Climate Change, Bioenergy and Population Growth as they Stress the Food-Energy-Water Nexus

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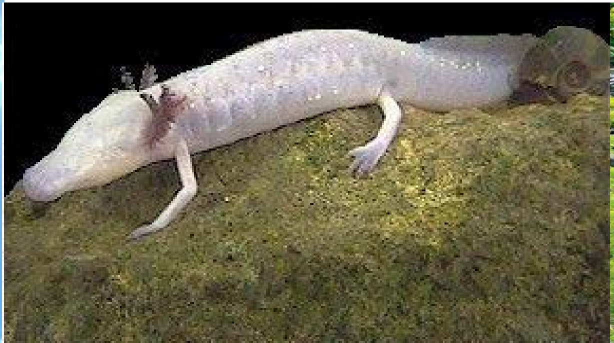

FEW Nexus

- Food-Energy-Water Nexus Analysis considers way sectors interact in the food, energy and water space and in cases ways in which actions by some parties in the FEW sectors can benefit total regional welfare.
- We are involved in Nexus Analysis in 2 settings
  - Nexus analysis under Water scarcity: Limited supply and increasing demand for water are **driving Nexus forces**
  - Nexus Analysis under major bioenergy decisions – US renewable fuel standard and whether we will expand cellulosic ethanol production plus use marginal land
- Today I will mainly talk from the first project as that is one I am leading

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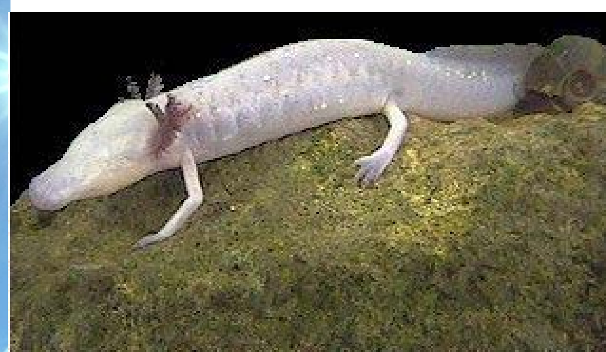
FEW Nexus – Water Scarcity

- Water Scarcity FEW Nexus Analysis is stressed by evolving climate and population
  - Climate
    - Increases water demand in form of desired water use per acre, per household, for electrical cooling and for some other industries
    - In study area lowers water supplies and increases variability
    - In area lowers yields per unit land, lessening food supply
  - Population growth
    - Increases household and supporting industry water demand.
    - Also increases demands for energy and food
- Collectively makes Water scarcity worse
  - Lowering supply and increasing demand for water plus adding energy and food demands while lowering food supply

FEW Nexus – Water Scarcity

- In our study we examine FEW Nexus actions in the form of new water related sectoral investments and altered operating strategies- we collectively call these **<u>projects</u>**
- We are working on defining projects:
  - Agriculture related projects
  - Water related projects
  - Energy related projects
- We also examine who gains and who loses as we feel Compensation and mechanisms to achieve it will be a big issue

Background on Regional Issues



Study Region - Geographic & Hydrologic Scope

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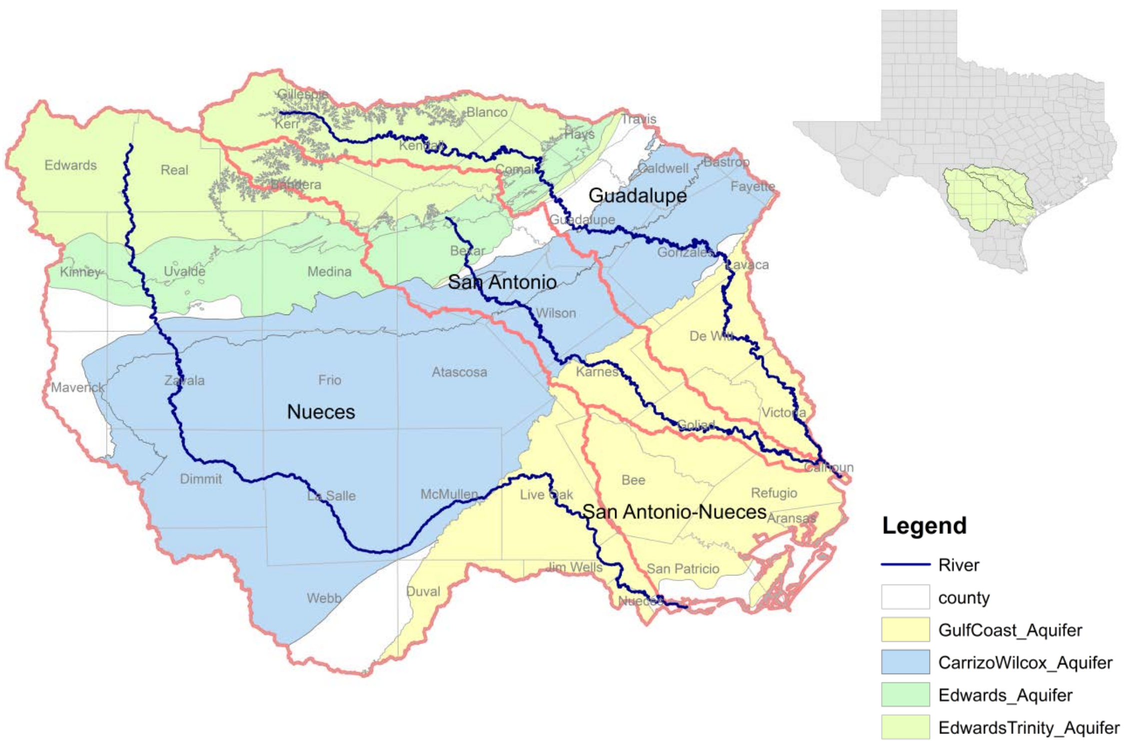


Water Sources

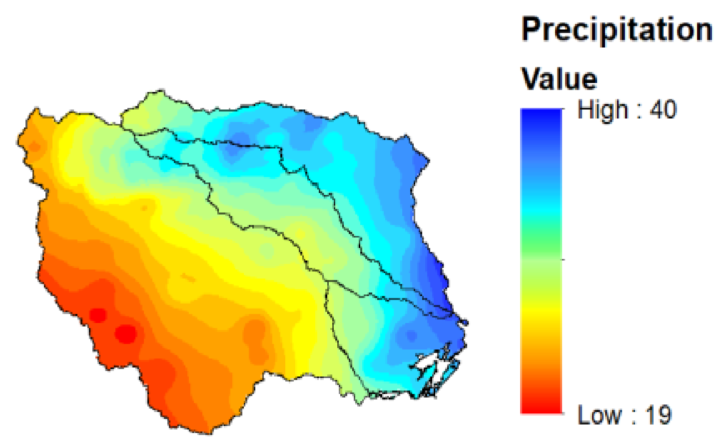
- 4 River Basins
- 5 Aquifers
- 2 Springs
- 5 Lakes/Reservoirs

Users

- Agriculture
- Municipality
- Industry
- Energy - power plants and fracking)
- Recreational
- Environmental

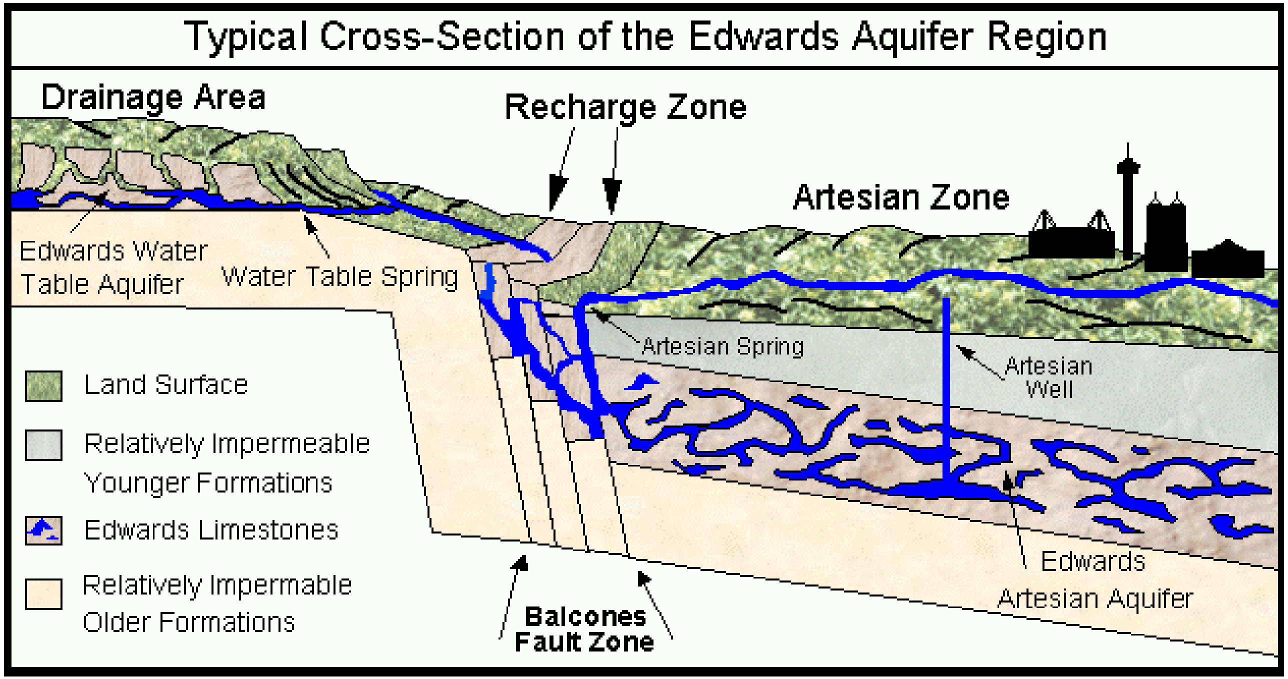
Limited water supply : Rivers

- Average precipitation in the region varies from 20 -30 inches (50-75 cm) per year in the ag areas in west to about 40 inches (100 cm) per year in the east
- Sufficient flows needed for downstream water use and flows to Estuary to protect fishery and species.
- Interaction with ground water
  - Springs from Edwards Aquifer provide 30-80% of base flow in eastern river under drought
  - Overpumping of groundwater will lower river flows



Limited water supply : Aquifers

- Edwards Aquifer



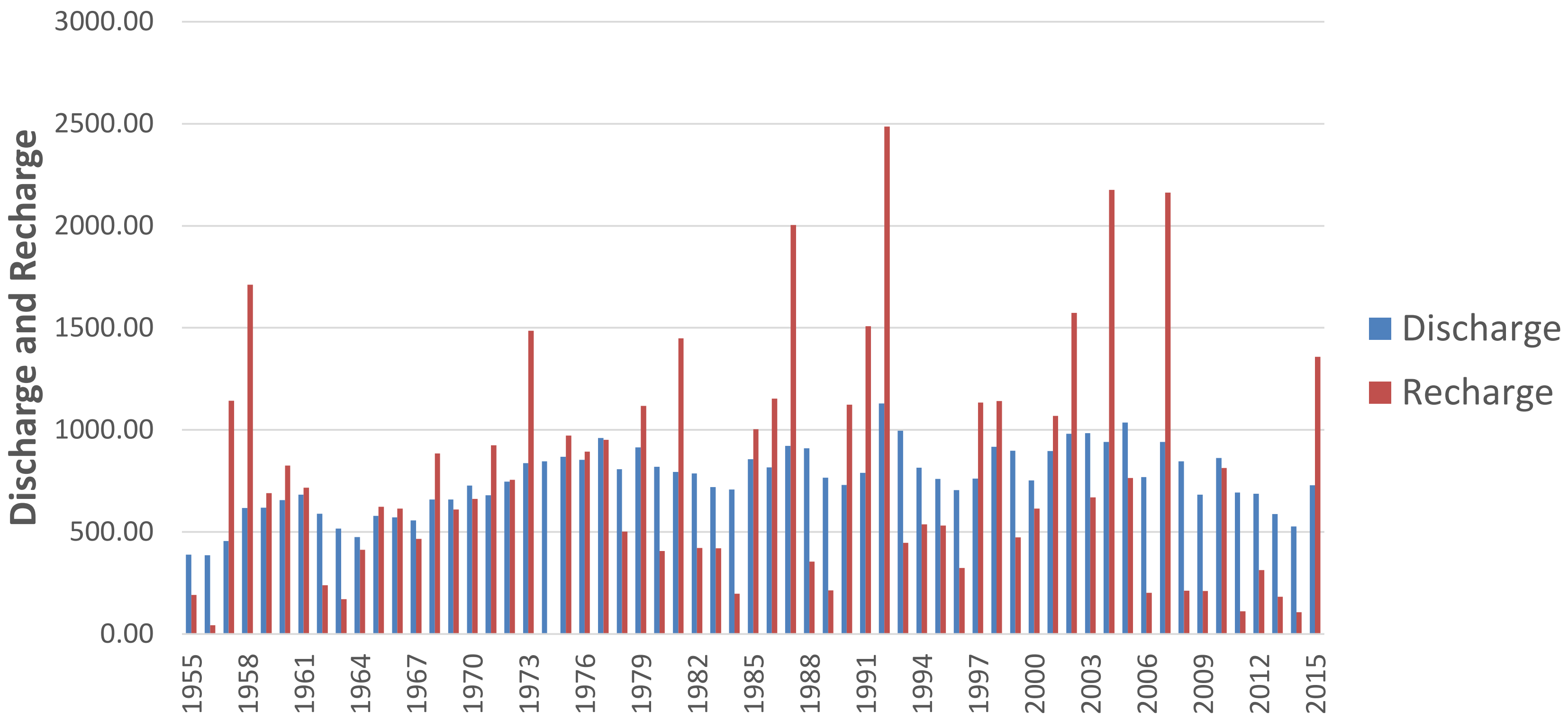
Source: Edwards Aquifer Website http://www.edwardsaquifer.net/intro.html

