Center *of* Advanced Materials *for* the Purification of Water *with* Systems

Impact of Water on Sustainability: Nexus to the Economy, Energy and Environment

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waterCAMPWS

What is the *WaterCAMPWS*?

- Center of Advanced Materials for the Purification of Water with Systems
- Science and Technology Center Awarded late 2002, $4 m/yr from NSF, $400k Illinois
- 9 universities, 6 partners, 12 industrial affiliates, ~120 students, ~50 faculty

Mission and Purpose of the *WaterCAMPWS*

Our mission is to develop **revolutionary new materials and systems** to purify water for *human use*.

Our purpose is to educate a diverse body of students and the public in the *value, science, and technology* of water purification.

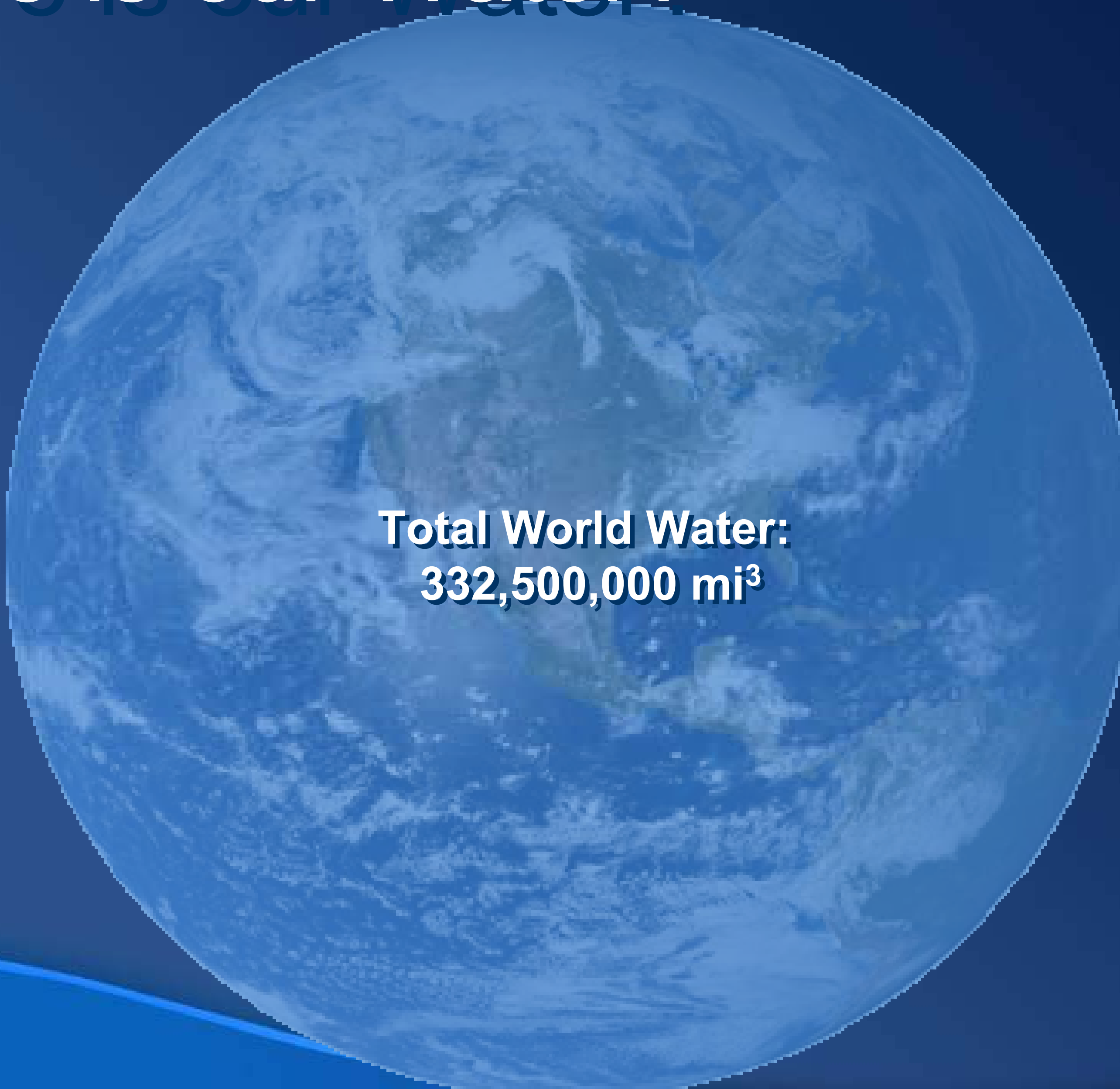
My purpose today is to talk about the problems to sustainably supply water for human needs, and the vital role that people from all walks of life, can do to help solve these problems.

Value of Water

- Low Cost: Cheapest, highest quality product produced
- Impact Huge: Energy, agriculture, livestock, industry, homes, health
- Affects EVERY Aspect of Economy: More water, lower cost, more wealth
- Traditional Concerns: Safety and health

HARD TO OVERESTIMATE IMPORTANCE, BUT TAKEN FOR GRANTED BY MOST IN U.S.

Where is our Water?



Total World Water:
332,500,000 mi^3

Where is our Water?

Ice Caps, Glaciers, & Perm. Snow
1.74%
5,773,000 mi^3
(68.7% fresh)

Ground Ice & Permafrost
.022%
71,970 mi^3
(.86% Fresh)

Accessible With Additional Research

Saline Lakes
.006%
20,490 mi^3

Saline Groundwater
.94%
3,088,000 mi^3

Oceans, Seas, & Bays
96.5%
321 million mi^3

Currently Accessible for Human Use

30% shortfall in 30 yrs

Lakes
.007%
21,830 mi^3
(.26% fresh)

Rivers
.0002%
509 mi^3
(.006 Fresh)

Groundwater
.76%
2,526,000 mi^3
(30.1% fresh)

Atmosphere
.001%
3,095 mi^3
(.04% Fresh)

Biological
.0001%
269 mi^3
(.0036% Fresh)

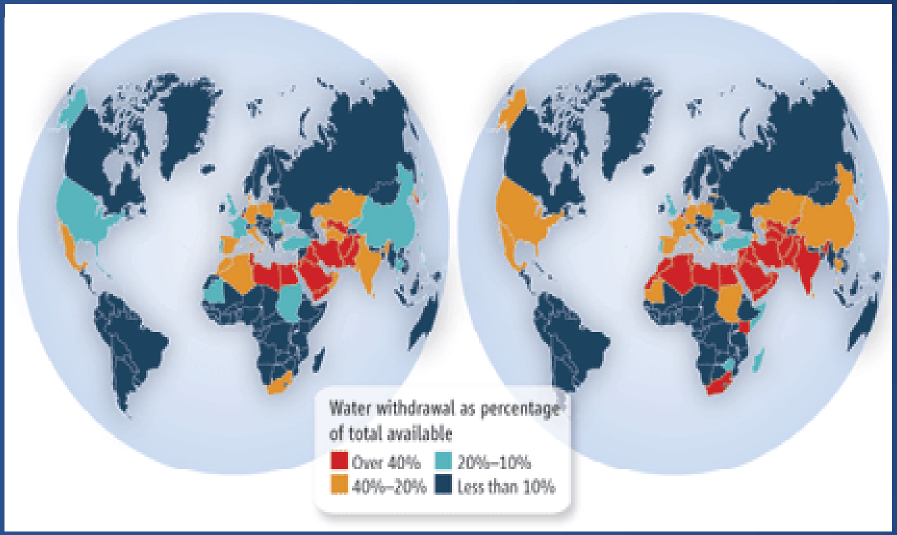
Swamps
.0008%
2752 mi^3
(.03% fresh)

Soil Moisture
.001%
3,959 mi^3
(.05% Fresh)

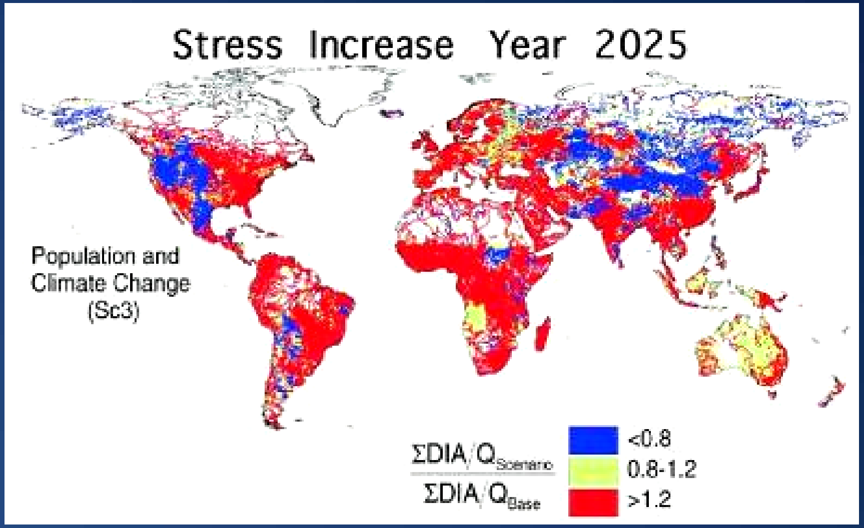
99.23% currently unusable for most humans

Major Problems Facing World

- 1.2 Billion people at risk from lack of clean water
- 2.6 Billion people lack adequate sanitation
- It is only going to get worse



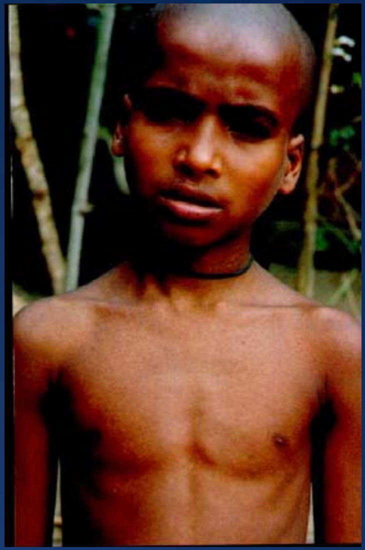
World Map showing water consumption world-wide as percentage of total available water.



World Map showing affect of population and climate change on water stress.

Major Problems Facing World

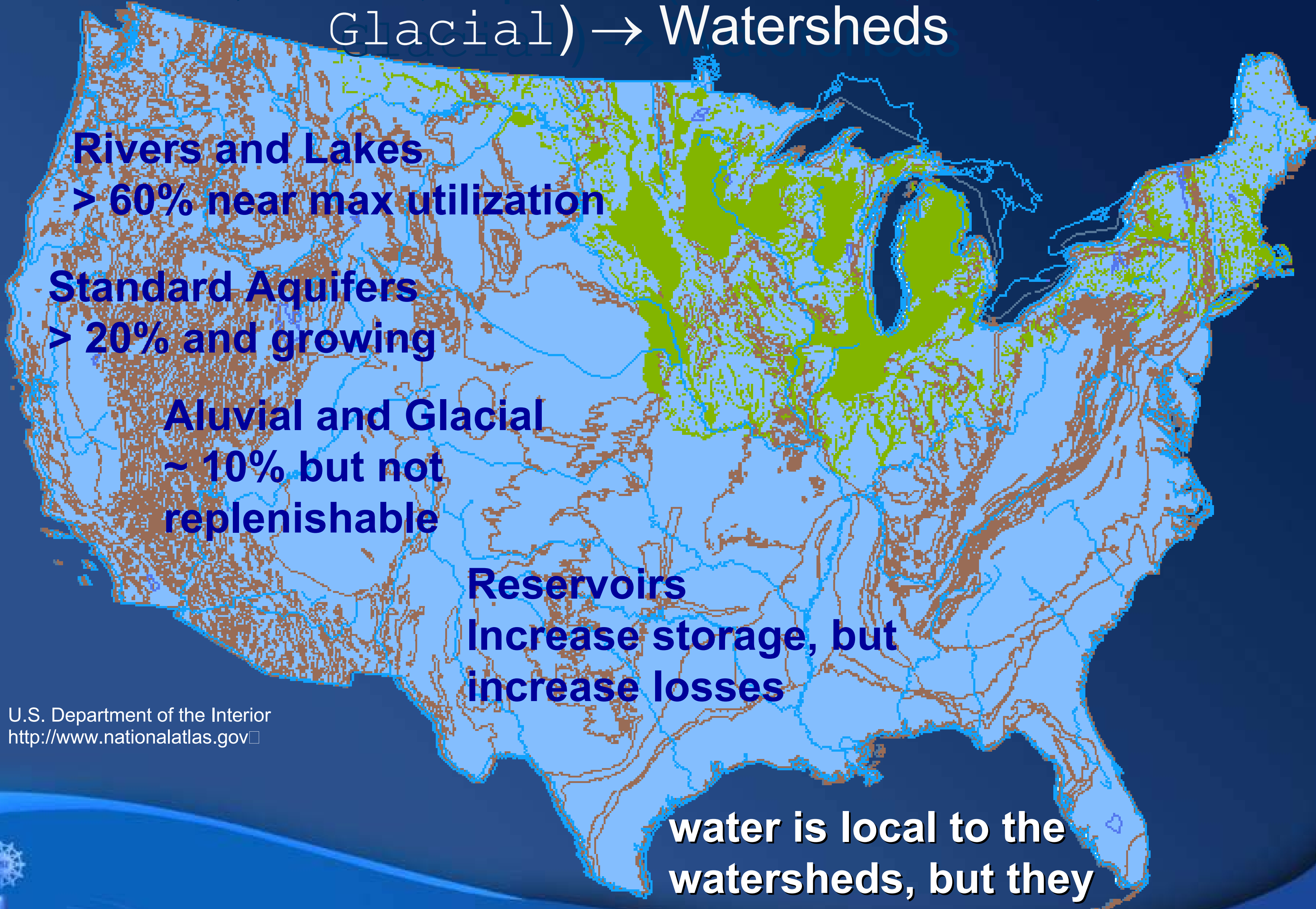
- 35% of people in developing world die from water related problems, over 2 million/year
- Diarrheal diseases from bad water a leading cause of malnutrition and food pressures
- 27 children die every 10 minutes from water problems
- 30 plus million in Bengal suffer from arsenic poisoning



Mega-Trends Making it Worse

- Era of Infrastructure Replacement: $550/capita owed in U.S.
- Population Growth: >1% per year drives increase demand in water, food, and energy
- Energy Growth: Largest withdrawal of water for mining, refining, and generation of electricity
- Contamination of Source Waters: Increasing and cross-contamination of surface and aquifers is growing, reducing dilution solutions – *more aggressive treatment and new facilities needed.*
- Snowpack storage and glacial melting: Major river systems will see periodic shortages during dry months (Brahmaputra, Ganges, Yellow, Yangtze, and Mekong Rivers that serve China, India, and Southeast Asia, Western U.S., Africa)

Lakes, Rivers, Aquifers (Standard, Aluvial, and Glacial) → Watersheds



Rivers and Lakes
> 60% near max utilization

Standard Aquifers
> 20% and growing

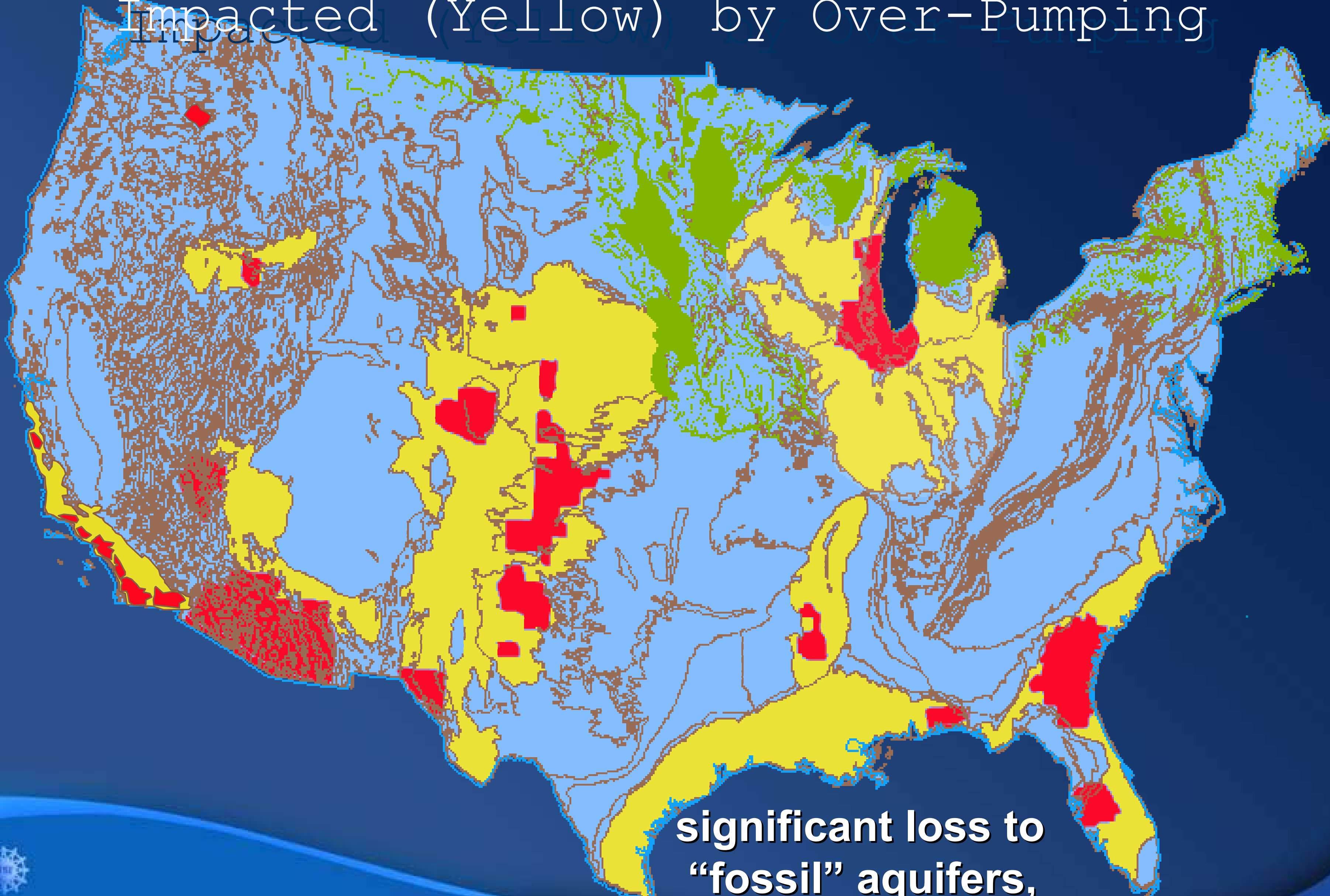
Aluvial and Glacial
~ 10% but not replenishable

Reservoirs
Increase storage, but increase losses

water is local to the watersheds, but they are interconnected

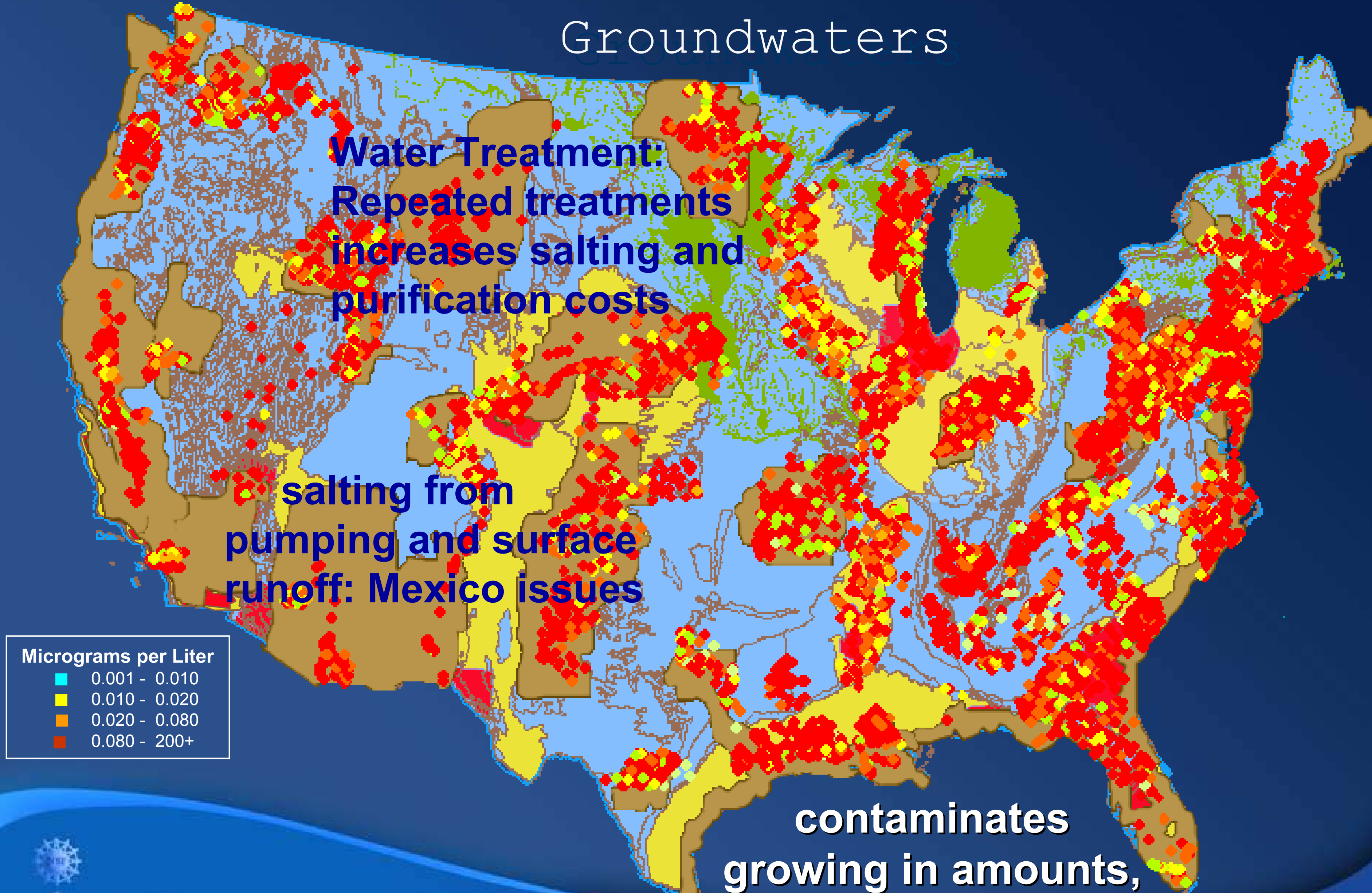
U.S. Department of the Interior
http://www.nationalatlas.gov

Aquifers - Currently Stressed (Red) and Impacted (Yellow) by Over-Pumping



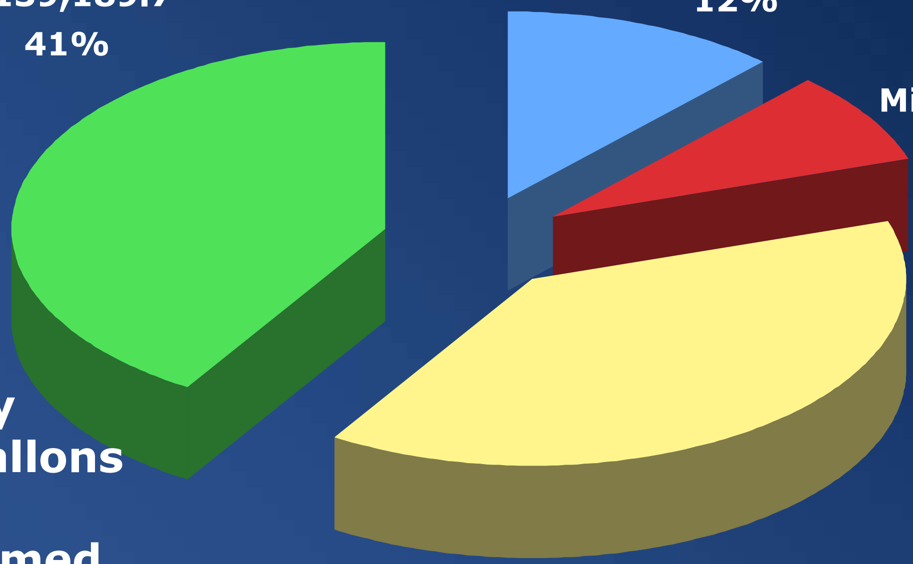
significant loss to "fossil" aquifers, south, southwest, and heartland

EPA Critical Drinking Water Contaminants and Salts in Surface and Groundwaters



Volume of Water Withdrawn for All Uses

(Million Gallons per Day)



Total Water Withdrawn per day 339,487 million Gallons

Total Water Consumed per Year 123.9 Trillion Gallons

costs directly related to withdrawals: source matters

"Consumptive Water Use for U.S. Power Production,
P. Torcellini, et.al., National Renewable Energy Laboratory, 2003.

