Adaptive Water Management

Agriculture, Ecosystems, Urban Growth, Climate, and Energy Demand Drivers

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Christopher Scott

Currently: University of Arizona (http://aquasec.org/wrpg)

1996 – 2005: International Water Management Institute (www.iwmi.org)

What is Adaptation?

- Conventionally understood as complementary to mitigation (e.g., of emissions causing climate change)
- A means to address and incorporate uncertainty, not attempt to overcome it
- Considers systems as dynamic
  - Interlinking human-biophysical interactions
- Non-linear
  - Multiple potential outcomes, not 1-to-1 deterministic, hysteresis (system memory)
- Non-stationary
  - Statistical relations between climate, hydrology, and water resources are evolving, sometimes in poorly understood ways

Adaptation & Resilience

- Adaptive cycle (C.S. Hollings, Lance Gunderson)
  - Change is eposidic, caused by inter-action of fast and slow variables.
  - Spatial attributes are patchy and discontinuous; can not scale up from small to large simply by aggregation.
  - Ecosystems have multiple equilibria. Destabilizing forces maintain diversity and resilience, stabilizing forces create productivity.
  - Policies that apply fixed rules will lead to loss of resilience in ecosystems.

Adaptation & Resilience

- Adaptive cycle (C.S. Hollings, Lance Gunderson)

  - r = exploitation, rapid colonization of recently disturbed areas (r often exponential growth)
  - K = conservation, sustained plateau or maximum population
  - These two make up traditional theory of ecological succession
  - Authors add two new dimensions that close the loop (making the infinity symbol)
  - Omega = release = creative destruction, accumulation of biomass and nutrients becomes overconnected, fragile, until a release, such as drought, fire, or pests.
  - Alpha = reorganization = soil processes minimize nutrient loss so available for next phase of exploitation, condition of greatest uncertainty
  - Front-loop stage = from r to K, slow, incremental phase of accumulation and growth

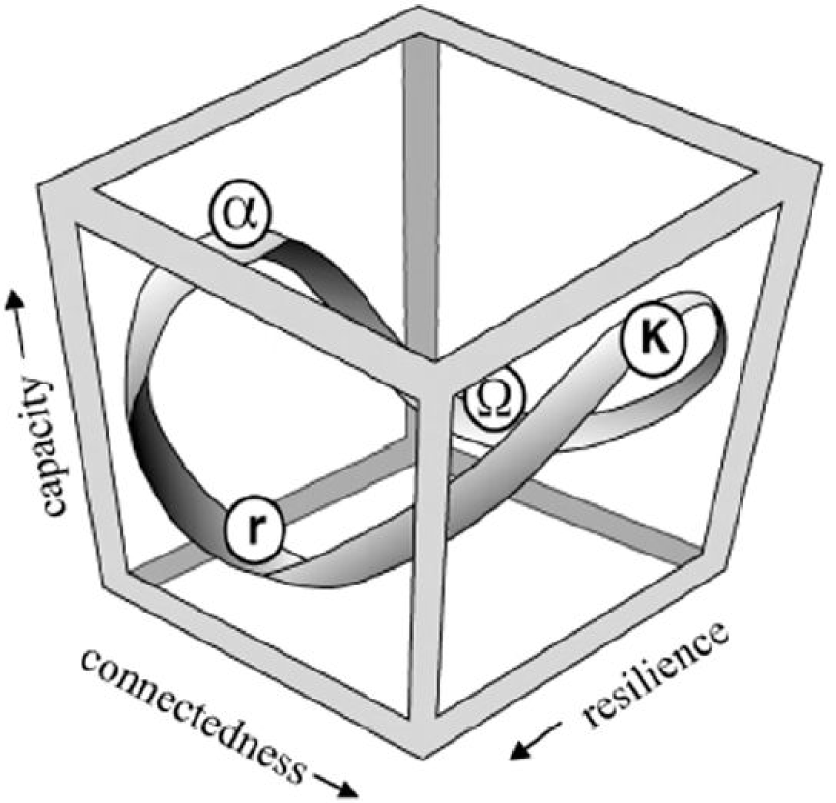


Figure 1 Adaptive Management Cycle in three dimensions showing capacity, connectedness and resilience. Source: Holling and Gunderson, 2002

Adaptive Water Management

- Social & institutional learning
  - “Learning to manage while managing to learn” (Claudia Pahl-Wostl)
- Multiple techniques to address uncertainty, including Scenario Planning, will be presented during this Training Institute

www.sciencemag.org SCIENCE VOL 319 1 FEBRUARY 2008
Published by AAAS

POLICY FORUM

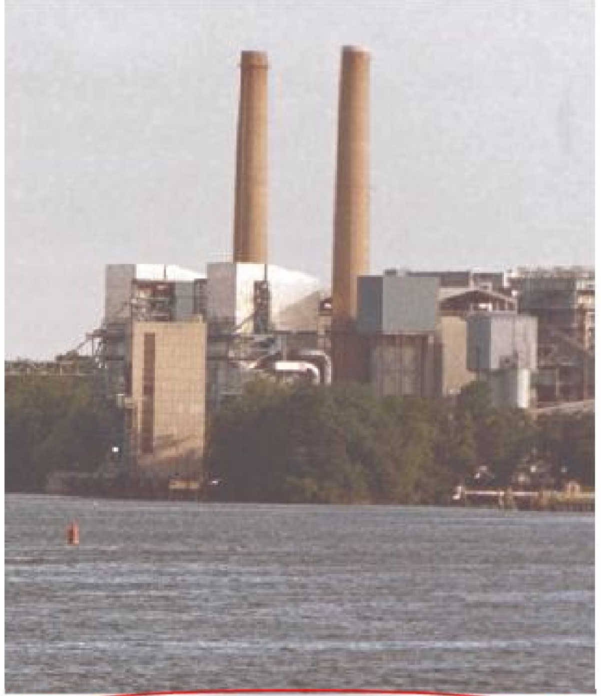
CLIMATE CHANGE

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 foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, water-



An uncertain future challenges water planners.

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 have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (*11*, *12*). Accounting for the substantial uncertainties of climatic parameters estimated from short records (*13*) effectively hedged against small climate changes. Additionally, climate projections were not considered credible (*12*, *14*).

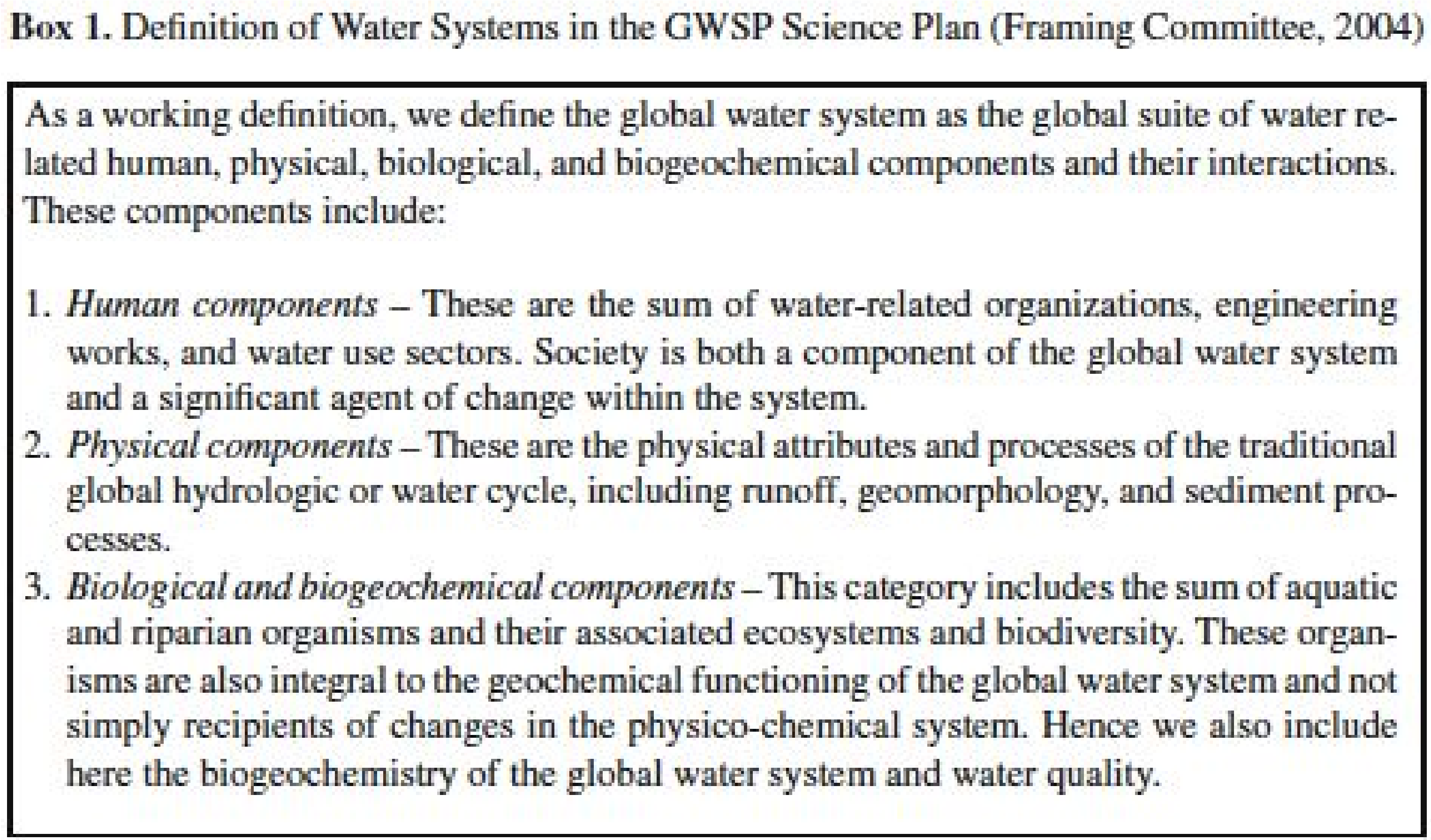
Recent developments have led us to the opinion that the time has come to move beyond the wait-and-see approach. Projections of runoff changes are bolstered by the

Water Resour Manage (2007) 21:49–62
DOI 10.1007/s11269-006-9040-4

ORIGINAL ARTICLE

Transitions towards adaptive management of water facing climate and global change

Claudia Pahl-Wostl



Box 1. Definition of Water Systems in the GWSP Science Plan (Framing Committee, 2004)

As a working definition, we define the global water system as the global suite of water related human, physical, biological, and biogeochemical components and their interactions. These components include:

1. *Human components* – These are the sum of water-related organizations, engineering works, and water use sectors. Society is both a component of the global water system and a significant agent of change within the system.
2. *Physical components* – These are the physical attributes and processes of the traditional global hydrologic or water cycle, including runoff, geomorphology, and sediment processes.
3. *Biological and biogeochemical components* – This category includes the sum of aquatic and riparian organisms and their associated ecosystems and biodiversity. These organisms are also integral to the geochemical functioning of the global water system and not simply recipients of changes in the physico-chemical system. Hence we also include here the biogeochemistry of the global water system and water quality.

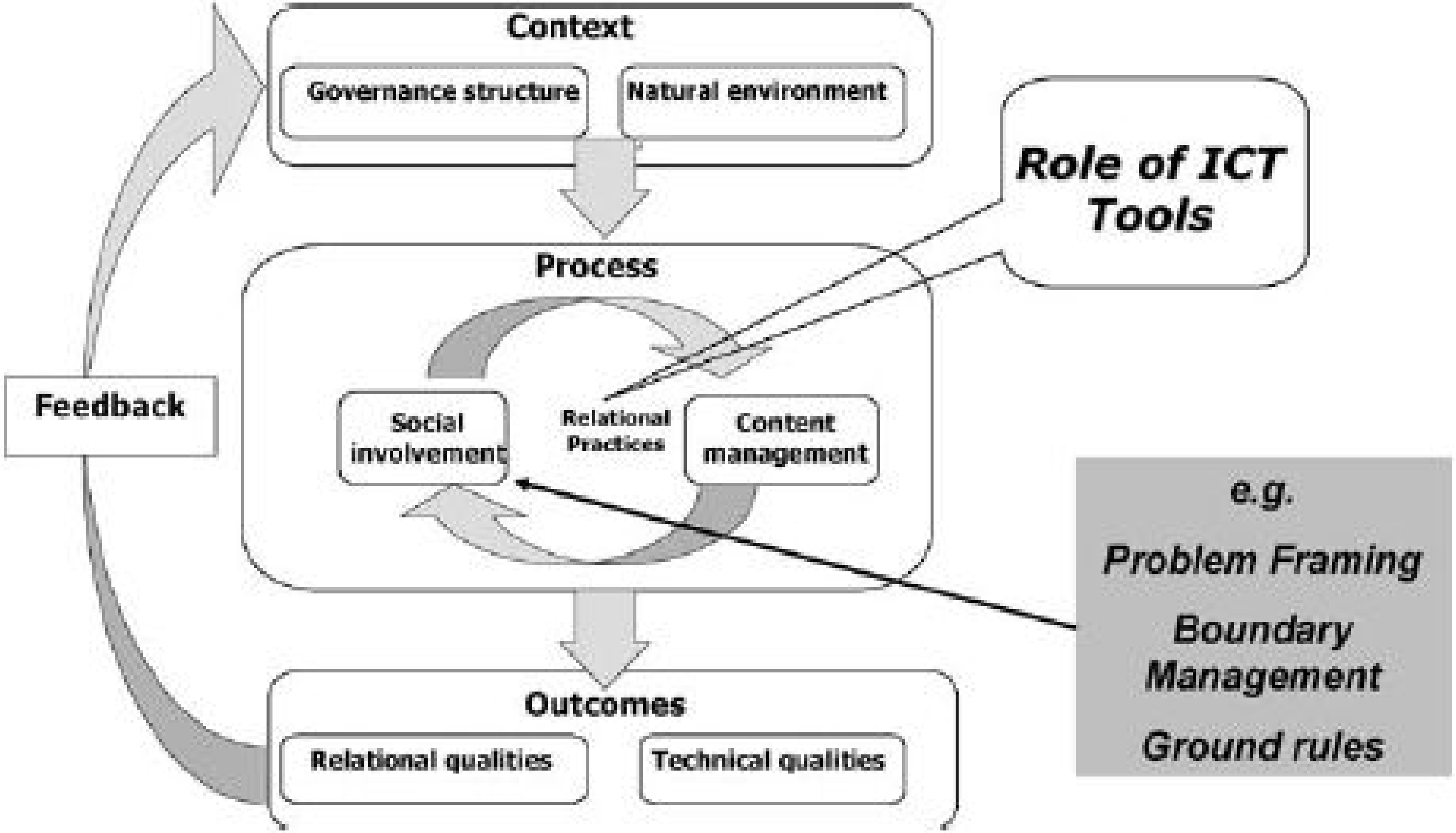
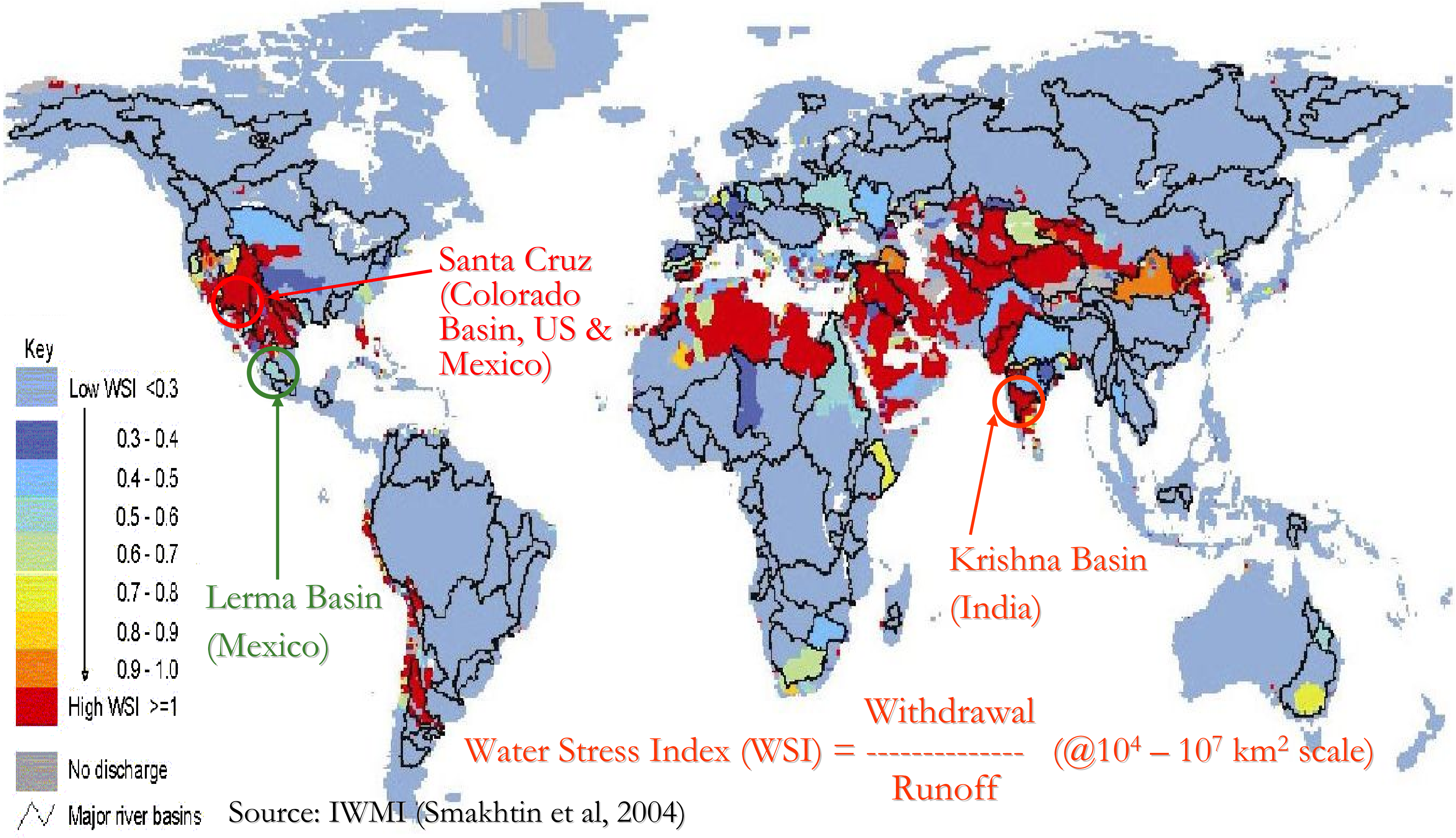