Limited water supply : Edwards Aquifer

- Problems
  - Limited water supply (recharge)
  - Heavy discharge (pumping and springs)
  - Environment concerns and endangered species finding

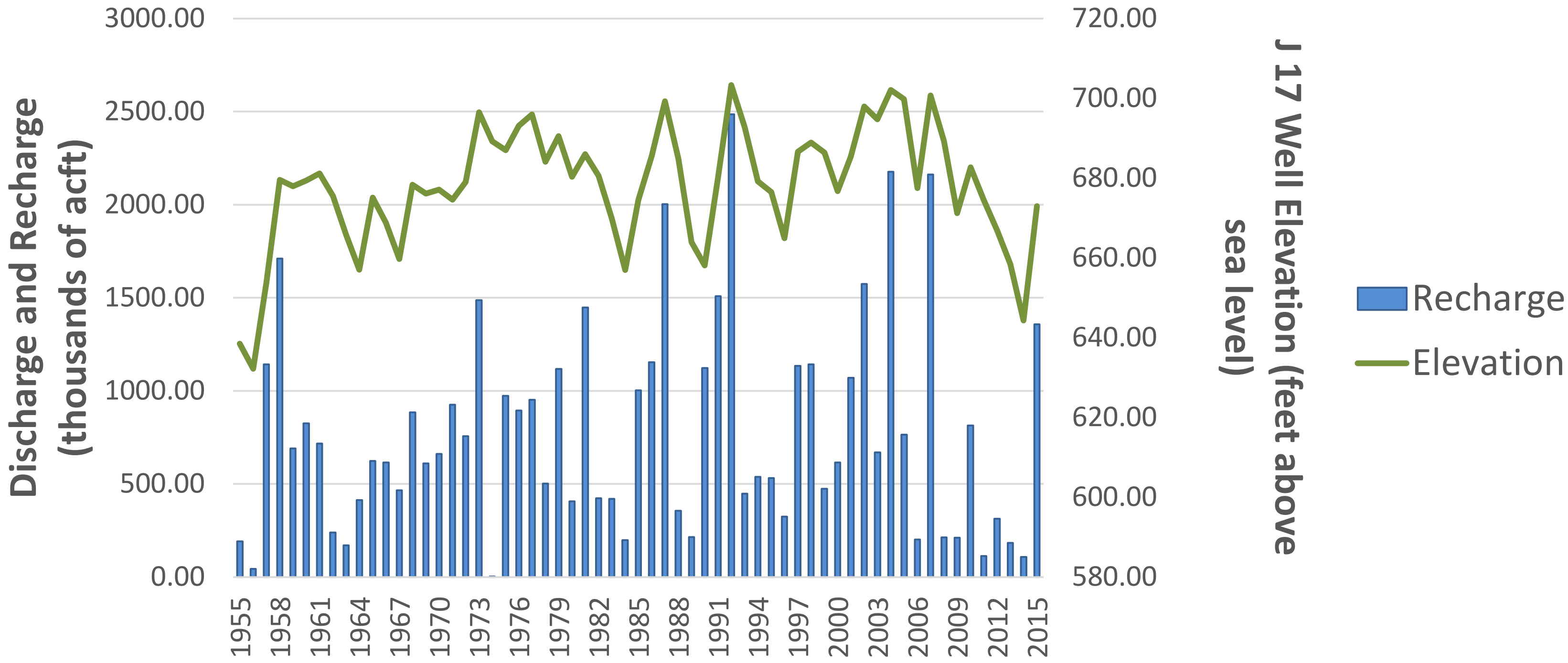
- EAA solution
  - Edwards Aquifer Authority (EAA) issued permits to limit pumping and regulated withdraw amount based on water level
  - Permit trading is allowed in EAA (water market)

Stochastic water supply Edwards Aquifer



Unit is thousands of acft which is 1,233 cubic meters)

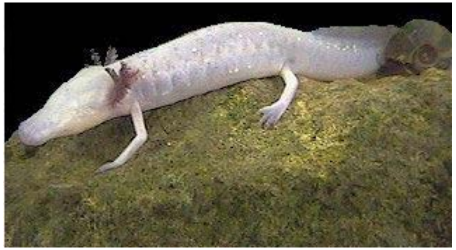
Stochastic water supply : Aquifers



Edwards Aquifer does not retain water

Environmental Issue - Edwards

- Aquifer supports Endangered species



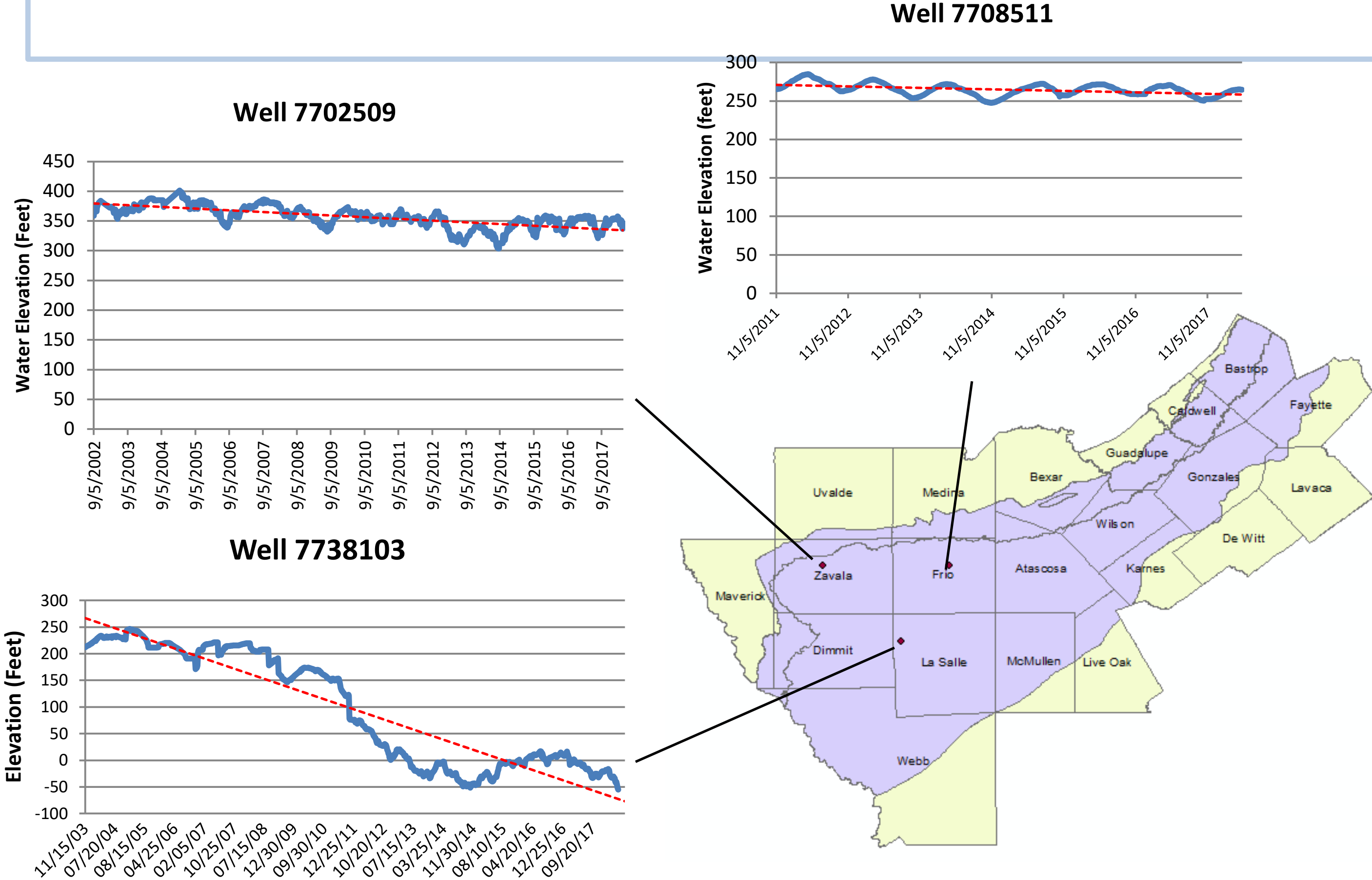
Texas Blind Salamander

Fountain Darter

San Marcos Gambusia

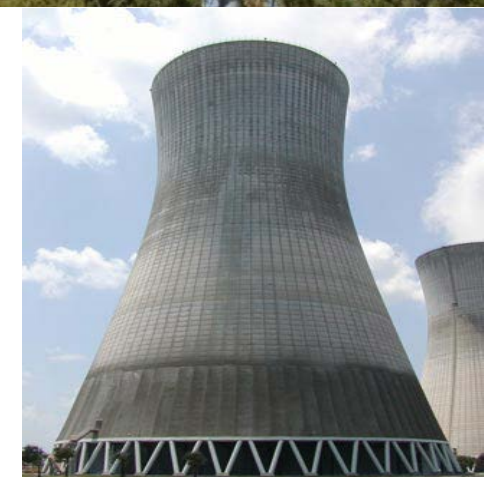
San Marcos Salamander

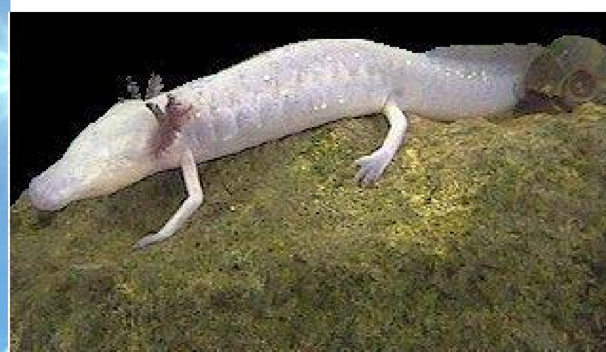
Carrizo-Wilcox Aquifer Water Level falling



In Groundwater Management area 13 covering southern segment of Carrizo-Wilcox Aquifer, desired 2070 condition is no more than 48 feet average drawdown relative to 2012

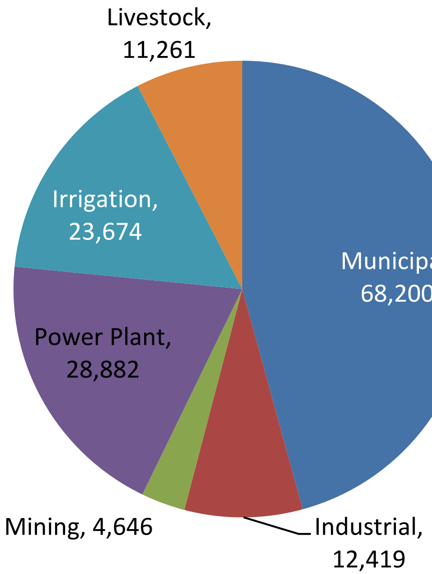
Background on Demand and Population



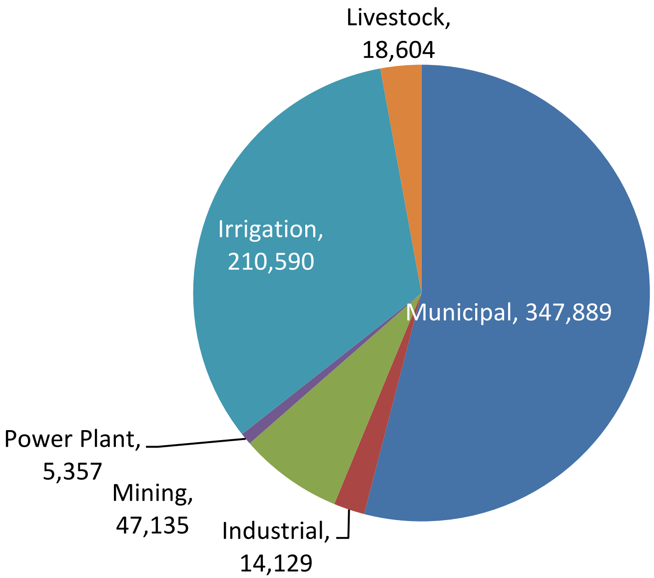


Regional Water Usage by Sector - 2015

Surface Water Usage (149k Acft)