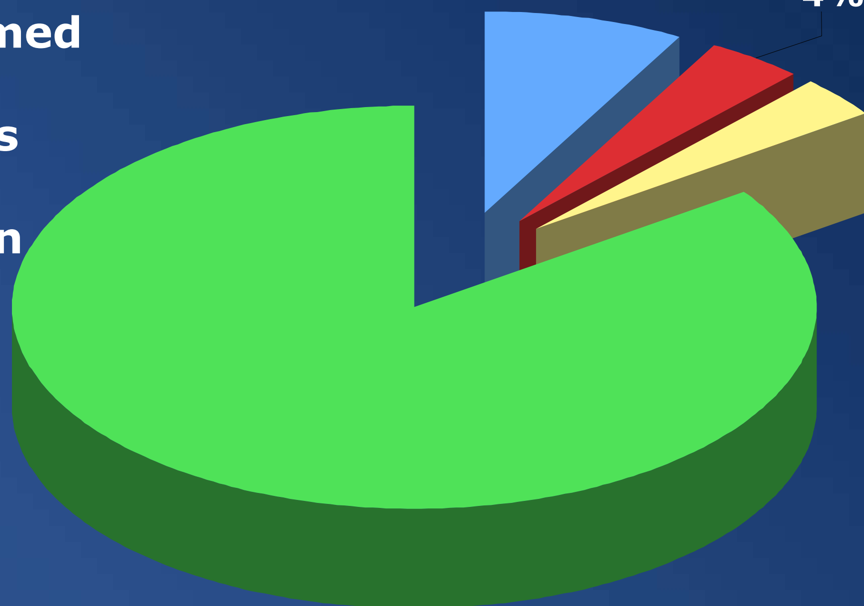
Volume of Water Consumed

Total Water Consumed per day
100,320 million Gallons

Total Water Consumed per Year
36.6 Trillion Gallons

~30% of withdrawn

(Million Gallons per Day)



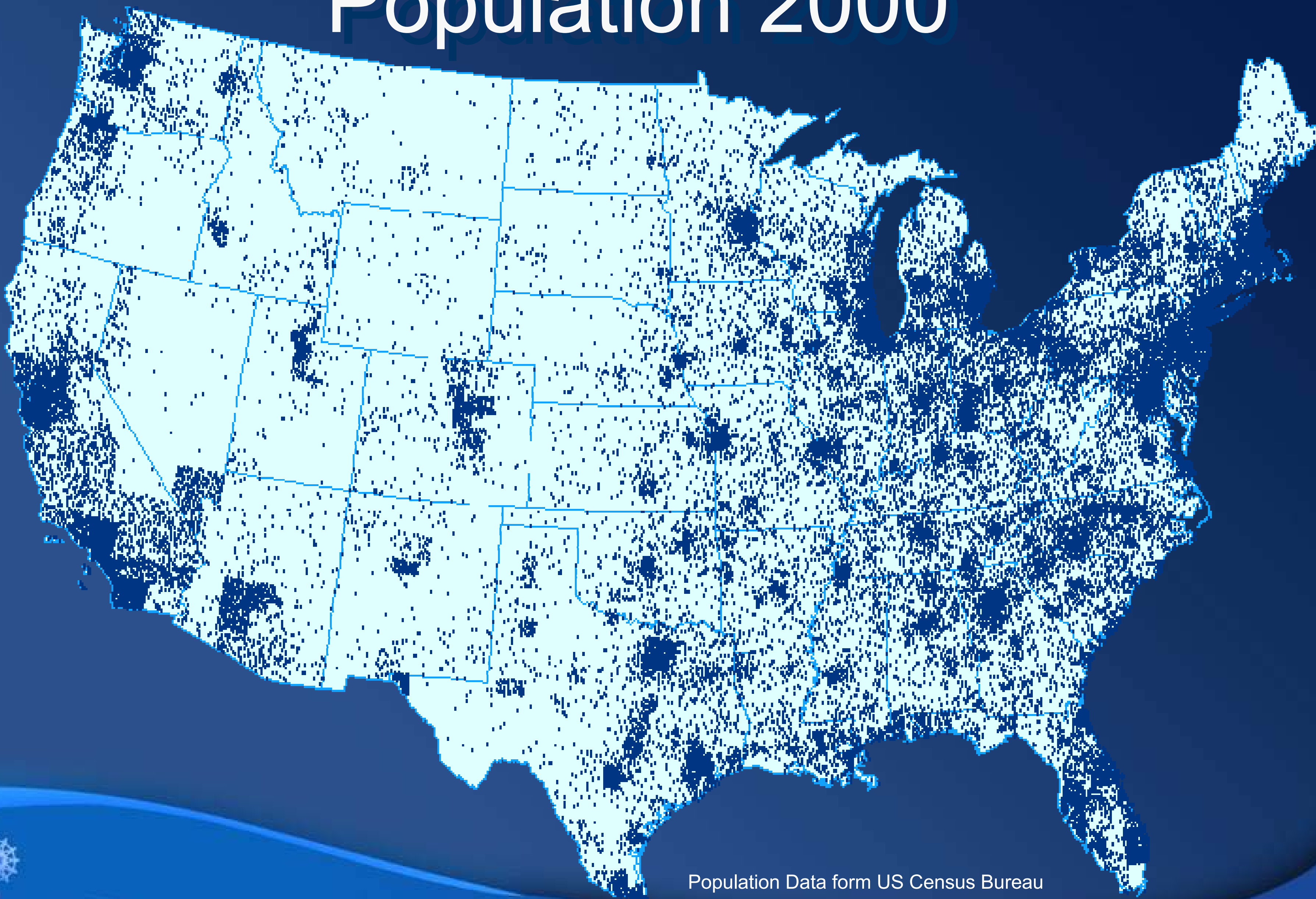
consumption directly affects source amounts available

"Consumptive Water Use for U.S. Power Production,
P. Torcellini, *et.al.*, National Renewable Energy Laboratory, 2003.

Projections

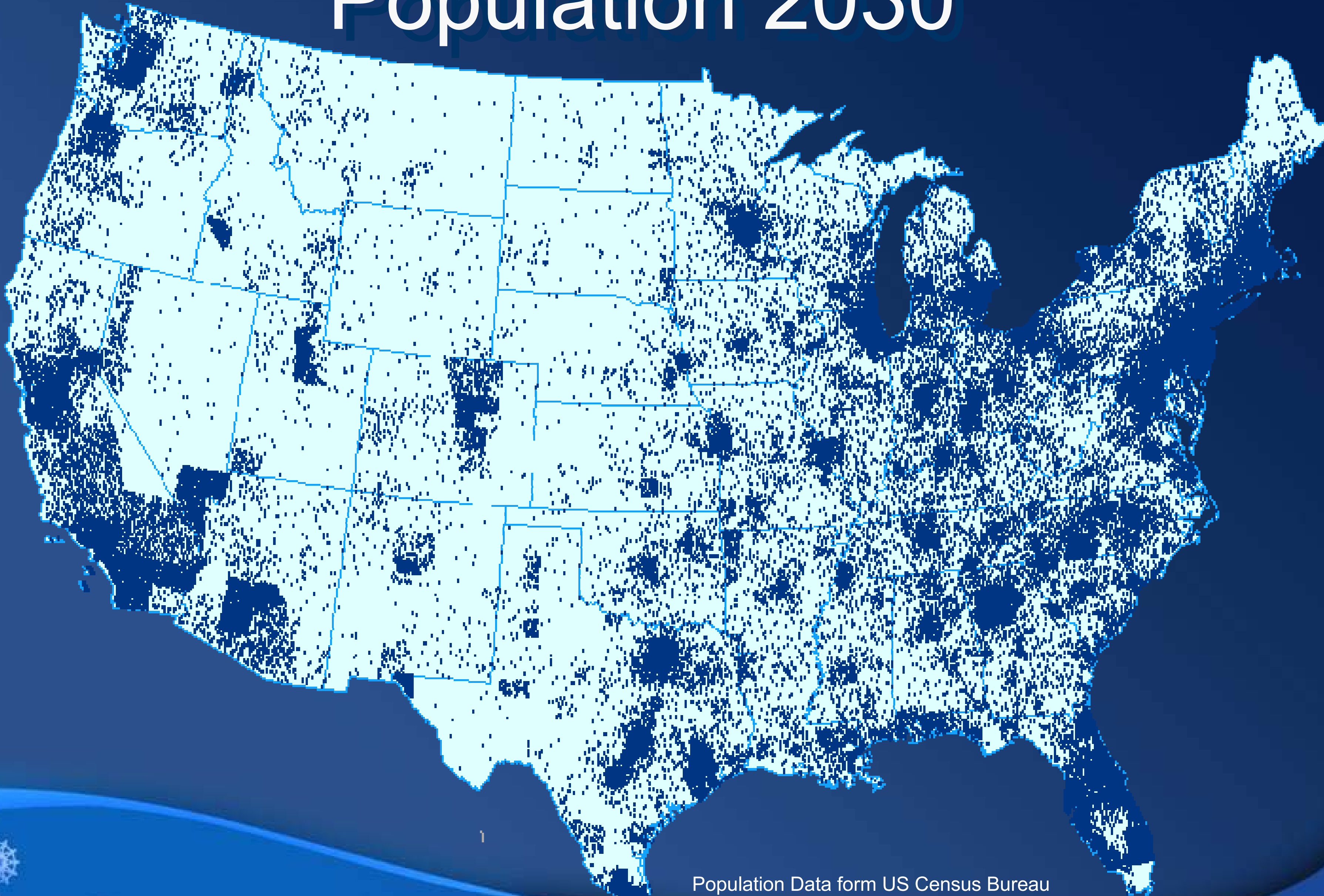
- Population driven
- Application driven
- Source driven

Population 2000



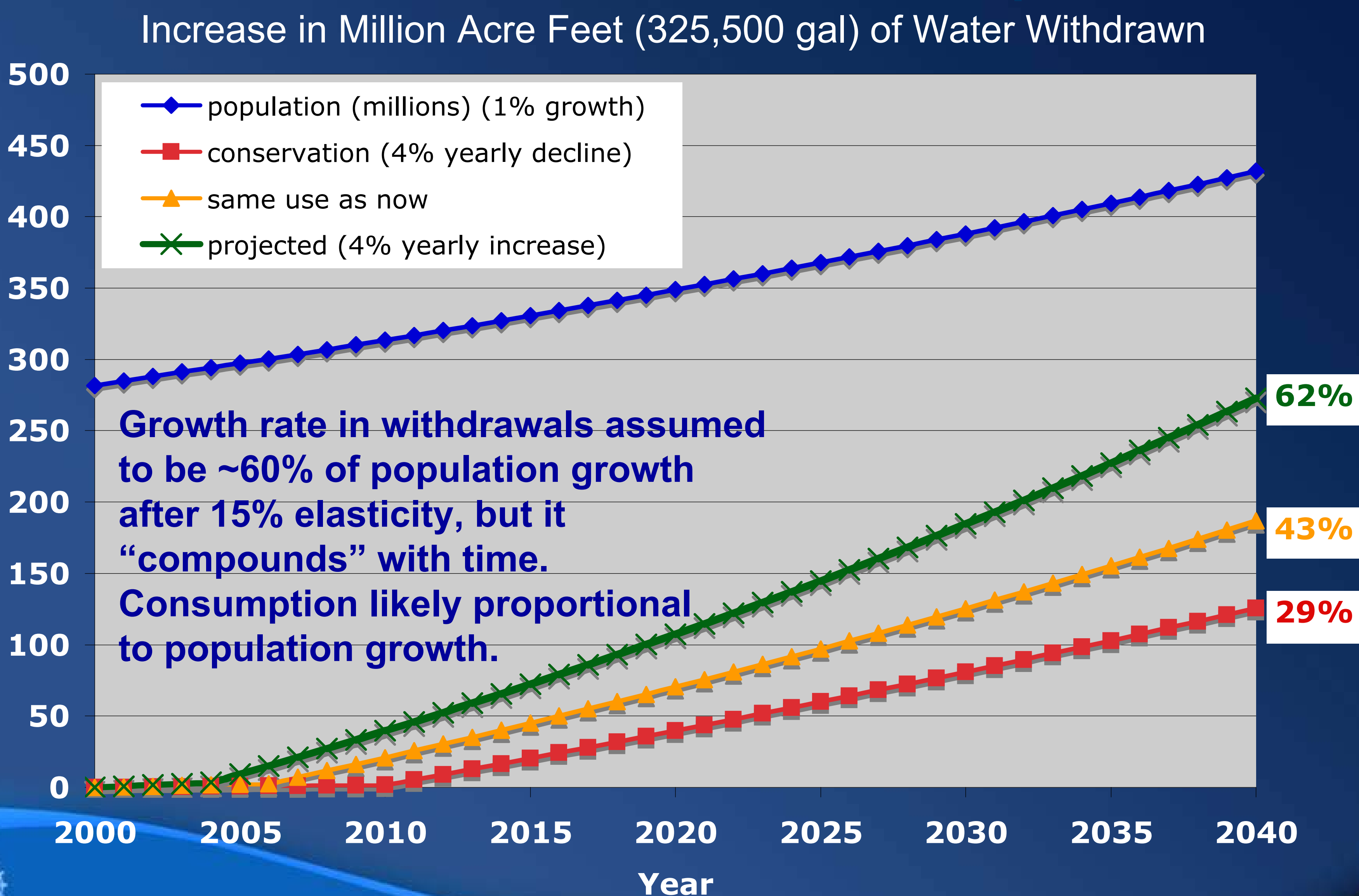
Population Data form US Census Bureau

Population 2030



Population Data form US Census Bureau

Water Use Growth With Population



Population Data form US Census Bureau

2030 Projected Increase in % of Use Since 2000

Averages don't tell the real story: Growth problems will be local.

Population data and projections from U.S. Census Bureau
http://www.census.gov/population/www/projections/stproj.html
http://www.census.gov/popest/datasets.html
Water Use Data from USGS (http://web1.er.usgs.gov/NAWQAMapTheme/index.jsp)
Projections for water use based on Texas Water Use 60 yr projections (http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2007/2007StateWaterPlan/2007StateWaterPlan.htm)

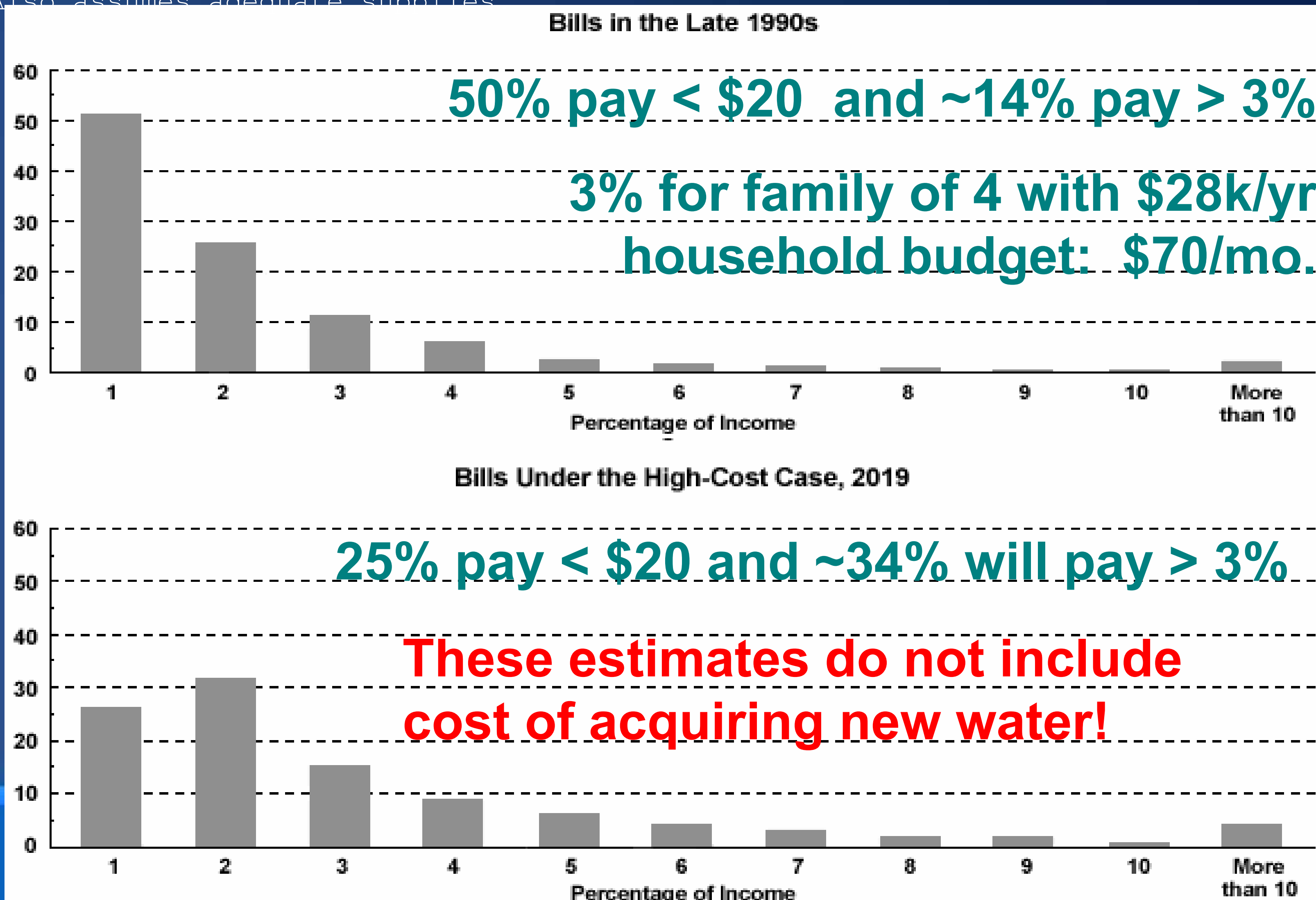
U.S. Economic Issues

- More than $1 trillion (2001 dollars) spent on water treatment, in past 20 years: $10,000 invested in infrastructure for every American
- More than $1 trillion (2001 dollars) more needed for infrastructure, and treatment in next 20 years
- Demand for potable water currently exceeds available resources in parts of U.S. New waters in next 35 years > $2 trillion
- Major water projects will require large capital at a time when it will potentially be scarce & expensive

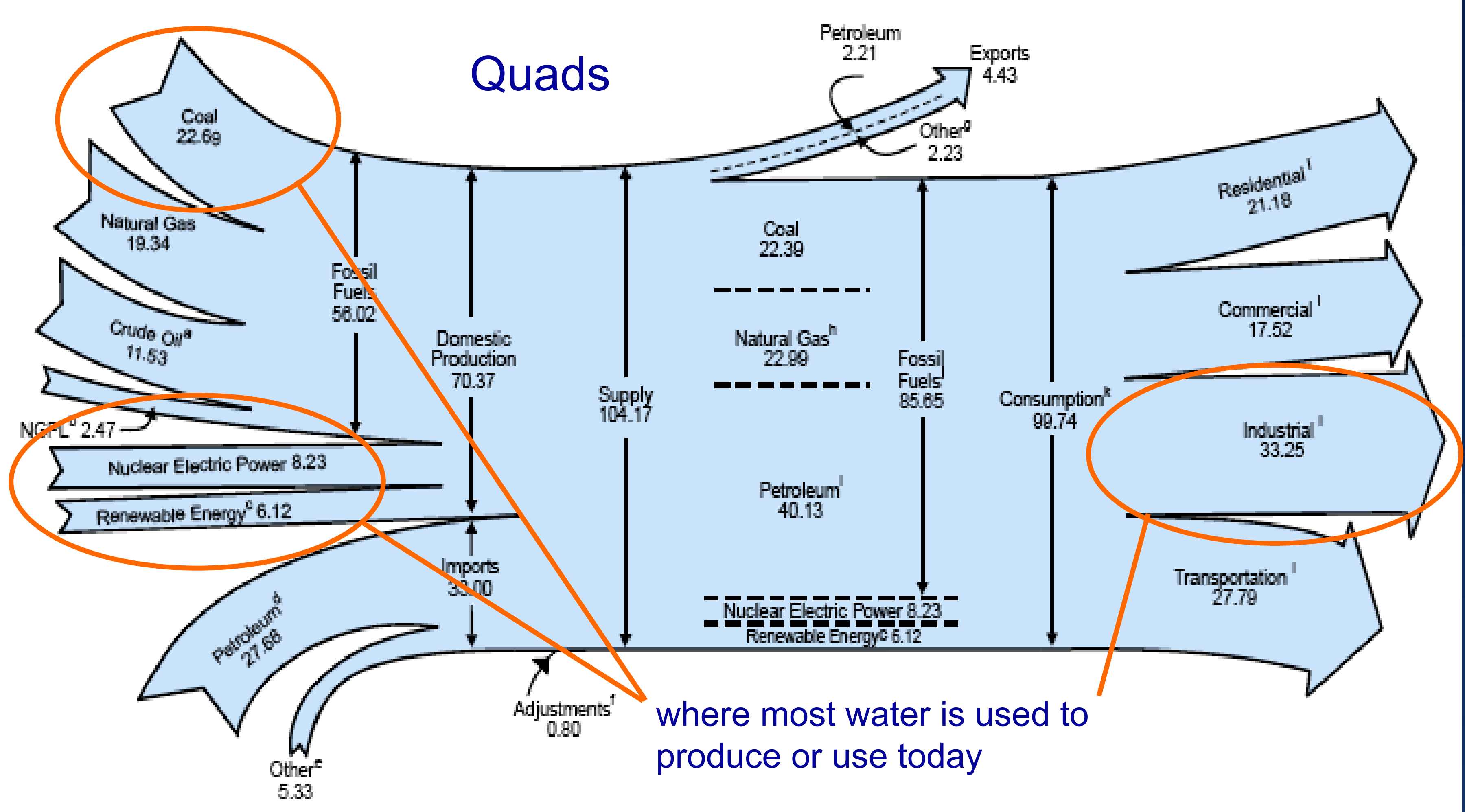
Economic security at risk if lack of clean water

Effect on Consumer for Water Costs

CBO's estimates assume steady levels of support financed by taxpayers and constant shares of water costs paid by household and non-household ratepayers. Also assumes adequate supplies



Flow of Energy in U.S.