Fig. 2 Conceptual framework for social learning in resources management. Information and communication technology tools may play a decisive role in supporting and shaping relational practices that link social involvement and content management. This implies also a new role for simulation models in such processes

Human Use of Water is Increasingly in Conflict with the Environment



Santa Cruz (Colorado Basin, US & Mexico)

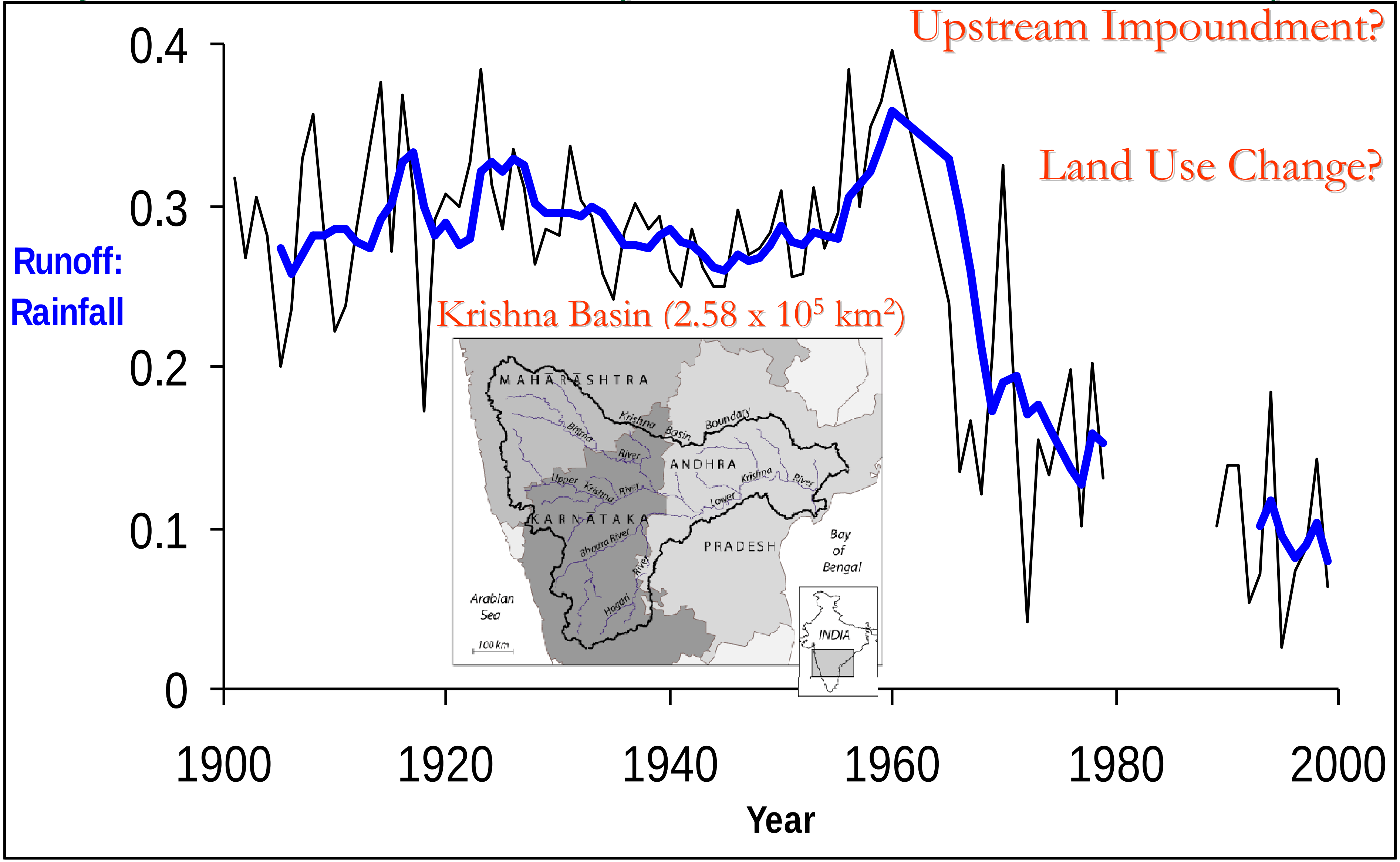
Lerma Basin (Mexico)

Krishna Basin (India)

Water Stress Index (WSI) = $\frac{\text{Withdrawal}}{\text{Runoff}}$ (@$10^4 – 10^7$ km^2 scale)

Source: IWMI (Smakhtin et al, 2004)

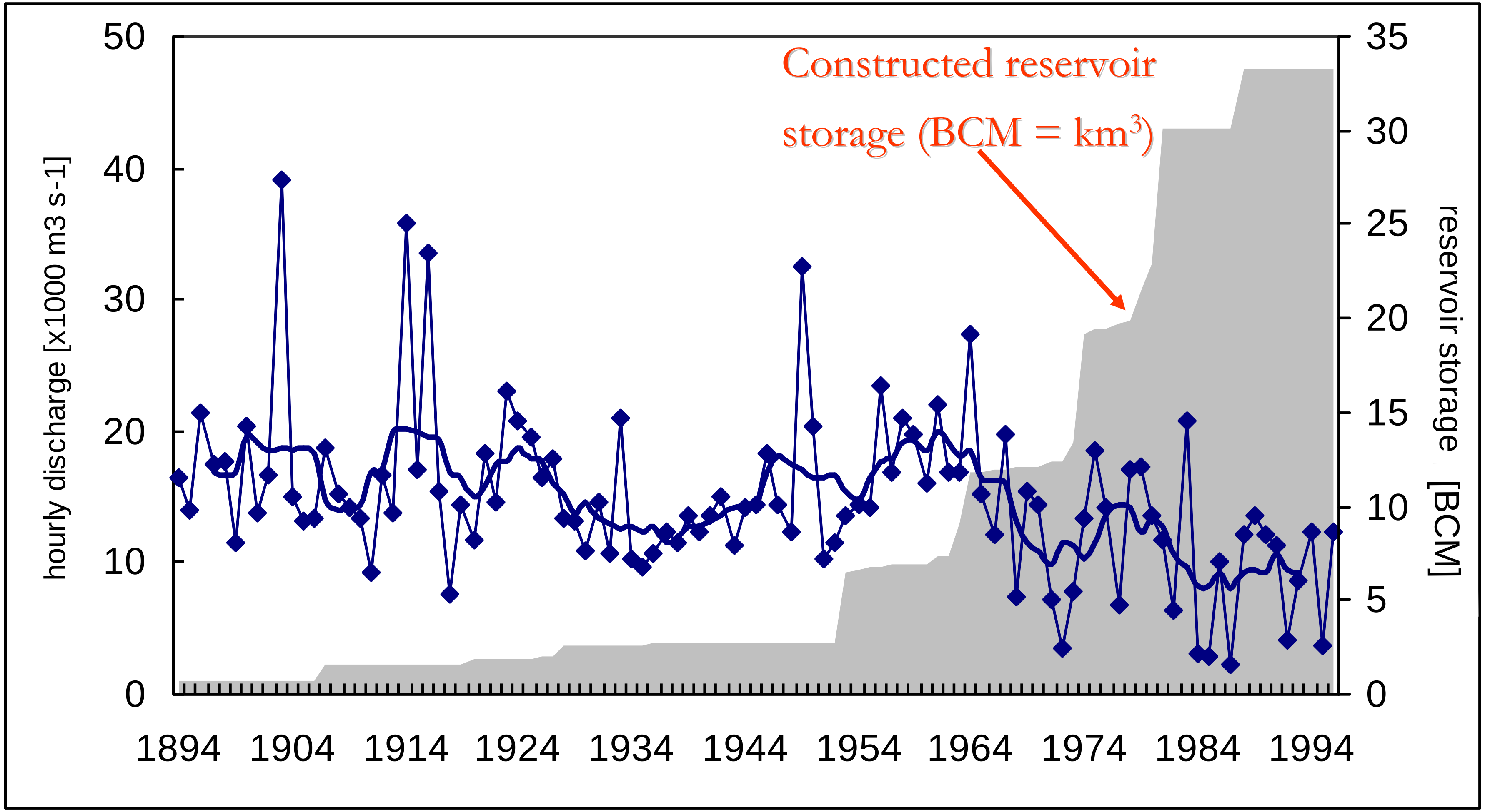
Long-Term Runoff Declines (Krishna Basin, India 2.58 x 10^5 km^2)



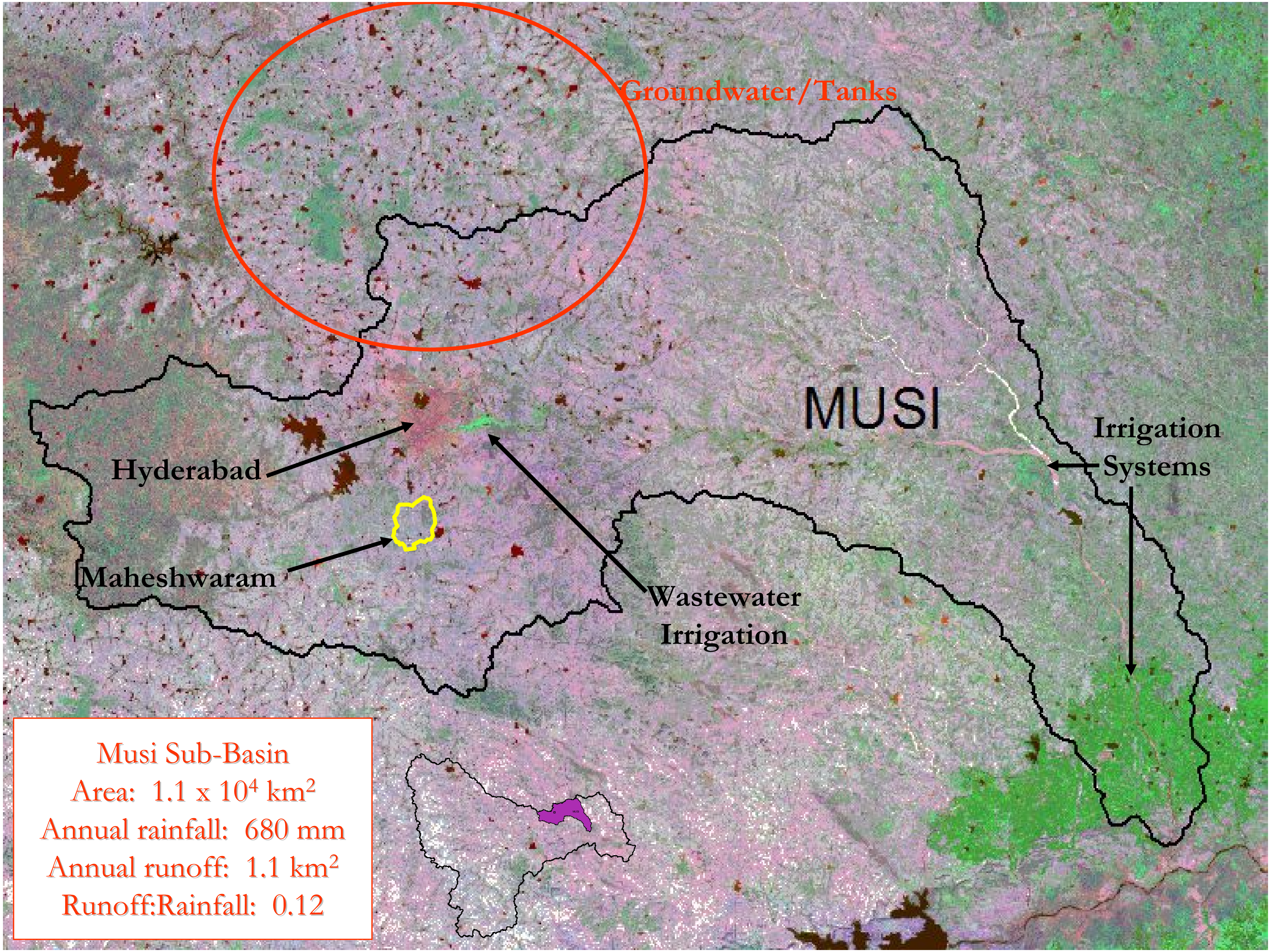
Upstream Impoundment?

Land Use Change?

Lower Krishna River Gauge Flow



“Tanks” in Krishna Basin



Musi Sub-Basin
Area: 1.1 x 10^4 km^2
Annual rainfall: 680 mm
Annual runoff: 1.1 km^2
Runoff:Rainfall: 0.12