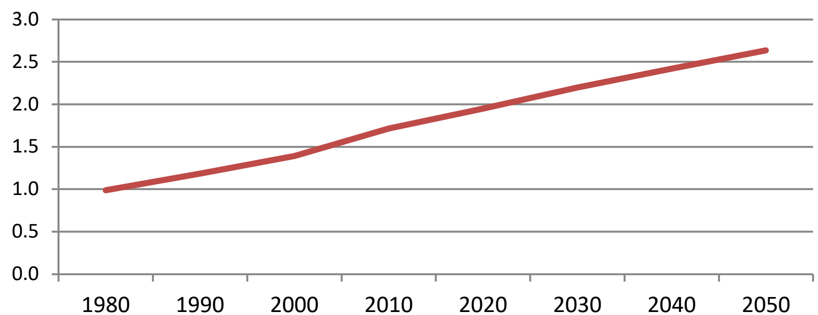
Ground Water Usage (643k Acft)



- **Heavy water usage by municipal sector**
- **Irrigation uses mainly groundwater**

Rapid Population Growth

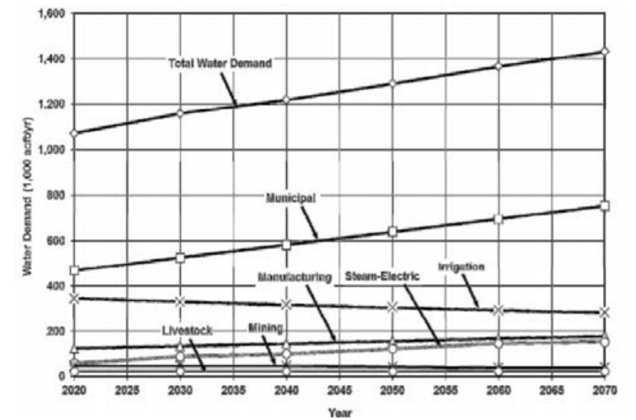
Bexar County Historical and Projected Population (Million)



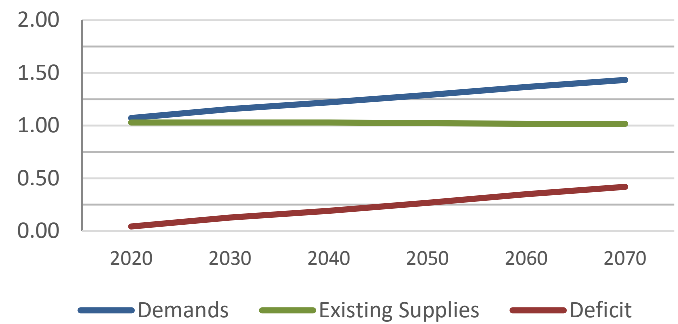
Population growth leads to

- Rapid municipal industrial and electricity cooling demand
- Growing deficit

Figure 2-5 Total Water Demand Projections South Central Texas Region – 2020 to 2070

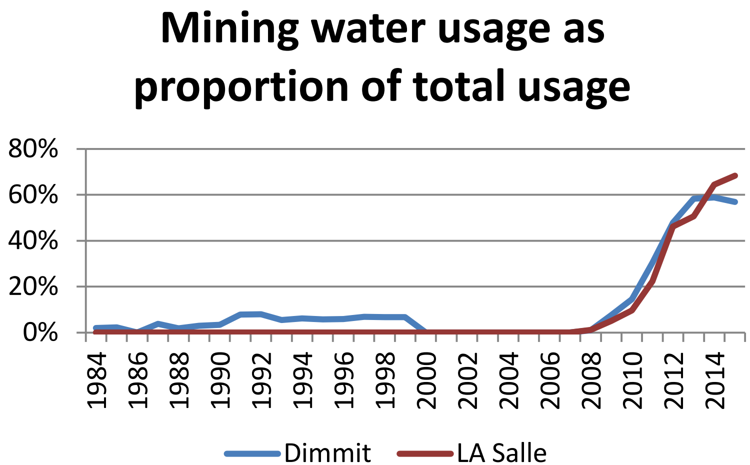


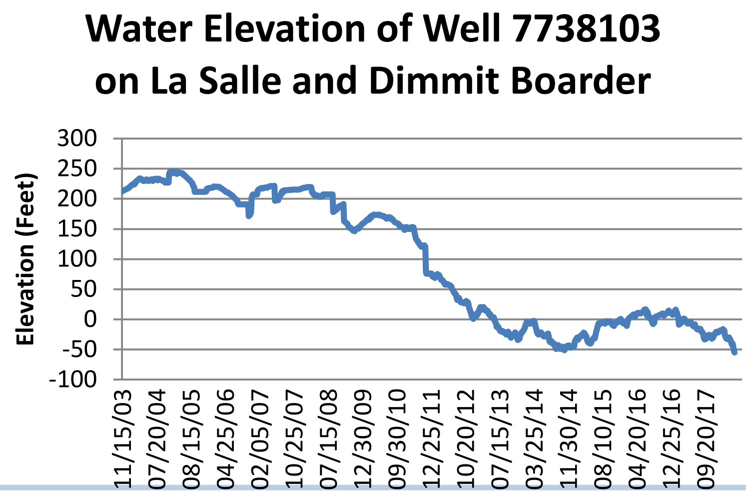
South Central Texas Demand Supply and Gap (Million Acft)



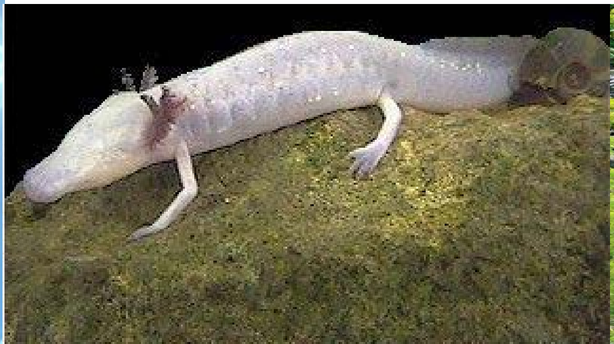
Challenges from Fracking

- Between 2000 and 2014, water used to drill a horizontal natural gas well increased from 177,000 to 5.1 million gallons per well
- Fracking (mining) is largest water use in some counties.
- Heavy fracking in winter garden increased Carrizo-Wilcox drawdown.

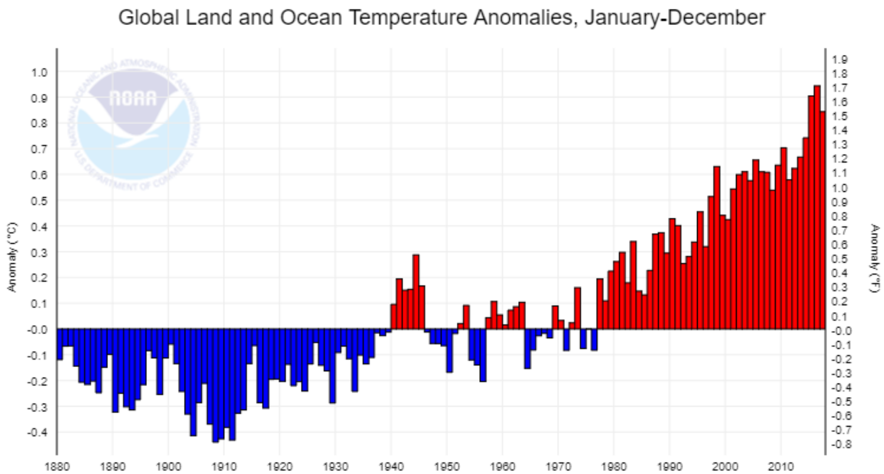




Climate Change



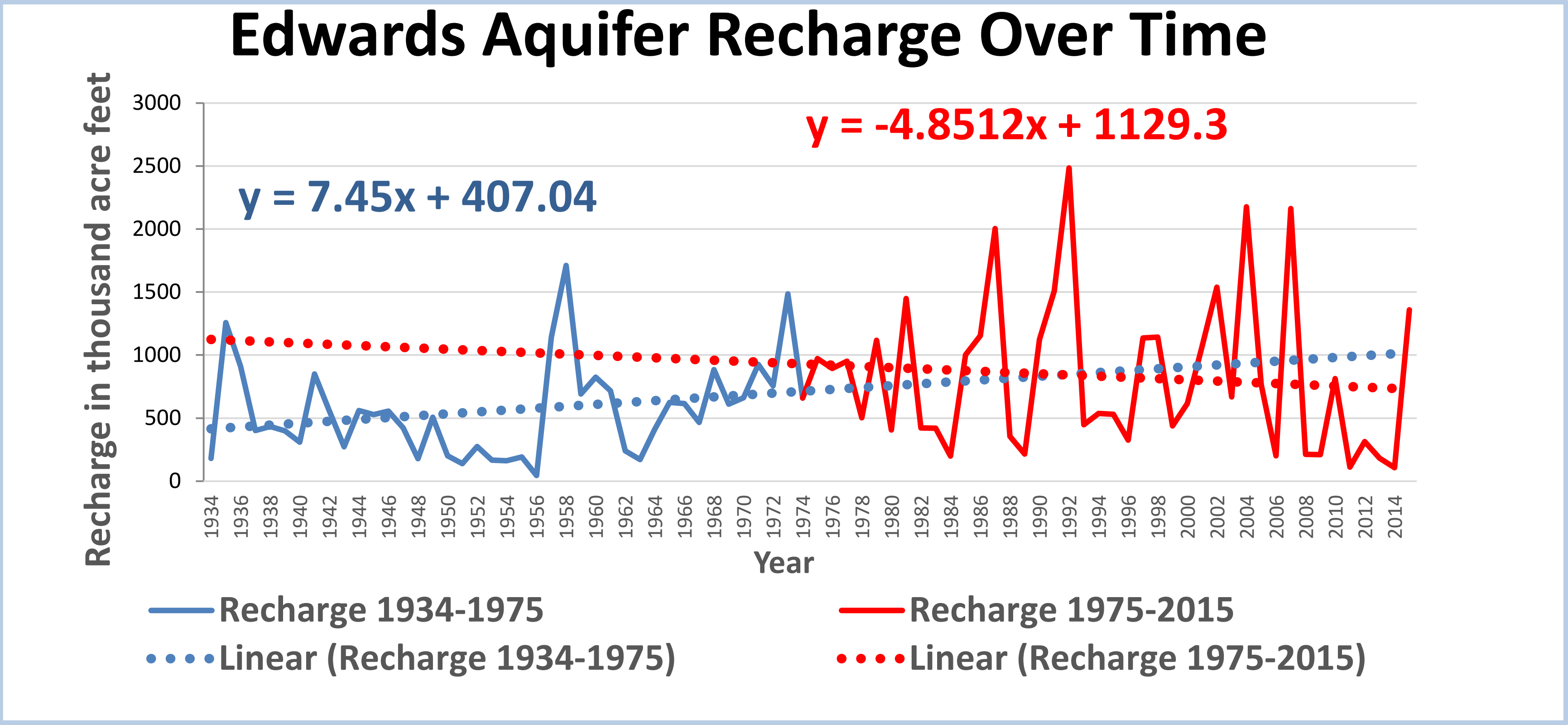
Temperature history



Year	Change from 20th Century Average	Rank out of 138 years
2014	0.74°C	135
2015	0.90°C	137
2016	0.94°C	138
2017	0.84°C	136

- 2017 was the third warmest year in NOAA's 138-year series.
- 41ht consecutive year (since 1977) that annual temperature is above 20th century average.
- All 17 years of 21st century rank are among seventeen warmest on record (1998 is ninth)
- Six warmest years have all occurred since 2010
- Four warmest have been last 4
- Temperatures in 2015-2016 were majorly influenced by strong El Niño
- Increased 0.07°C (0.13°F) per decade since 1880 and 0.17°C (0.31°F) since 1970

Climate Change is making things non stationary



http://www.edwardsaquifer.net/data.html

Climate Change is making things non stationary

POLICYFORUM

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

P. C. D. Milly,[1*] Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a

that has emerged from climate models (see figure, p. 574).