Energy and Water

Without sufficient water:

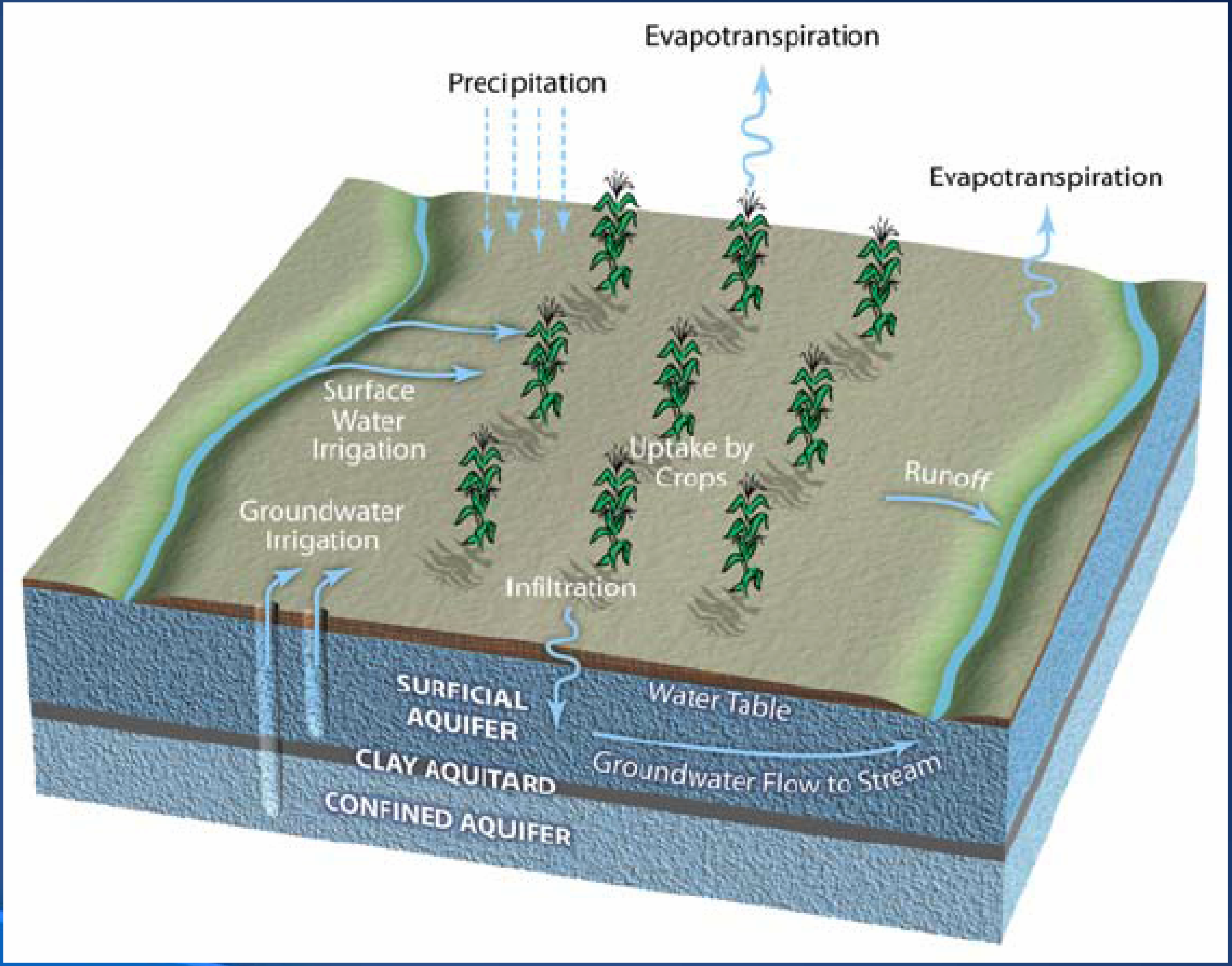
- Meeting the energy needs of the growing population will be impacted
- Transfer to a hydrogen economy, biomass and clean coal derived fuels will be impacted
- We're the Saudi Arabia of Oil Shale, but we can't utilize it without lots of water
- Plug-in hybrid vehicles will be impacted, from restricted electric generation

Without sufficient energy:

- We cannot supply sufficient clean water!

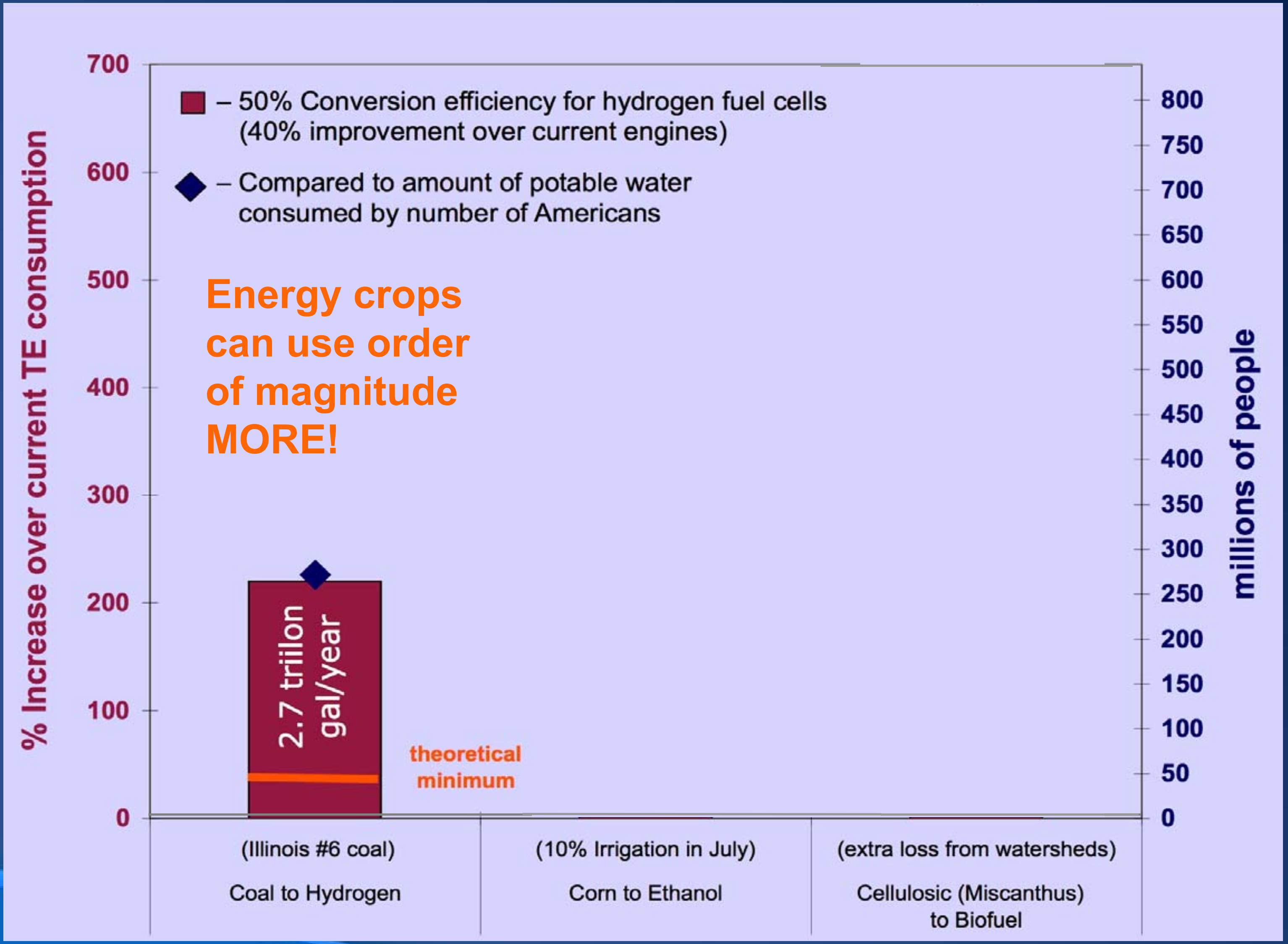
The Agricultural Water Cycle

Inputs and outputs to a crop include rainfall and irrigation from surface water and groundwater, pan runoff and evaporation, infiltration, and evapotranspiration.



SOURCE: “Water Implications of Biofuels Production in the United States," National Academies Press (2007).

Trends in Water with New Energy

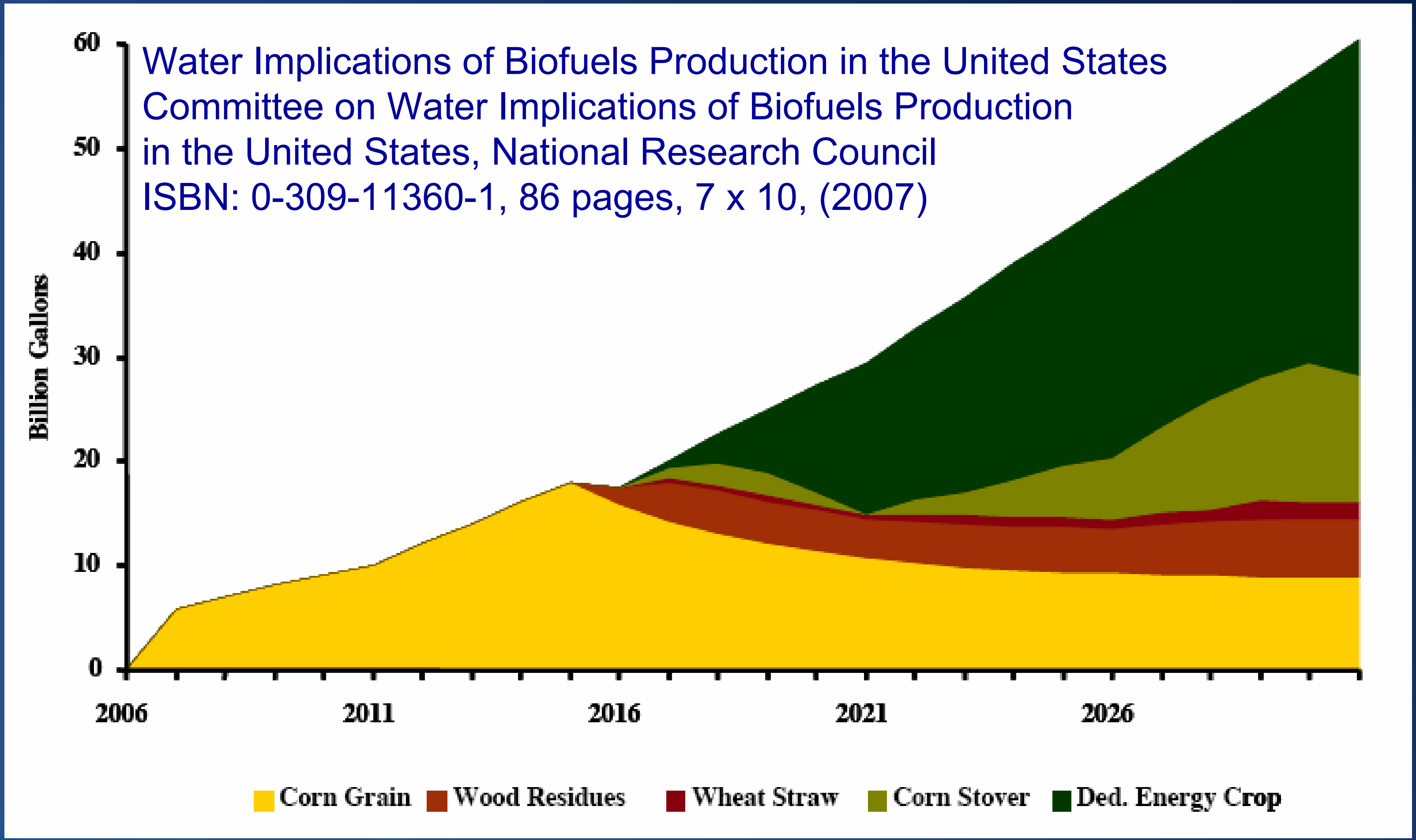


watercampws

Mark A. Shannon http://watercampws.uiuc.edu

Trends in Biofuels

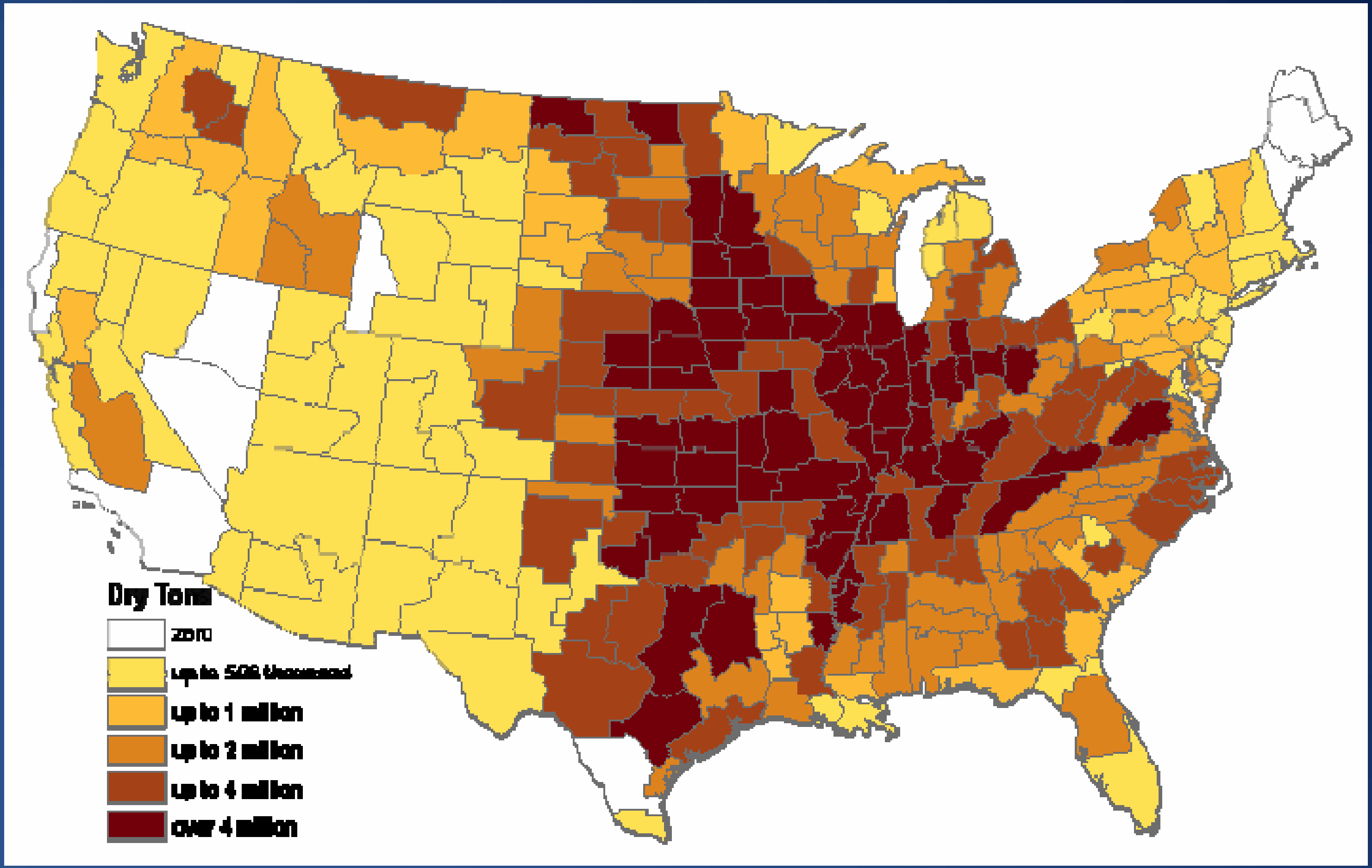
Projection of ethanol production by feedstock assuming cellulose-to-ethanol production begins in 2015.



SOURCE: Reprinted, with permission, from D. Ugarte, University of Tennessee, written commun., July 12, 2007.

Trends in Biofuels

Distribution of the production of cellulosic materials in dry tons by the year 2030.



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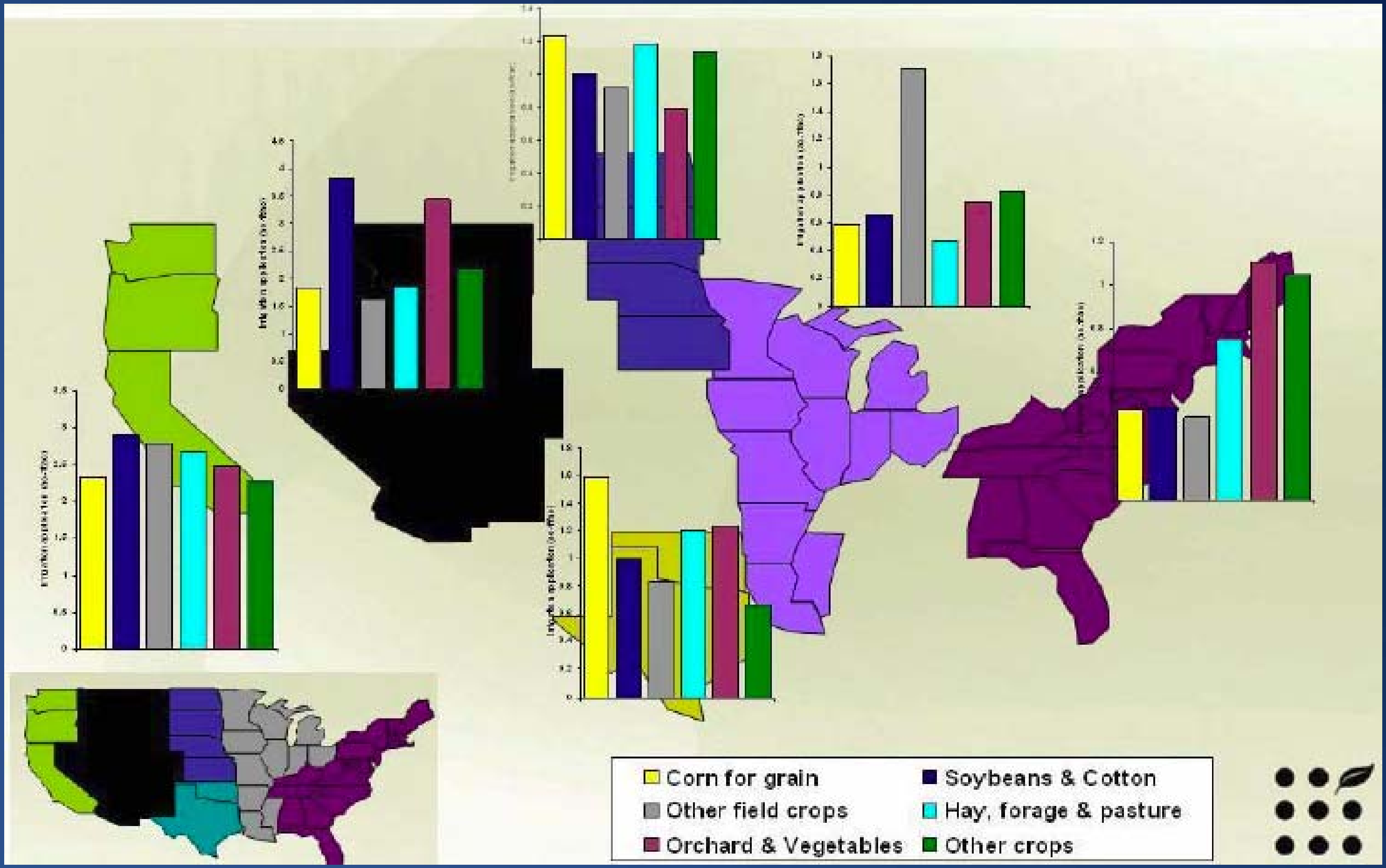
Trends in Crop Irrigation

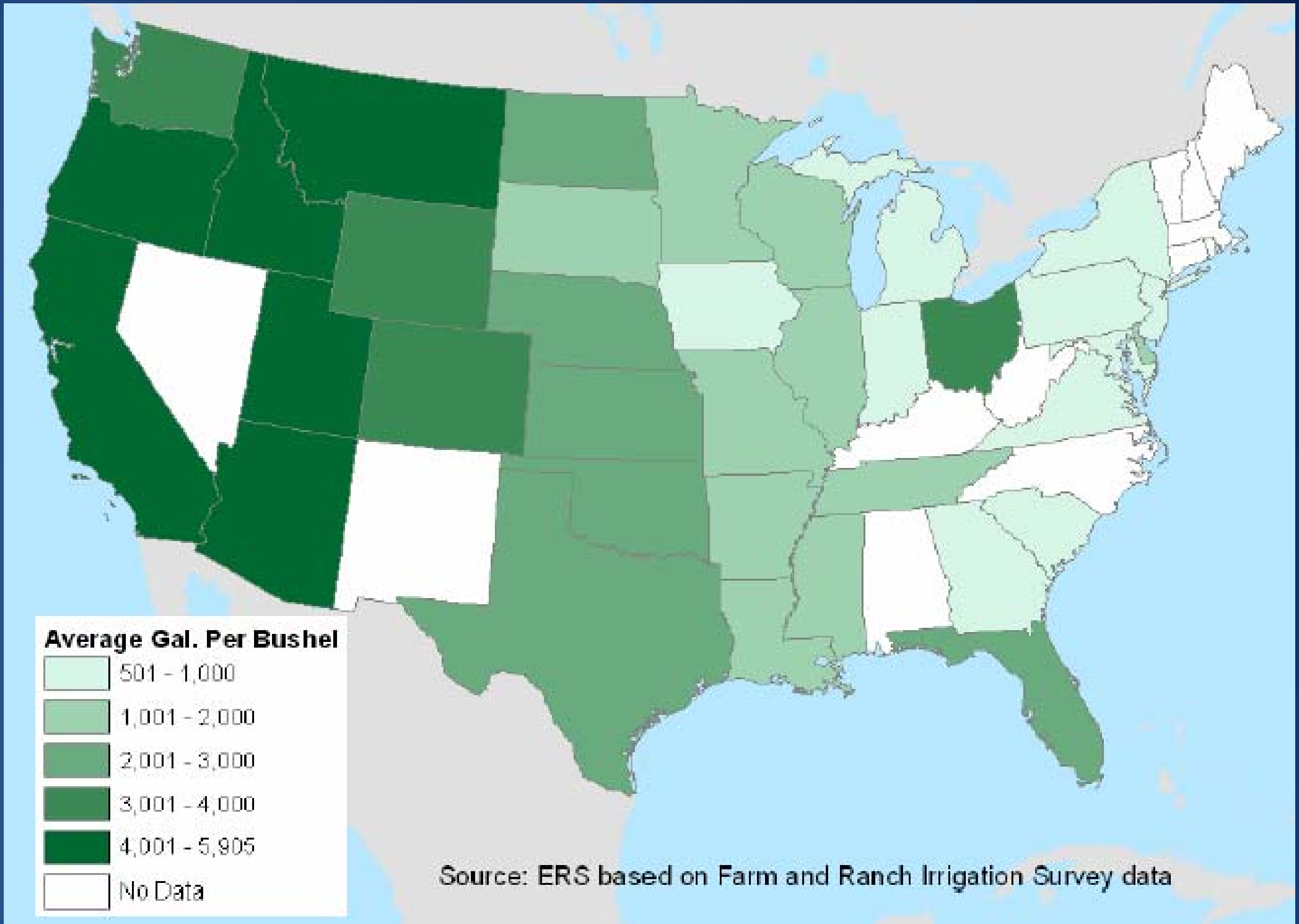
Regional irrigation water application for various crops for six regions of the United States.



SOURCE: N. Gollehon, U.S. Department of Agriculture (USDA) Economic Research Service (ERS), written commun., July 12, 2007. Based on data from USDA Census of Agriculture.