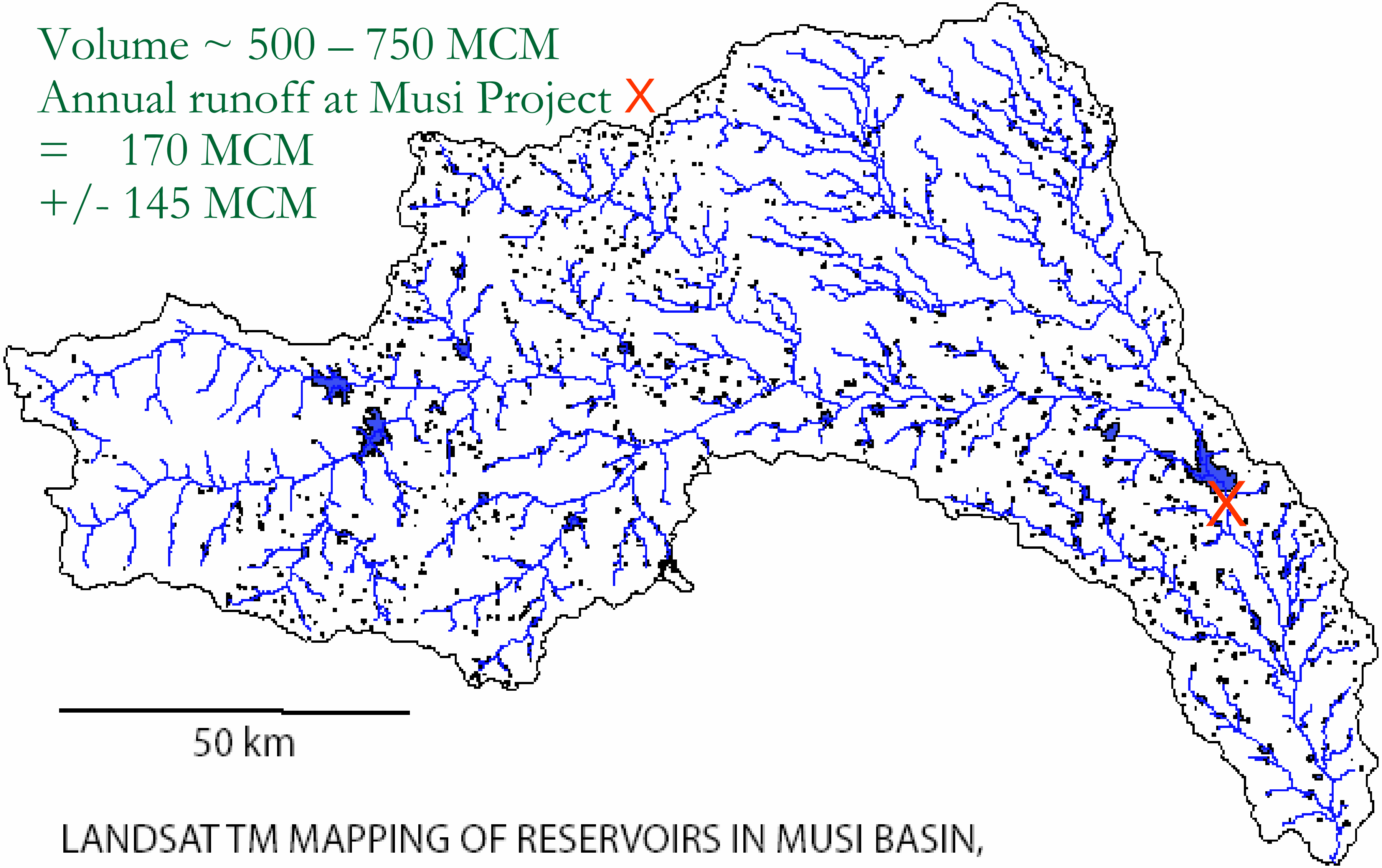
1160 tanks of 1–100 ha surface area

Volume ~ 500 – 750 MCM

Annual runoff at Musi Project X

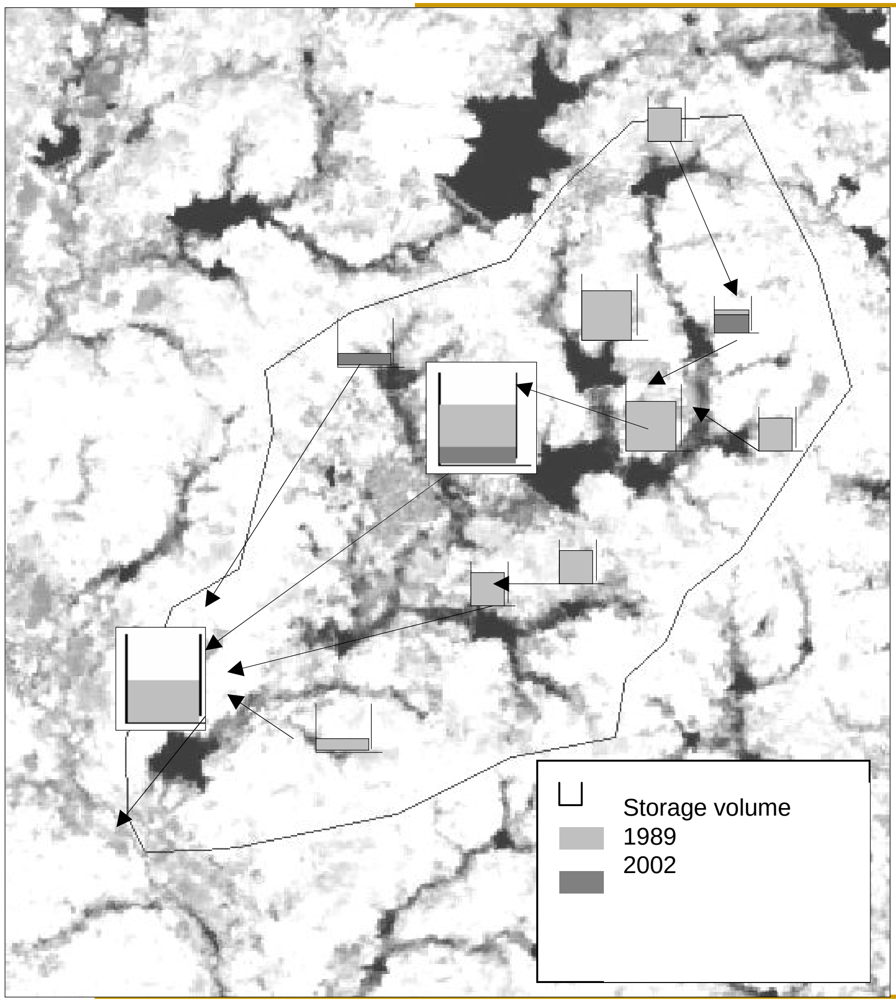
= 170 MCM

+/- 145 MCM



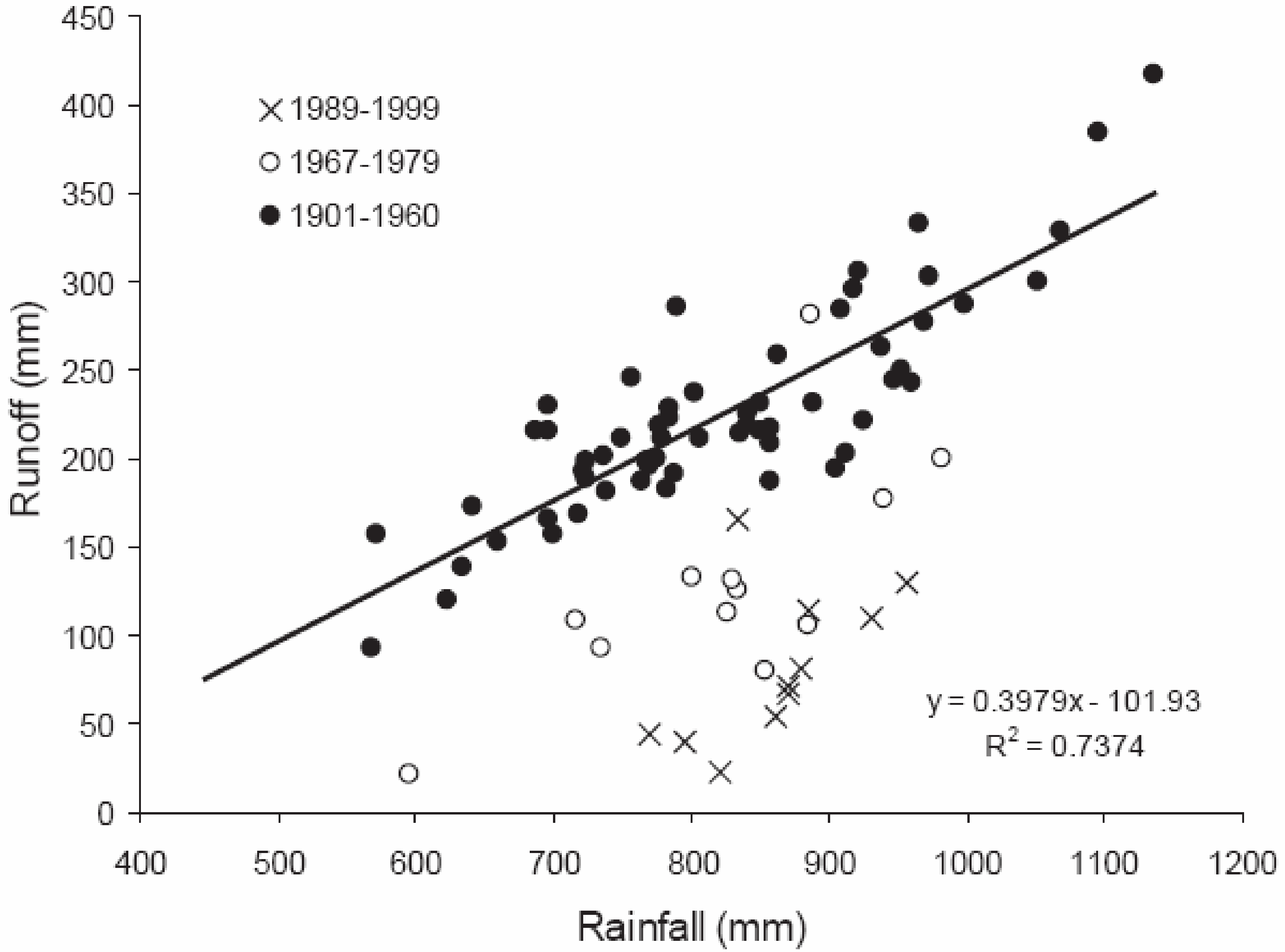
LANDSAT TM MAPPING OF RESERVOIRS IN MUSI BASIN,
OCTOBER 2000 IMAGERY

100% Runoff Harvested, 0 Outflow

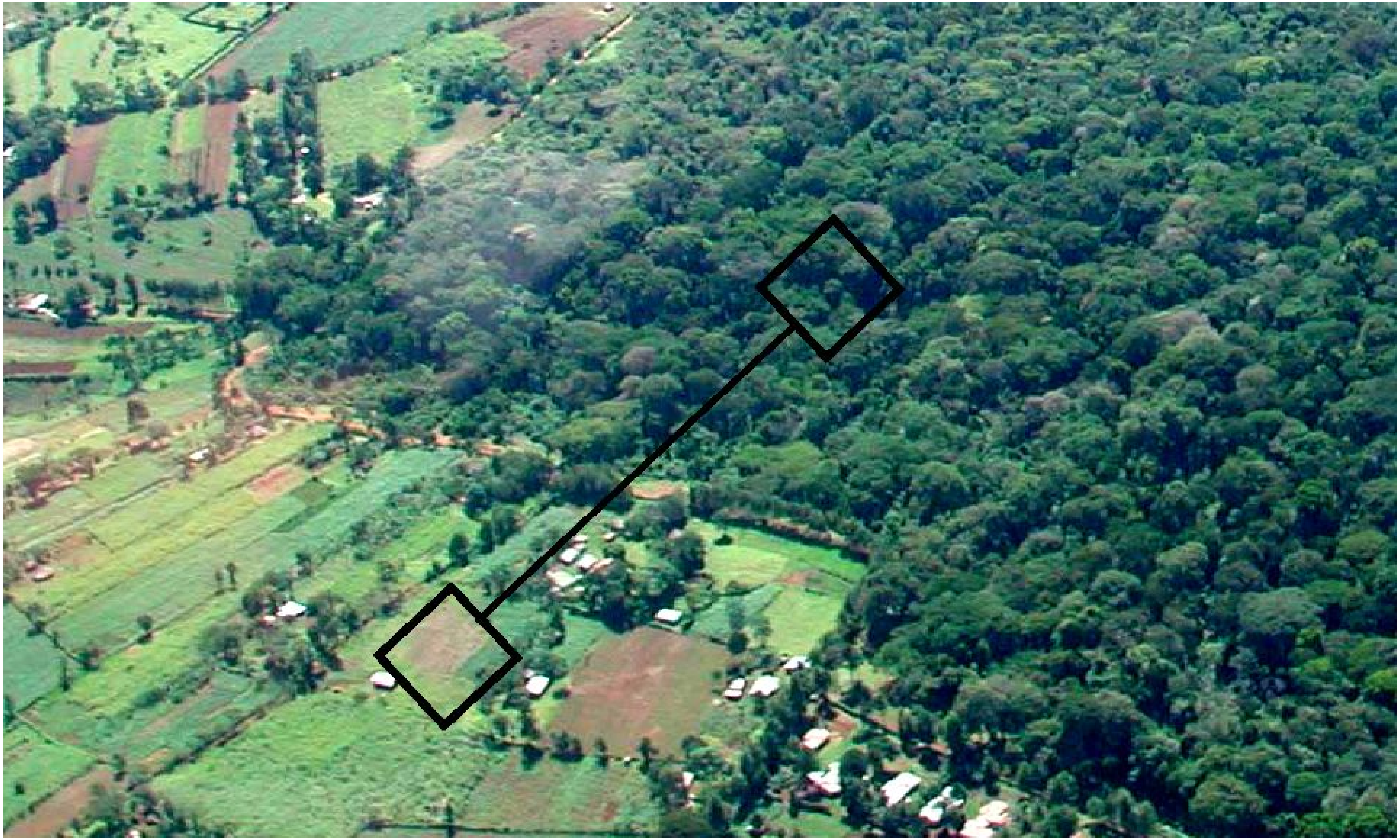


Name	No.	Max. storage (m^3)	Storage Nov. '89 (m^3)	Max. Storage 2002 (m^3)	% tank of total capacity	% of storage capacity 1989	% of storage capacity 2002
Langamcheru	1	345,600	271,872	3,600	8	79	1.0
Clarmankuta	2	180,000	134,592	90,000	4	75	50.0
Patalcheru	3	600,000	477,600	1,200	13	80	0.2
Abilcheru	4	240,000	191,424	1,500	5	80	0.6
Nagulacheru	5	1,440,000	1,076,256	210,000	26	75	17.5
Kadampalli	6	1,200,000	490,080	0	26	41	0.0
Masaipalli	7	360,000	41,760	0	10	12	0.0
Dewicheru	8	192,000	34,752	27,000	3	18	18.8
Other	9	36,000	23,712	0	1	66	0.0
	10	216000	147,744	0	3	68	0.0
	11	36,000	22,080	0	1	61	0.0
Total	11	4,845,600	2,911,872	333,300	100%		
TOTAL storage (mm)		140	84	9.6			
% of capacity		100	60	6.9			