Why now? That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity

Climate Change and Future Analysis: Is Stationarity Dying?

Bruce A. McCarl, Xavier Villavicencio, and Ximing Wu

Economists often do risk analysis in support of management decisions. Commonly, such analyses are based on probability distributions arising from historical data where the distributions developed are based on at least a partial assumption of stationarity. For example, in water-based risk analysis one typically assumes the distribution is stationary, and uses the 100 year drought. In yield-related analyses analysts typically assume the mean is changing with time (proxying for technological progress along with monetary inflation) but that the variance is stationary.

assessments (2007, 2001) or the U.S. National Assessment (Reilly et al. 2002). Many studies indicate that climate change alters mean yields (e.g., Adams et al. 1990; Reilly et al. 2002; Deschenes and Greenstone 2007) and/or land values (Mendelsohn, Nordhaus, and Shaw 1994). Chen, McCarl, and Schimmelpfennig (2004) also indicate that in addition to climate change affecting mean yields, it will contribute to a change in crop yield variability, while Mearns, Rosenzweig, and Goldberg (1992) provide crop simulation results to the same point.

Water

Can we use 100 year flood?

Milly, PCD, J. Betancourt, M. Falkenmark, 2008. Climate Change: Stationarity Is Dead: Whither Water Management?, Science, Vol. 319. No. 5863, pp. 573 – 574.

Ag yields

Can we history to assess risk?

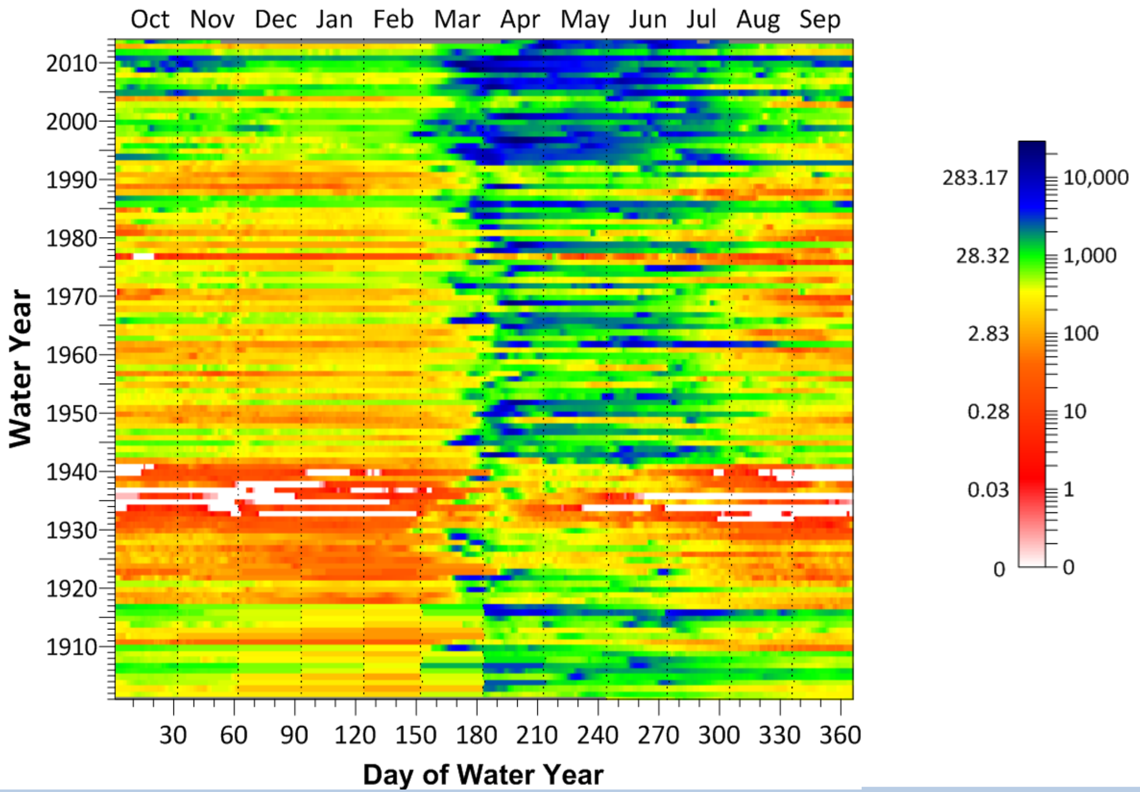
McCarl, Bruce A., Xavier Villavicencio, and Ximing Wu. "Climate change and future analysis: is stationarity dying?." American Journal of Agricultural Economics 90.5 (2008): 1241-1247.

Climate Change is making things non stationary

USGS 05054000 RED RIVER OF THE NORTH AT FARGO, ND

Where is the dark Blue?

Note it is more common recently



https://www.ndsu.edu/fargoflood/images/red_river_of_the_north_raster_plot_august_2014.pdf

Yet more could happen

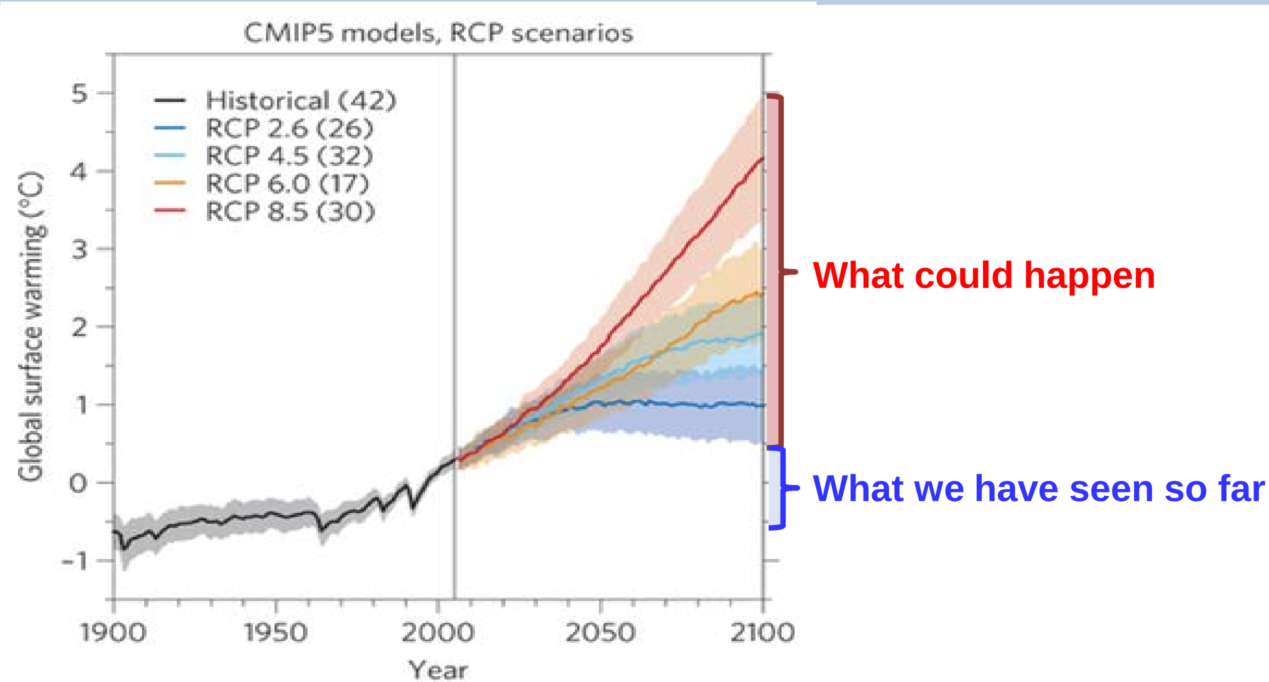


Figure 1: Global temperature change and uncertainty. From Robustness and uncertainties in the new CMIP5 climate model projections
Reto Knutti & Jan Sedláček, Nature Climate Change 3, 369–373 (2013) doi:10.1038/nclimate1716,

Climate Change

- Use data for 2030 and 2090

Canadian Climate Center Model (CCC)

Hadley Climate Center Model (HAD)

Average changes for the 10 year periods

Climate Change Scenarios	Temperature (^{0}F)	Precipitation (Inches)
HAD 2030	3.2	-4.1
HAD 2090	9.01	-0.78
CCC 2030	5.41	-14.36
CCC 2090	14.61	-4.56

Less water in much of Southwest region

(IPCC, WH2 AR5 chapter 3)

Projections – Edwards Aquifer

Results for EA Recharge Prediction

(% change from the BASE)	Hadley		Canadian	
Recharge in Drought Years	-20.59	-	-29.65	
Recharge in Normal Years	-19.68	-	-28.99	-
Recharge in Wet Years	-23.64	-	-34.42	-

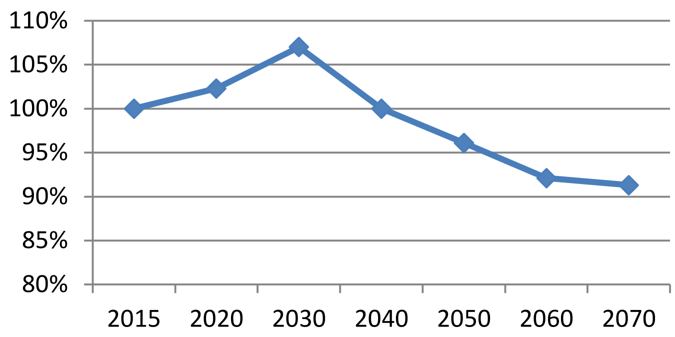
Municipal Demand

Forecasted that climate change will increase municipal water demand by 1.5% (HAD) to 3.5% (CCC).

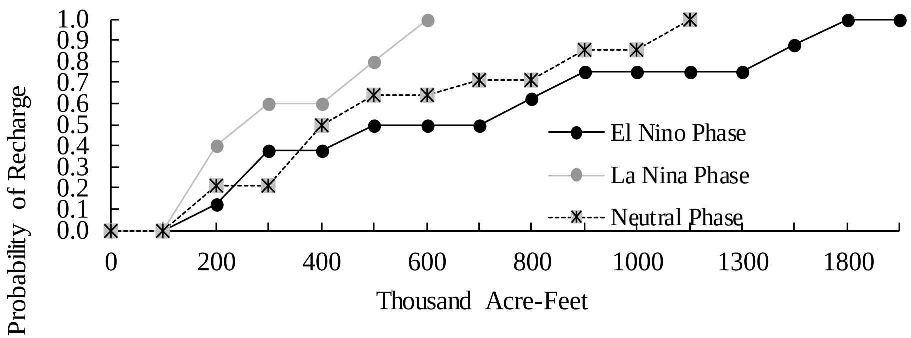
Climate Change

- Edwards Aquifer is vulnerable under climate change, much less recharge under La Nina
- Decreasing precipitation in far future makes Groundwater more vulnerable

Precipitation Changing Rate Under Canadian GCM



Edwards Aquifer Recharge



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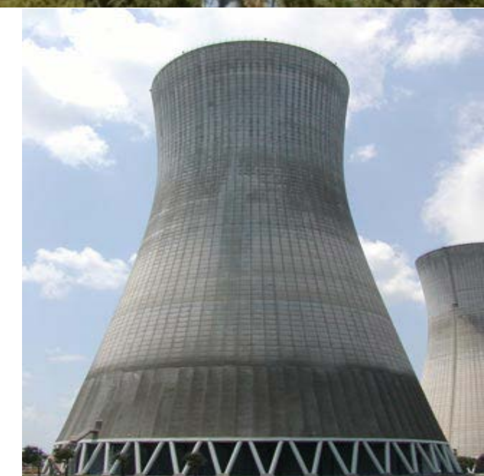
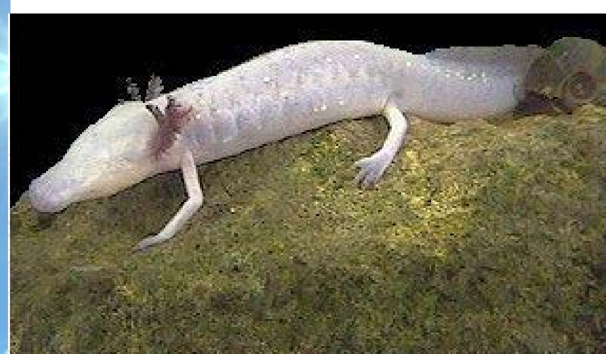
Modeling