Trends in Crop Irrigation

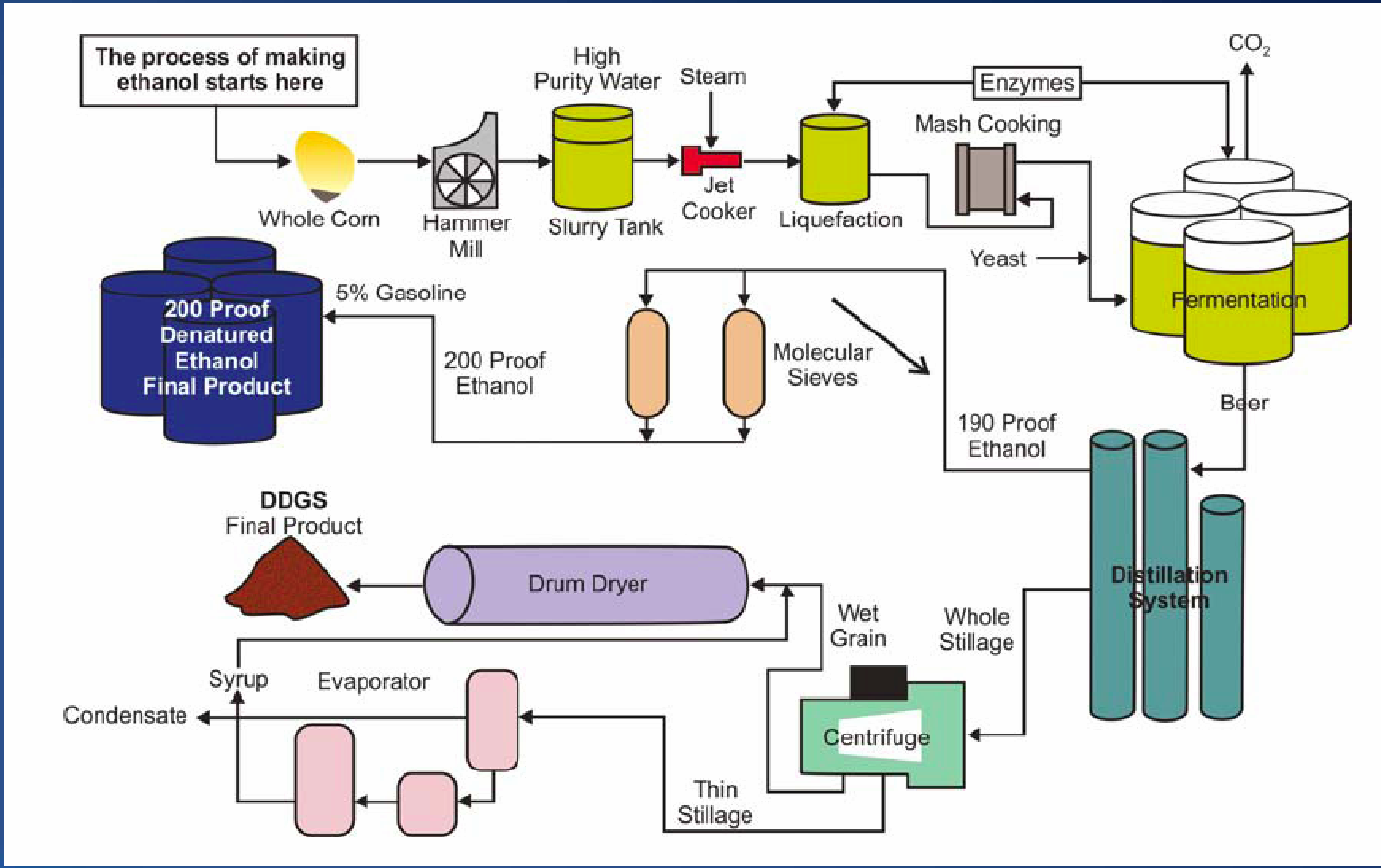
State-by-state water requirements in 2003 of irrigated corn (gal/bushel of irrigation water).



SOURCE: N. Gollehon, U.S. Department of Agriculture (USDA) Economic Research Service (ERS), written commun., July 12, 2007. Based on data from USDA Census of Agriculture.

Ethanol Production Facility

Water use throughout the processing of corn to ethanol.



SOURCE: Parkin et al (2007).

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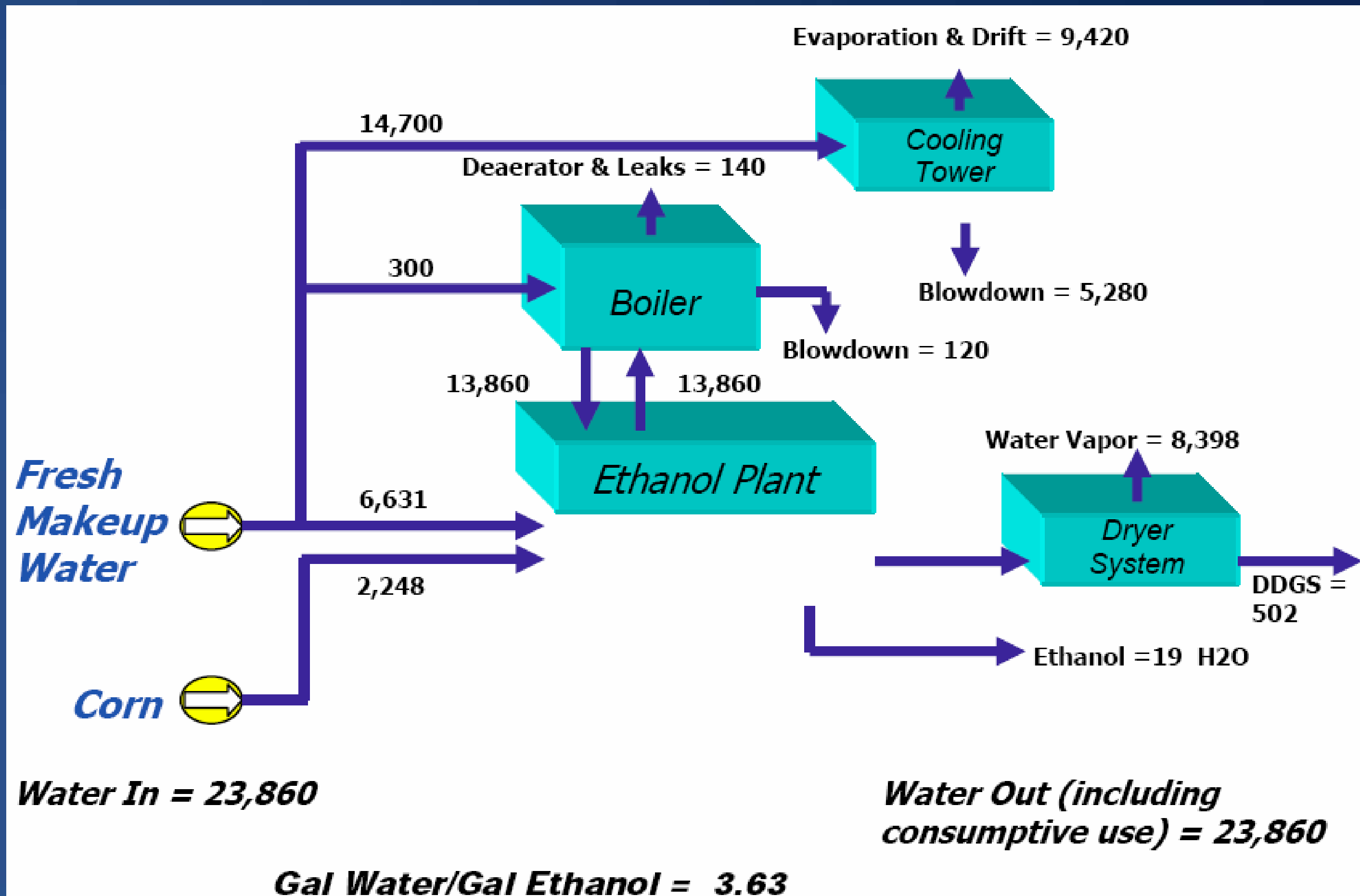
Overall Water Balance

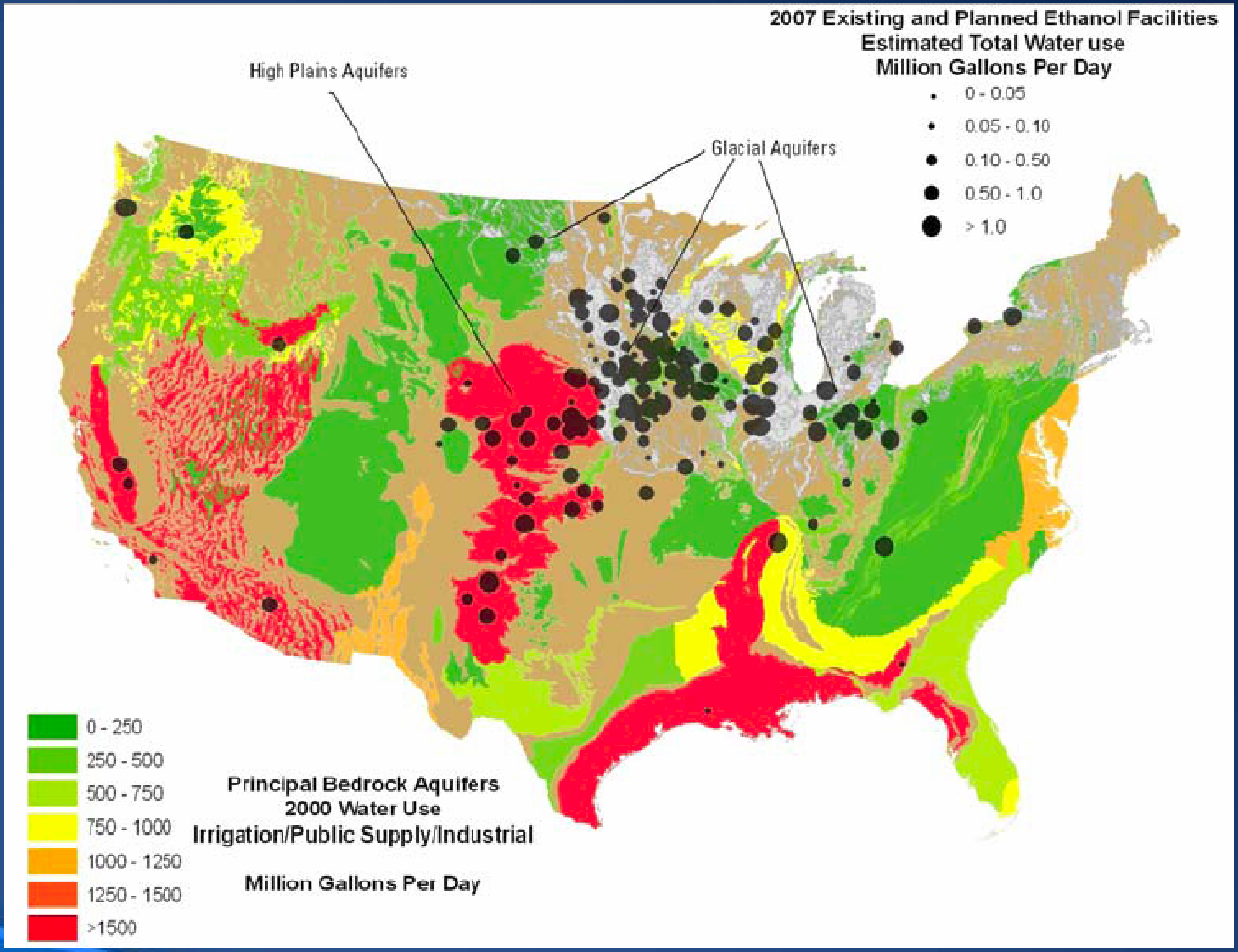
Water use for a 50 million/gallon year dry-mill ethanol processing plant.



SOURCE: Courtesy of Delta-T Corp.

Ethanol Facility Impact on Water

Existing and planned ethanol facilities (2007) and their estimated total water use mapped with the principal bedrock aquifers of the United States and total water use in year 2000.



SOURCE: Janice Ward, U.S. Geological Survey, personal commun., July 12, 2007.

Impact of "New" Energy on Water

- Total water lost via evapotranspiration to generate sufficient energy from biomass: in excess of 140 trillion gallons per year.
  - Total Withdrawn U.S./yr currently ~ 124 T gal
  - Outflow Mississippi Basin/yr ~ 132 T gal
- Mean Rain Mississippi Basin ~ 835 mm/yr
- Need: Corn/soybean ~ 440 mm/yr. Energy Grasses ~ 550 mm/yr.
- Irrigated seed and field corn needed for ethanol add another 4 to 7 gal of water for each gal fuel
- Irrigating marginal land will need 1000 times more

Water for Ethanol Refining: Source Matters!

Industrial Processing Water Use in Minnesota, 2004

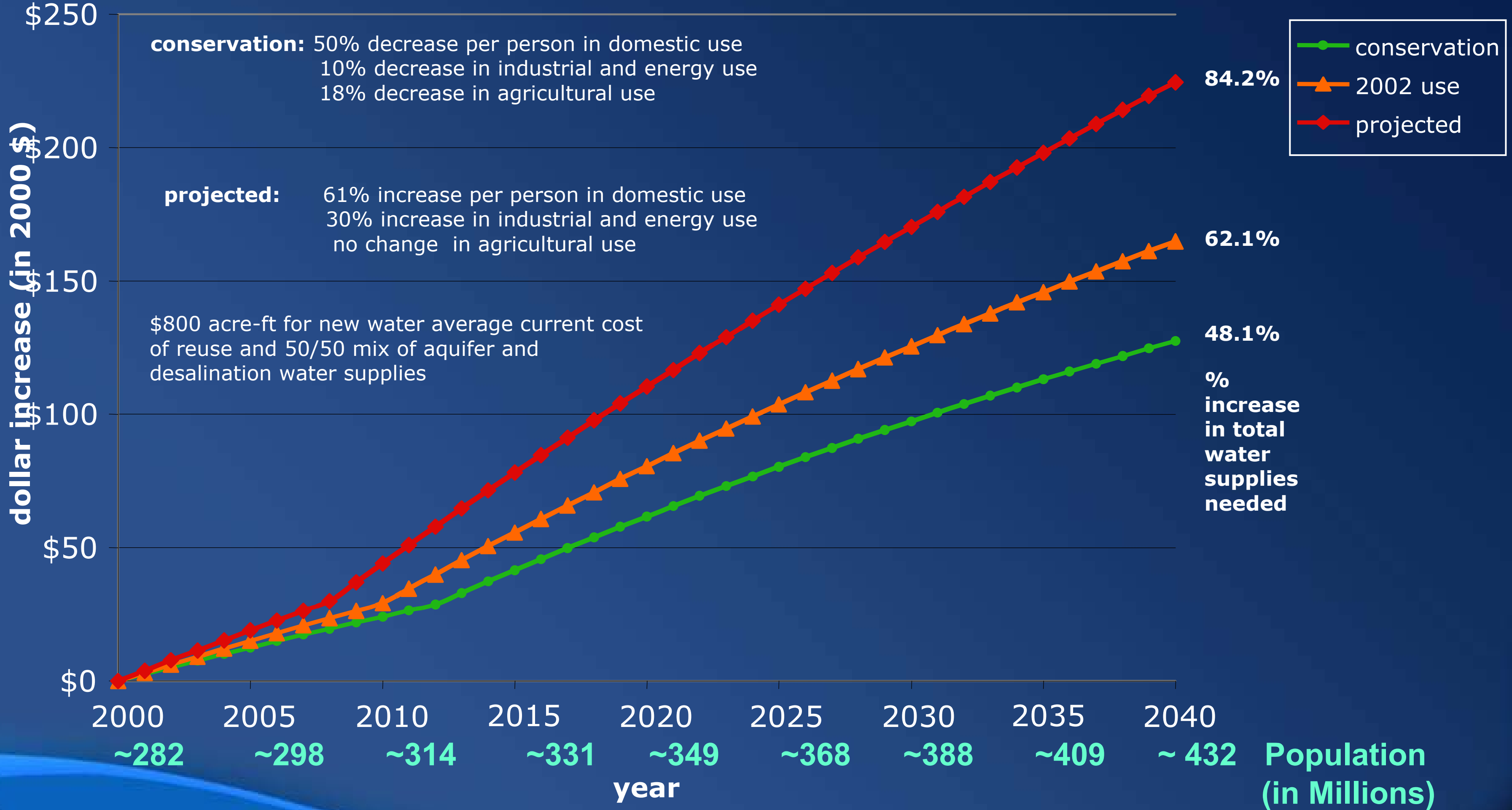
	Water Use, mgd		
Category	Ground Water	Surface Water	Total
Agricultural processing (food & livestock)	25.2	0.1	25.3
Pulp and paper processing	2.3	80.3	82.6
Mine processing (not sand & gravel washing)	0.5	296.5	297.0
Sand and gravel washing	3.8	7.5	11.3
Industrial process cooling once-through	5.8	0.5	6.3
Petroleum-chemical processing, ethanol	10.9	0.4	11.3
Metal processing	3.9	0.0	3.9
Non-metallic processing (rubber, plastic, glass)	3.0	0.0	3.0
Industrial processing	1.0	0.0	1.0
Total	56.3	385.4	441.7

Source: MDNR Water Appropriations Permit Program, 2004

20% of aquifer draw

Water Cost Growth With Population

New water supplies at $800 acre-ft with 1% population growth, and 10% aquifer depletion



waterCAMPwS

Water Problems Coupled & Growing

- Contaminated and impaired waters need research on how to sense and mitigate: Decontamination
- Population, energy and agriculture growth need research in how to increase water supplies: Desalinate and Reuse
- Health and viral threat, as well as global disaster in waterborne illness need research to make water safe from pathogens: Disinfection
- **Population growth exacerbates problems**: Impacts energy, food, health, water withdrawals, contaminated sources, more aquifer depletion, …

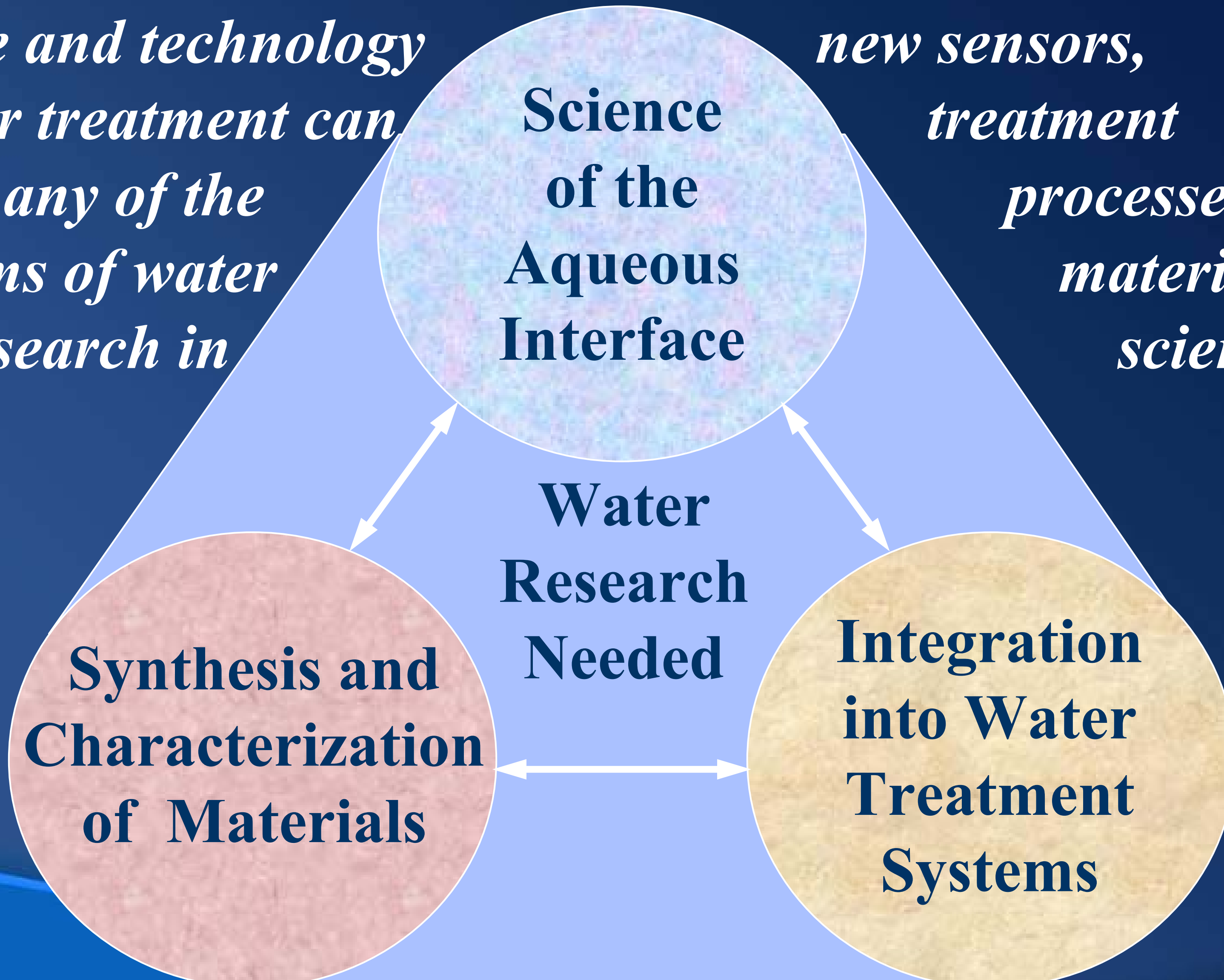
But there are good reasons for hope!

Opportunities

- Physically, we are far from the thermodynamic limits for separating unwanted species from water.
- New materials are being developed that exploit physics of the nanoscale at the water interface.
- Energy/water nexus just starting to be connected.

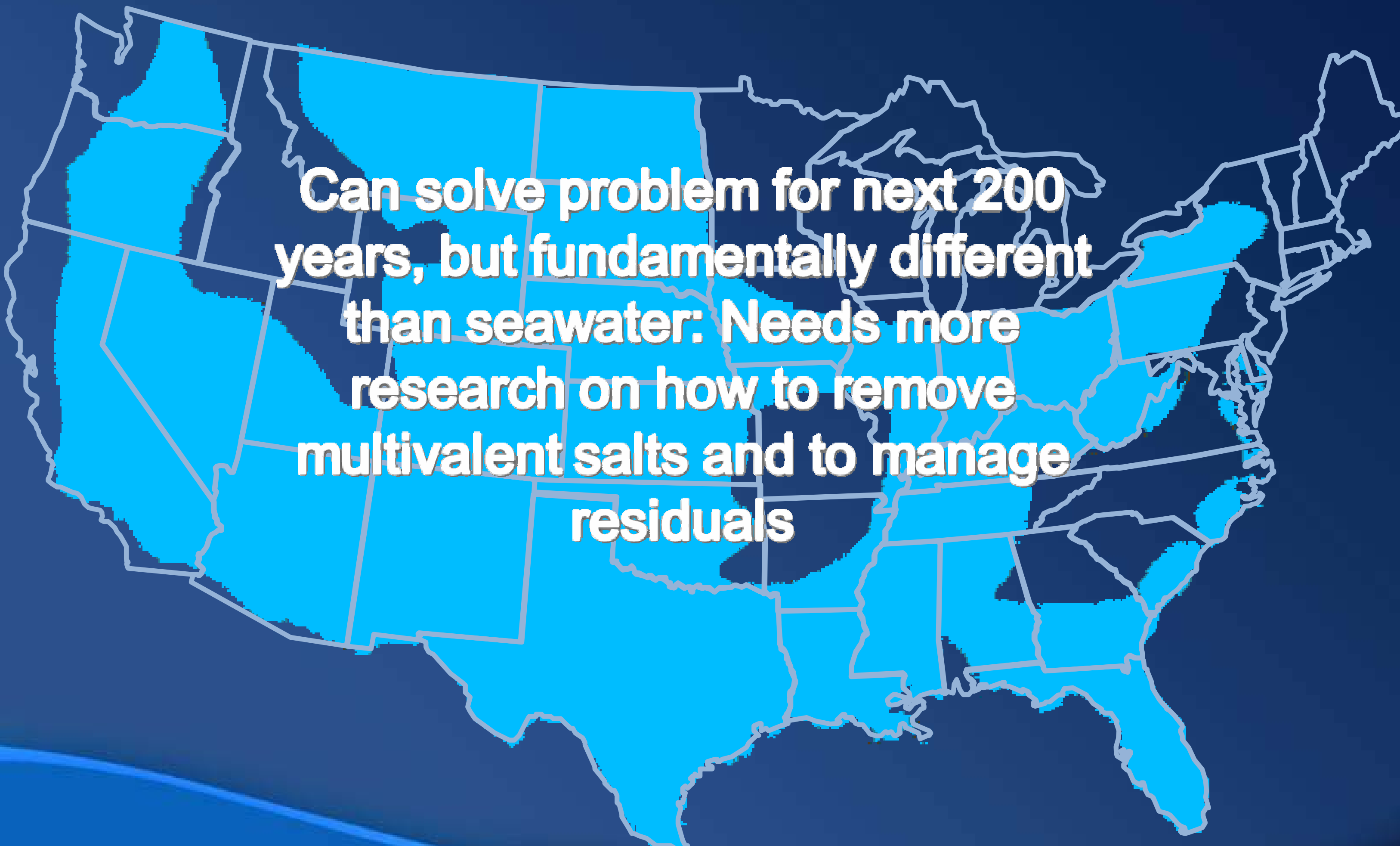
Science, Synthesis and Systems

Science and technology of water treatment can solve many of the problems of water with research in new sensors, treatment processes & material science.



