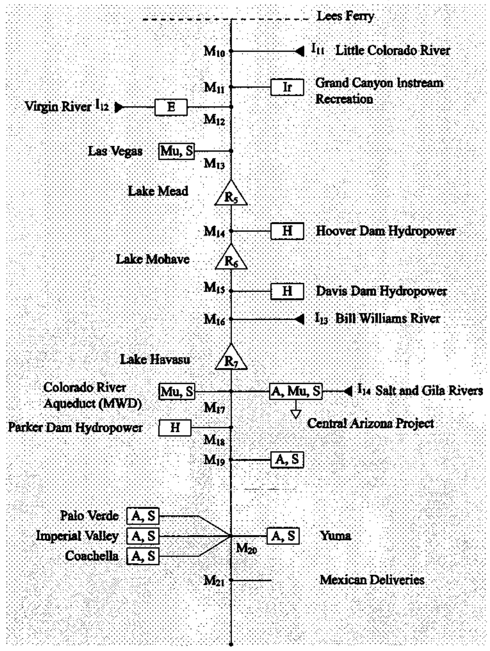
Economic Efficiency:
Graduate Story – Two Sector Market



Colorado River Model (Upper Basin)



Colorado River Model (Lower Basin)



Model Structure: Objective

Objective Function: MAX CPS by choosing F_{nt}, S_{rt}, X_{t}, H_{t}

$CPS = \sum_{t} DF_t * [\sum_{i} (a_{ni} + .5 b_{ni} W_{nit} - .5 c_{ni} W_{nit}) W_{nit}$	consumptive use
$\sum_{i} W_{ni0}(\bar{V}_{ni} - V_{ni0}) + V_{ni0}(\frac{W_{nit}}{W_{ni0}})^{\beta_{ni}}$	(COBEM only)
$+ \sum_{r \in N} h_r \cdot P \cdot H_{rt}$	hydropower benefits
$+ \sum_{n} (1 + e^{l_n + m_n F_{nt}})$	navigation benefits
$- \sum_{n} (f_n + g_n FL_{nt}) FL_{nt}$	flood damages (above threshold)
$- \sum_{n} K_n (1 - (1 - e^{k_n F_{nt}}))$	thermal waste heat (opportunity costs)
$+ \sum_{n} q_n F_{nt}$	secondary wastewater treatment benefits
$- \sum_{n} [(\frac{SL_{nt}}{\bar{F}_n}) \cdot C \cdot \sum_{i} 2 r_{ni} W_{nit}]$	advanced wastewater treatment costs

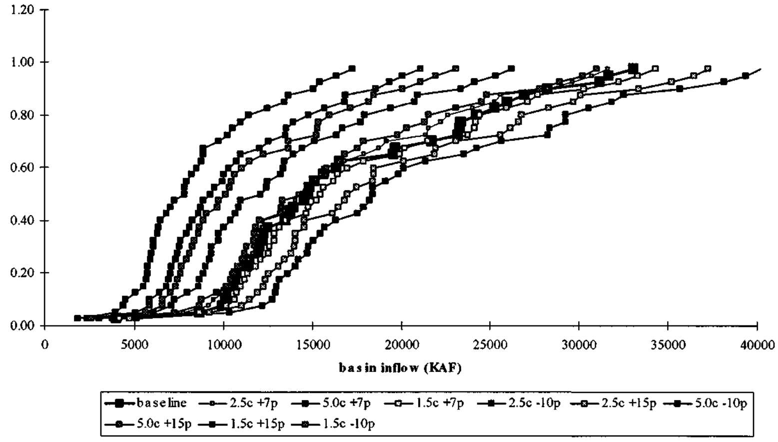
Model Structure: Constraints

Subject to:

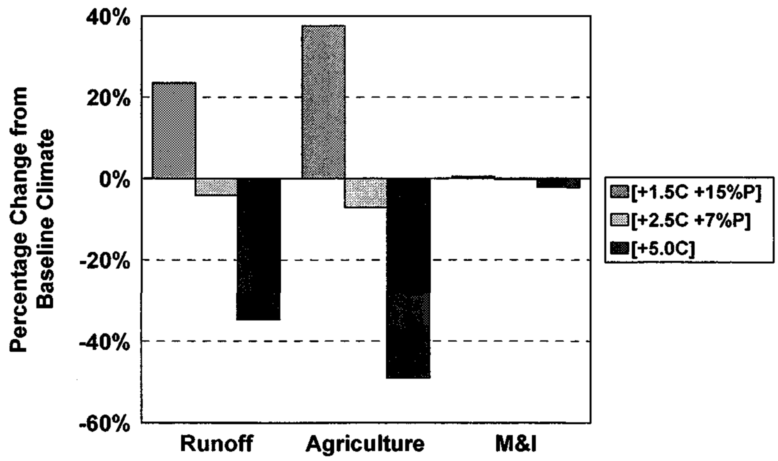
$F_{nt} = F_{n-1,t} + I_{nt} + R_{nt} + \sum_{i} r_{ni} W_{n-1,i,t} - \sum_{i} W_{nit}$	flow balance
$S_r^{min} \leq S_{rt} - S_{r,t-1} + R_{rt} + E_{rt} \leq S_r^{max}$	storage balance
$S_{rT} = S_{r0}$	terminal storage constraint
$FL_{nt} \geq F_{nt} - FT_n$	flood level constraint
$GW_{nit} \leq \bar{GW}_{ni}$	groundwater supply
$H_{nt} - F_{nt} + SP_{nt} \leq \bar{H}_r$	hydropower capacity constraint
$E_{rt} = 0.5(PET_{rt} + \frac{PET_{rt}}{S_r^{max}} S_{rt})$	reservoir evaporation constraint