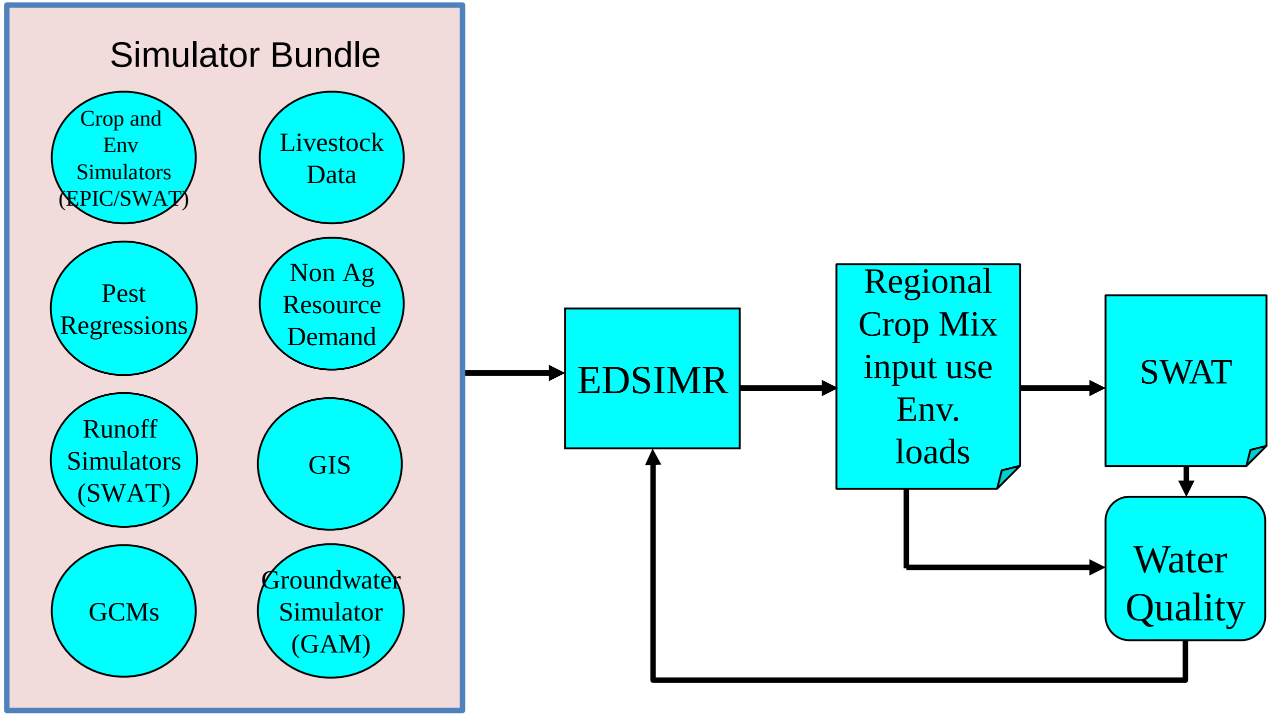

EDSIMR – the concept

Unify

- Detailed aquifer hydrologic model
- Regionalized economic Model
- Surface water flow model
- Hydrology embedded in regional economic model via regression (Keith Keplinger dissertation)

1. Keith O. Keplinger. "An investigation of Dry Year Options for the Edwards Aquifer. " Ph.D. Thesis, TAMU, 1996.
2. File Number 598 - Keplinger, K.O., and B.A. McCarl, "Regression Based Investigation of Pumping Limits and Springflow Within the Edwards Aquifer", Texas A and M University, 1995.
3. File Number 829 - Gillig, D., B.A. McCarl, and F.O. Boadu, "An Economic, Hydrologic, and Environmental Assessment of Water Management Alternative Plans for the South-Central Texas Region", Journal of Agricultural and Applied Economics, 33, 1 (April), 59-78, 2001.

EDSIMR "System" (and friends/ancestors)



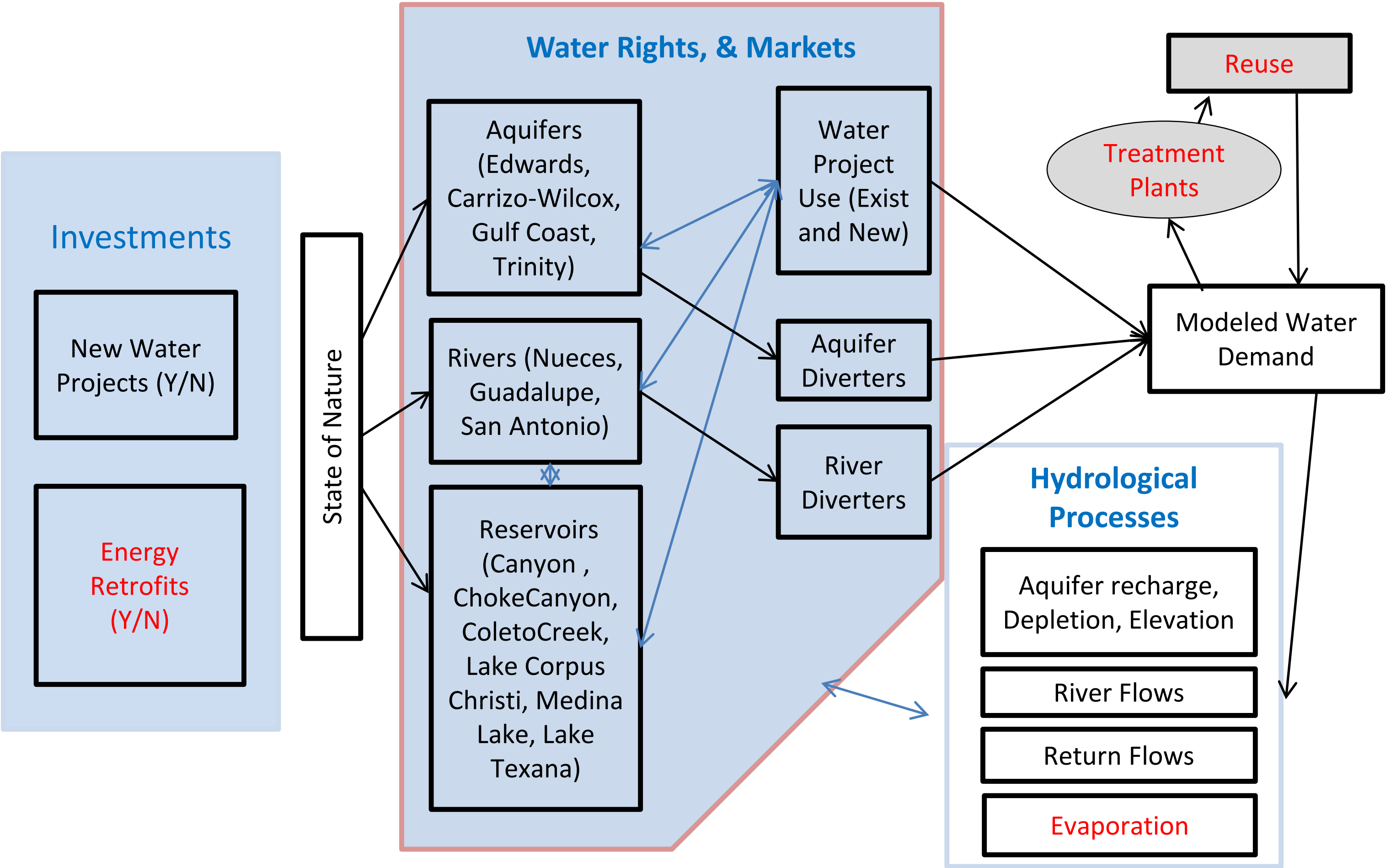
EDSIMR – Components

Edwards Aquifer Groundwater and River System Simulation Model

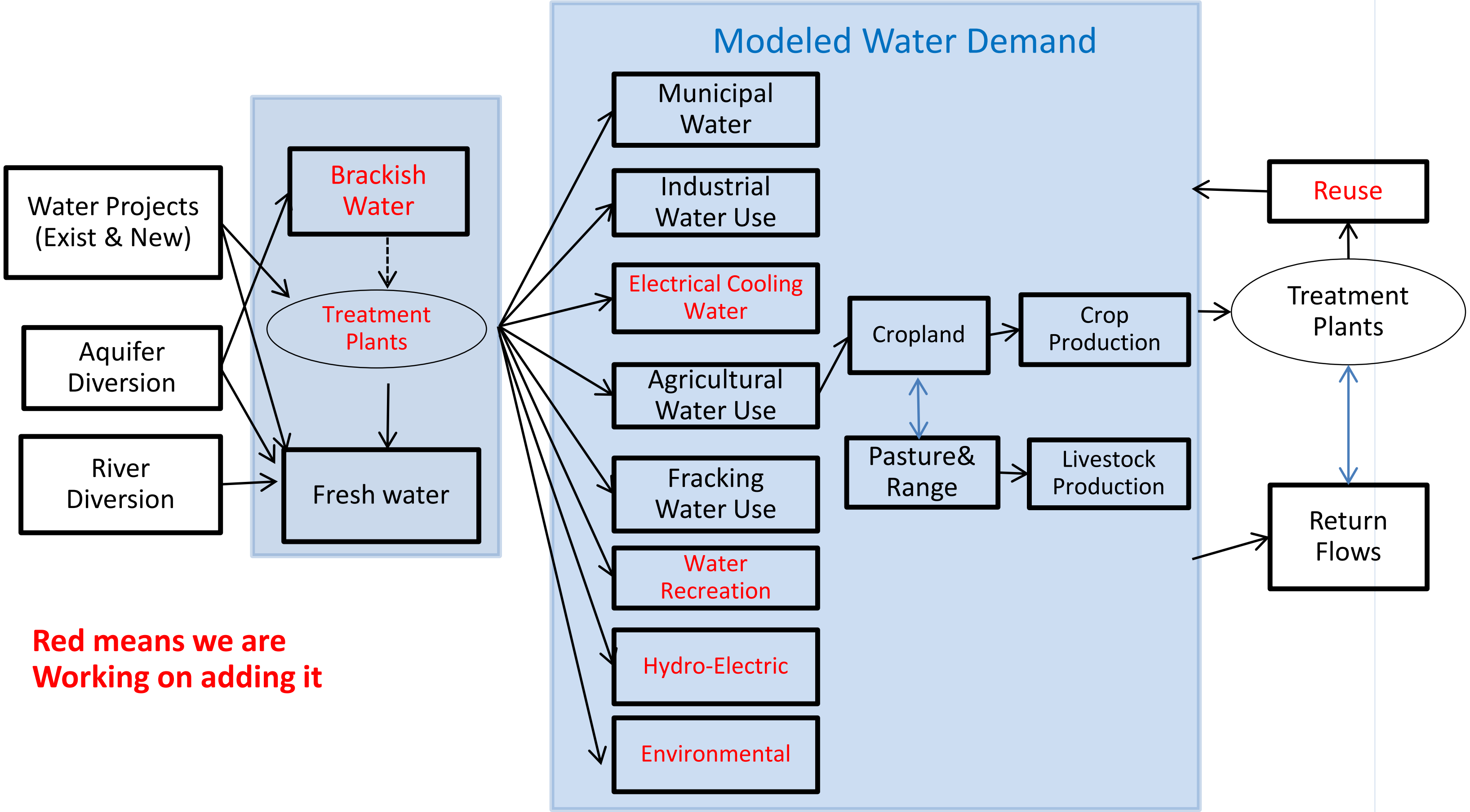
What is contained in EDSIMR ?