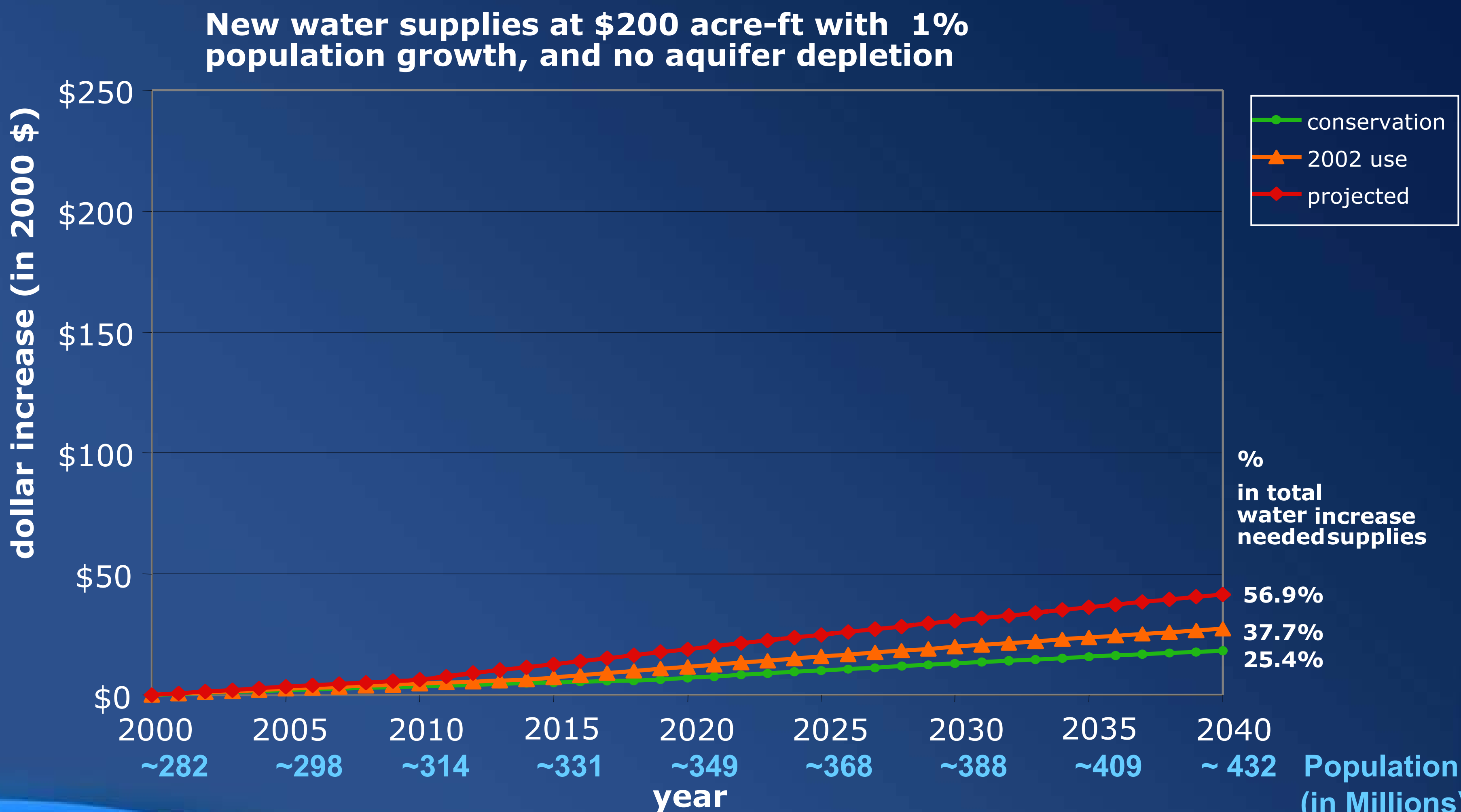
Growing the U.S. Water Supply

One solution is to utilize and reuse water from all sources such as saline aquifers shown above.



Desalination & Water Purification Technology Roadmap SNL& BoR (2003)

Water Cost Growth With Research



Research Objectives

Organized in Interdisciplinary CAMPWS Teams (ICT's) to address three major objectives identified for water purification by **CAMPWS, NAS, Sandia, and EPA** :

ICT I. Increase drinking water supplies, to gain new waters from reuse and desalination from the *"sea to sink to the sea again."*

ICT II. Remove contaminants from all types of water sources, to get the *"drop of poison out of an ocean of water."*

ICT III. Disinfect water from current and potentially emerging pathogens without producing toxins, to *"beat chlorination."*

Research Being Worked On By *WaterCAMPWS*

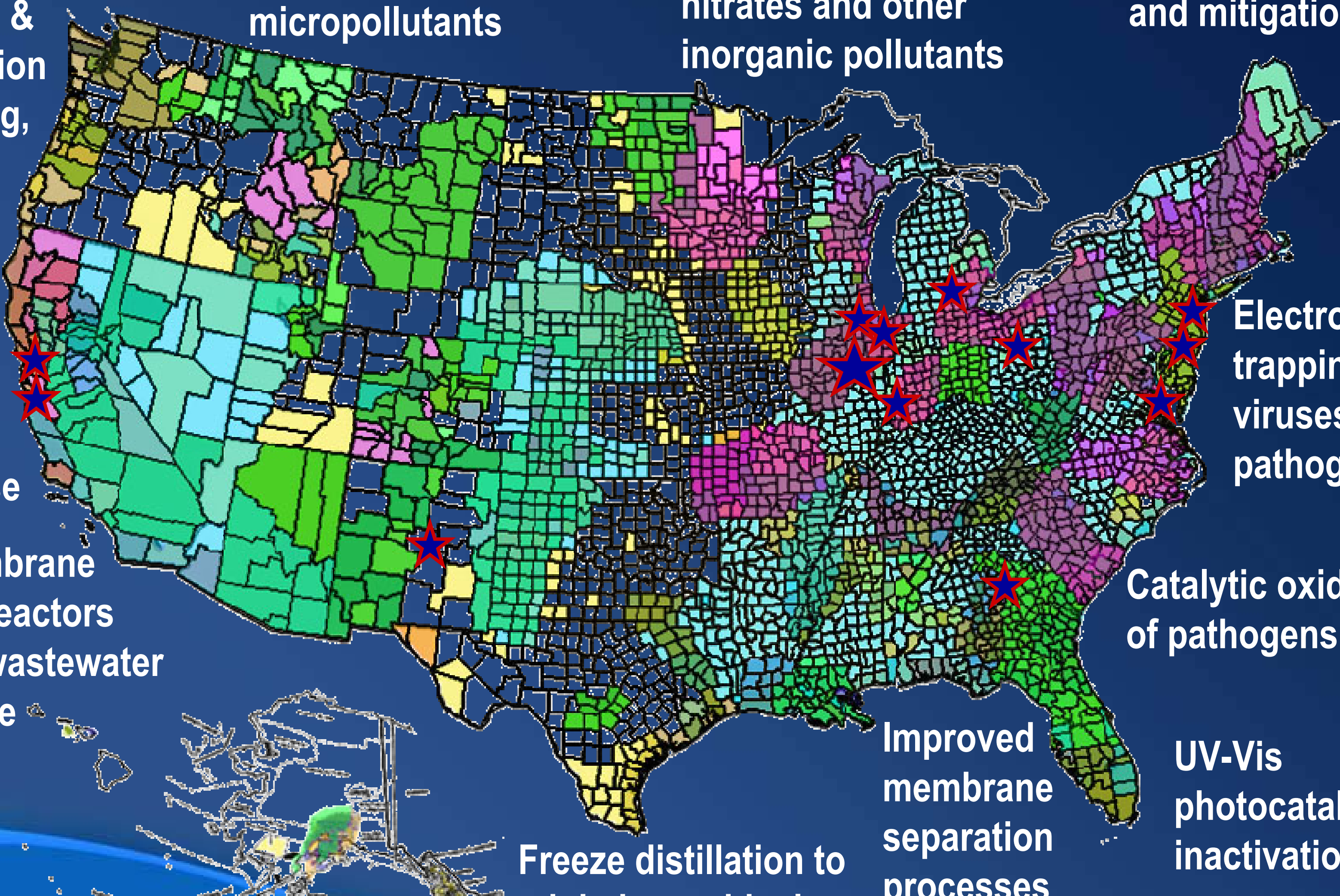
Selective sensing & adsorption of Pb, Hg, etc.

Catalytic oxidation of micropollutants

Catalytic reduction of nitrates and other inorganic pollutants

Fouling studies and mitigation

SFVS & new probes of material response



Electrostatic trapping of viruses and pathogens

Membrane Bioreactors for wastewater reuse

Catalytic oxidation of pathogens

Improved membrane separation processes

UV-Vis photocatalytic inactivation

Freeze distillation to minimize residuals

Molecular Gates – Drivers for Development

Molecular gates are a new micro-nanofluidic construct recently developed at UIUC (last 6 years) by Bohn, Shannon, and Sweedler, along with many colleagues (Drs. Cannon, Fa, Flachsbart, Kuo, Long, Swearington, Tulock,Prakash…).

- ***Nano-Chemical-Mechanical-Manufacturing Systems (Nano-CEMMS)***
  - Development of a nanomanufacturing system that utilizes molecular gates to meter attoliters of reactants in huge arrays.

nano-CEMMS

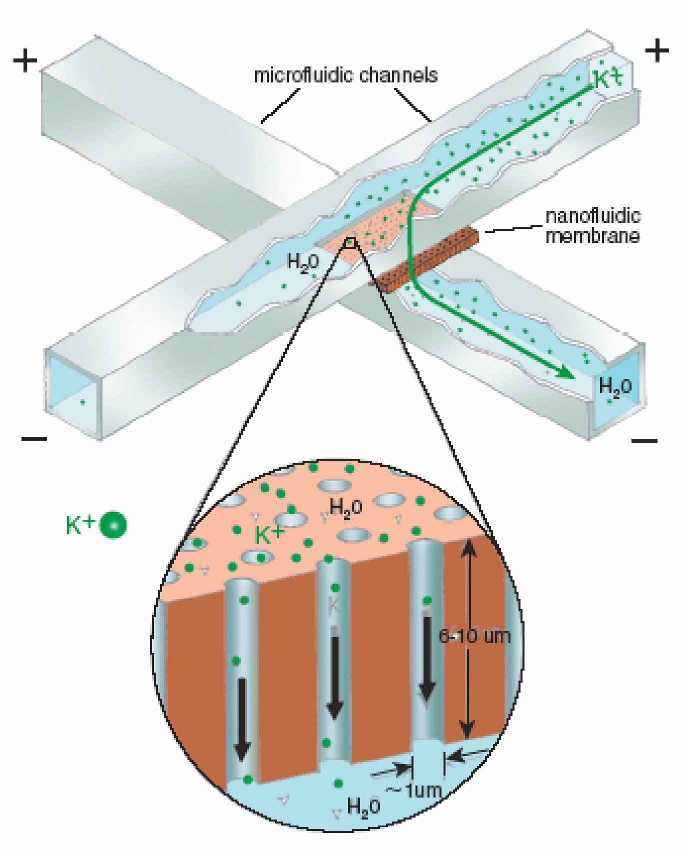
- ***Center for Advanced Materials for Purification of Water with Systems (The WaterCAMPWS)***
  - Utilizes molecular gates to separate ions from water
  - Detection of sub-ppb toxic substances in water

Fundamental Issues to Sense Trace Contaminates in Water

- ***Storage, Separating, Sensing, and Metering***
  - Sensing ultra-low concentrations of compounds: Needle in a trillion "haystacks" ($1:10^{12-20}$)
  - Meter out in ultra-low concentrations (down to attomolar)
- ***Transport of Molecules***
  - Due to composition, molecular structure and affinity, pH, ionic concentration, size, electrokinetic vs. pressure …
- ***Delivery of Molecules***
  - Resolution, concentration, interfacing with systems, in huge arrays, and all the hard problems we are only beginning to look at…

What is a Molecular Gate?

It is an *infinite aspect* ratio ***micro-nanoscale*** construct that:

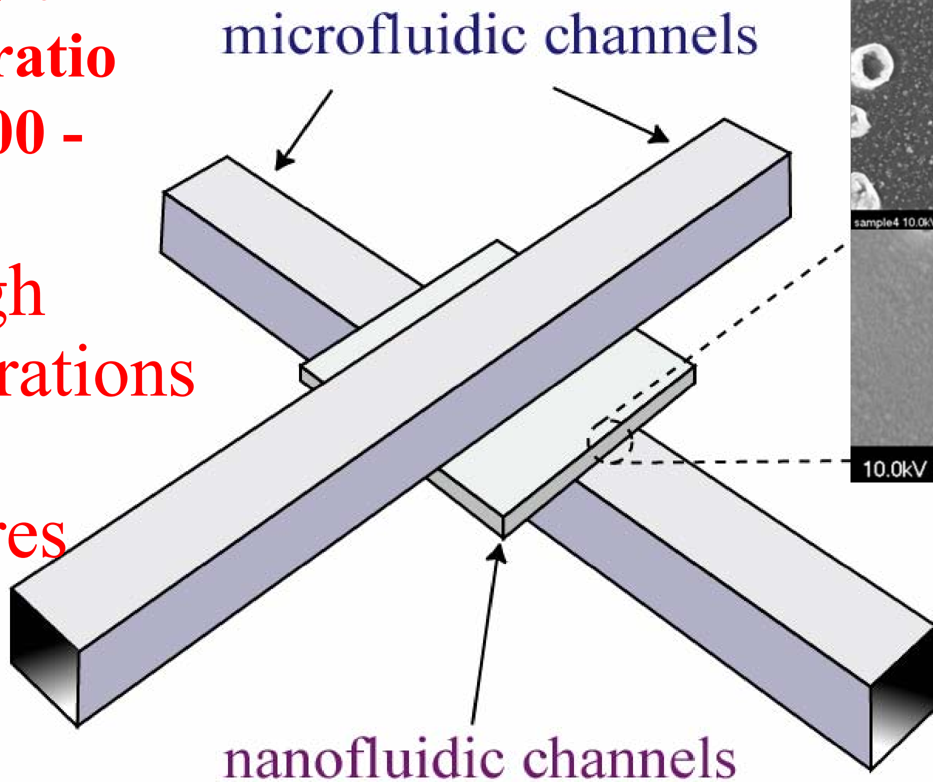


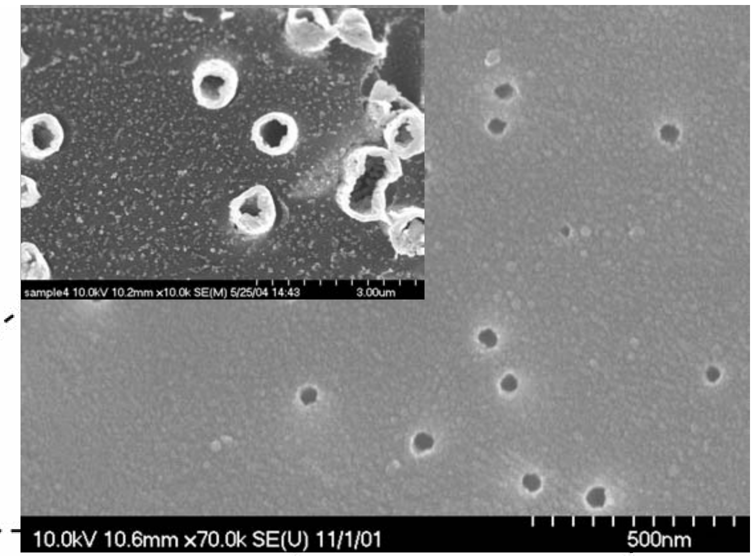
- Controls fluids like electronic devices control electrons
- Transport is proportional to applied bais (resistor) Transport can be made to move in one direction (diode)
- Active control of fluid transport accomplishes digital transfer of fluids and solvated molecules
- Allows selective gating functions based on mass/size/affinity of molecules in fluid

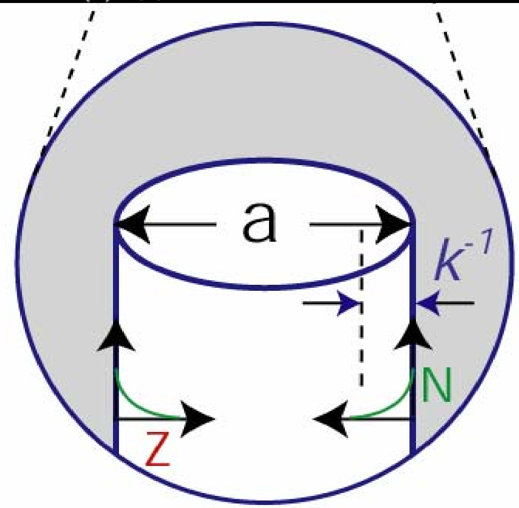
Micro/Nano Interconnect Creates a Gate

Pores with aspect ratio from 100 - 1000

very high concentrations within nanopores

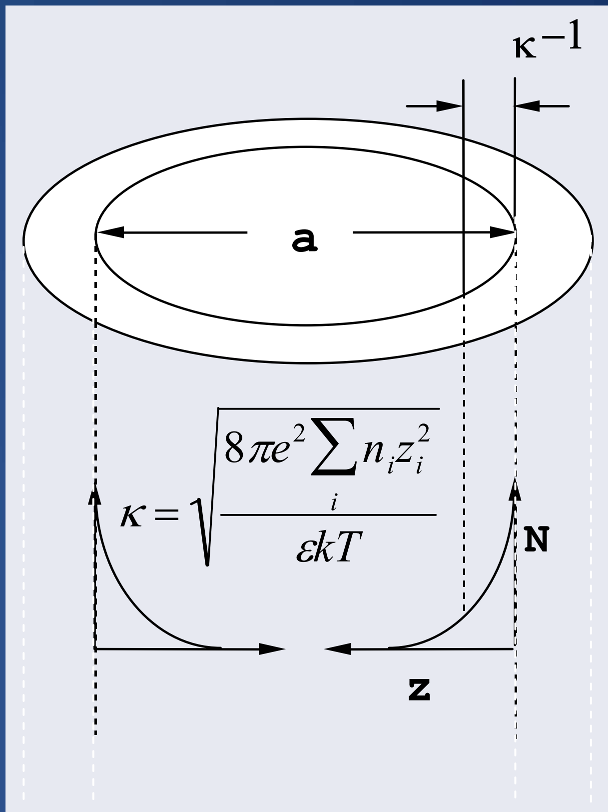


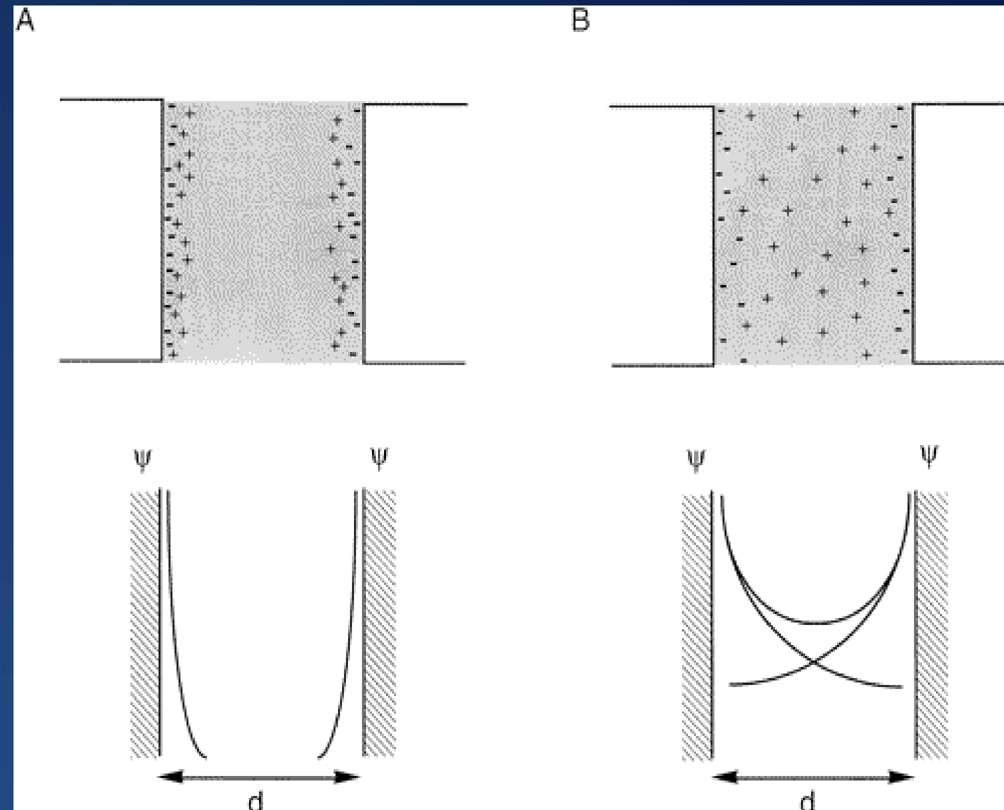




Zepto- (10^{-21}) to Attoliter (10^{-18}) volumes

When Will Nanofluidics Start to Dominate?