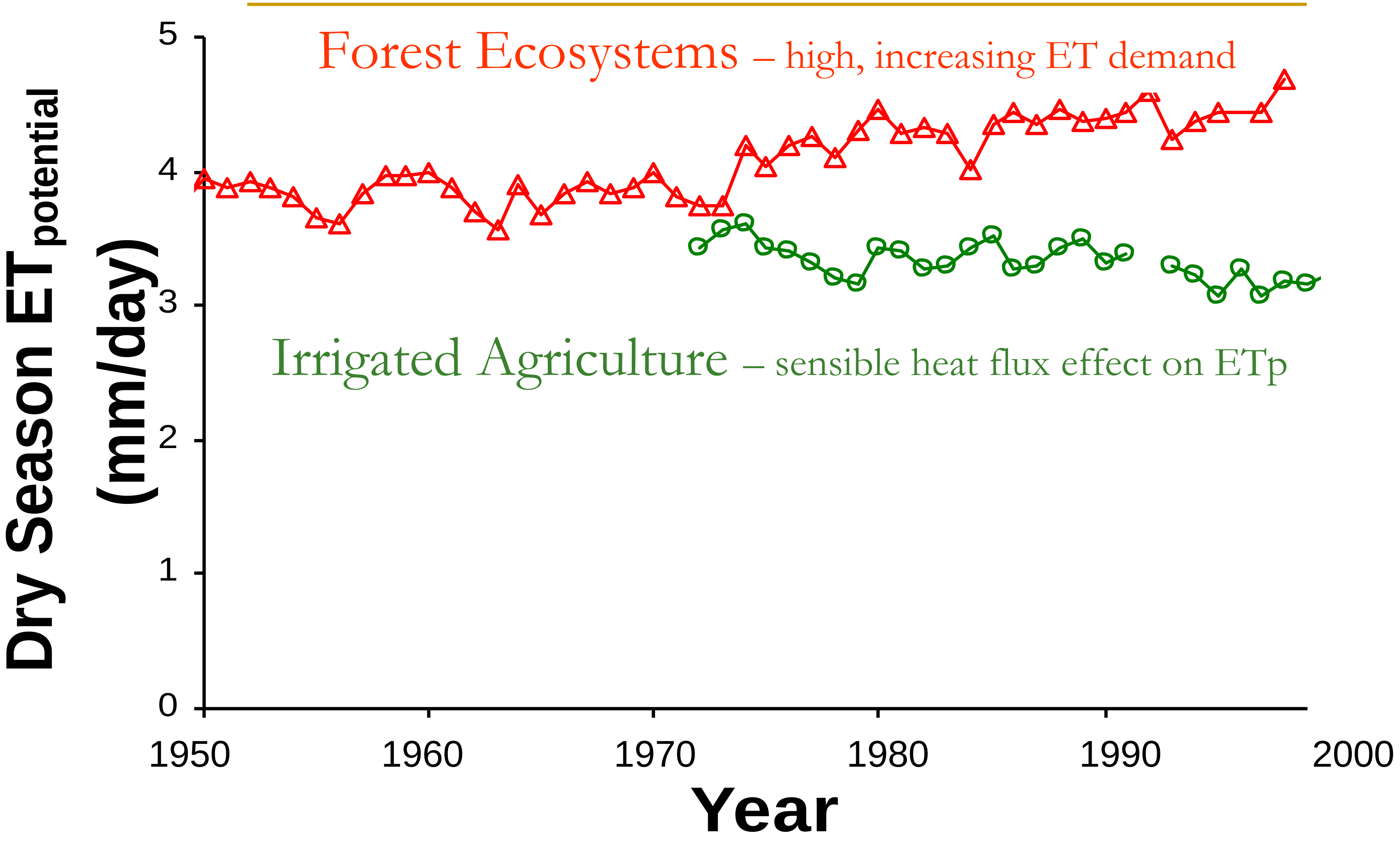
Reduced Runoff, Delayed Peak Flow



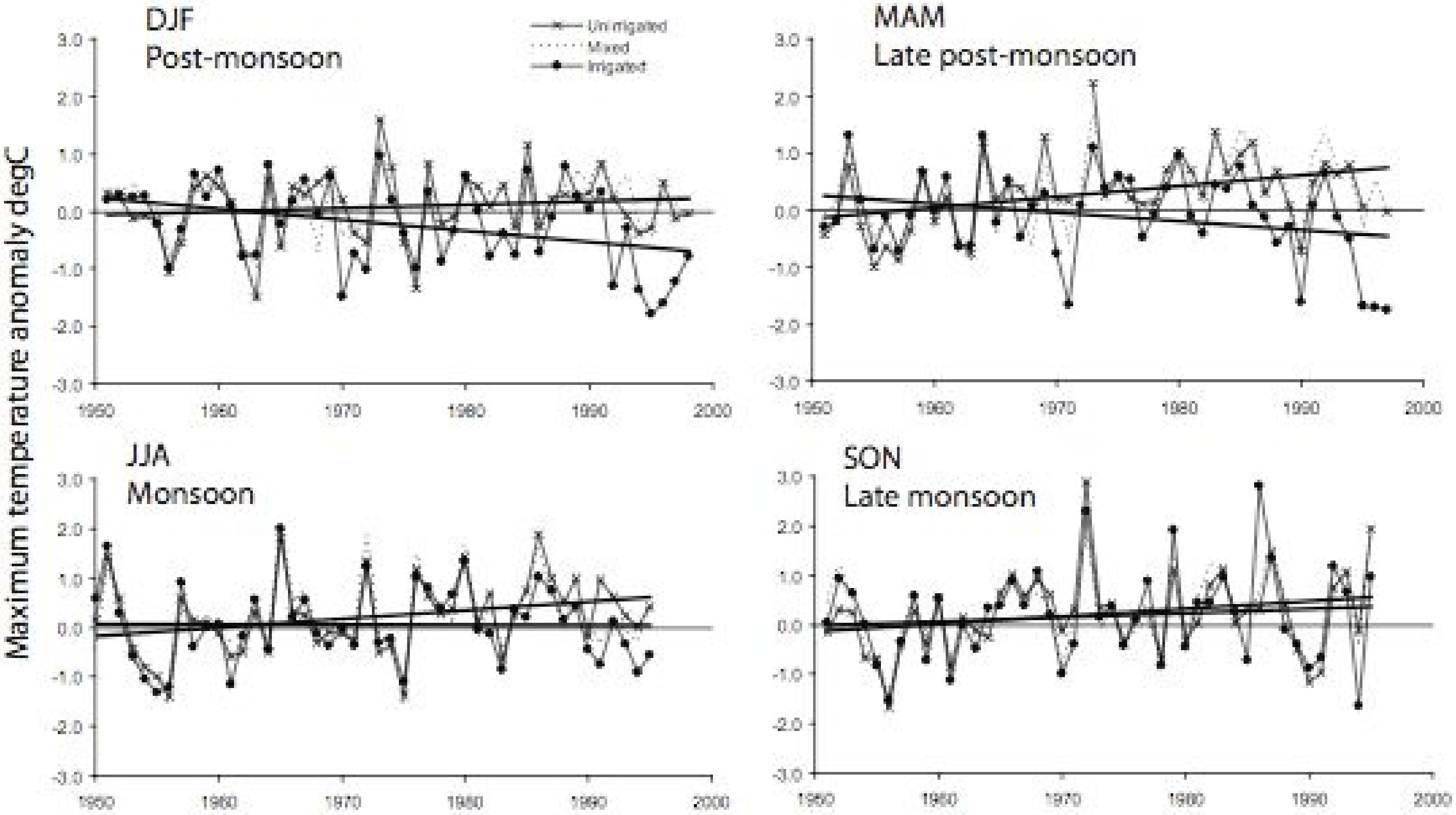
ET Impacts of Forest Conversion



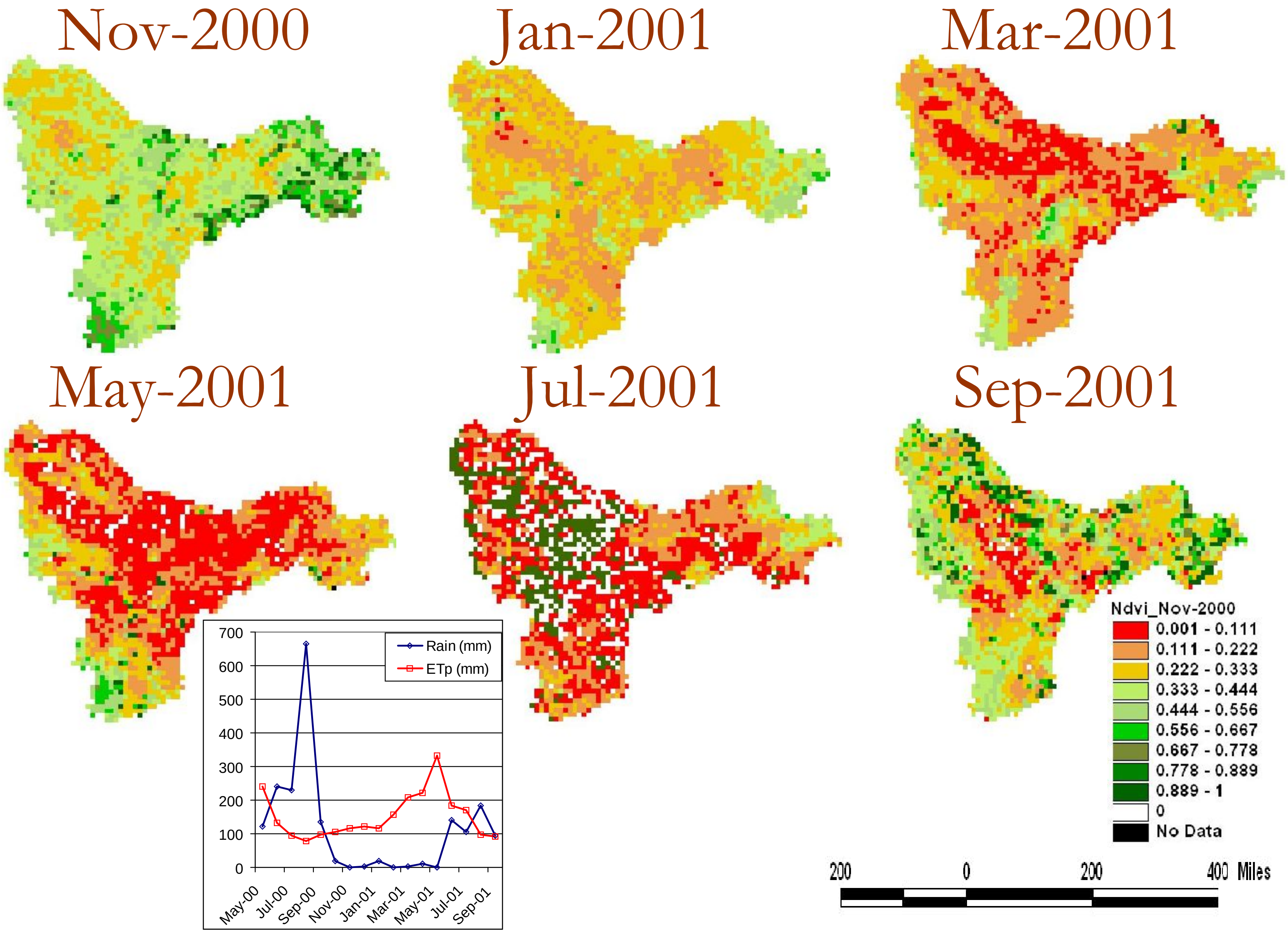
Forest $ET_{potential}$ Increasing



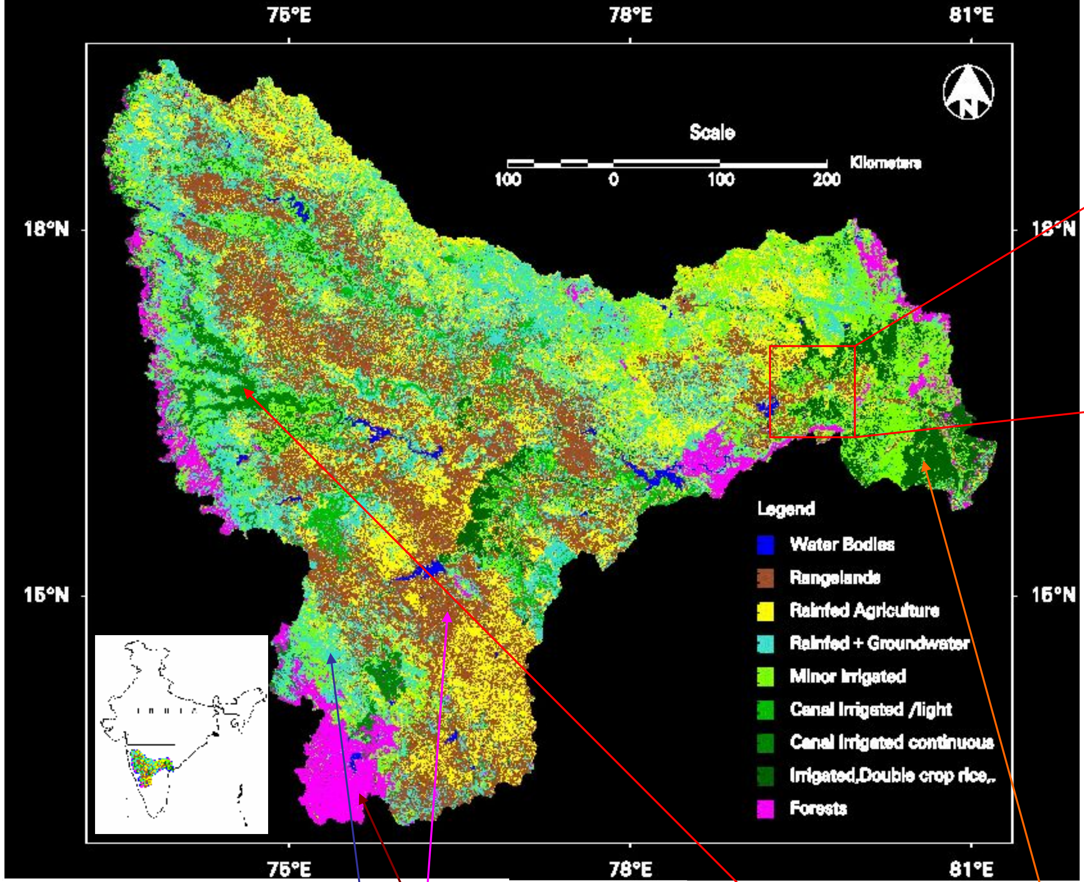
Irrigation Sensible Heat Flux

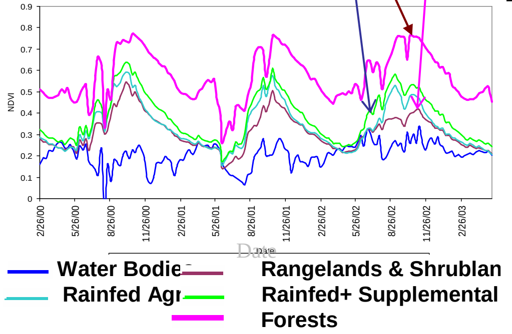


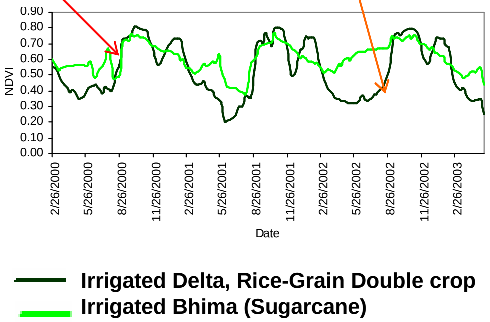
Krishna Basin NDVI (AVHRR)



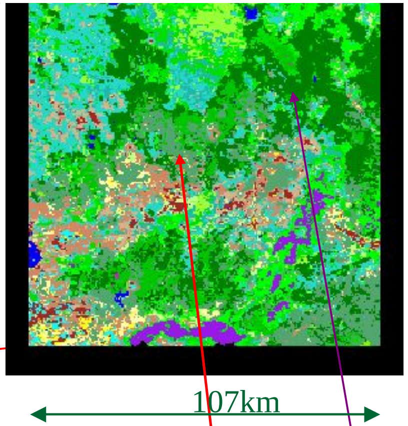
Krishna River Basin Land use/ land cover and Irrigated Mapping using Continuous Streams of MODIS data

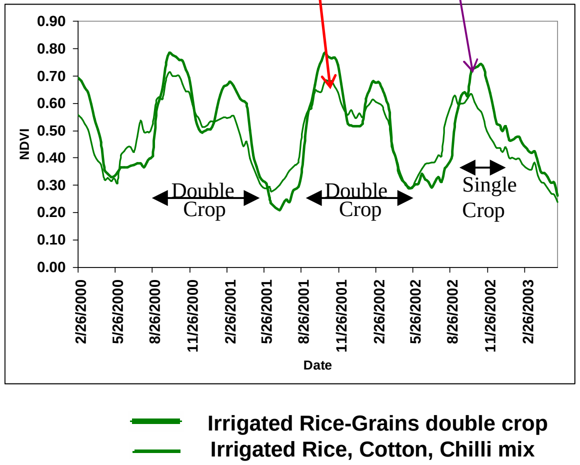






Nagarjuna Sagar Command area (Change Detection:Double crop to single crop)