- **Simulation Model (GAM)**
  Springflow, beginning/ending aquifer elevations, pumping
- **Econometric Model**
  Springflow/ending = f (beginning, recharge, pumping)
- **Mathematical Linear Programming**
  - Components : objective function
    : ag, M&I power and fracking decision variable
    : constraints
    : Surface water Network flow
    : ground water characteristics
  - Linkage : **Ground Water** + **Surface Water**

EDSIMR – the scope



EDSIMR – Demand Scope



Red means we are Working on adding it

EDSIMR – Objective function terms

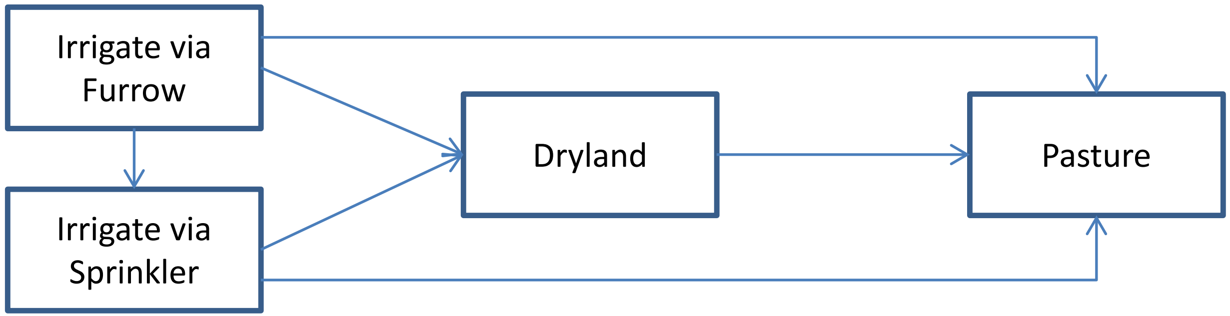
- Max Expected Regional Net Benefit
  - Agricultural sector => revenues – production cost
  - Non-agricultural sector => areas under demand – supply curves
  - Power – operations cost and rev from fixed price
  - Fracking – operations cost and fixed demand
  - Env sector – to be determined
  - Project cost and retrofit cost (water, power, fracking)

EDSIMR – Agriculture Sector Land Modeling

- Land Balance:

  Cropland + Pasture <= Total available land

- Land Transfer



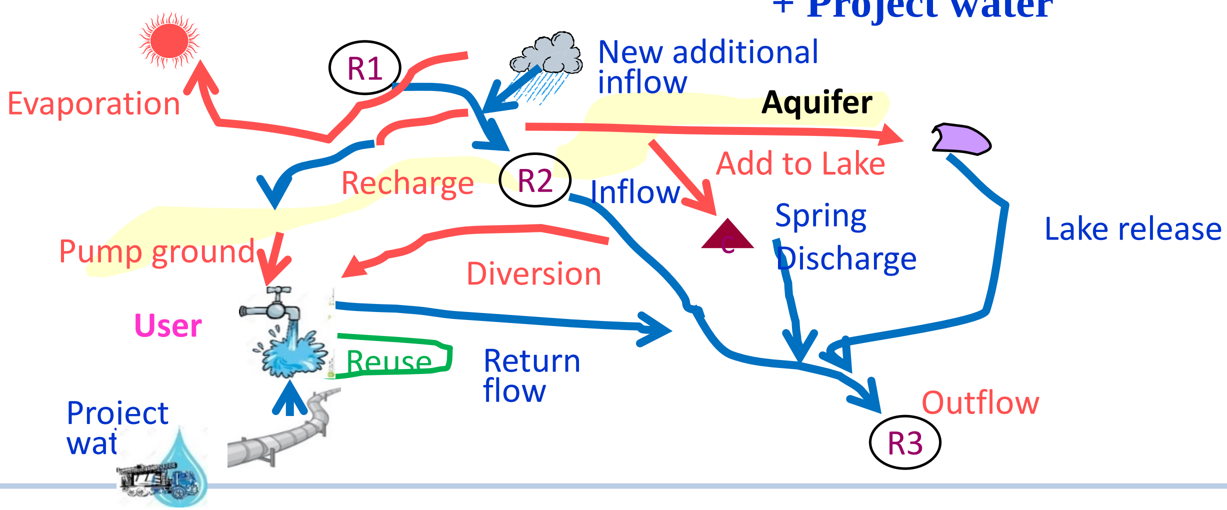
- Land use decisions are made in Stage 1 of the model (CROPACRES and LIVEPROD)

EDSIMR – River flow detail

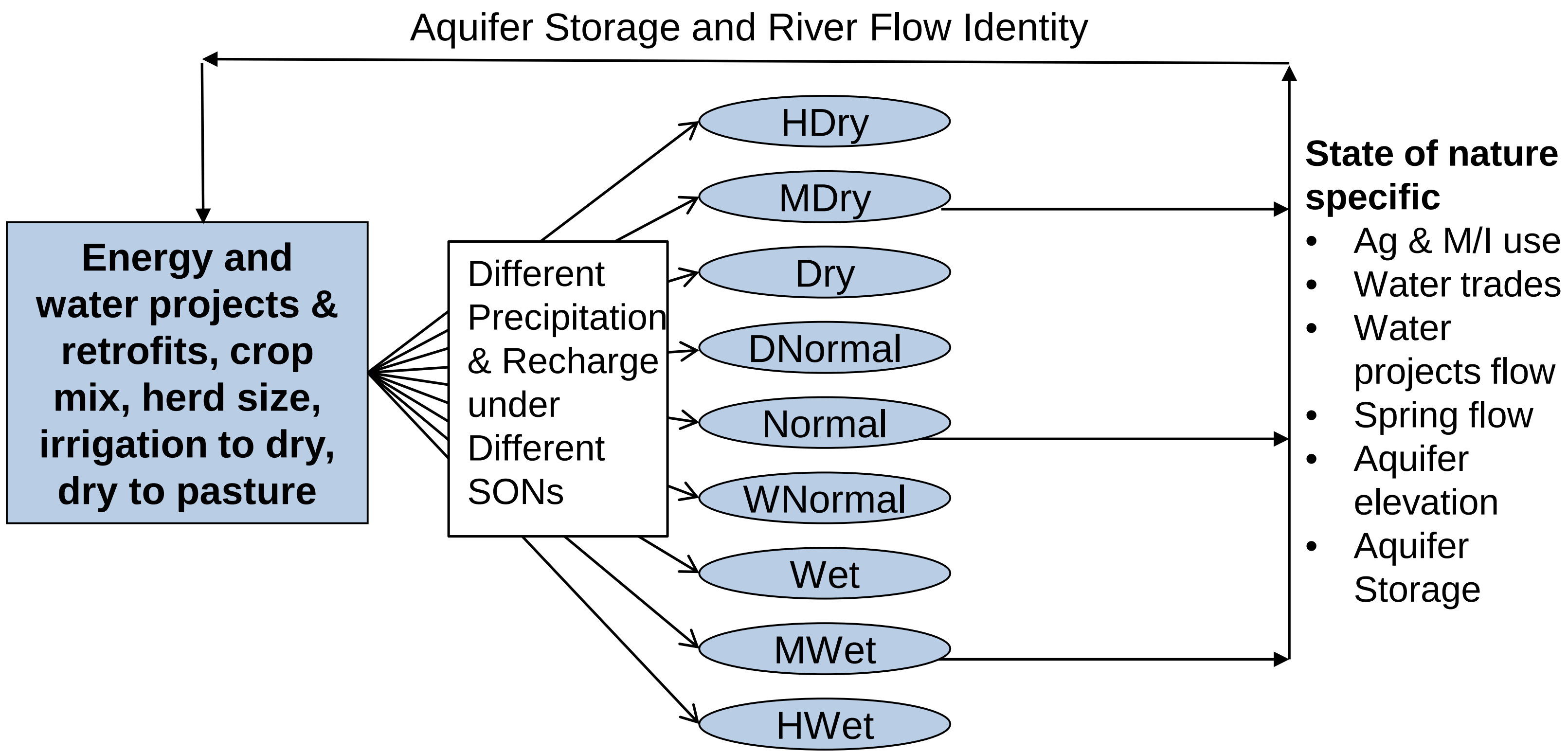
Diversion
+ Aquifer recharge
+ Evaporation
+ Lake addition
+ Downstream/bay outflow

=

Upstream inflow
+ New Additional inflow
+ Return flow
+ Spring discharge
+ Lake release
+ Treated reuse
+ Project water



Stochastic Model



EDSIMR Objective Expected Net Benefits Maximization

The objective function is a probabilistically weighted across the states of nature to reflect stochastic weather

MAXIMIZE

$$
\sum_{r} prob_r * \langle \sum_{pc} (irrprofit_{cr} * IRRCROPPROD_{pcr}) + \sum_{pc} (dryprofit_{cr} * DRYCROPPROD_{pcr}) + \sum_{ac} (liveprofit_{ar} * LIVESTOCK_{acr})
$$

Net Ag income from Irr and dry Crop and animalproduction

$$
+ \sum_{pm} \left(\int gmundem_{pmr}(GMUN_{pmr})\, dGMUN_{pmr} + \int ginddem_{pmr}(GIND_{pmr})\, dGIND_{pmr} \right) + \sum_{n} \left(\int smundem_{nmr}(SMUN_{nmr}) dSMUN_{nmr} + \int sinddem_{nmr}(SIND_{nmr}) dSIND_{nmr} \right)
$$

areas under M&I demand curves

$$
- \sum_{pm} groundagpumpcost_{pr} * GAGWATER_{pmr} - \sum_{nm} surfaceagpumpcost_{nr} * SAGWATER_{nmr}
$$

Ag

$$
- \sum_{pm} groundmunindpumpcost_{pr} * (GMUN_{pmr} + GIND_{pmr}) - \sum_{nm} surfmunindpumpcost_{nr} * (SMUN_{nmr} + SIND_{nmr})
$$

M&I

pumping delivery costs

$$
+ \mathrm{EnvBenefit} * (\mathrm{Instream} + \mathrm{reserviorrec} + \mathrm{bayestuaryinflow}) - \sum_{p} (transaction * TRANSFERS_{pr}) \rangle
$$

Water Mkt Transaction costs

Less SON independent costs

$$
- \sum_{dm} annualcost_d * NEWPROJECTS_{dmr}
$$

Annual project dev costs - Integer

- Planting cost — **Crop plant cost**
- Animal herd cost — **Animal acquisition annual cost**
- Land transfer cost — **Cost of irr to dry or dry to past**

EDSIMR – Agriculture Sector

Crop Mix Modeling

- Crop Mix Balance
  - Crop mix should be a convex combination of historical crop land allocation
  - Dryland and Irrigated crops mixes are counted separately

$$\sum_{zones} CROPACRE_{county,zones,crops,irrigstatus} \leq \sum_{mixesa} [CROPMIX_{county,irrigstatus,mixesa} * cropmixdata_{county,crops,irrigstatus,mixesa}] \quad \forall county, crops, irrigstatus$$

EDSIMR –Water rights, and Markets

- Diversion Constraint:

Amount of water diverted from river by one permit

+Sold to others

-Buy from others

<= Permitted Capacity

EDSIMR – Projects

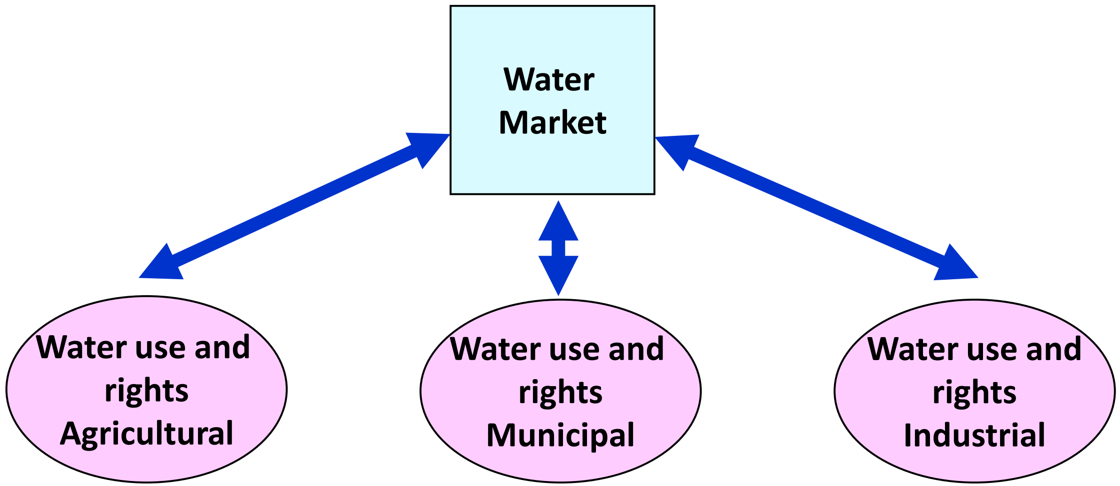
Water, Power, Fracking

- Integer variables in most cases
- Capacity Constraint
  - Water from projects <= the project capacity if the project is built. 0, otherwise
- Project capacity may be stochastic
- Operating cost per acre foot
- Fixed amortzed construction costs per project
- State of nature (stage 2) operation
- Injection Balance
  - Water could only be recovered in the Hdry state
  - Water recovered in the Injection projects in Hdry state <= water injected into aquifer in other state of nature

EDSIMR – Basics of Stochastics

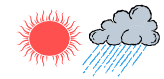
- Stochastics
  - Temp and precipitation
  - Crop Yields and Water Requirements and pest costs
  - Livestock stocking rate
  - Livestock performance
  - M&I demand
  - Cooling requirements
  - Water available

EDSIMR – Incorporating Water Markets



Includes friction in mkt ($50 in Edwards)

EDSIMR – Basics of Stochastics

- Discrete Stochastic Model :9 weather states 
- 2 Stage Decision
- Stage 1
    - Water and energy projects
    - Crop mix
    - Livestock numbers
    - Initial levels of aquifers and reservoirs
- Stage 2
    - Crop water use strategy
    - Recharge and surface inflows
    - Pumping/diversion
    - Water flows