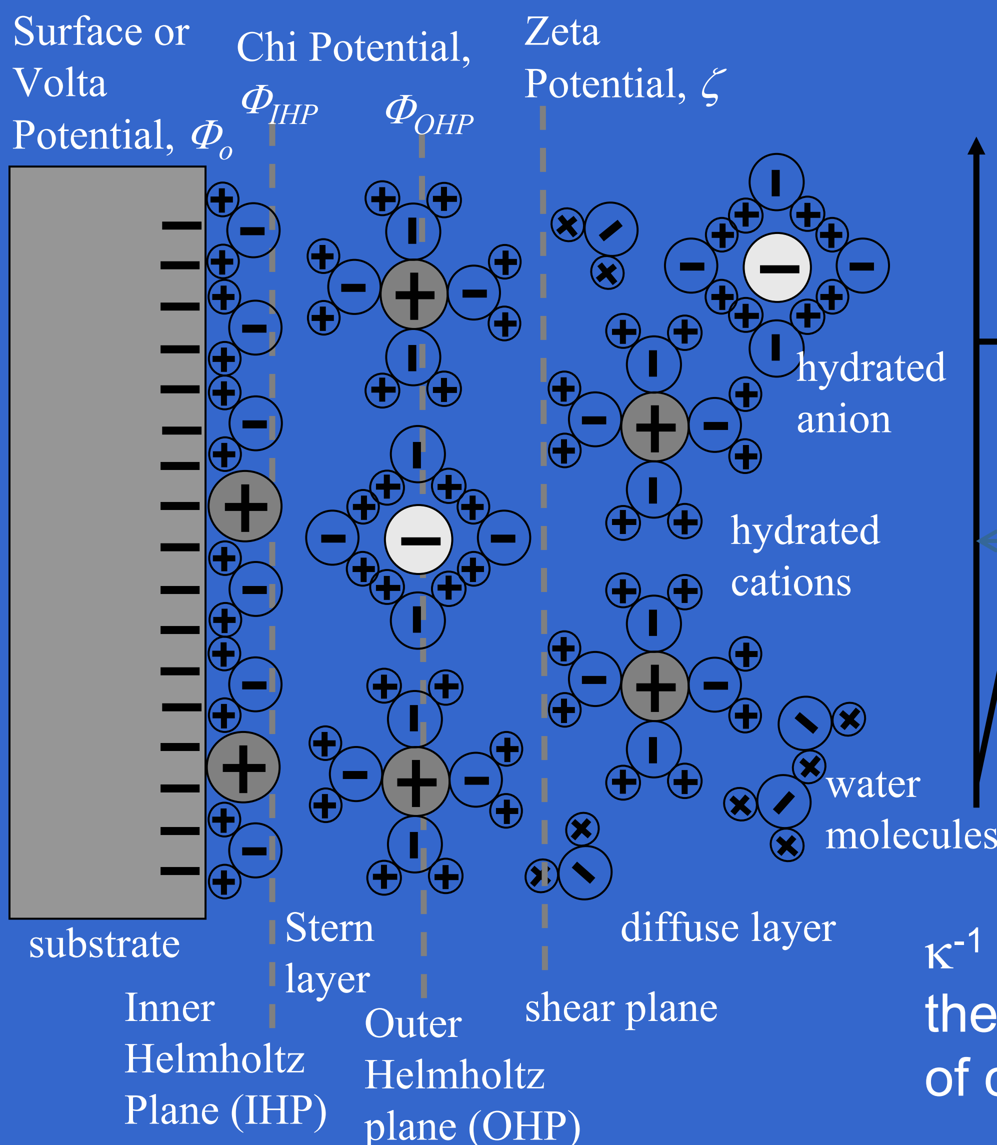


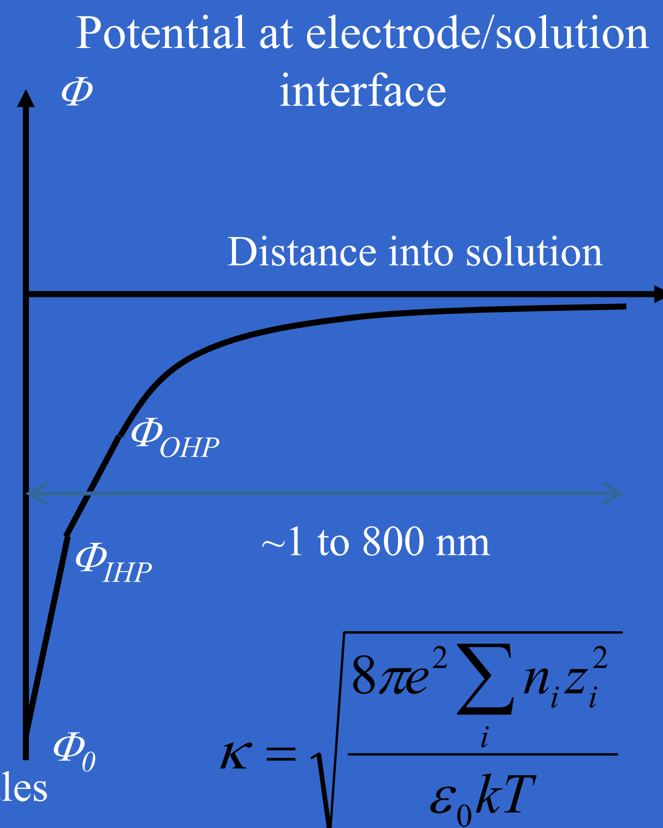
Schematic diagram representing the electrical double layer structures and potential profiles within nanopores at the extreme conditions where (A) κa > 1 and (B) κa < 1.

Paula J. Kemery, Jack K. Steehler, and Paul W. Bohn
Langmuir, **1998,** *14(10)*, 2884.

- Ionic strength adjusts κa
- At κa << 1 electroosmotic flow dominates
- At κa >> 1 ion migration

The Electric Double Layer in Fluid





$$\kappa = \sqrt{\frac{8\pi e^2 \sum_i n_i z_i^2}{\varepsilon_0 kT}}$$

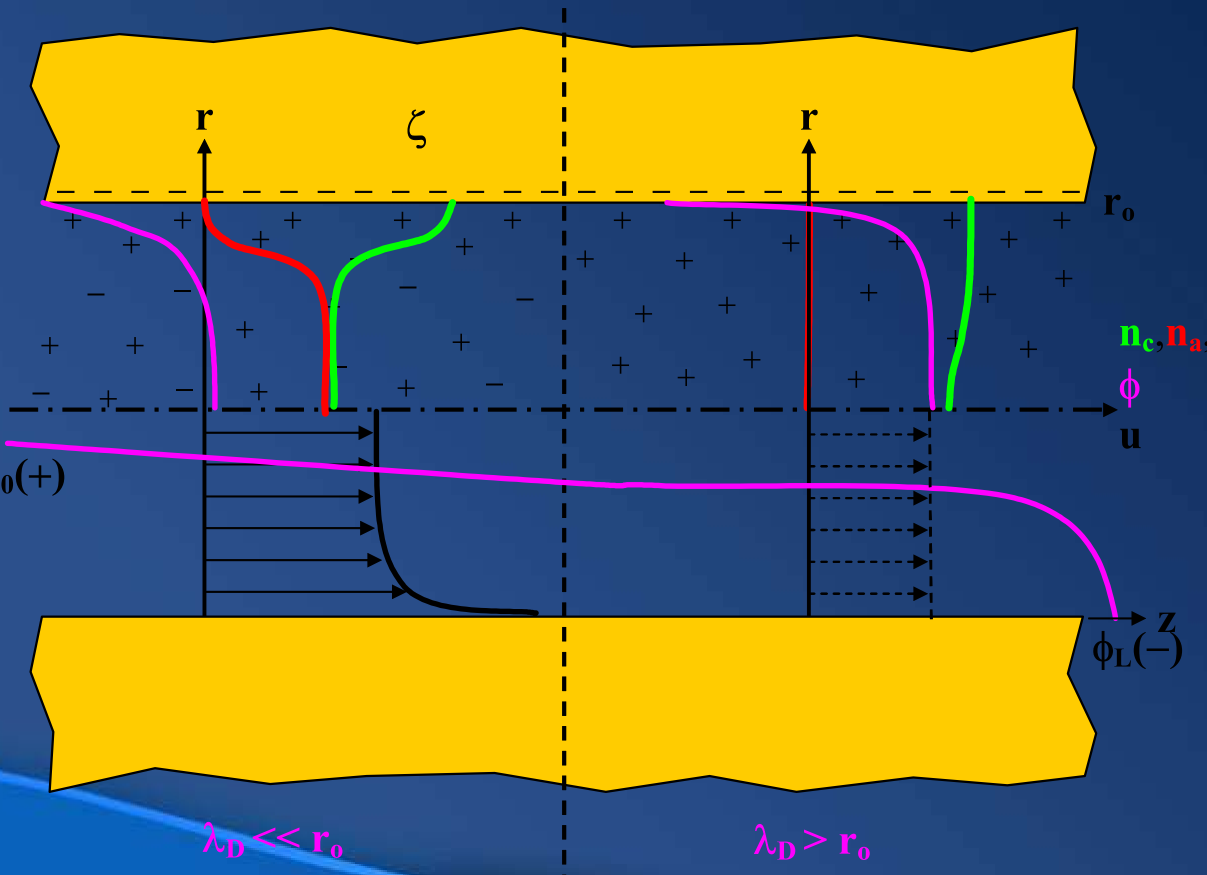
κ^{-1} is the Debye length, which is the effective shielding distance of charge in an ionic solution.

Effect of Debye Length, λ_D, on Profiles

- Non-linear transport at boundaries (ballastic and non-linear electrophoretic velocities: Helmholtz-Smoluchowski assumption violated)

$\partial E / \partial P = \zeta\varepsilon/\eta\sigma$

$u_p = \mu_p E$

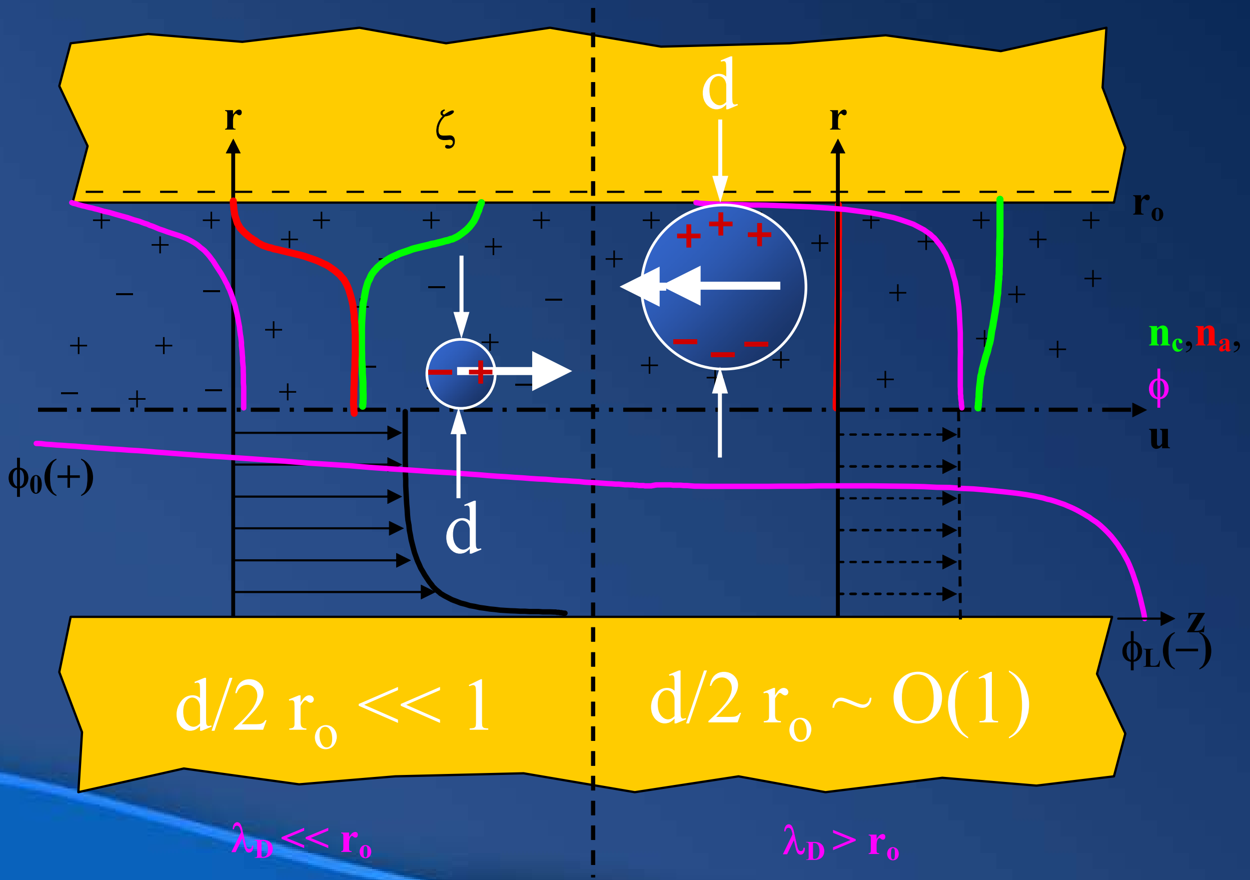


$\partial E / \partial P \neq \zeta\varepsilon/\eta\sigma$

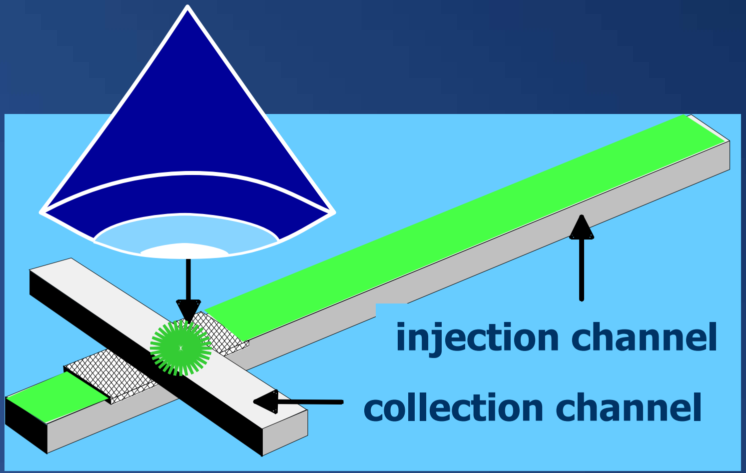
$u_p \sim \mu_p E^n$

Effect of Debye Length, λ_D, on Profiles

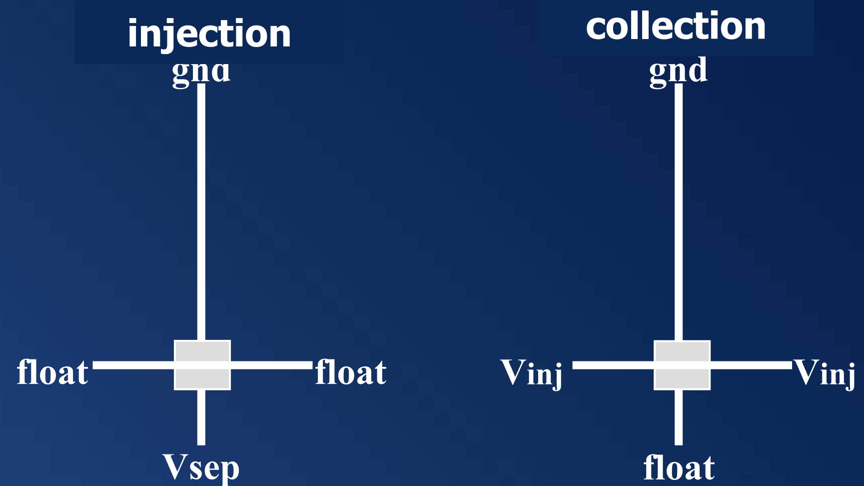
- Spatial distribution of large molecules in channels favored at walls, leading to unusual molecular transport mechanisms.



Molecular Gate Operation



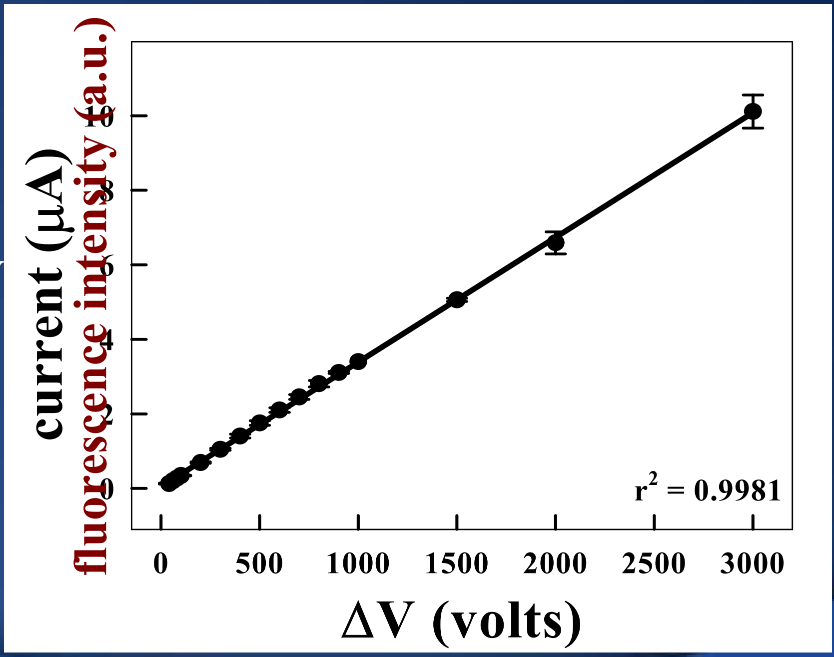
voltage pathways used for transport



Pressure driven flow not suitable: Vanishingly small flows and pressure induced rupture occurs.

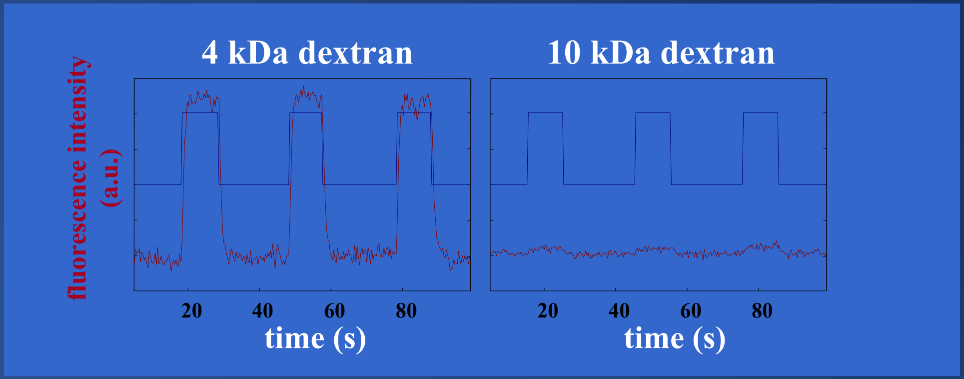
Electrokinetic flows extremely efficient: mm/s flows.

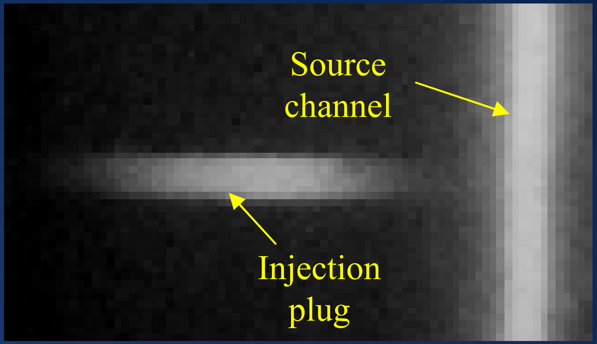
Operated by applying a voltage potential at the ends of the channels.



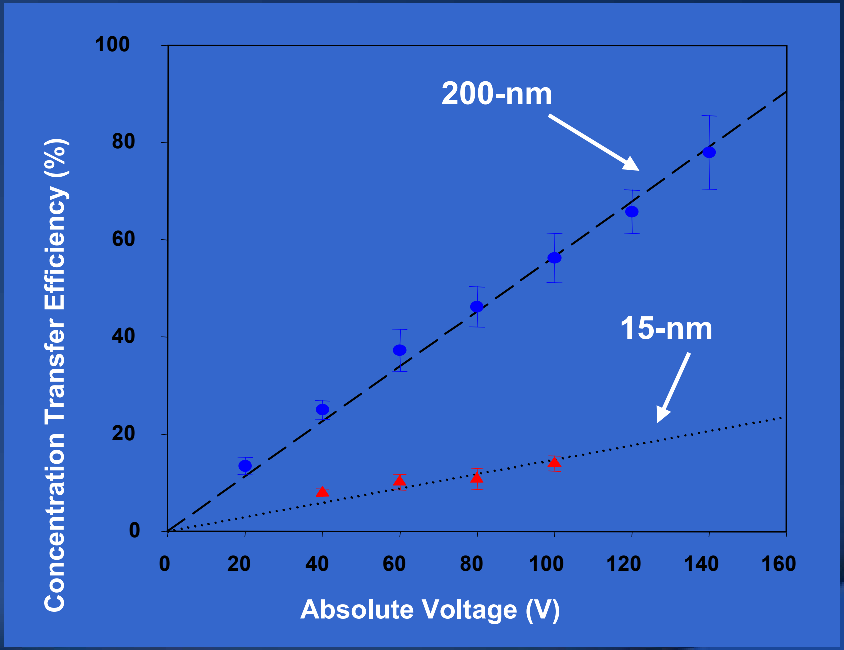
Control of Attomoles of Reactants

Active control of fluid transport accomplishes digital transfer of fluids and molecular species between microchannels.



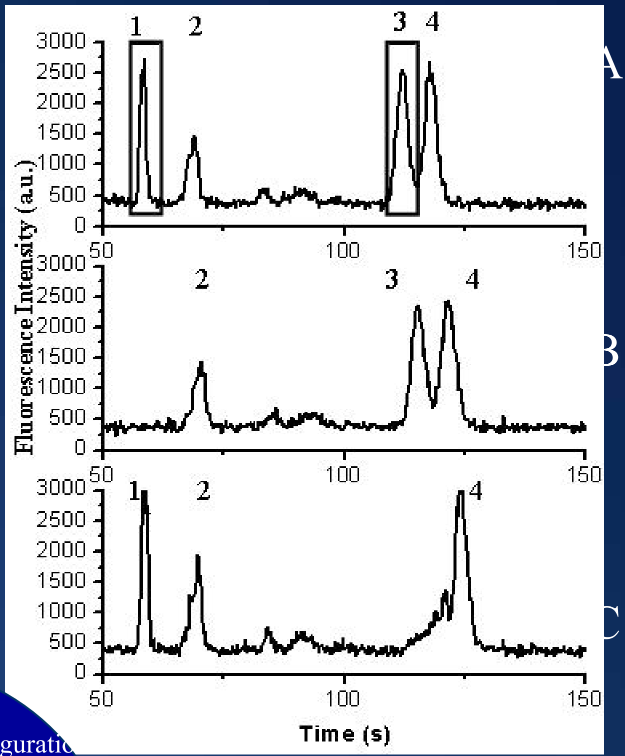


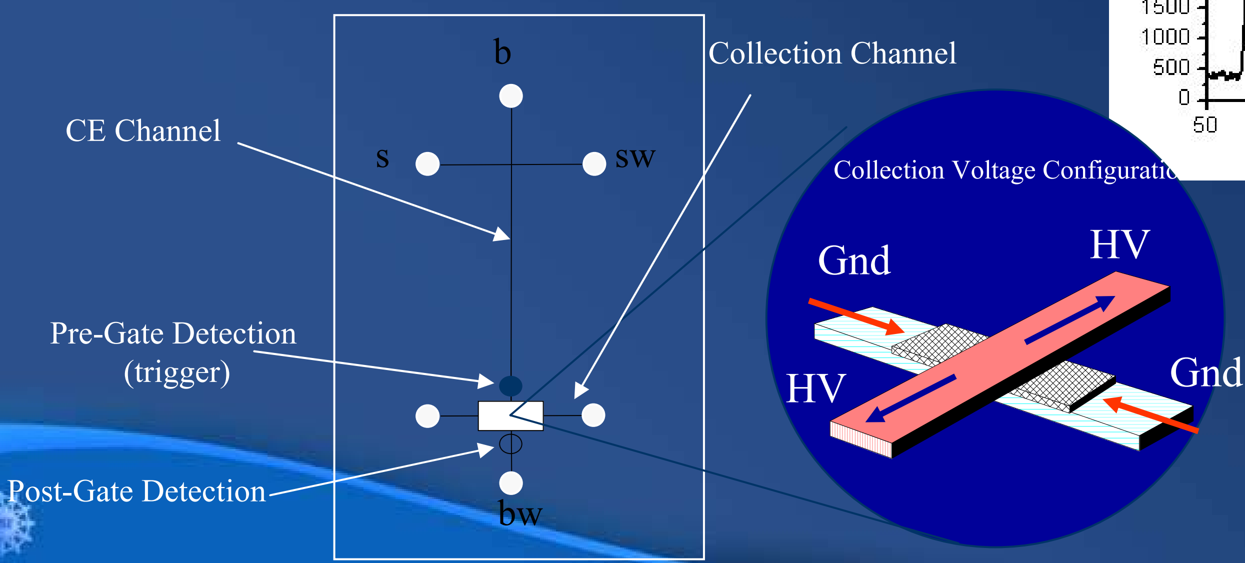
QuickTime™ and a Video decompressor are needed to see this picture.