How Climate Change Could Alter Colorado Watershed Runoff:

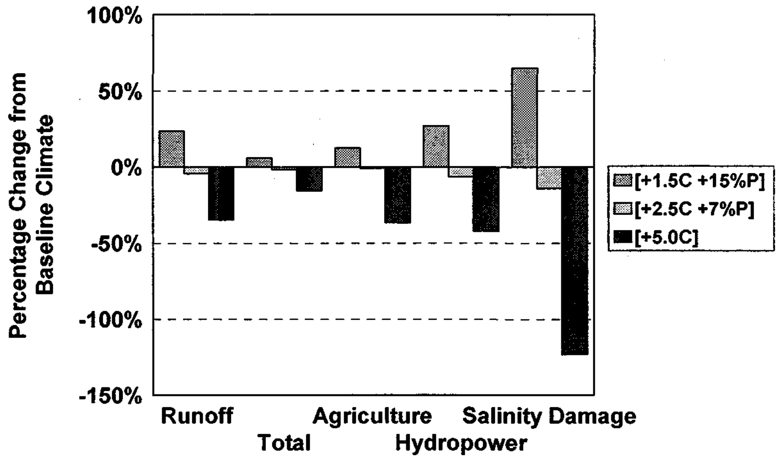
the driving data



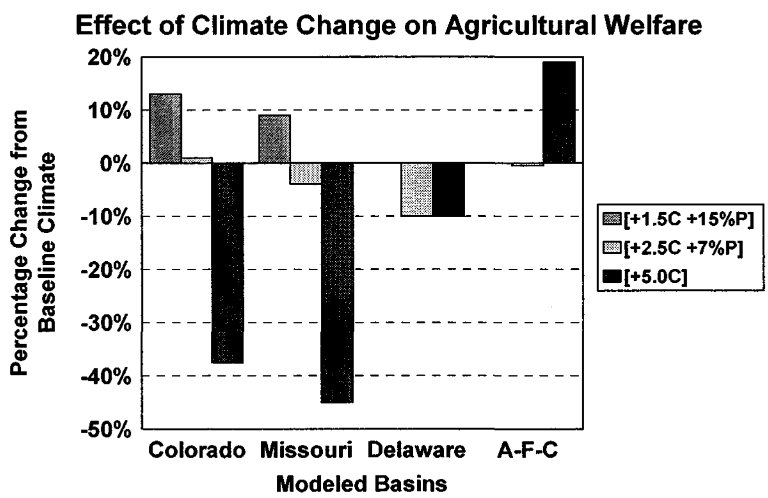
Modeled Runoff and Allocation Changes in the Lower Colorado Basin



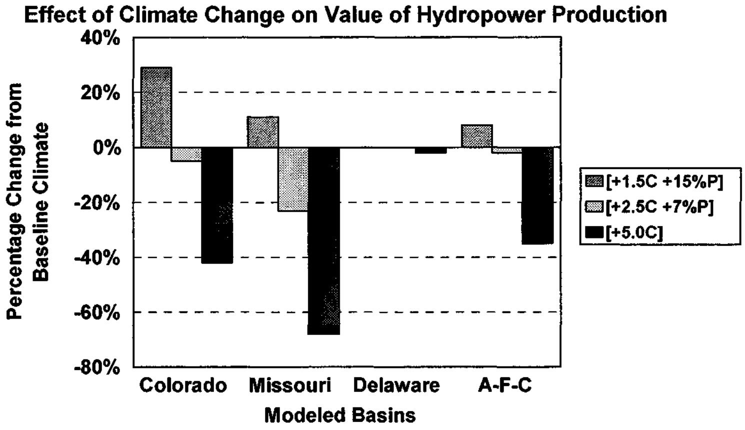
Colorado Basin Sectoral Impacts



Basin Results: Agriculture



Basin Results: Hydropower



Basin Results: Total Welfare