EDSIMR – Conceptual Results

- Projects built
- Water Use Pattern and Trading
- Economic Effect by party
    - regional ag farm income + non-ag net surplus
    - regional water prices and costs
- Hydrologic Effect
    - EA elevation at the J-17 well index and river flows
- Environmental Effect
    - spring flows, river flows, and the Estuary bay flows
- Social Effect

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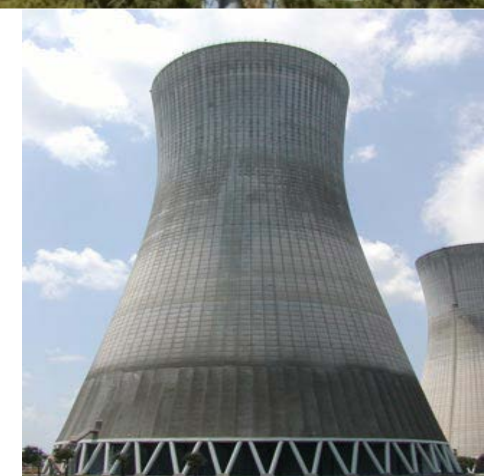
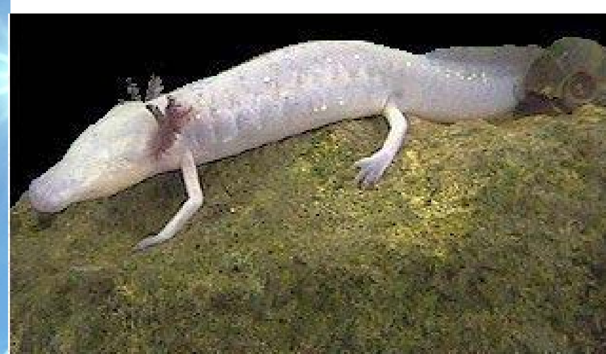
ENVIRONMENTALLY SENSITIVE AREA


Projects



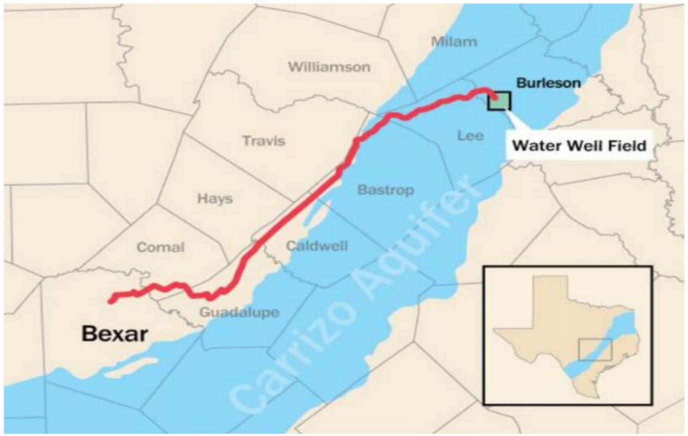



WEF Alternatives – a starting point

Ag	Irrigation methods and practices	Alternative crops
	Land to dryland or grazing	Removing minimum limits
	Degraded water use	Crop mix
	Dry year option	
Water	Use of more distant aquifers	Injection &recovery
	Reservoirs	Saline sources
	Enhanced recharge	Conservation
	Reuse	Broader markets and leasing
	Interbasin transfer	
Energy	Alternative cooling	Coal to Natural Gas
	Renewable sources wind solar	Import more
	Fracking water reuse	Fracking technology

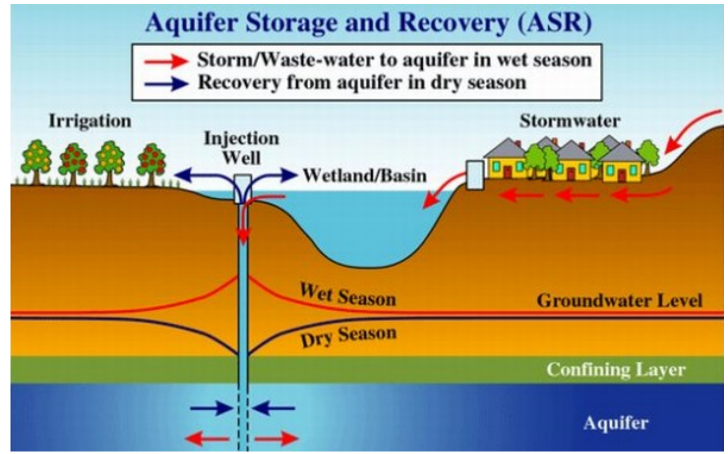
Water Projects Examples

Figure 5.2.23-1 Vista Ridge Project Location



Out-of-Region Water Project: Vista Ridge

- 143 miles pipelines
- Yield: 50,000 acft/yr
- Water cost full operation $1,976 /acft
- Total cost of facility: $493 million
- Pumping Energy: 156,691 MWh/year



ASR Project: Luiling ASR

- Total cost of facility: $23 million
- Annual cost of water: $1,086 / acft
- Energy Consumption for pumping: 1,617 MWh/year

Power Plant Retrofit

- Boiler retrofit (coal to natural gas)
- Cooling retrofit
  - (Once-through to Recirculating to Dry-cooling)
- Switch to renewable source: Wind, solar and Nuclear.
- Add new capacity in or outside region
  - Could export water use
  - Wind and solar reliability are issue
- Retrofit and new capacity cost will be in first stage of the model

Public Goods Concern

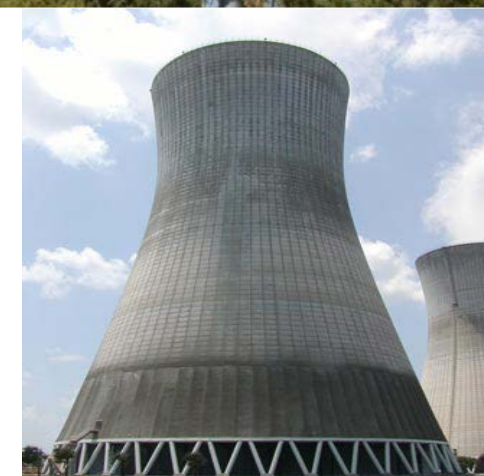
- Some Nexus actions will not be adopted by private individuals as they benefit the public not just the individual. In such cases the public may need to get directly involved in adoption.
- Water Projects in our projects are public goods

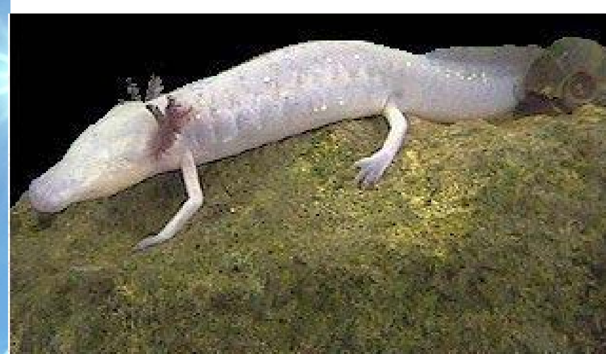
Compensation Reallocation

- When an entity like a Power plant could retrofit to save water but don’t do it because of cost
- We need provide subsidy or compensation to the power plants to increase their incentive of cooling and heating retrofit.



Preliminary Result



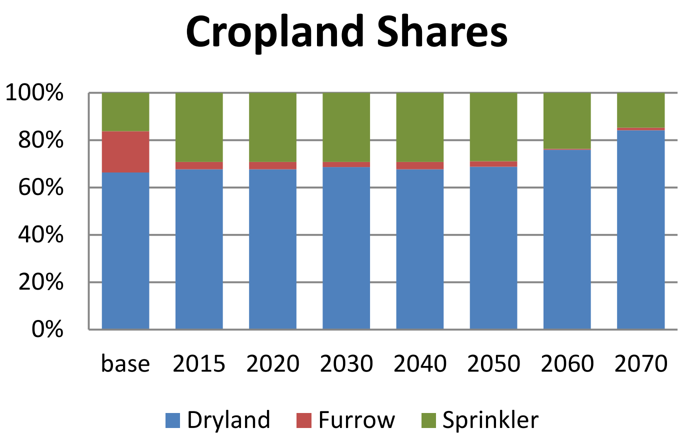


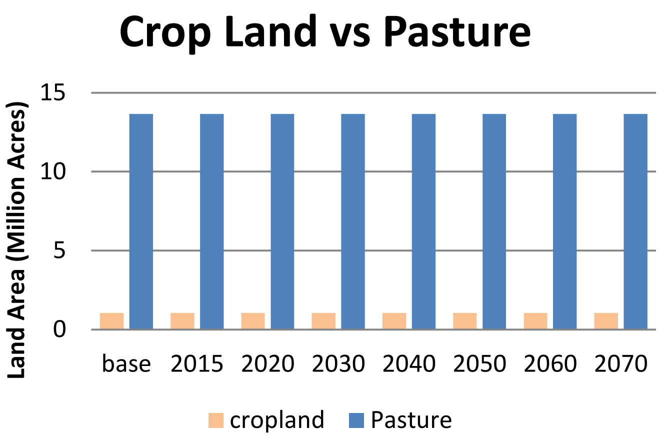

EDSIMR – Example Analysis Objectives

- Evaluate the economic and environmental consequences of a set of water management and energy project plans
- Determine the “best” mix of water and energy retrofit options for a given demand and environmental constraints
- Undertake a comparative assessment of the model “best” set of water management and energy project plans.

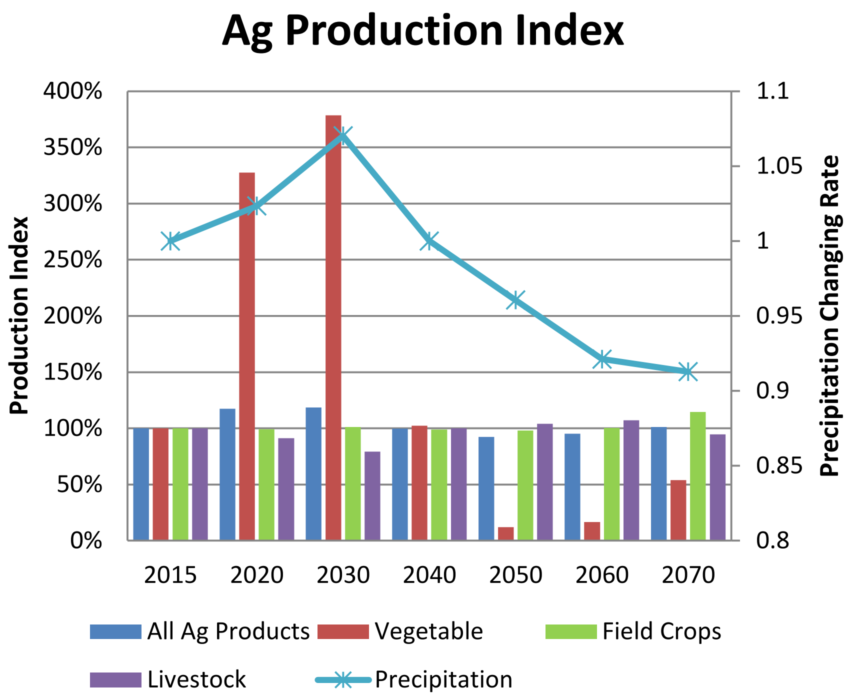
Base run -Agriculture Land

- Land transfers from irrigated land to dry land and sprinkler irrigation is preferred to save water even with higher cost.
- Few crop lands transfers to pasture





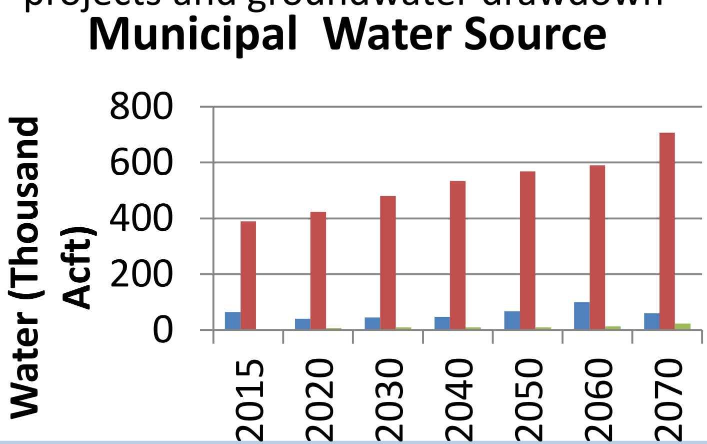
Agriculture Production Index

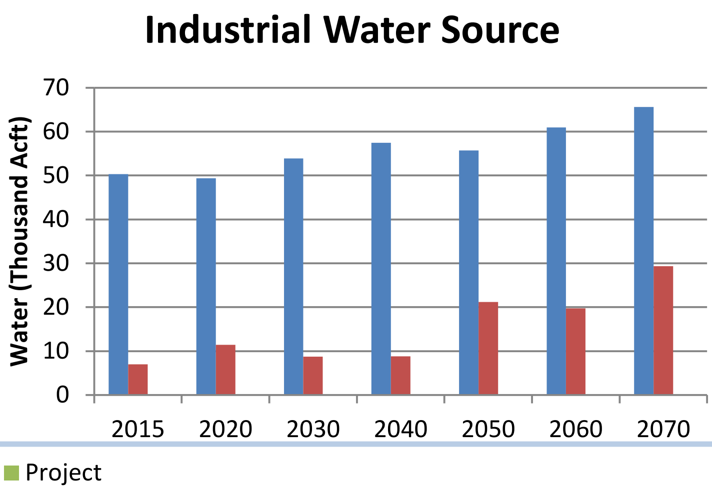


- Vegetable production is very sensitive to precipitation. It is preferred during wet years (2020s, 2030s) but spurned in the dry years (2050s, 2060s).
- Production index of all ag products also varies with precipitation.