Capture of Analytes with Molecular Gates

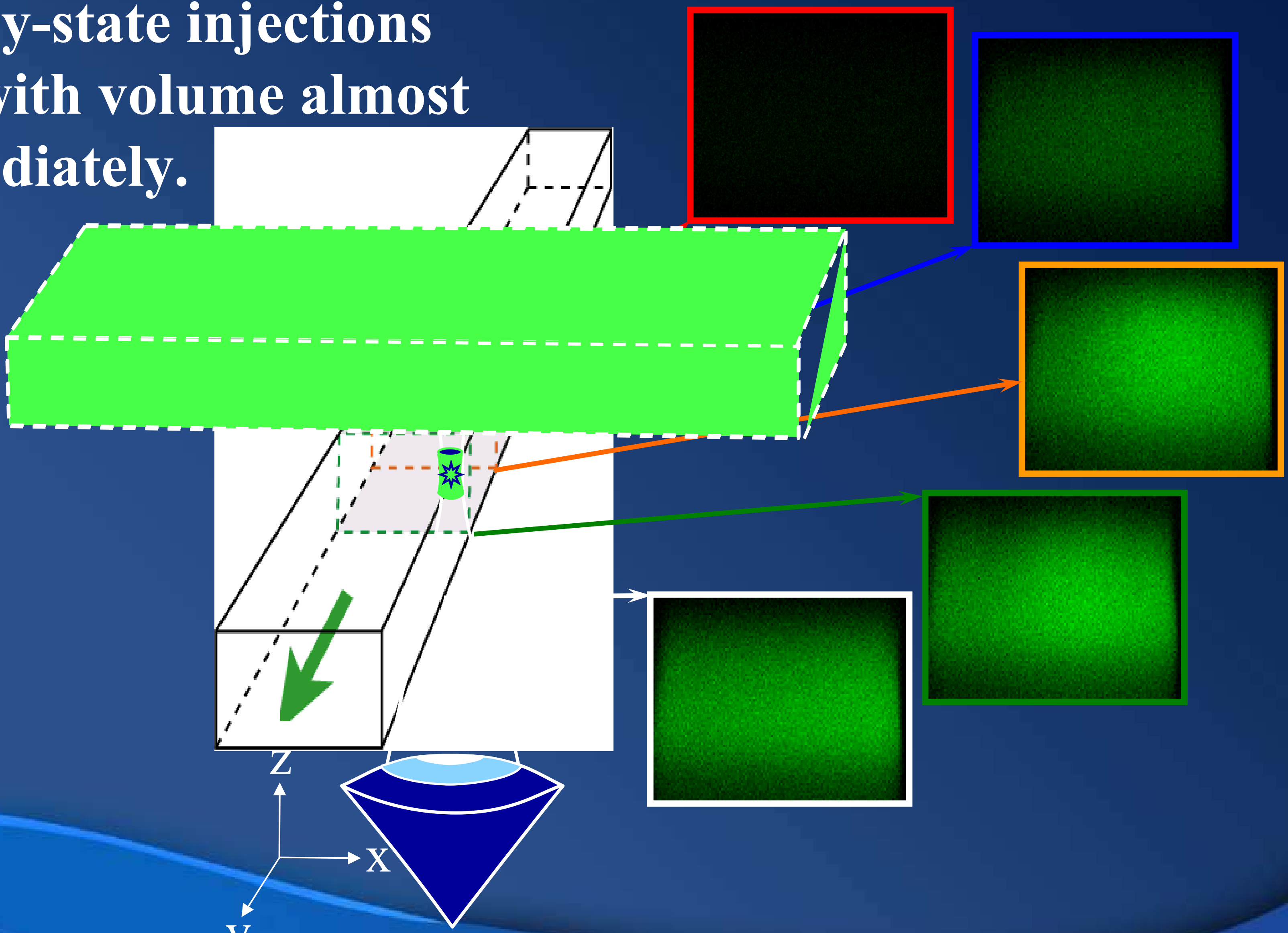
Electrophoretic Separation and capture of FITC-Labeled Glutamate and Arginine in 50mM Borate Buffer (E = 170 kV/cm).



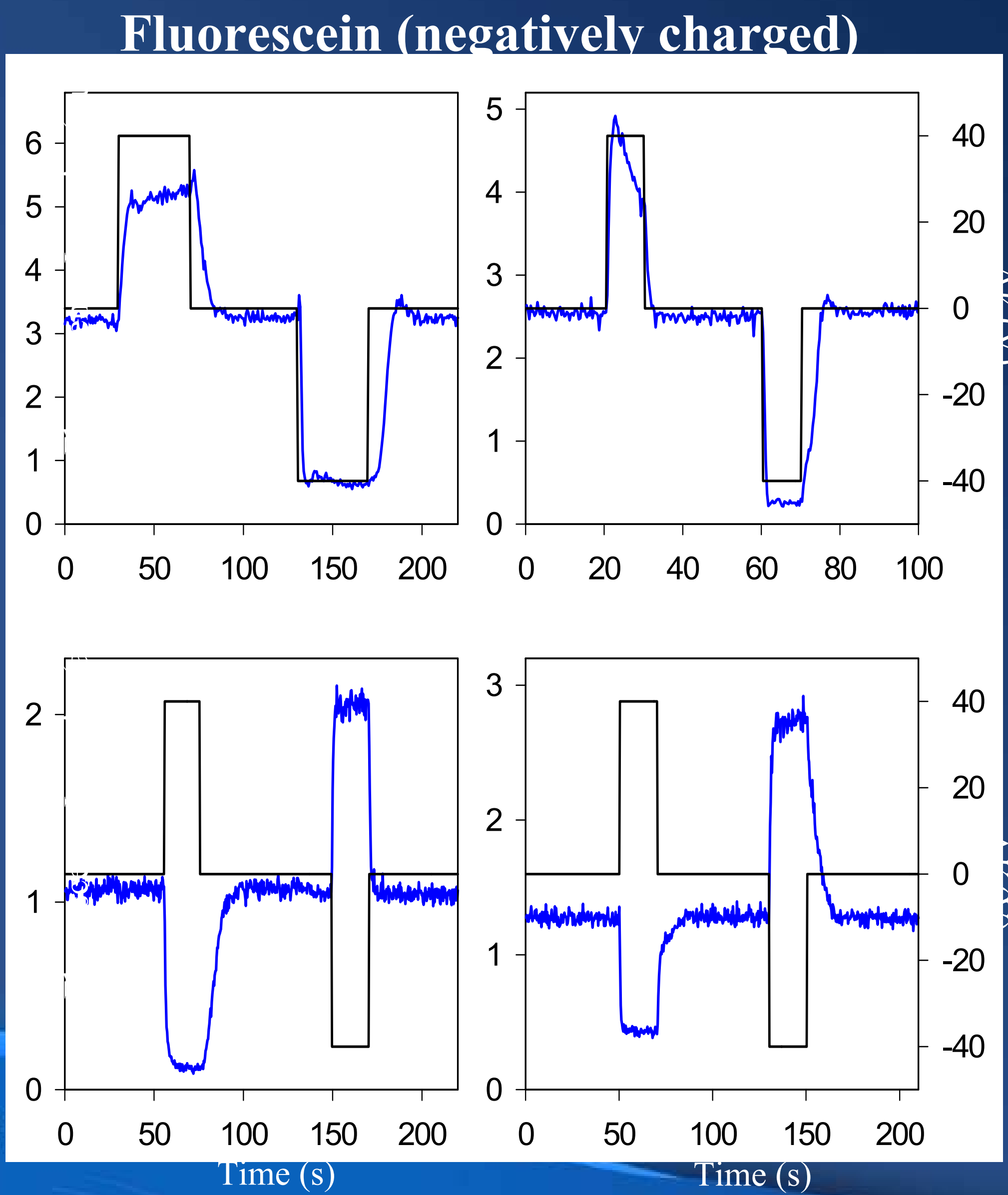


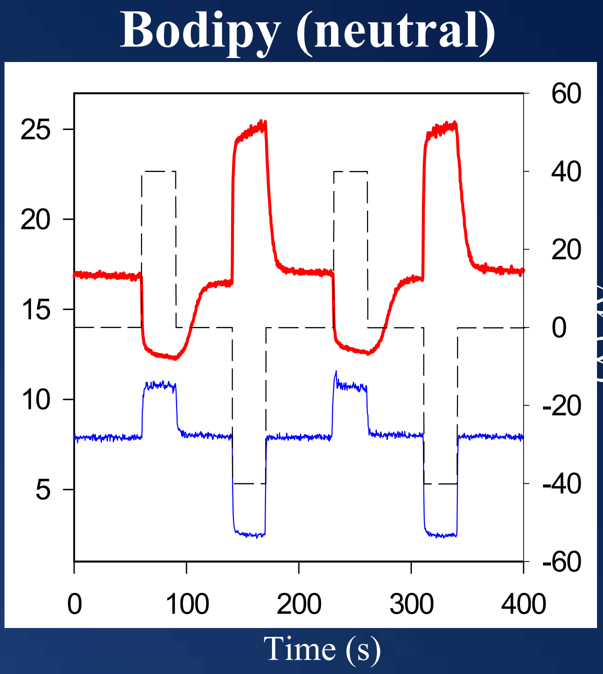
Rapid Volumetric Mixing **Re << 1 Laminar**

Steady-state injections mix with volume almost immediately.



Effect of Pore Size on Transport Response

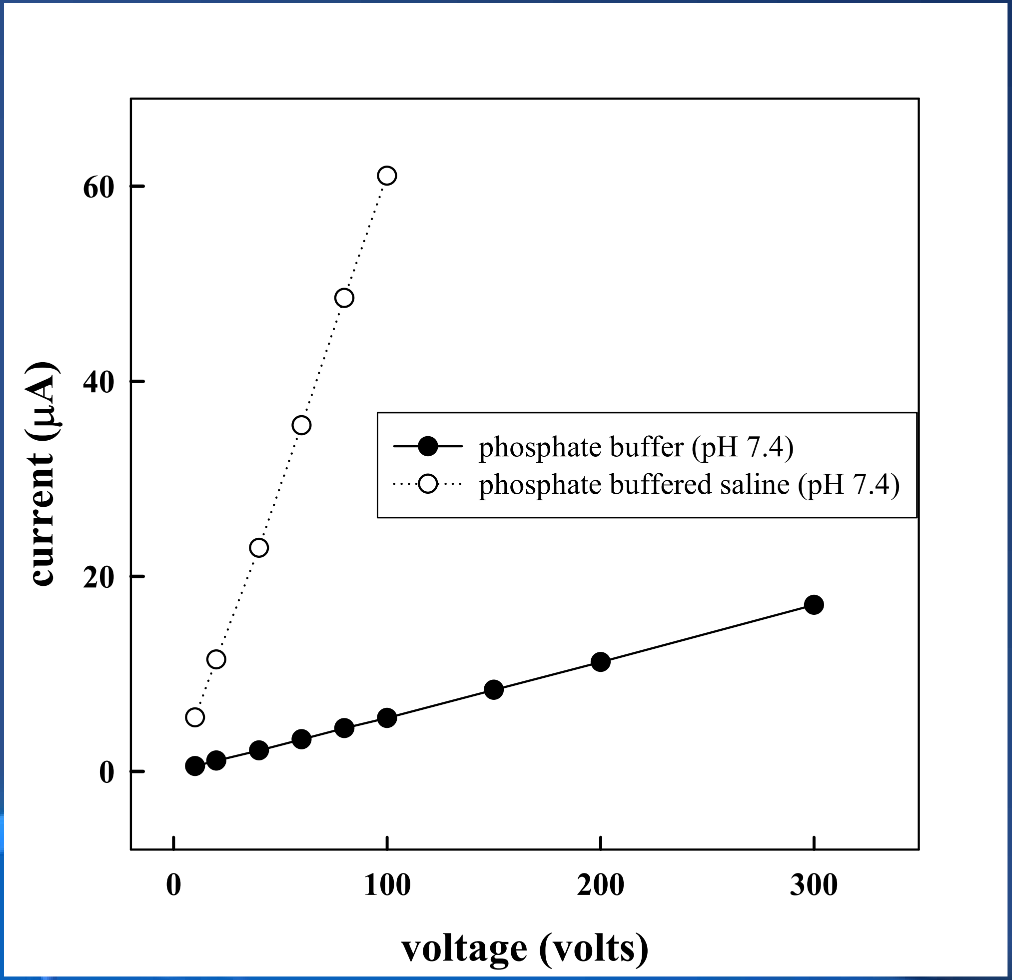


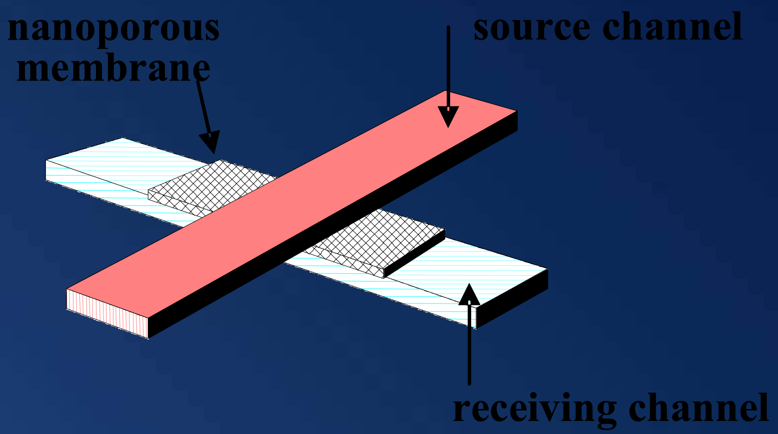


Flow direction for a given bias determined by wall charge, ionic strength, and pore diameter.

Gradients Across Channels

Injection of molecule from one solution to another.





Across 25 nm pores for two cases:

phosphate buffer (10 mM)

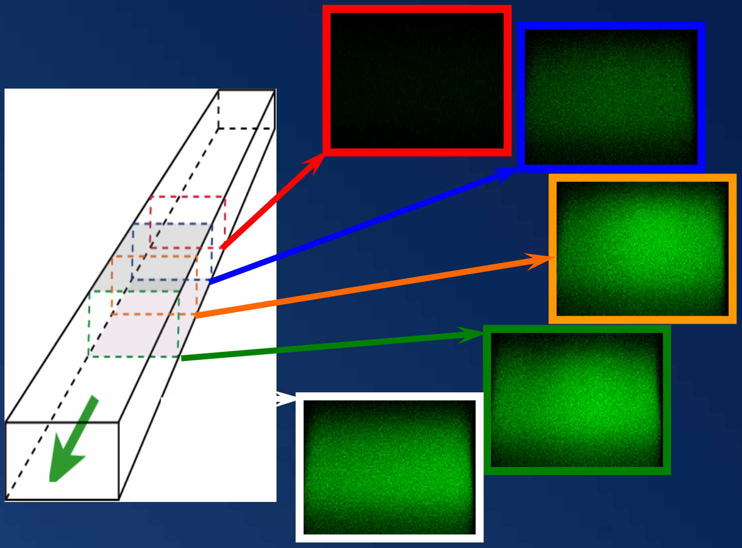
vs.

phosphate buffered saline (10 mM)

(138 mM NaCl; 2.7 mM KCl)

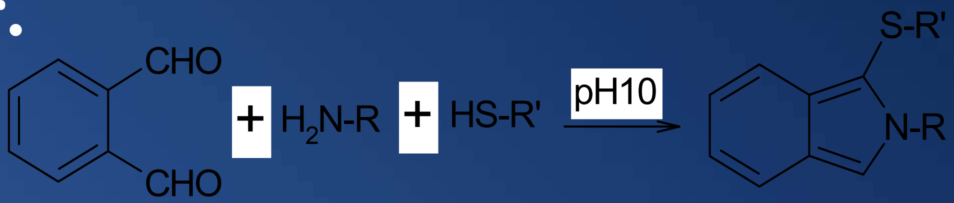
Challenges with Integrating Molecular Gates

Molecules are not electrons: Distinguishably different, and behave differently for same elements.



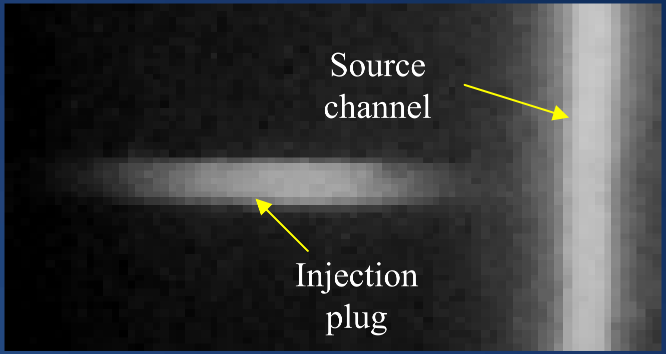
Challenges with Integrating Molecular Gates

Reactions: Change composition and behavior.

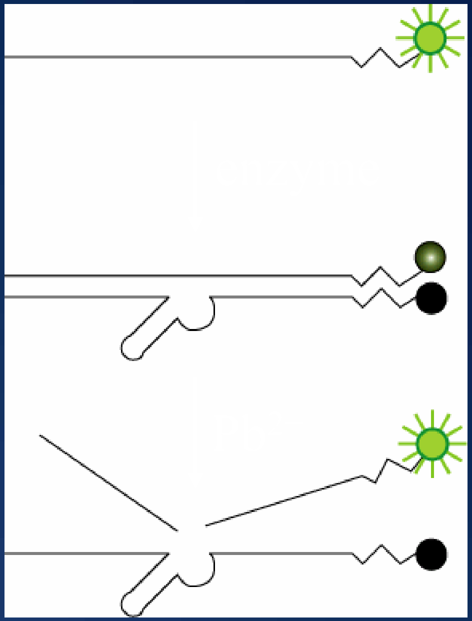


Challenges with Integrating Molecular Gates

Fluid Flow Strongly Coupled: Active control of fluid transport affected by previous interactions.

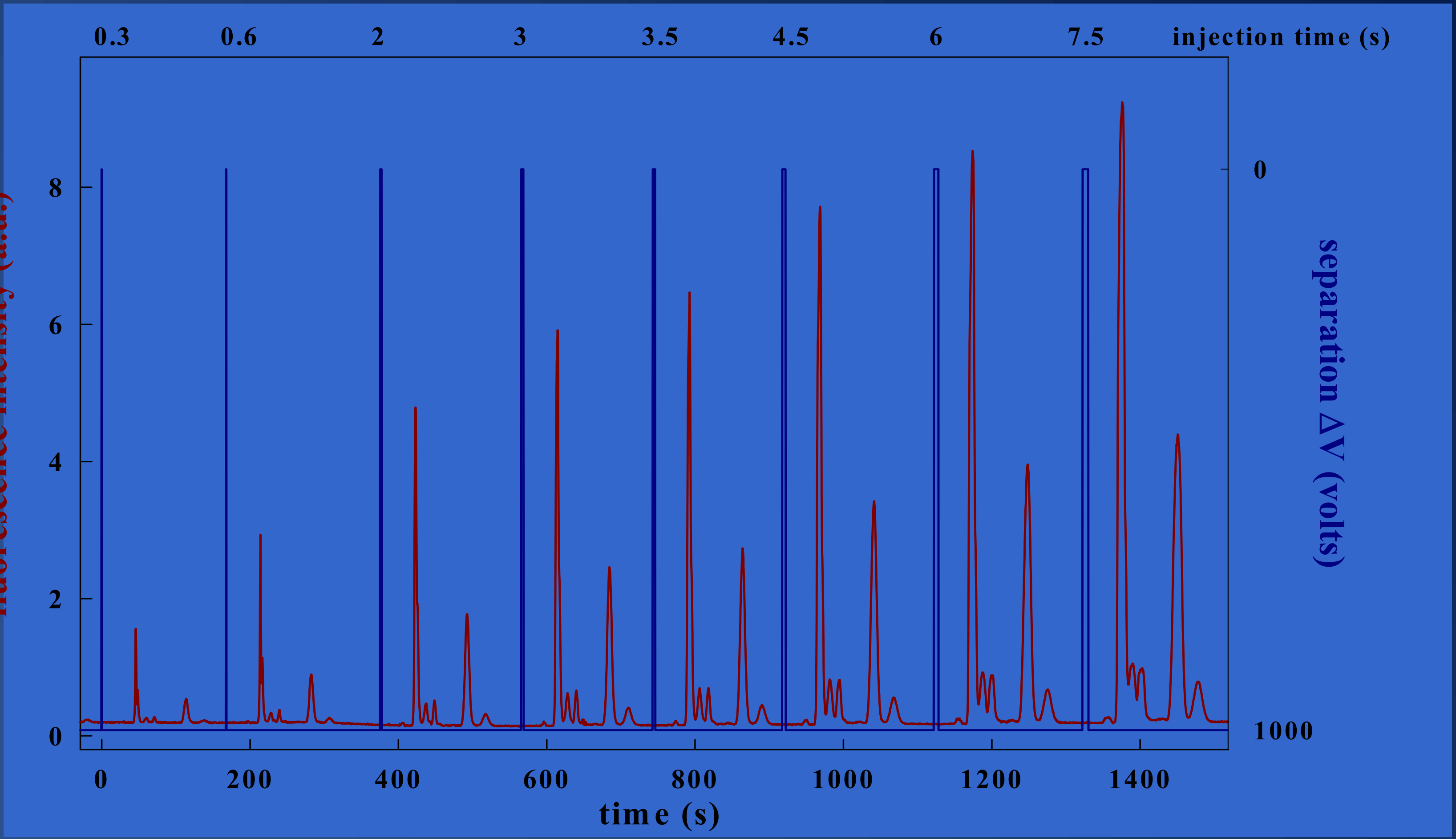


Challenges with Integrating Molecular Gates



Affinity to Specific Species: Integrating, controlling, and utilizing molecular recognition elements

Challenges with Integrating Molecular Gates



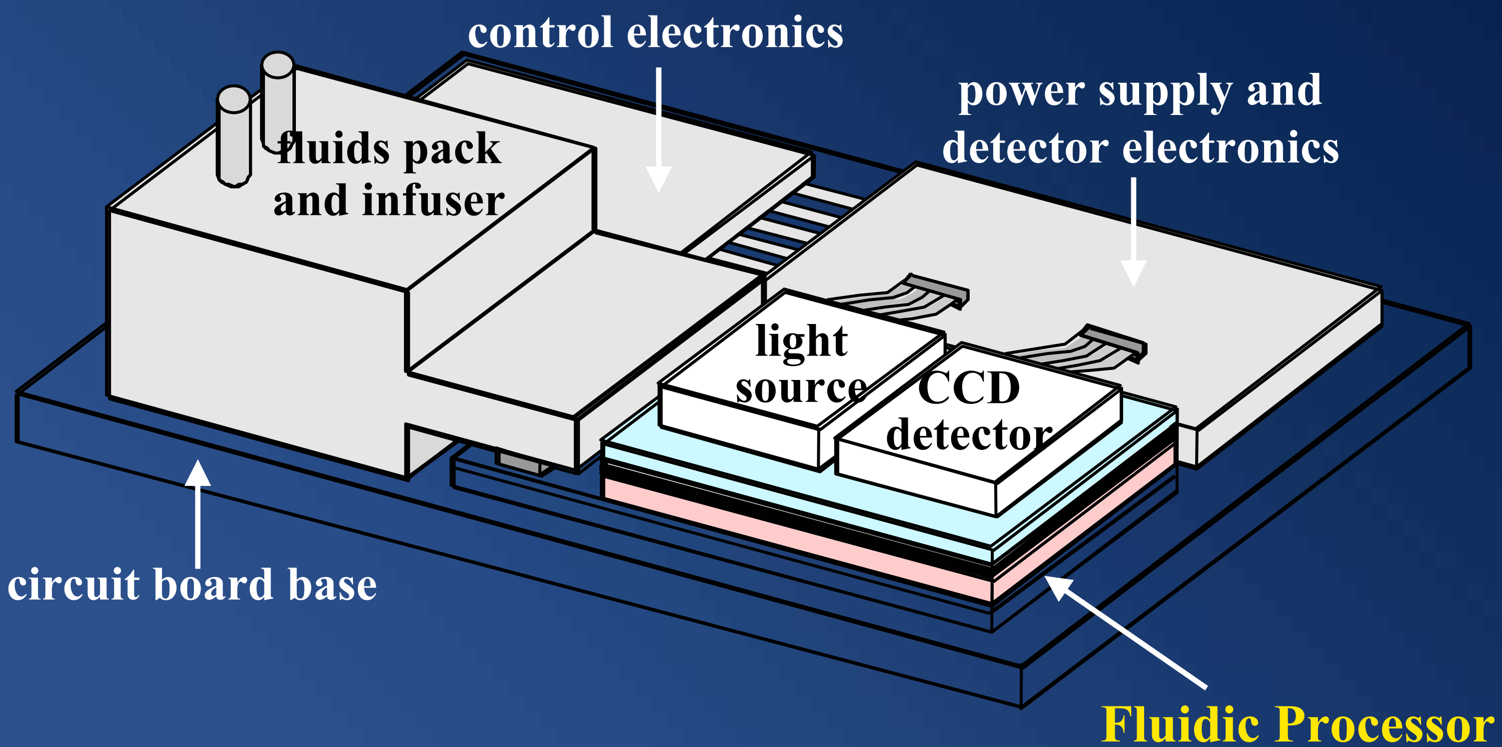
Transport & Separations: Strongly affected by different phenomena, e.g. chemical composition, molecular size, electrophoretic mobility.