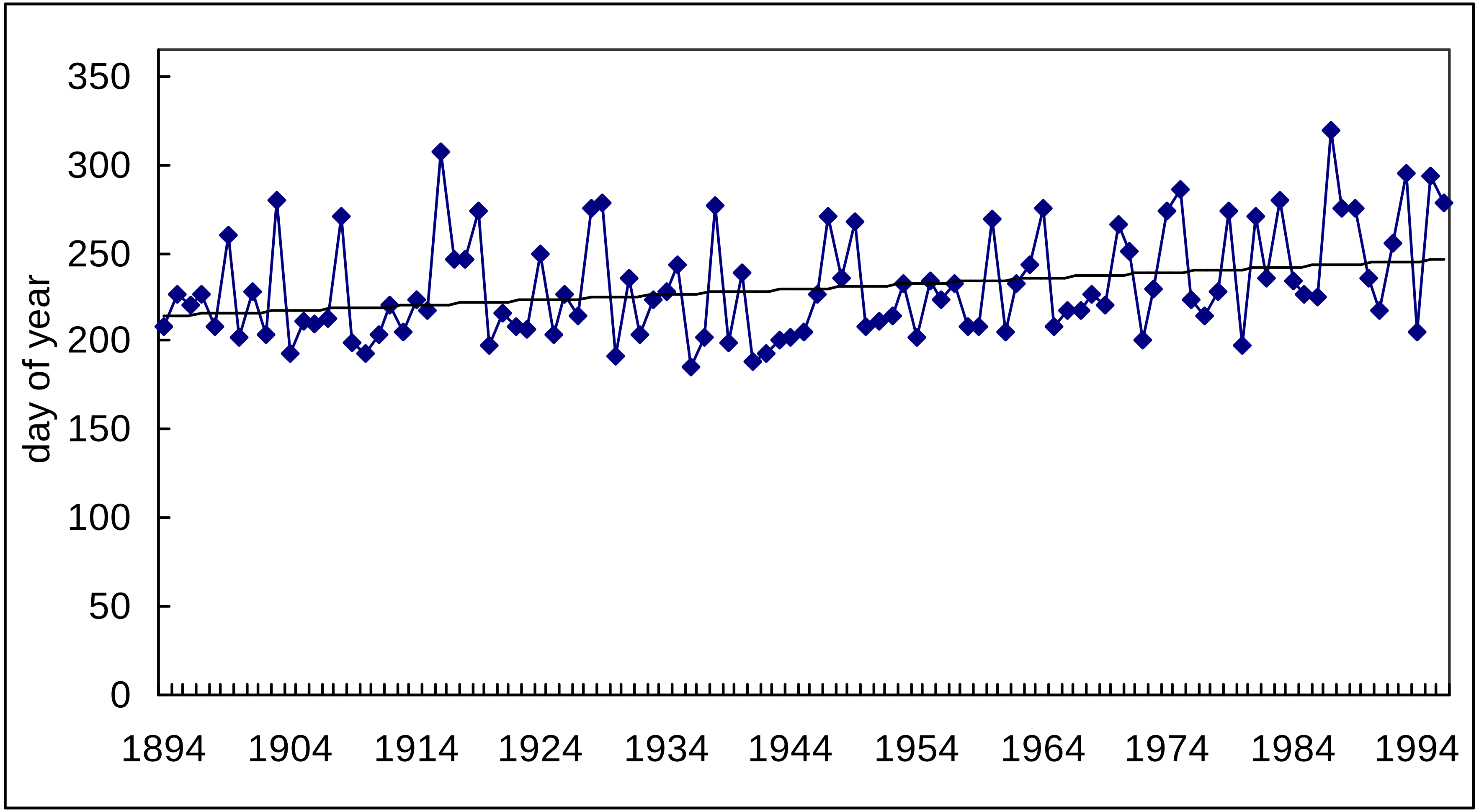


NDVI: Normalized Difference Vegetative Index

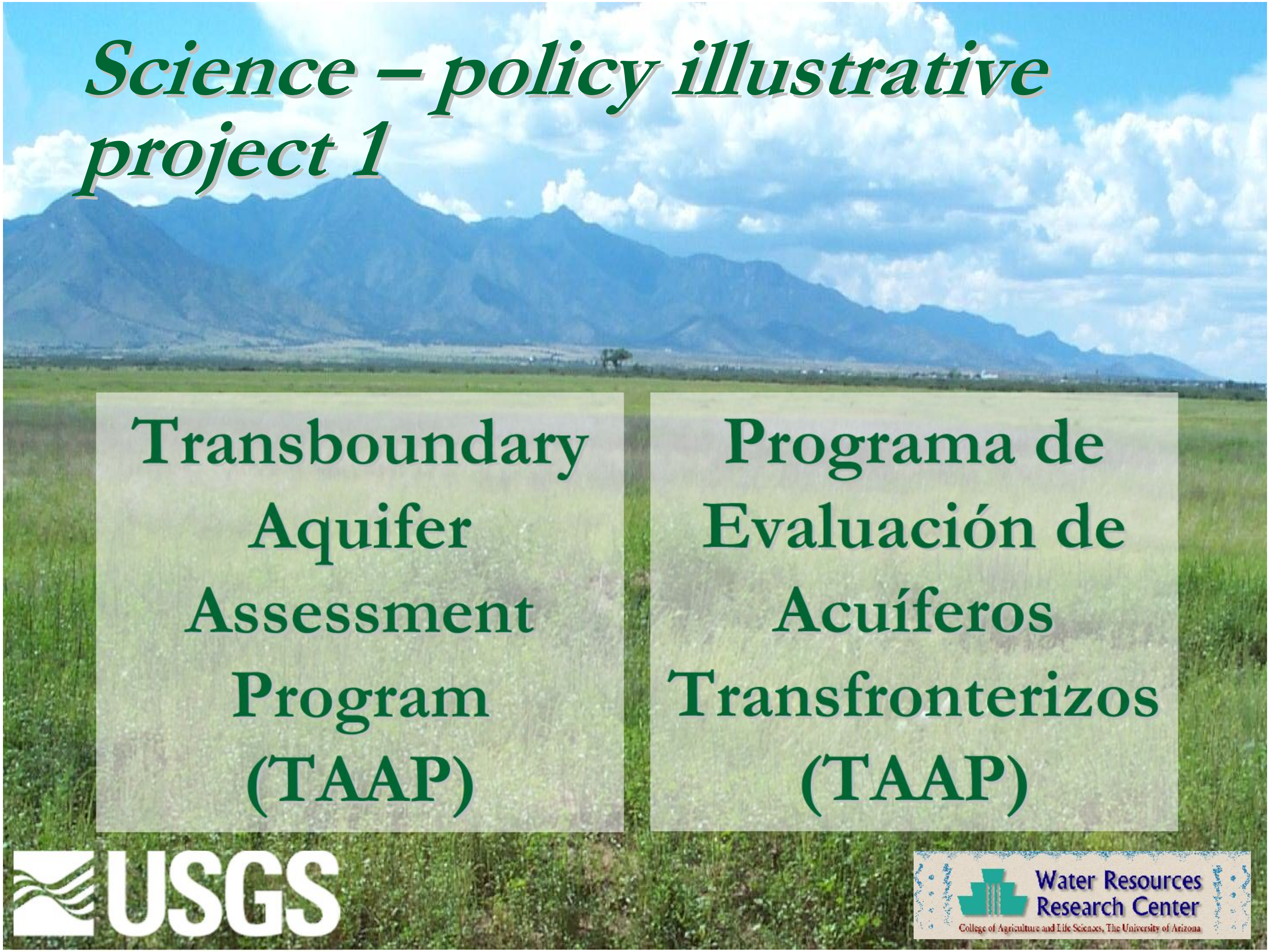
IWMI International Water Management Institute

Remote Sensing and Geographic Information System (RS/GIS) Unit

Krishna Estuary Peak Flow Date (critical ecosystems implications)



Science – policy illustrative project 1



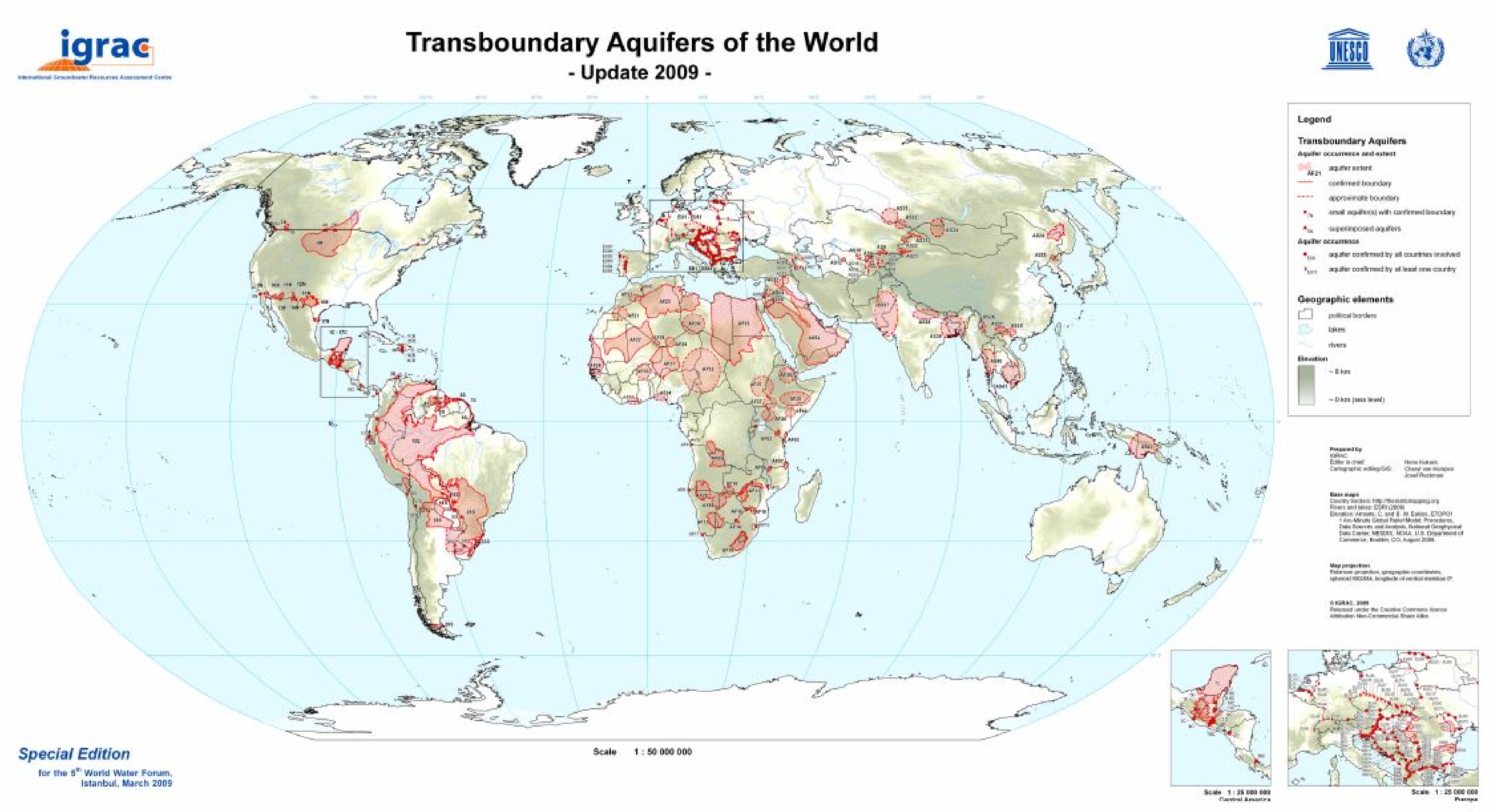
Transboundary Aquifer Assessment Program (TAAP)

Programa de Evaluación de Acuíferos Transfronterizos (TAAP)

USGS

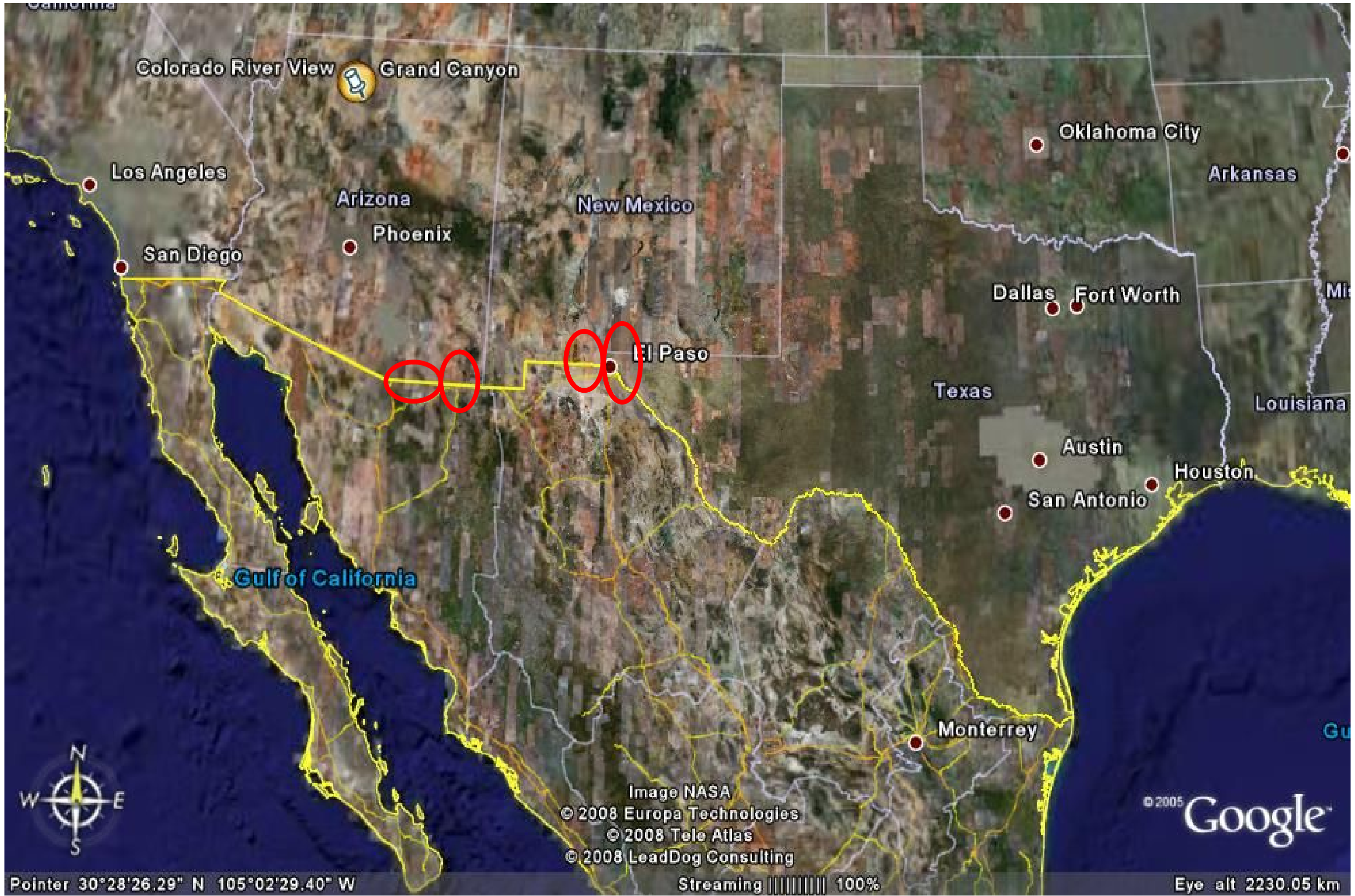
Water Resources Research Center

College of Agriculture and Life Sciences, The University of Arizona

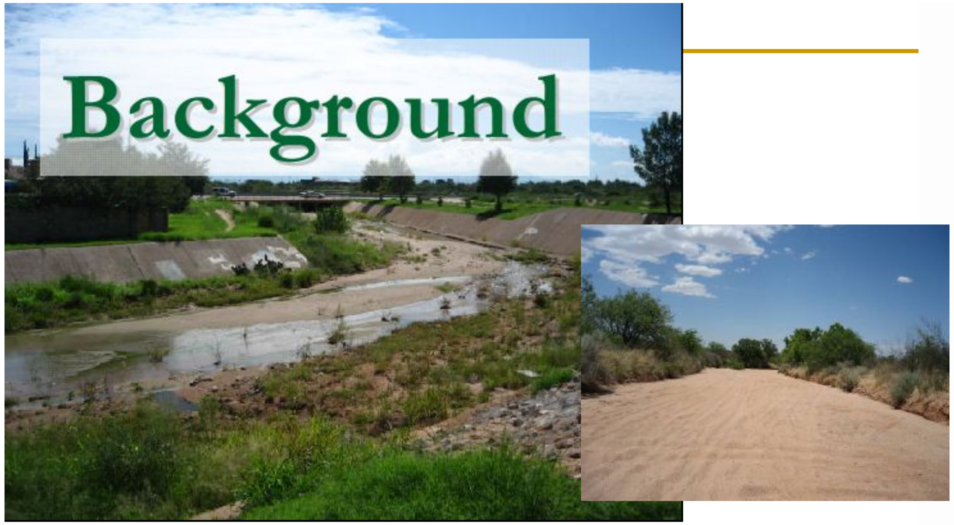

igrac
International Groundwater Resources Assessment Centre
Transboundary Aquifers of the World
- Update 2009 -
UNESCO
Legend
Transboundary Aquifers
Aquifer occurrence and extent
AF21 aquifer extent
confirmed boundary
approximate boundary
small aquifer(s) with confirmed boundary
superimposed aquifers
Aquifer occurrence
aquifer confirmed by all countries involved
aquifer confirmed by at least one country
Geographic elements
political borders
lakes
rivers
Elevation
~ 8 km
~ 0 km (sea level)
Prepared by
Base maps
Map projection
Special Edition
for the 5th World Water Forum,
Istanbul, March 2009
Scale 1 : 50 000 000
Scale 1 : 25 000 000
Central America
Scale 1 : 25 000 000
Europe