Water Source by Sector

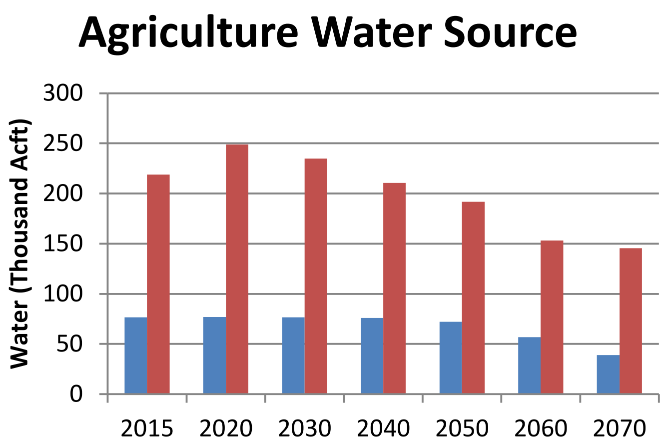
- Demand increases over time with the growing population.
- Municipal water needs driving expensive water projects proposed by Texas Water Development Board, or being implemented.
- Municipal sector owns less surface water permits than agriculture and industrial sector in the region. Plus has means of financing.
- Industrial water relies more on surface water over time, due to the shortage of water projects and groundwater drawdown

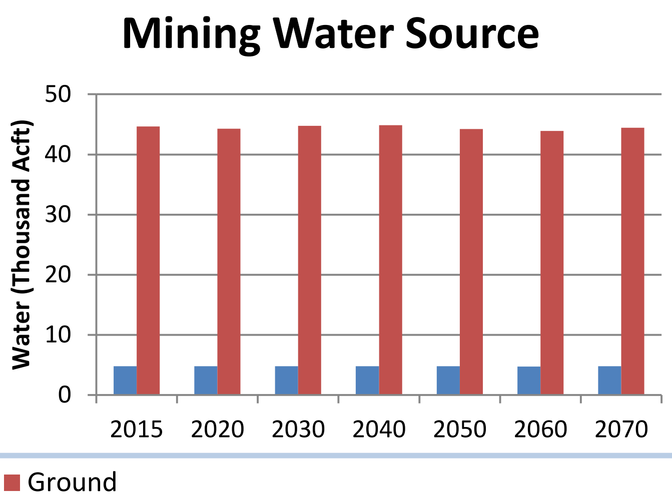




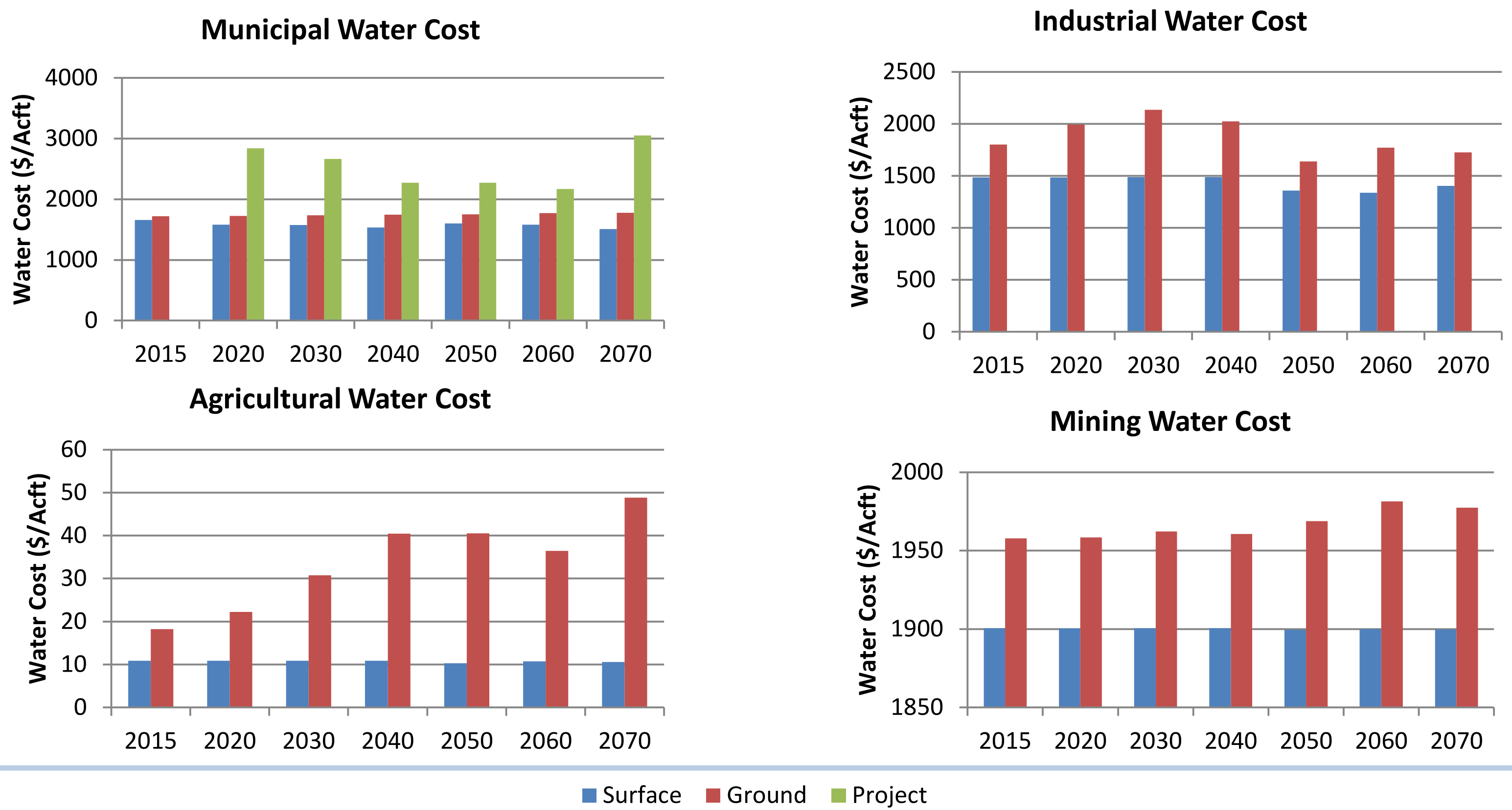
Water Source by Sector

- Agriculture use less water under climate change, because the increasing demand of groundwater draw down the aquifer and make the water too expensive for agriculture usage.
- Mining relies on ground water due to the shortage of surface water permits





Average Water Cost by Sector



Water Projects Selection

	Available Projects	2015	2020	2030	2040	2050	2060	2070
Surface Water Projects	4							
Ground Water Projects	34	0	4	5	5	5	5	6
Aquifer Storage and Recovery	7	0	2	2	2	2	2	2
Off-Channel Reservoir	5							
Outside Water Projects	7							
Fixed cost(Million $)			3.87	3.89	0.02			17.60
Variable cost(Million $)	0	0.00	29.18	35.28	35.17	35.12	40.82	72.69
Energy Consumption(MWh)			3152	4274	4267	4263	5835	20220

EDSIMR – Sample Analysis Results

- There is a distinct tradeoff in the EA region between the economic well being of pumping users and regional environmental attributes.
- Leaving behind the *rule of capture* to take on the highest of the HCP motivated pumping limits reduces regional pumping user related welfare by $246 million per year. The most extreme limit examined (175,000 acft) under the emerging HCP raises the welfare loss to $633 million per year.
- The emergence of the EA water market improves regional welfare to pumping users but worsens environmental attributes unless the East-West pools could somehow be factored into its design.
- Water development from alternative sources will be stimulated greatly by HCP related EA use restrictions.
- The EA region will have to develop an expanded set of water development alternatives if the severe Habitat Conservation Plan based restrictions are imposed.

EDSIMR – Sample Analysis Results

Table 2. Economic and Hydrologic Effects of Water Management Plans

	2050 Base[a]	Optimal 400	Optimal 200	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
		---------------------------- change from the 2050 Base ----------------------------						
Average Welfare Measures (Mil.$):								
Agricultural Income	19.1	**-31.5%**	**-9.8%**	-12.7%	-41.2%	-10.0%	-16.9%	-72.3%
Non-agricultural Surplus	878.0	**2.2%**	**0.9%**	**-5.7%**	-7.2%	-12.1%	-8.2%	2.0%
Other Regional Agricultural Income	59.1	0.02%	0.02%	-2.1%	-2.1%	-2.1%	0.02%	-2.3%
Other Regional Non-Agricultural Surplus	216.5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total Regional Welfare	1232.8	1.1%	0.5%	-4.2%	-5.9%	-8.8%	-6.1%	0.2%
Agricultural Activity Measures (10^3 acres):								
Edwards Aquifer Irrigated Acres Harvested	74.5	-35.7	-21.6	-21.9	-45.4	-21.8	-25.1	-64.4
Edwards Aquifer Dry Land	17.2	-5.9	-6.6	-8.1	-1.6	-6.9	-7.6	-5.8
Purchased Edwards Aquifer Irrigated Land	N/A	40.4	27.9	28.4	45.1	28.2	31.1	59.2
Leased Edwards Aquifer Irrigated Land	N/A	1.9	0.4	1.5	1.5	0.3	1.5	8.6
Average Hydrologic Measures:								
Comal Spring Flow (cfs/year)	196.0	-46.0	**125.6**	-8.7	71.9	128.7	-16.9	-44.5
Corpus Bay Inflow (10^3 acft)	1025.7	-4.7	-1.6	5.5	7.6	0.4	-38.1	-9.2

- **The EA ag sector is worse off.**
- **The economic gain accrues to the EA non-agricultural sector, but is basically offset by the water development costs.**

Gillig, D., B.A. McCarl, and F.O. Boadu, "An Economic, Hydrologic, and Environmental Assessment of Water Management Alternative Plans for the South-Central Texas Region", Journal of Agricultural and Applied Economics, 33, 1 (April), 59-78, 2001.

EDSIMR – Sample Analysis Results

Table 1. Water Management Options Used in the Alternative Plans

Water Option	Optimal400	Optimal 200	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Surface Water Diversion/Transfer							
Lower Guadalupe River diversion	x	x	x	x			
Colorado River in Colorado County					x		
Colorado River in Bastrop				x			
Joint development of water supply with CCC/LCC system						x	
Medina Lake							
Canyon Reservoir			x	x	x	x	x
Wimberley & Woodcreek Reservoirs			x	x	x	x	x
Cibolo Reservoir			x				
Lockhart Reservoir			x				x
Purchase/lease surface water irrigation rights	x	x					
Groundwater Pumping/Recharge/Recovery							
EA irrigation transfers	x	x	x	x	x	x	x
EA recharge Type 2	x		x	x	x	x	x
Guadalupe River diversion near Comfort							x
Springflow recirculation		x		x	x		x

Conclusion

- Agriculture transfer land from furrow irrigation to sprinkler irrigation to dryland to save fresh water and avoid high pumping cost
- Building more water projects could destress water scarcity and increase social welfare.
- More water projects are built over time. ASR and Groundwater projects are preferred due to extra water source and lower fixed and operating cost

Future Research

- Enhance the preliminary electrical energy part improving data and modeling on cooling alternatives and the use of electricity when developing the water projects
- Add Edwards Aquifer Authority water management strategies/regulation and water marketing into the model.
- Add alternative strategies via which fracking can reduce its usage of fresh water
- Develop information on how water supply, crop yield and irrigated crop water use are affected by climate change scenarios in interaction with the SWAT, hydrological modeling group.



Preliminary Result