Summary of Findings

- ***Molecular Gates Create High-Electric Fields***
  - High fields (>10 KV/cm) for low voltages (>10V)
- ***Collection mass efficiency near 100%***
  - Attomoles and smaller amounts can be collected
- ***Transport of Molecules***
  - Ion velocities high for mobility's $10^{-6 \text{ to } -4}$ cm^2/Vs
- ***Injection Velocities Lead to Rapid Mixing***
  - Fills injection volumes in milliseconds and within microns of the injection port.

Molecular gates allow rapid collecting, injecting, mixing, and reacting for μTAS applications

Sensor work at UIUC (Bohn, Lu, Shannon, Sweedler)



A fluidic processor, which exploits *both* **micro-** *and* **nanofludics, to manipulate attomoles** of **toxic** species, such as *C. botulinum* neurotoxin A (BoNT/A), ppb of Pb, Hg, and ppt of polyaromatic hydrocarbonds (NDMA).

What More is Needed With Water Issues Facing U.S.

- We need better information of aquifers (fresh *and* saline), quantities, flows, and constituents, and interconnection of watersheds
- Bold new research program on new methods to desalinate seawater *and* inland aquifers with waste residual management.
- New research in the science and technology of water purification for water reuse, contaminates removal, and disinfection.

BUT WE NEED THE PUBLIC, SCIENTISTS, AND POLICY MAKERS TO KNOW THE REAL VALUE OF WATER.

Future Directions

- Set a national Strategic Plan for water technology with *U.S. Strategic Water Initiative* (USSWI) for the next twenty years: Major USSWI Congress in New Orleans April 2008
- Need industrial input into strategic planning process
- Public/Private Partnership: billions to trillions at stake
- Build infrastructure to pilot plant ideas from research to create historical data needed to move bold new ideas into practice:

WE NEED A PIPELINE

USSWI

How Can the U.S. Respond?

- A new, 10 year, multi-Agency program in the science and technology of water purification, including DOD, DOI, BOR, DHS, DOE, HHS, NSF, USDA, USEPA, USGS,…
- Development of public/private facilities for multiyear pilot and demonstration of treatment methodologies: Verification based on new accepted water source classes.
- Development of unified treatment modalities for categories of source waters and contaminates.

A Future Water-based Economy?

- The worldwide market for water purification technologies will be in the trillions in the next two decades.
- Water is already unaffordable for billions.
- Who is going to pay for the technological solutions it needs?
- If water is the oil of the 21^{st} century, who will command the world market place for water and solutions?

How can this be equitable for people from all walks of life?

watercAMPwS

Watershed Maps

- Aquifers, Rivers, Lakes & Usage for 2000
  - http://nationalatlas.gov/atlasftp.html
- State Boundaries, District Maps
  - ARC GIS Template Maps (USGS)
- Saline Aquifer Map
  - Desalination & Water Purification Technology Roadmap SNL& BoR (2003)

Water Withdrawal & Consumption Data

- Consumptive Water Use for U.S. Power Production, P. Torcellini, et.al., National Renewable Energy Laboratory, 2003.

Water Use Projection Model Based on:

- Texas Water Development Board 2007 Plan and Projections http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2007/2007StateWaterPlan/2007StateWaterPlan.htm

Energy Use & Water Nexus:

- Energy Demands On Water Resources: Report To Congress On The Interdependency Of Energy And Water, U.S. Department Of Energy, December 2006

Population Data

- Population Estimates
  - U.S. Census Bureau County Population http://www.census.gov/popest/datasets.html
- Population Projections
  - U.S. Census Bureau Population Projections http://www.census.gov/population/www/projections/stproj.html

Contaminant Data

- Water quality sampling data sets from U.S. Geologic Survey: http://web1.er.usgs.gov/NAWQAMapTheme/index.jsp
- Alley, W.M., T.E. Reilly, and O.L. Franke, “Sustainability of Ground-Water Resources,” U.S. Geological Survey Circular 1186, 1999.
- Anderson, M.T., and L.H. Woosley, Jr., “Water Availability for the Western United States -- Key Scientific Challenges,” U.S. Geological Survey Circular 1261, 2005.
- Anderson, R.M., K.M. Beer, T.F. Buckwalter, M.E. Clark, S.D. McAuley, J.I. Sams, III, and D.R. Williams, “Water Quality in the Allegheny and Monongahela River Basins --Pennsylvania, West Virginia, New York, and Maryland, 1996–98,” U.S. Geological Survey Circular 1202, 2000.
- Anthony, S.S., C.D. Hunt, Jr., A.M.D. Brasher, L.D. Miller, and M.S. Tomlinson, “Water Quality on the Island of Oahu -- Hawaii, 1999–2001,” U.S. Geological Survey Circular 1239, 2004.
- Atkins, J.B., H. Zappia, J.L. Robinson, A.K. McPherson, R.S. Moreland, D.A. Harned, B.F. Johnston, and J.S. Harvill, “Water Quality in the Mobile River Basin -- Alabama, Georgia, Mississippi, and Tennessee, 1999–2001,” U.S. Geological Survey Circular 1231, 2004.
- Ator, S.W., J.D. Blomquist, J.W. Brakebill, J.M. Denis, M.J. Ferrari, C.V. Miller, and H. Zappia, “Water Quality in the Potomac River Basin -- Maryland, Pennsylvania, Virginia, West Virginia and the District of Columbia, 1992–96,” U.S. Geological Survey Circular 1166, 1998.
- Ayers, M.A., J.G. Kennen, and P.E. Stackelberg, “Water Quality in the Long Island-New Jersey Coastal Drainages -- New Jersey and New York, 1996–98,” U.S. Geological Survey Circular 1201, 2000.
- Barlow, P.M., “Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast,” U.S. Geological Survey Circular 1262, 2003.
- Becker, M.F., B.W. Bruce, L.M. Pope, and W.J. Andrews, “Ground-Water Quality in the Central High Plains Aquifer -- Colorado, Kansas, New Mexico, Oklahoma, and Texas, 1999,” U.S. Geological Survey Water-Resources Investigation Report 02-4112, 2002.
- Belitz, K., S.N. Hamlin, C.A. Burton, R. Kent, R.G. Fay, and T. Johnson, “Water Quality in the Santa Ana Basin -- California, 1999–2001,” U.S. Geological Survey Circular 1238, 2004.
- Berndt, M.P., H.H. Hatzell, C.A. Crandall, M. Turtora, J.R. Pittman, and E.T. Oaksford, “Water Quality in the Georgia-Florida Coastal Plain -- Georgia and Florida, 1992–96,” U.S. Geological Survey Circular 1151, 1998.
- Bevans, H.E., M.S. Lico, and S.J. Lawrence, “Water Quality in the Las Vegas Valley Area and the Carson and Truckee River Basins -- Nevada and California, 1992–96,” U.S. Geological Survey Circular 1170, 1998.
- Bruce, B.W., M.F. Becker, L.M. Pope, and J.J. Gurdak,” “Ground-Water Quality Beneath Irrigated Agriculture in the Central High Plains Aquifer, 1999–2000,” U.S. Geological Survey Water-Resources Investigation Report 03-4219, 2003.
- Bush, P.W., A.F. Ardis, L. Fahlquist, P.B. Ging, C.E. Hornig, and J. Lanning-Rush, “Water Quality in South-Central Texas -- Texas, 1996–98,” U.S. Geological Survey Circular 1212, 2000.

Contaminant Data

- Clark, G.M., T.R. Maret, M.G. Rupert, M.A. Maupin, W.H. Low, and D.S. Ott, "Water Quality in the Upper Snake River Basin -- Idaho and Wyoming, 1992–95," U.S. Geological Survey Circular 1160, 1998.
- Clark, G.M., R.R. Caldwell, T.R. Maret, C.L. Bowers, D.M. Dutton, and M.A. Beckwith, "Water Quality in the Northern Rockies Intermontane Basins -- Idaho, Montana, and Washington, 1999–2001," U.S. Geological Survey Circular 1235, 2004.
- Cordy, G.E., D.J. Gellenbeck, J.B. Gebler, D.W. Anning, A.L. Coes, R.J. Edmonds, J.A.H. Rees, and H.W. Sanger, "Water Quality in the Central Arizona Basins -- Arizona, 1995–98," U.S. Geological Survey Circular 1213, 2000.
- Demchek, D.K., R.W. Tollett, S.V. Mize, S.C. Skrobialowski, R.B. Fendick, C.M., Swarzenski, and S. Porter, "Water Quality in the Acadian-Pontchartrain Drainages -- Louisiana and Mississippi, 1999–2001," U.S. Geological Survey Circular 1232, 2004.
- Dennehy, K.F., D.W. Litke, C.M. Tate, S.L. Qi, P.B. McMahon, B.W. Bruce, R.A. Kimbrough, and J.S. Heiny, "Water Quality in the South Platte River Basin -- Colorado, Nebraska, and Wyoming, 1992–95," U.S. Geological Survey Circular 1167, 1998.
- Denver, J.M., S.W. Ator, L.M. Debrewer, M.J. Ferrari, J.R. Barbaro, T.C. Hancock, M.J. Brayton, and M.R. Nardi, "Water Quality in the Delmarva Peninsula -- Delaware, Maryland, and Virginia, 1999–2001," U.S. Geological Survey Circular 1228, 2004.
- Domagalski, J.L., D.L. Knifong, P.D. Dileanis, L.R. Brown, J.T. May, V. Connor, and C.N. Alpers, "Water Quality in the Sacramento River Basin -- California, 1994–98," U.S. Geological Survey Circular 1215, 2000.
- Dubrovsky, N.M., C.R. Kratzer, L.R. Brown, J.M. Gronberg, and K.R. Burow, "Water Quality in the San Joaquin-Tulare Basins -- California, 1992–95," U.S. Geological Survey Circular 1159, 1998.
- Ebbert, J.C., S.S. Embrey, R.W. Black, A.J. Tesoriero, and A.L. Haggland," "Water Quality in the Puget Sound Basin -- Washington and British Columbia, 1996–98," U.S. Geological Survey Circular 1216, 2000.
- Fahlquist, L., "Ground-Water Quality of the Southern High Plains Aquifer -- Texas and New Mexico, 2001," U.S. Geological Survey Open-File Report 03–345, 2003.
- Fenelon, J.M., "Water Quality in the White River Basin -- Indiana, 1992–96," U.S. Geological Survey Circular 1150, 1998.
- Fischer, J.M., K. Riva-Murray, R.E. Hickman, D.C. Chichester, R.A. Brightbill, K.M. Romanok, and M.D. Bilger, "Water Quality in the Delaware River Basin -- Pennsylvania, New Jersey, New York, and Delaware, 1998–2001," U.S. Geological Survey Circular 1227, 2004.
- Frenzel, S.A., R.B. Swanson, T.L. Huntzinger, J.K. Stamer, P.J. Emmons, and R.B. Zelt, "Water Quality in the Central Nebraska Basins -- Nebraska, 1992–95," U.S. Geological Survey Circular 1163, 1998.
- Frick, E.A., D.J. Hippe, G.R. Buell, C.A. Couch, E.H. Hopkins, D.J. Wangsness, and Jerry W. Garrett, "Water Quality in the Apalachicola-Chattahoochee-Flint River Basin -- Georgia, Alabama, and Florida, 1992–95," U.S. Geological Survey Circular 1164, 1998.
- Fuhrer, G.J., J.L. Morace, H.M. Johnson, J.F. Rinella, J.C. Ebbert, S.S. Embrey, I.R. Waite, K.D. Carpenter, D.R. Wise, and C.A. Hughes, "Water Quality in the Yakima River Basin -- Washington, 1999–2000," U.S. Geological Survey Circular 1237, 2004.

Contaminant Data

- Garabedian, S.P., J.F. Coles, S.J. Grady, E.C.T. Trench, and M.J. Zimmerman, "Water Quality in the Connecticut, Housatonic, and Thames River Basins -- Connecticut, Massachusetts, New Hampshire, New York, and Vermont, 1992–95," U.S. Geological Survey Circular 1155, 1998.
- Glass, R.L., T.P. Brabets, S.A. Frenzel, M.S. Whitman, and R.T. Ourso, "Water Quality in the Cook Inlet Basin -- Alaska, 1998–2001," U.S. Geological Survey Circular 1240, 2004.
- Groschen, G.E., M.A. Harris, R.B. King, P.J. Terrio, and K.L. Warner, "Water Quality in the Lower Illinois River Basin -- Illinois, 1995–98," U.S. Geological Survey Circular 1209, 2000.
- Groschen, G.E., T.L. Arnold, M.A. Harris, D.H. Dupré, F.A. Fitzpatrick, B.C. Scudder, W.S. Morrow, Jr., P.J. Terrio, K.L. Warner, and E.A. Murphy, "Water Quality in the Upper Illinois River Basin -- Illinois, Indiana, and Wisconsin, 1999–2001," U.S. Geological Survey Circular 1230, 2004.
- Hampson, P.S., M.W. Treece, Jr., G.C. Johnson, S.A. Ahlstedt, and J.F. Connell, "Water Quality in the Upper Tennessee River Basin -- Tennessee, North Carolina, Virginia, and Georgia, 1994–98," U.S. Geological Survey Circular 1205, 2000.
- Hughes, W.B., T.A. Abrahamsen, T.L. Maluk, E.J. Reuber, and L.J. Wilhelm, "Water Quality in the Santee River Basin and Coastal Drainages -- North and South Carolina, 1995–98," U.S. Geological Survey Circular 1206, 2000.
- Kalkhoff, S.J., K.K. Barnes, K.D. Becher, M.E. Savoca, D.J. Schnoebelen, E.M. Sadorf, S.D. Porter, and D.J. Sullivan, "Water Quality in the Eastern Iowa Basins -- Iowa and Minnesota, 1996–98," U.S. Geological Survey Circular 1210, 2000.
- Kleiss, B.A., R.H. Coupe, G.J. Gonthier, and B.G. Justus, "Water Quality in the Mississippi Embayment -- Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky, 1995–98," U.S. Geological Survey Circular 1208, 2000.
- Land, L.F., J.B. Moring, P.C. Van Metre, D.C. Reutter, B.J. Mahler, A.A. Shipp, and R.L. Ulery, "Water Quality in the Trinity River Basin -- Texas, 1992–95," U.S. Geological Survey Circular 1171, 1998.
- Levings, G.W., D.F. Healy, S.F. Richey, and L.F. Carter, "Water Quality in the Rio Grande Valley -- Colorado, New Mexico, and Texas, 1992–95," U.S. Geological Survey Circular 1162, 1998.
- Lindsey, B.D., K.J. Breen, M.D. Bilger, and R.A. Brightbill, "Water Quality in the Lower Susquehanna River Basin -- Pennsylvania and Maryland, 1992–95," U.S. Geological Survey Circular 1168, 1998.
- Maupin, M.A., and N.L. Barber, "Estimated Withdrawals from Principal Aquifers in the United States, 2000," U.S. Geological Survey Circular 1279, 2005.
- McGuire, V.L., M.R. Johnson, R.L. Schieffer, J.S. Stanton, S.K. Sebree, and I.M. Verstraeten, "Water in Storage and Approaches to Ground-Water Management, High Plains Aquifer, 2000," U.S. Geological Survey Circular 1243, 2003.
- McPherson, B.F., R.L. Miller, K.H. Haag, and A. Bradner, "Water Quality in Southern Florida -- Florida,1996–98," U.S. Geological Survey Circular 1207, 2000.

Contaminant Data

- Myers, D.N. M.A. Thomas, J.W. Frey, S.J. Rheaume, and D.T. Button, "Water Quality in the Lake Erie-Lake Saint Clair Drainages -- Michigan, Ohio, Indiana, New York, and Pennsylvania, 1996–98," U.S. Geological Survey Circular 1203, 2000.
- National Atmospheric Deposition Program, "Annual Isoplenth Map -- Field pH," http://nadp.sws.uiuc.edu, 2004.
- Paybins, K.S., T. Messinger, J.H. Eychaner, D.B. Chambers, and M.D. Kozar, "Water Quality in the Kanawha–New River Basin -- West Virginia, Virginia, and North Carolina, 1996–98," U.S. Geological Survey Circular 1204, 2000.
- Peters, C.A., D.M. Robertson, D.A. Saad, D.J. Sullivan, B.C. Scudder, F.A. Fitzpatrick, K.D. Richards, J.S. Stewart, S.A. Fitzgerald, and B.N. Lenz, "Water Quality in the Western Lake Michigan Drainages -- Wisconsin and Michigan, 1992–95," U.S. Geological Survey Circular 1156, 1998.
- Petersen, J.C., J.C. Adamski, R.W. Bell, J.V. Davis, S.R. Femmer, D.A. Freiwald, and R.L. Joseph, "Water Quality in the Ozark Plateaus -- Arkansas, Kansas, Missouri, and Oklahoma, 1992–95," U.S. Geological Survey Circular1158, 1998.
- Peterson, D.A., K.A. Miller, T.T. Bartos, M.L. Clark, S.D. Porter, and T.L. Quinn, "Water Quality in the Yellowstone River Basin -- Wyoming, Montana, and North Dakota, 1999–2001," U.S. Geological Survey Circular 1234, 2004.
- Robinson, K.W., S.M. Flanagan, J.D. Ayotte, K.W. Campo, A. Chalmers, J.F. Coles, and T.F. Cuffney, "Water Quality in the New England Coastal Basins -- Maine, New Hampshire, Massachusetts, and Rhode Island, 1999-2001," U.S. Geological Survey Circular 1226, 2004.
- Rowe, Jr., G.L., D.C. Reutter, D.L. Runkle, J.A. Hambrook, S.D. Janosy, and L.H. Hwang, "Water Quality in the Great and Little Miami River Basins -- Ohio and Indiana, 1999–2001," U.S. Geological Survey Circular 1229, 2004.
- Spahr, N.E., L.E. Apodaca, J.R. Deacon, J.B. Bails, N.J. Bauch, C.M. Smith, and N.E. Driver, "Water Quality in the Upper Colorado River Basin -- Colorado, 1996-98," U.S. Geological Survey Circular 1214, 2000.
- Spruill, T.B., D.A. Harned, P.M. Ruhl, J.L. Eimers, G. McMahon, K.E. Smith, D.R. Galeone, and M.D. Woodside, "Water Quality in the Albemarle-Pamlico Drainage Basin -- North Carolina and Virginia, 1992–95," U.S. Geological Survey Circular 1157, 1998.
- Stanton, G.P., and B.R. Clark, "Recalibration of a Ground-Water Flow Model of the Mississippi River Valley Alluvial Aquifer in Southeastern Arkansas, 1918-1998, with Simulations of Hydraulic Heads Caused by Projected Ground-Water Withdrawals through 2049," U.S. Geological Survey Water-Resources Investigations Report 03-4232, 2003.
- J.R. Stark, P.E. Hanson, R.M. Goldstein, J.D. Fallon, A.L. Fong, K.E. Lee, S.E. Kroening, and W.J. Andrews, "Water Quality in the Upper Mississippi River Basin -- Minnesota, Wisconsin, South Dakota, Iowa, and North Dakota, 1995–98," U.S. Geological Survey Circular 1211, 2000.
- Stoner, J.D., D.L. Lorenz, R.M. Goldstein, M.E. Brigham, and T.K. Cowdery, "Water Quality in the Red River of the North Basin -- Minnesota, North Dakota, and South Dakota, 1992–95," , U.S. Geological Survey Circular 1169, 1998.

Contaminant Data

- Waddell, K.M., S.J. Gerner, S.A. Thiros, E.M. Giddings, R.L. Baskin, J.R. Cederberg, and C.M. Albano, "Water Quality in the Great Salt Lake Basins -- Utah, Idaho, and Wyoming, 1998–2001," U.S. Geological Survey Circular 1236, 2004.
- Wall, G.R., K. Riva-Murray, and P.J. Phillips, "Water Quality in the Hudson River Basin -- New York and Adjacent States, 1992–95," U.S. Geological Survey Circular 1165, 1998.
- "Water Use 2000 - Total Ground and Surface Water Withdrawals, Fresh and Saline," http://nationalatlas.gov/natlas/Natlasstart.asp.
- Wentz, D.A., B.A. Bonn, K.D. Carpenter, S.R. Hinkle, M.L. Janet, F.A. Rinella, M.A. Uhrich, I.R. Waite, A. Laenen, and K.E. Bencala, "Water Quality in the Willamette Basin -- Oregon, 1991–95," U.S. Geological Survey Circular 1161, 1998.
- Williamson, A.K., M.D. Munn, S.J. Ryker, R.J. Wagner, J.C. Ebbert, and A.M. Vanderpool, "Water Quality in the Central Columbia Plateau -- Washington and Idaho, 1992–95, U.S. Geological Survey Circular 1144, 1998.
- Woodside, M.D., A.B. Hoos, J.A. Kingsbury, J.R. Powell, R.R. Knight, J.W. Garrett, R.L. Mitchell III, and J.A. Robinson, "Water Quality in the Lower Tennessee River Basin -- Tennessee, Alabama, Kentucky, Mississippi, and Georgia, 1999–2001," U.S. Geological Survey Circular 1233, 2004.

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