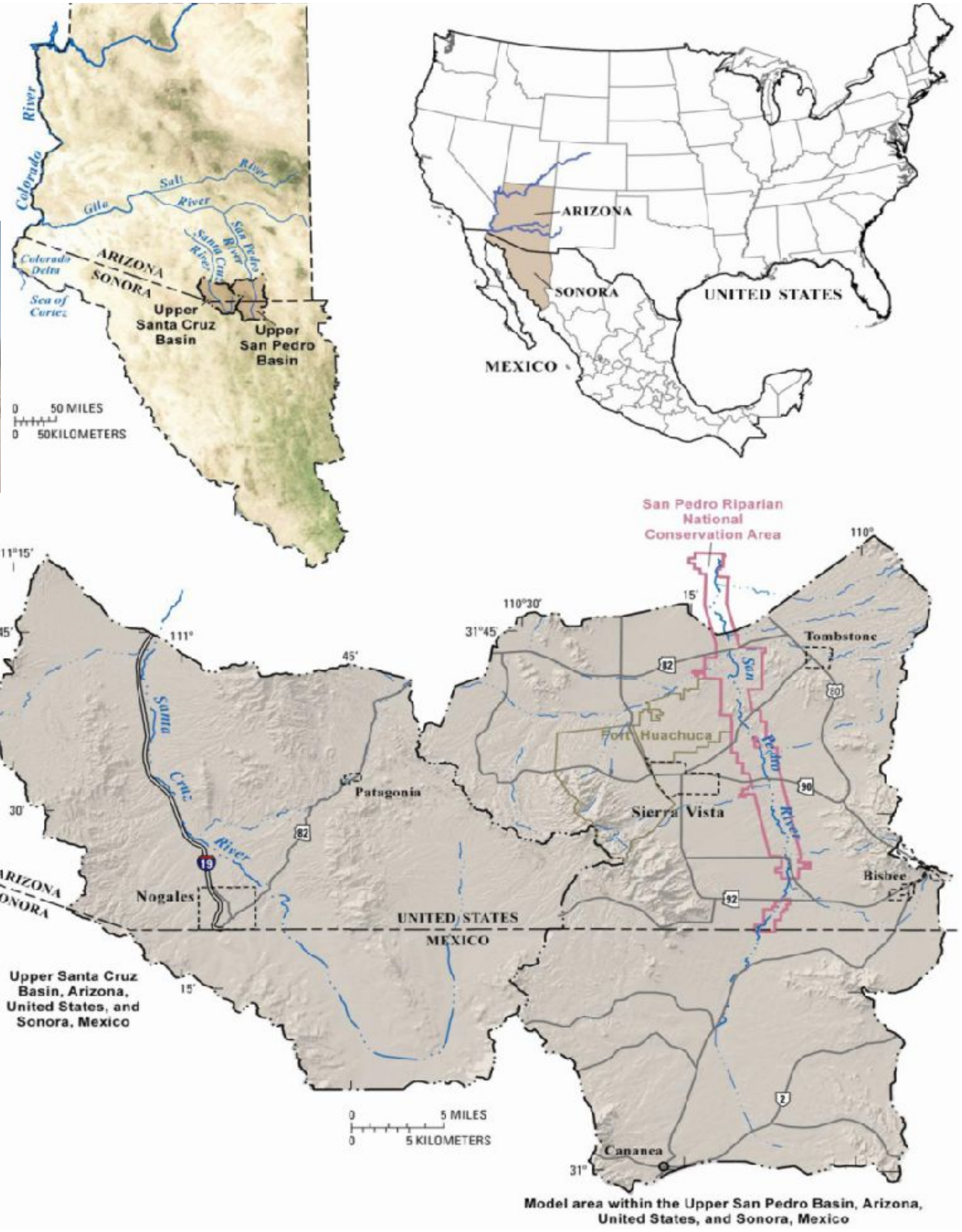
United States - Mexico Transboundary Aquifer Assessment Program U.S. Public Law 109-448 (Dec. 22, 2006)

Currently designated priority transboundary aquifers



Background





- 10 year project subject to appropriations
- Funds can be shared with Mexico with 50% match
- Institutional asymmetries
  - Role of national governments different with respect to groundwater
  - Federal responsibility alone in Mexico
  - Significant state level responsibility in US

Background

- Rapid economic growth
- Border current population over 12 million; projected to be 13 million to 15 million by 2010
- Arid environment, declining water tables, contamination; lack of sewage treatment in some Mexican cities
- Aquifers are sole or next available source of water
- Complex binational, bicultural environment
- Knowledge of the quantity, quality, and movement of water in priority transboundary aquifers is currently inadequate

Binational Workplan

Priority Studies

- Create a physically-based, binational, hydrologic model of each basin that integrates surface-, ground-, and unsaturated-zone water
- Summary of Approach:
    - Compile extant data
    - Examine existing models
    - Identify data gaps
    - Develop unified hydrologic framework
    - Model construction, calibration, and estimate of uncertainty
    - Model Prediction: climate change, urbanization, drought

Estudios Prioritarios

- Crear un modelo hidrológico físico de cada cuenca binacional que integra agua superficial, subterránea, y la zona no saturada
- Resumen del proceso:
    - Recopilar datos existentes
    - Examinar modelos existentes
    - Identificar falta de datos
    - Desarrollar estructura hidrológica única
    - Modelos: construcción, calibración, y estimación del incertidumbre
    - Predicción con modelos: cambio climático, urbanización, sequía

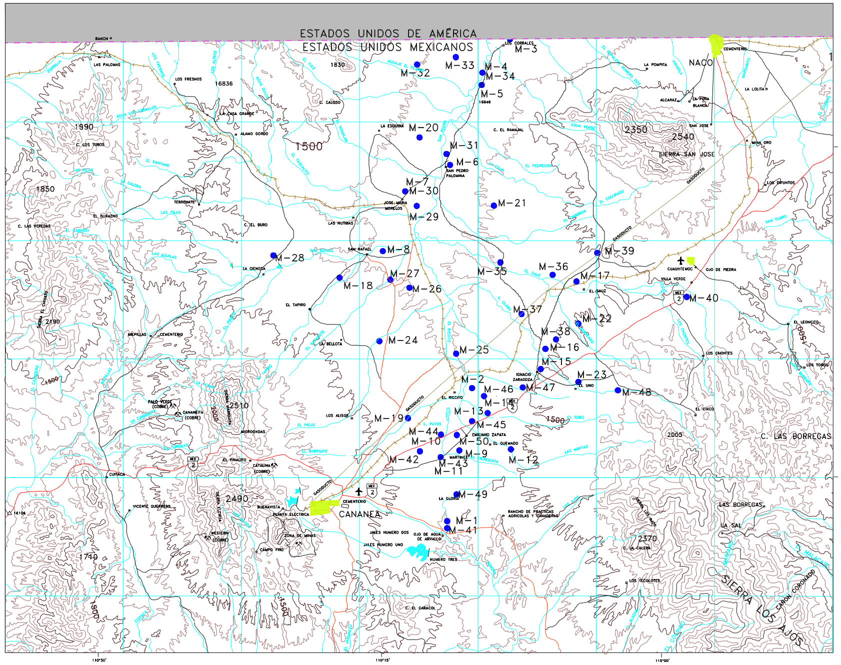
Extension with TAAP Stakeholders

Mexico, governmental	**U.S., governmental**	**Binational**	**Non-governmental**	**Mexican academic**
Comisión Nacional del Agua (CONAGUA)	Arizona Department of Water Resources (ADWR)	International Boundary & Water Commission (IBWC) / Comisión Internacional de Límites y Aguas (CILA)	Friends of the Santa Cruz River (FOSCR) Upper San Pedro Partnership	Universidad de Sonora, Instituto Tecnológico de Sonora (ITSON)
Comisión Estatal del Agua (CEA) Sonora	U.S. Bureau of Reclamation (USBOR)		Sonoran Institute	Colegio de Sonora
Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento (OOMAPAS) Nogales	City of Nogales, Arizona	UNESCO Internationally Shared Aquifer Resources Management (ISARM) program – Nov. 3-4, 2009 workshop	Water Committee of Arizona-Mexico Commission	Centro de Estudios Superiores del Estado de Sonora (CESUES)

Calidad del Agua

Data Sharing with Mexico

LOCALIZACIÓN DE APROVECHAMIENTOS MUESTREADOS

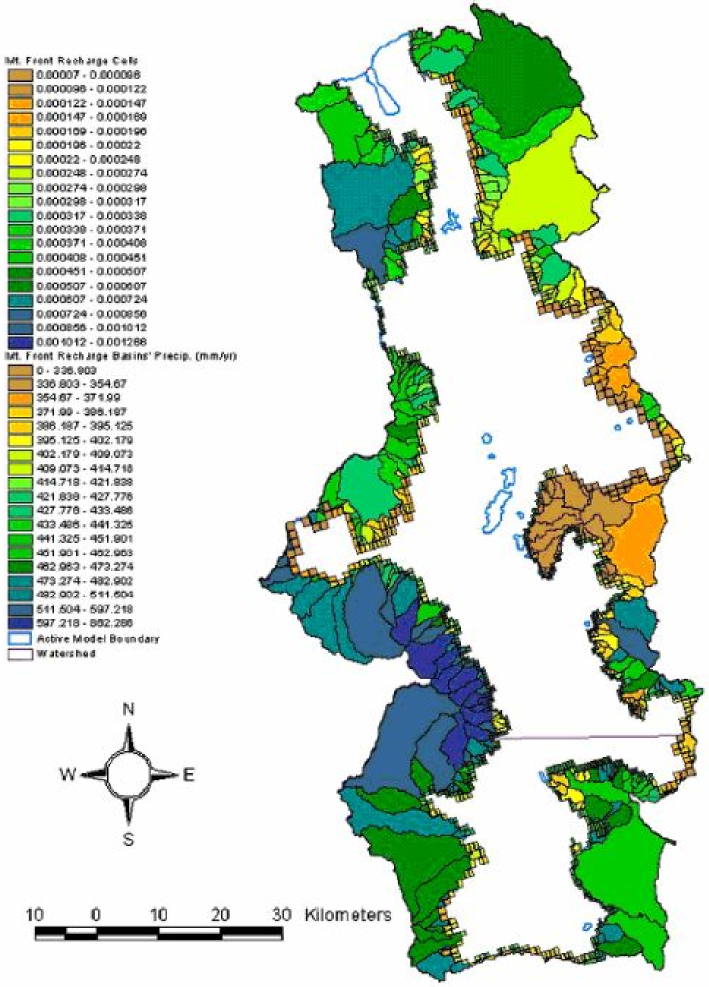


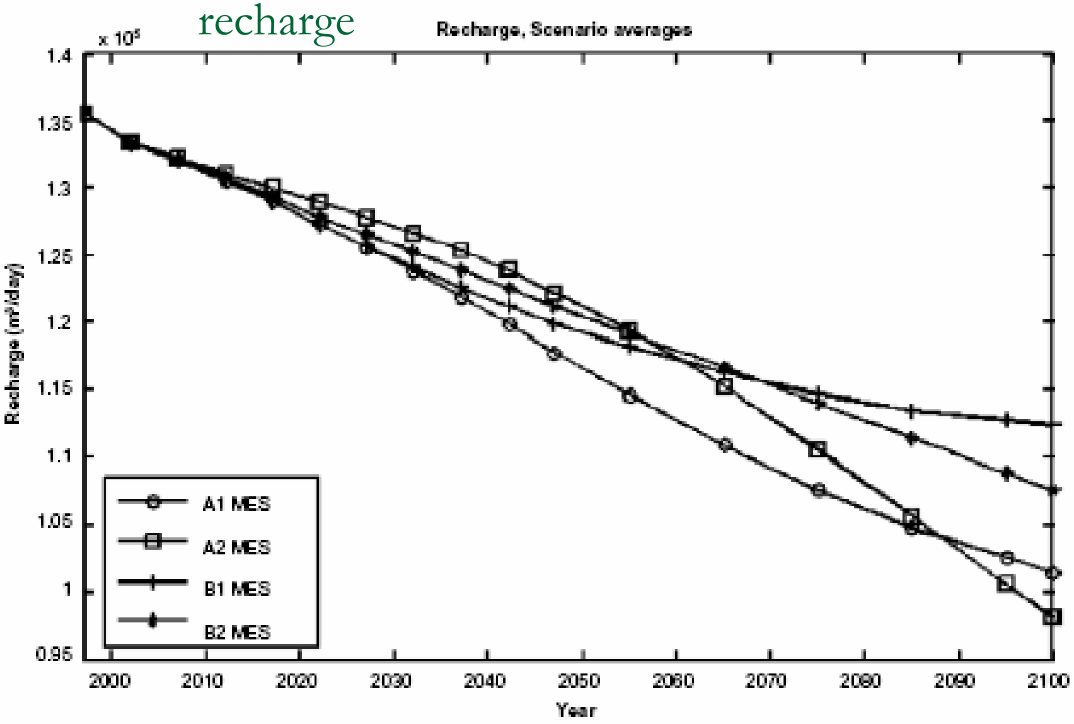
Estadísticas de piezometría
Acuífero Río San Pedro

	1997	2003	2005	2007
Niveles estáticos medidos	58	30	25	49
Mínima profundidad medida	1.97	5.39	2.79	1.60
Máxima profundidad medida	78.75	83.92	93.83	89.95

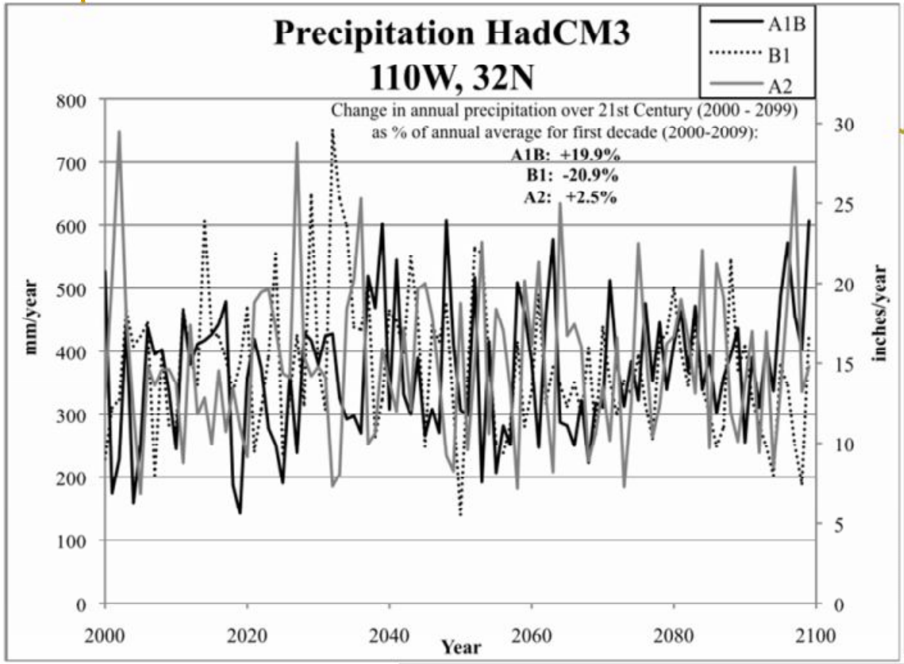
Climate Change Impacts on Groundwater Recharge

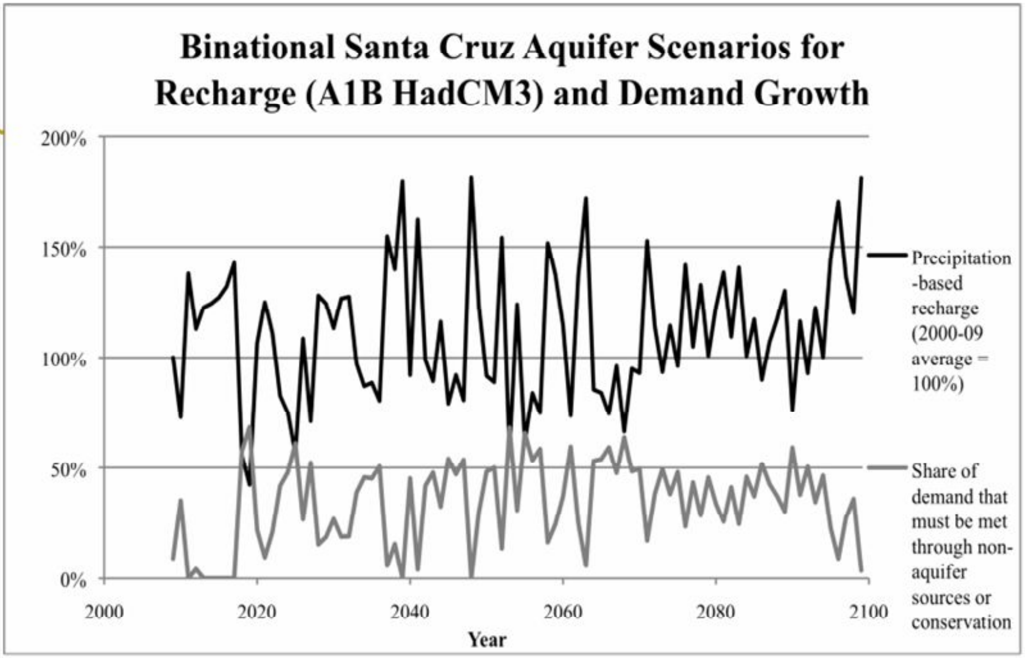
- Serrat-Capdevila et al, 2007
  - Recharge Scenarios
  - Anderson et al. (1992)
  - $\text{Log}(Q_{\text{rech}}) = -1.40 + 0.98 \cdot \text{Log}(P - 8)$
    - P = annual basin-wide precipitation (in)
    - Q_{rech} = annual mountain-front recharge (in)
    - only precipitation in excess of 8 in. yields recharge

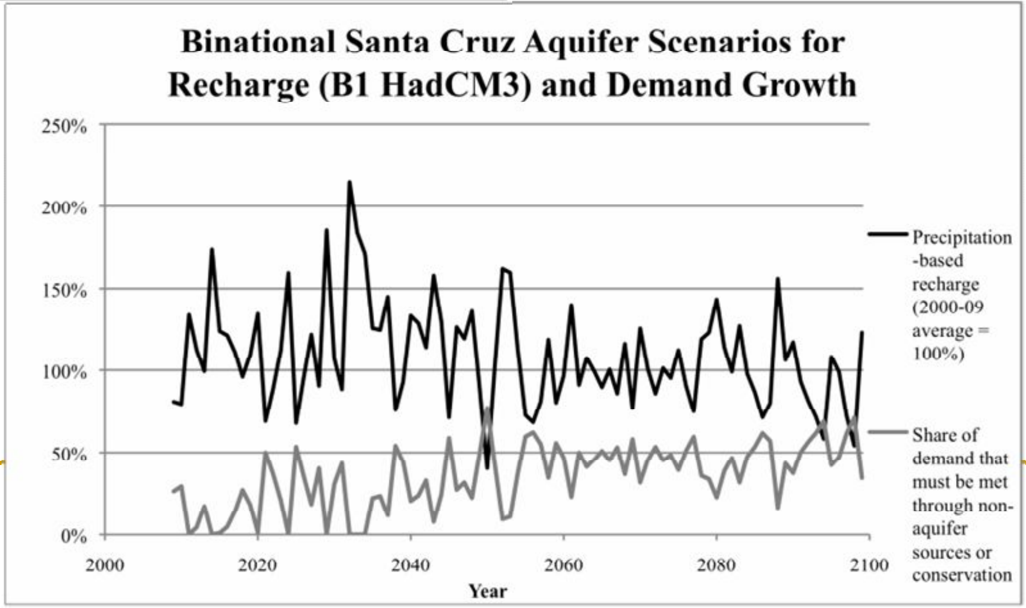




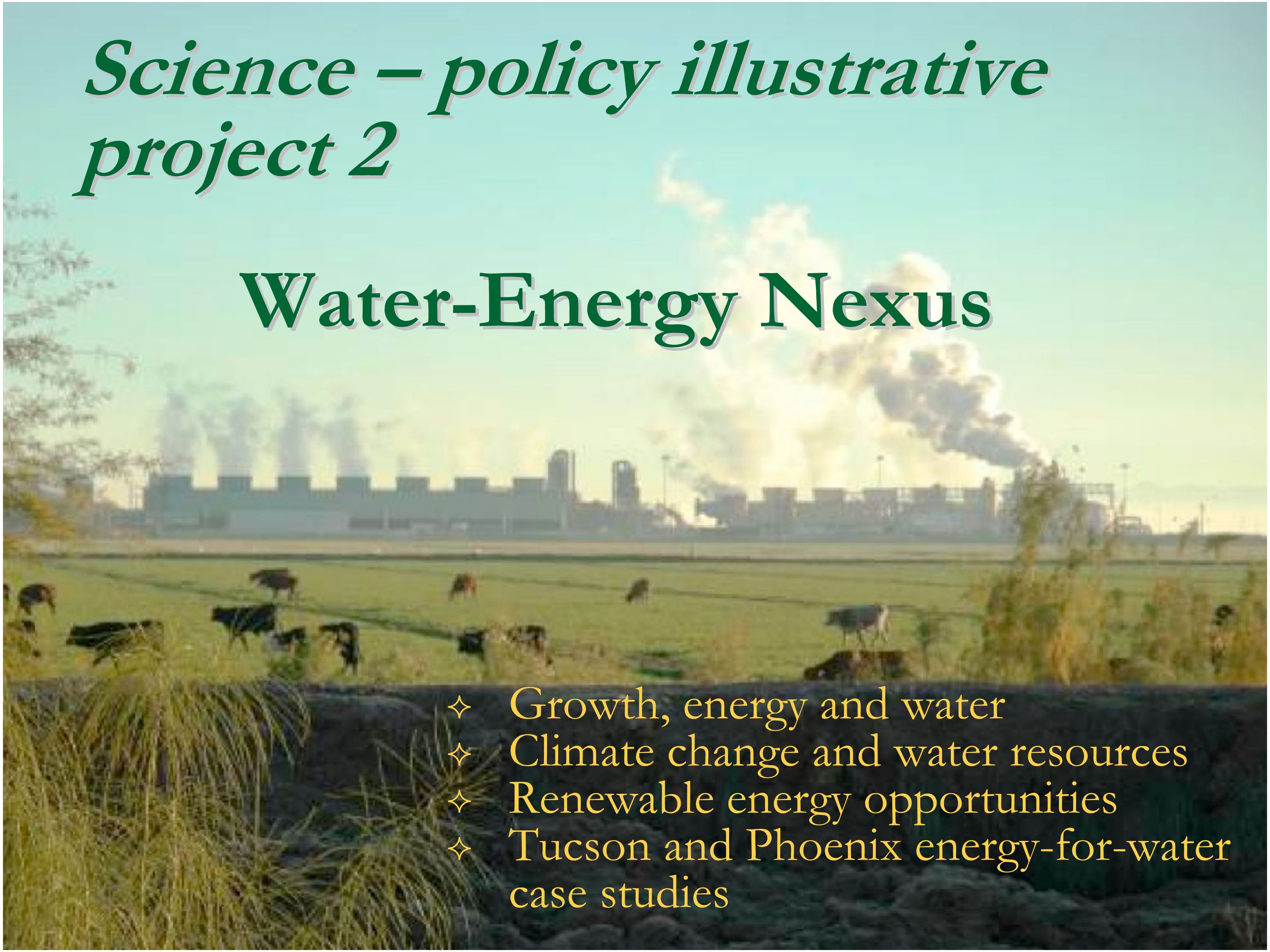
Climate Modeling: Santa Cruz Preliminary Results







Science – policy illustrative project 2



Water-Energy Nexus

- Growth, energy and water
- Climate change and water resources
- Renewable energy opportunities
- Tucson and Phoenix energy-for-water case studies

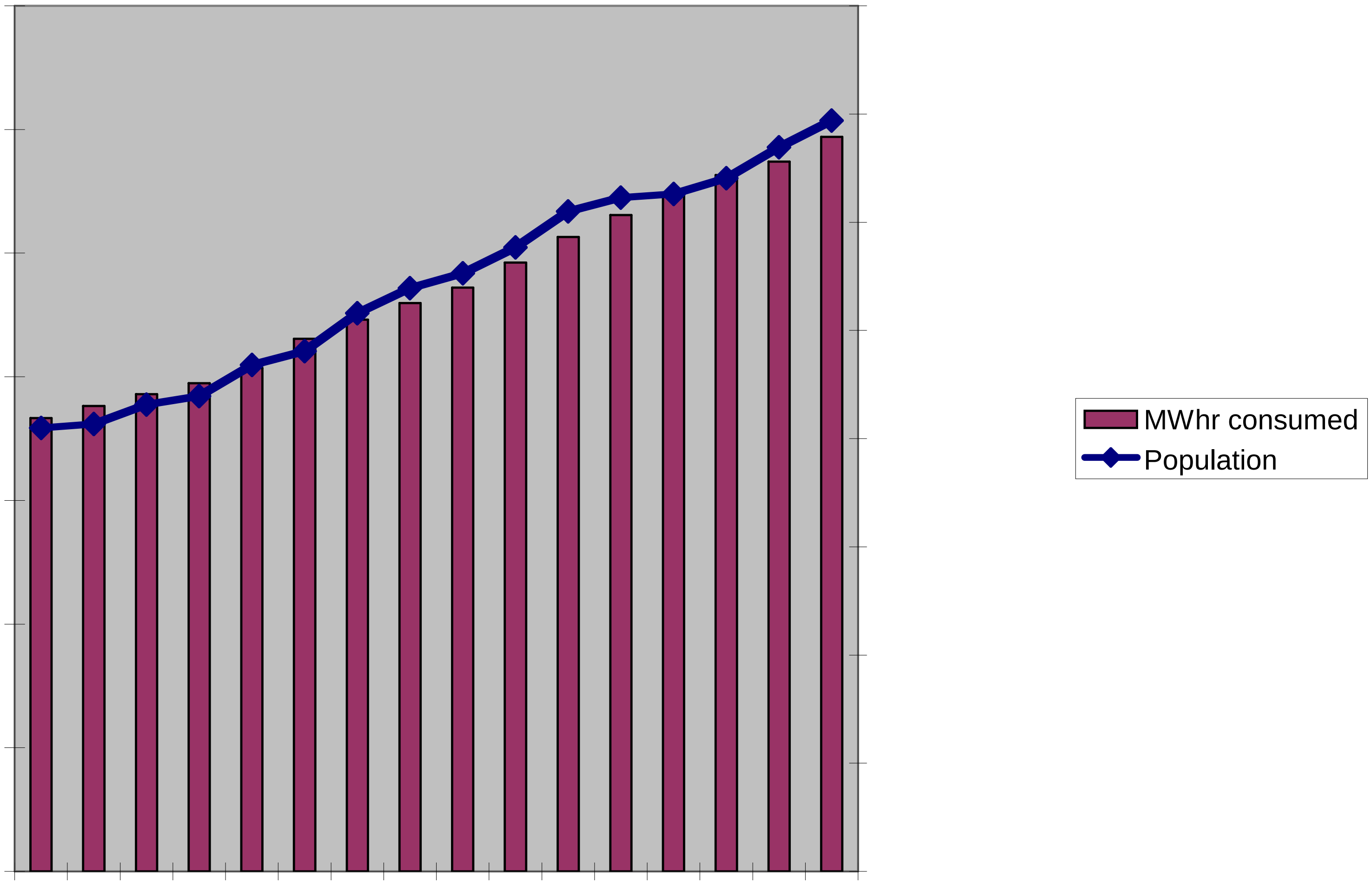
Additional Water Demand AZ 2030

	Pop. Change	%Pop. Change	WATER SCENARIOS		
	2006-2030	2006-2030	GPCD=218*	GPCD=177**	GPCD=150
Maricopa	2,443,534	59.5%	532,690,412	432,505,518	366,530,100
Pinal	582,571	14.2%	127,000,478	103,115,067	87,385,650
Pima	461,443	11.2%	100,594,574	81,675,411	69,216,450
Yavapai	142,740	3.5%	31,117,320	25,264,980	21,411,000
Mohave	135,661	3.3%	29,574,098	24,011,997	20,349,150
Yuma	120,659	2.9%	26,303,662	21,356,643	18,098,850
Navajo	52,975	1.3%	11,548,550	9,376,575	7,946,250
Cochise	52,936	1.3%	11,540,048	9,369,672	7,940,400
Coconino	41,003	1.0%	8,938,654	7,257,531	6,150,450
Santa Cruz	25,730	0.6%	5,609,140	4,554,210	3,859,500
Apache	18,756	0.5%	4,088,808	3,319,812	2,813,400
Gila	14,777	0.4%	3,221,386	2,615,529	2,216,550
Graham	8,683	0.2%	1,892,894	1,536,891	1,302,450
La Paz	6,585	0.2%	1,435,530	1,165,545	987,750
Greenlee	8	0.0%	1,744	1,416	1,200
Arizona	4,108,061	100.0%	895,557,298	727,126,797	616,209,150
			+66%	+53%	+45%

From 2006 base

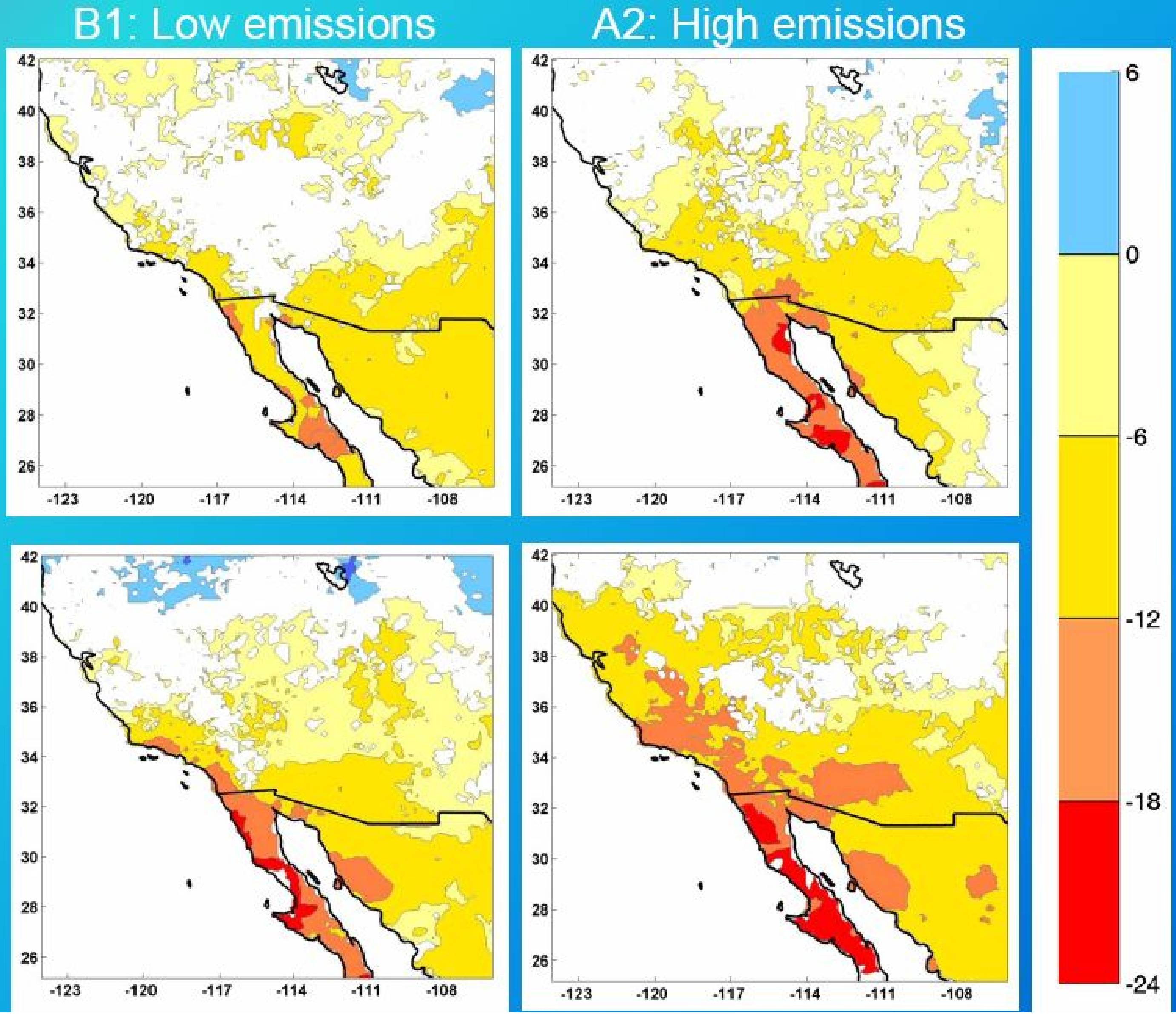
* Phoenix 2005; **Tucson 2005;
150=smart growth

Population vs Energy Demand (1990-2005)



Decadal change of precipitation (%) under B1 and A2 scenarios

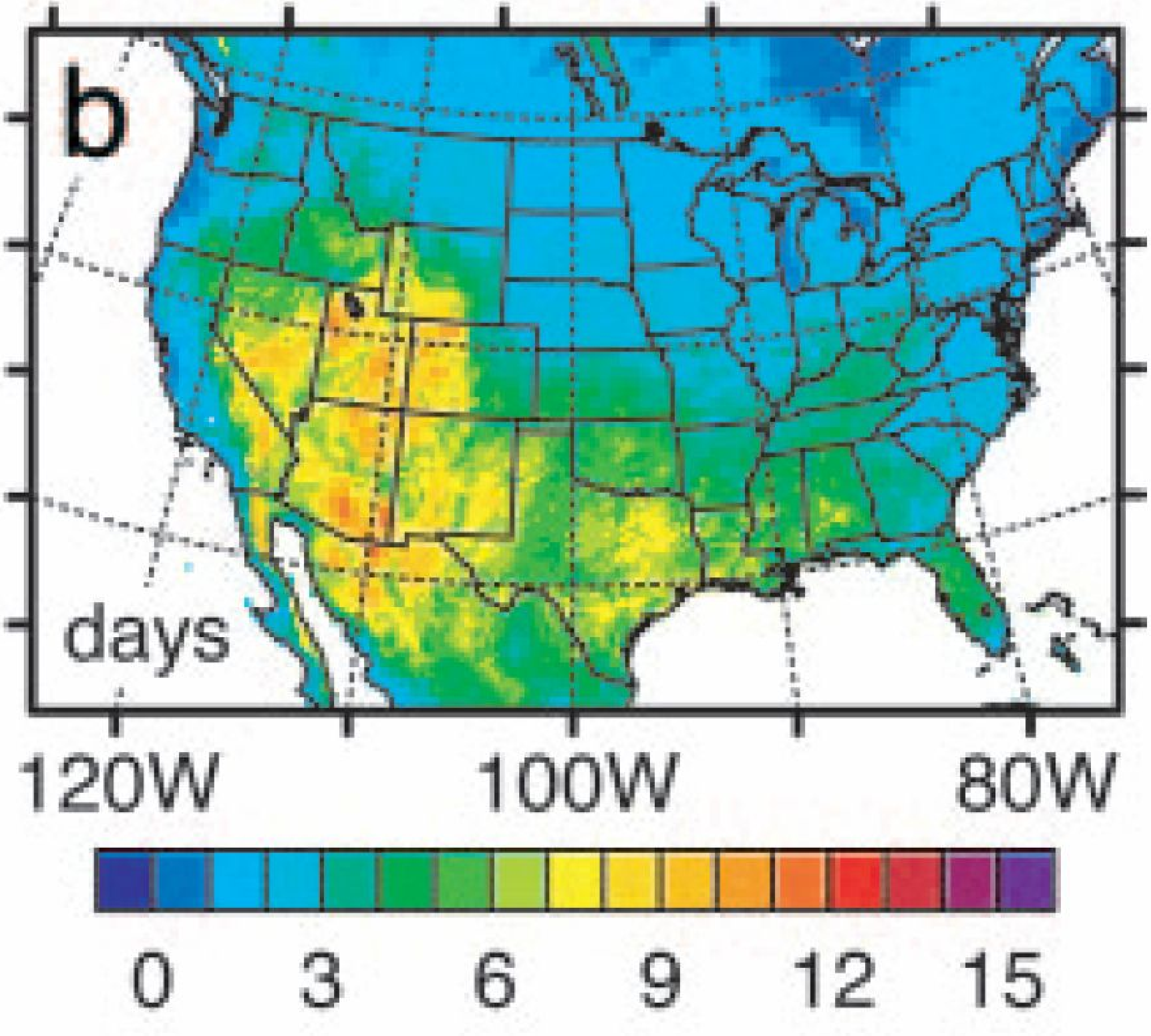
Plotted when 2/3 of the models agree on the sign of change, relative to 1961-1990



2010-2029

Cavazos and Arriaga, 2009 (in prep.)
CICESE
Presented at 2009 Border Gov. Drought Wkshp.

2030-2049



Longer Heat Waves

Diffenbaugh et al., 2005
Proceedings of the National Academy of Science

Brad Udall, WWA, Presented at 2009 Border Governors Drought Workshop

Recent Colorado River Studies Table

Source: Climate Change in Colorado, 2008

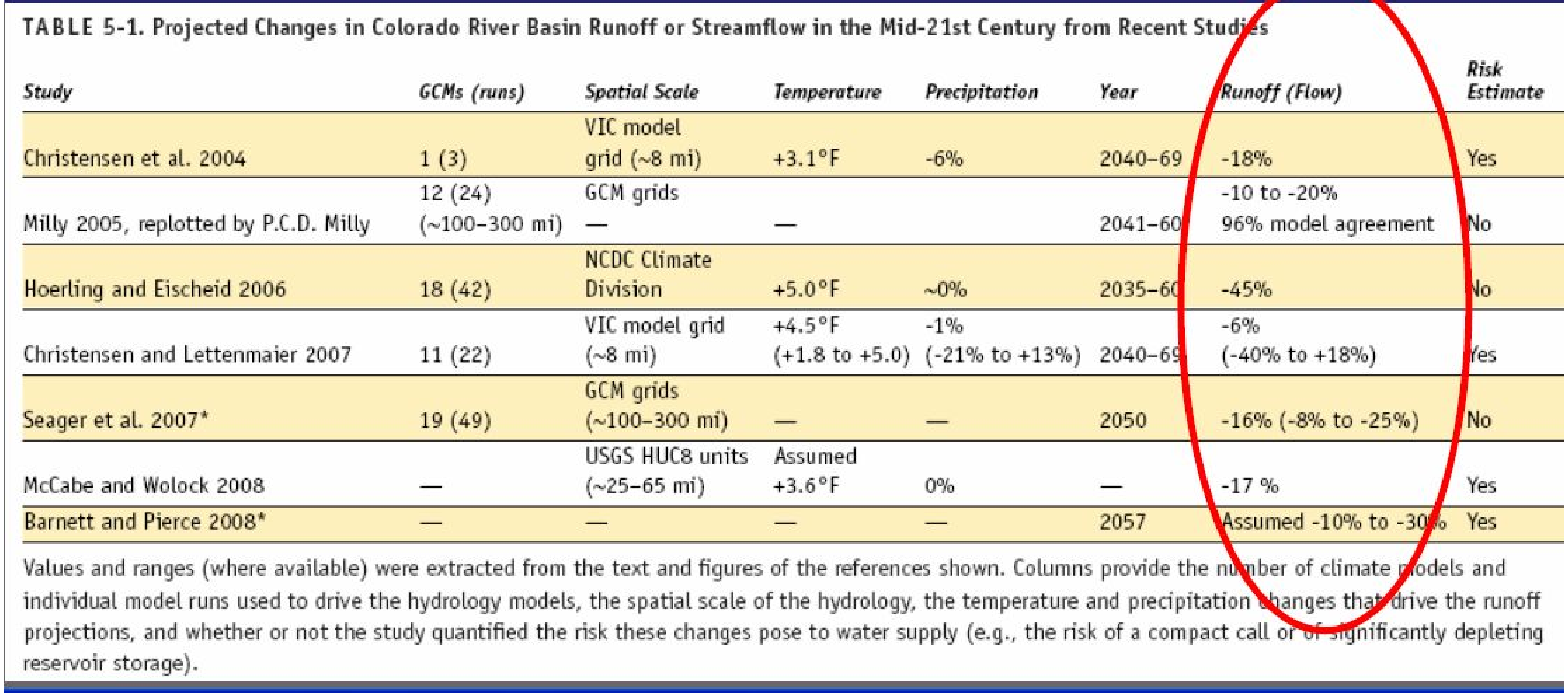
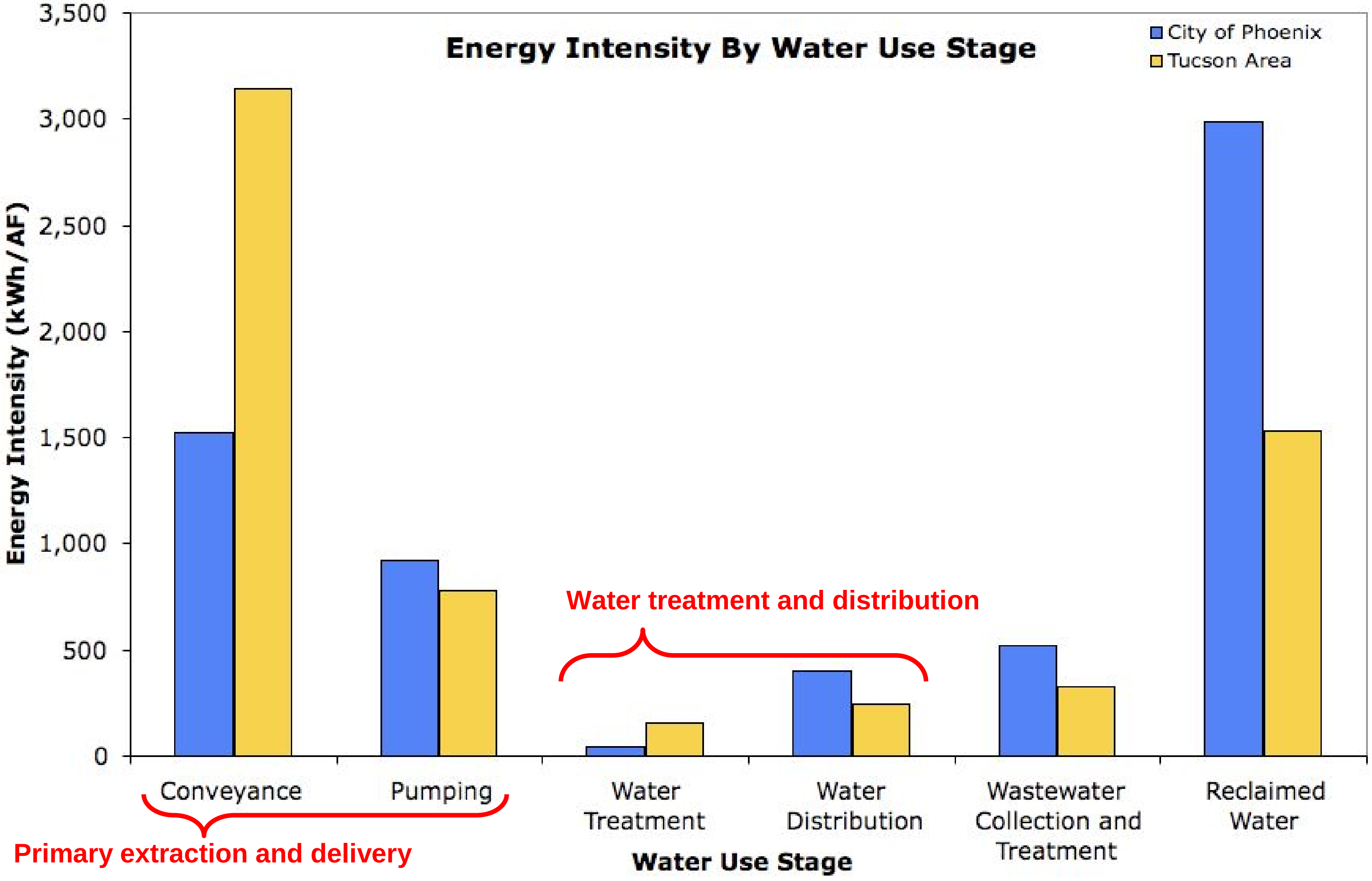


TABLE 5-1. Projected Changes in Colorado River Basin Runoff or Streamflow in the Mid-21st Century from Recent Studies

Study	*GCMs (runs)*	*Spatial Scale*	*Temperature*	*Precipitation*	*Year*	*Runoff (Flow)*	*Risk Estimate*
Christensen et al. 2004	1 (3)	VIC model grid (~8 mi)	+3.1°F	-6%	2040–69	-18%	Yes
Milly 2005, replotted by P.C.D. Milly	12 (24) (~100–300 mi)	GCM grids —	—		2041–60	-10 to -20% 96% model agreement	No
Hoerling and Eischeid 2006	18 (42)	NCDC Climate Division	+5.0°F	~0%	2035–60	-45%	No
Christensen and Lettenmaier 2007	11 (22)	VIC model grid (~8 mi)	+4.5°F (+1.8 to +5.0)	-1% (-21% to +13%)	2040–69	-6% (-40% to +18%)	Yes
Seager et al. 2007*	19 (49)	GCM grids (~100–300 mi)	—	—	2050	-16% (-8% to -25%)	No
McCabe and Wolock 2008	—	USGS HUC8 units (~25–65 mi)	Assumed +3.6°F	0%	—	-17 %	Yes
Barnett and Pierce 2008*	—	—	—	—	2057	Assumed -10% to -30%	Yes

Values and ranges (where available) were extracted from the text and figures of the references shown. Columns provide the number of climate models and individual model runs used to drive the hydrology models, the spatial scale of the hydrology, the temperature and precipitation changes that drive the runoff projections, and whether or not the study quantified the risk these changes pose to water supply (e.g., the risk of a compact call or of significantly depleting reservoir storage).

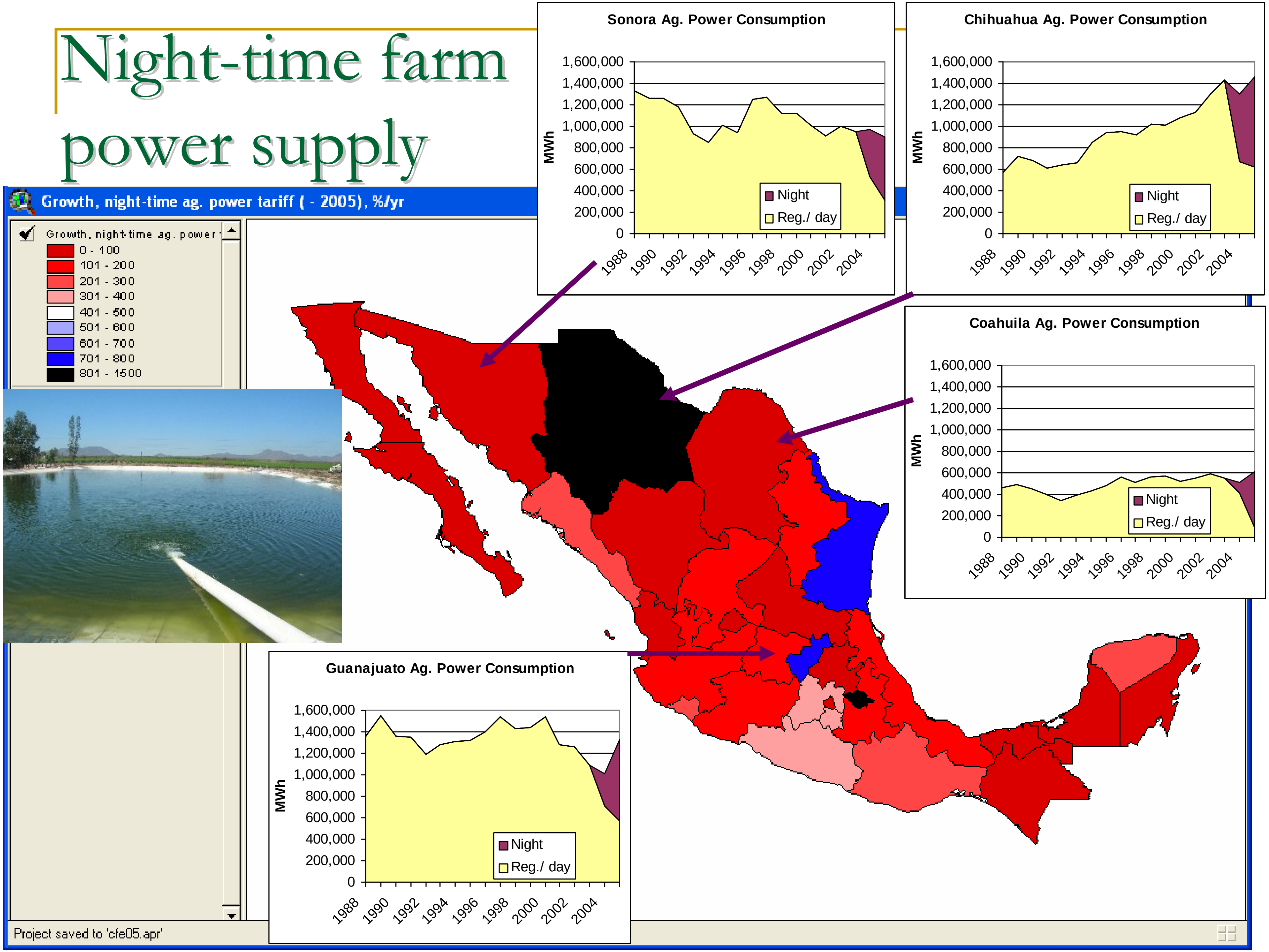
Urban Water-Energy Nexus



Water treatment and distribution

Primary extraction and delivery

Night-time farm power supply



Science-Policy Integration Synthesis: Adaptive Water Management

- Adaptation ⇨ innovation ⇨ mobilization
- Formal watershed, aquifer, and river basin organizations
- Legal instruments
- Integrated Water Resources Management (IWRM) and associated global water initiatives

Institutional and Technical Prescriptive Responses

- More crop per drop in agriculture
- Land use planning (native vegetation in place of invasive, high ET species)
- Urban eco-sanitation, water reuse
- Regulatory and economic instruments
- IWRM – multiple uses, multiple stakeholders

Science-Policy Extension

- Assessing the integration of watershed, aquifer, and water quality initiatives at river basin and political-administrative scales
- Groundwater management participatory, legal, and economic instruments
- Adaptation, innovation, and mobilization around global change processes at local scales
- IWRM and related global water initiatives: translating the concept into outcomes

Thank you.