Transformational Solutions for Climate Change Adaptation and Water Sustainability in the Colorado River Basin

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With full credit to faculty, postdoctoral researchers, and student collaborators

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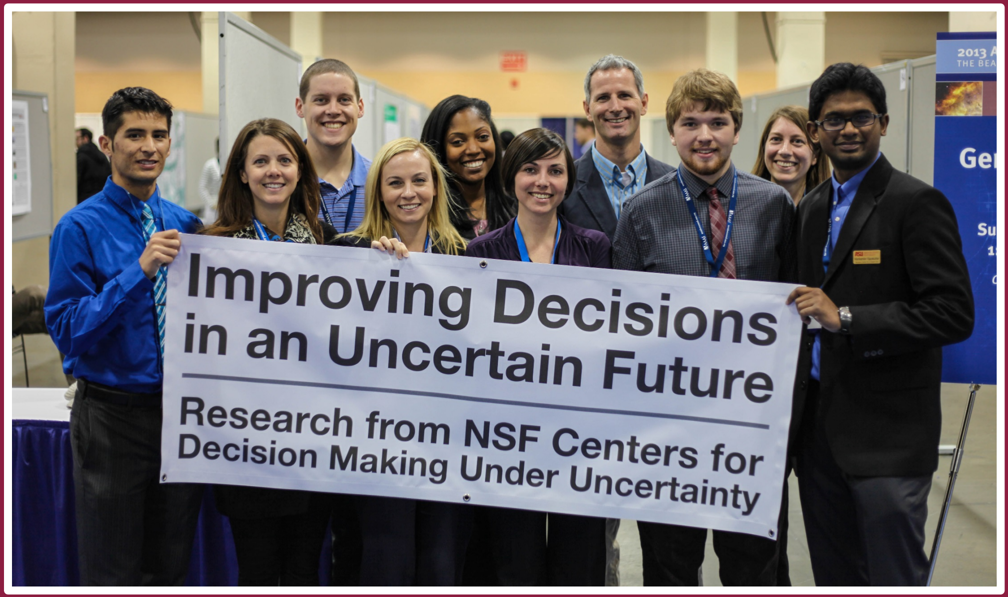

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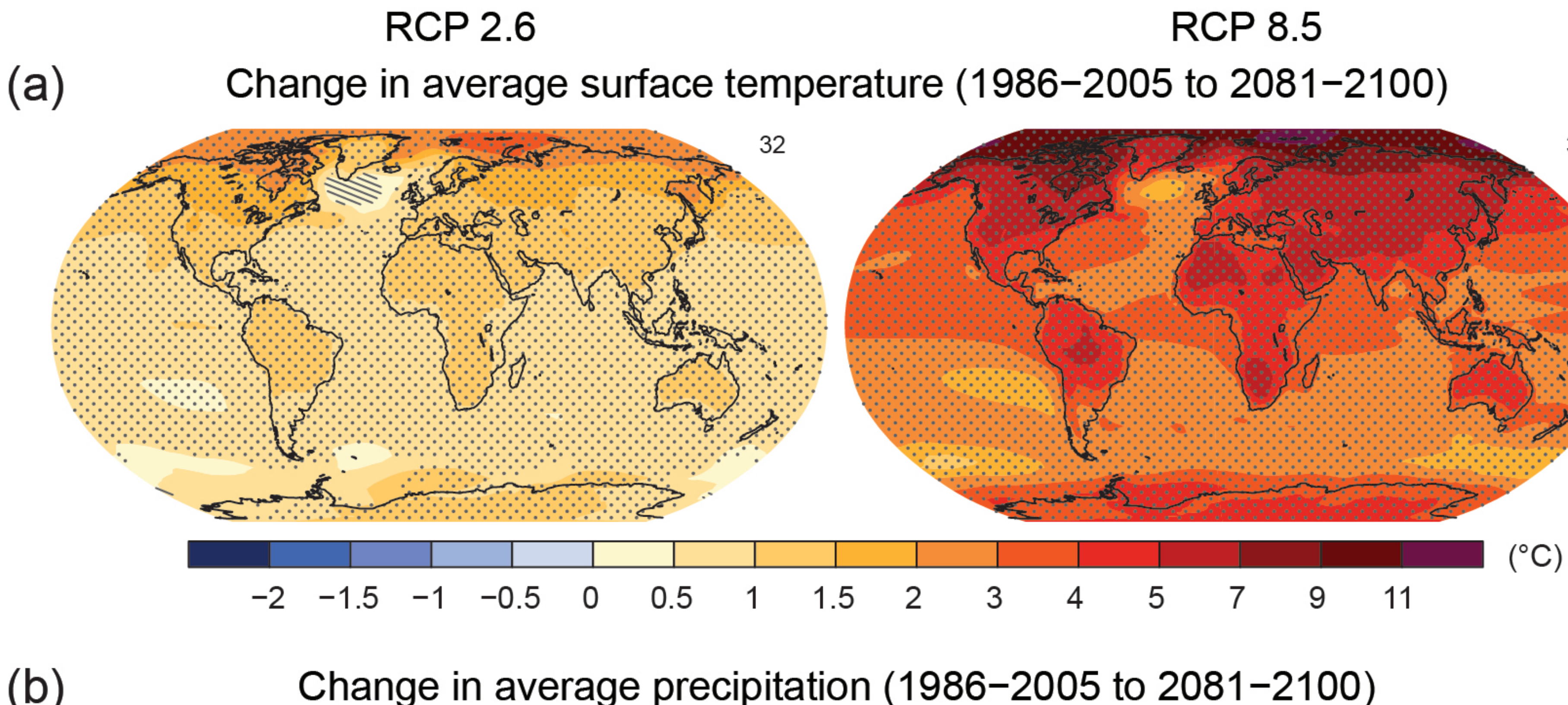
The coupled effects of global climate change and population dynamics on water systems are widely considered to be among the greatest urban sustainability challenges facing humanity in the Anthropocene.

Water Sustainability and Climate Change in the Colorado River Basin

Carly Jerla, US Bureau of Reclamation speaks as part of DCDC-sponsored forum on Water Reuse, October, 2013

IPCC has consistently reported, with high confidence, that the hydrologic effects of climate change in the West will be negative and significant (Jiménez Cisneros et al. 2014)



Warming, droughts, reduced snowpack, and decreased river flows are consistent with anthropocentric climate change and may be occurring faster than predicted (Overpeck and Udall, 2010)

CLIMATE CHANGE

Dry Times Ahead

The climate of the western United States could become much drier over the course of this century.

Jonathan Overpeck[1] and Bradley Udall[2]

In the past decade, it has become impossible to overlook the signs of climate change in western North America. They include soaring temperatures, declining late-season snowpack, northward-shifted winter storm tracks, increasing precipitation intensity, the worst drought since measurements began, steep declines in Colorado River reservoir storage, widespread vegetation mortality, and sharp increases in the frequency of large wildfires. These shifts have taken place across a region that also saw the nation's highest population growth during the same period.

The climate changes in western North America, particularly the Southwest, have outstripped change elsewhere on the continent, save perhaps in the Arctic. In the past decade, many locations, notably in the headwaters region of the Colorado River, have been more than 1°C warmer than the 20th-century average. This warming has been the primary driver in reducing late-season snowpack and the annual flow of the Colorado River (*1*, *2*). These reductions, coupled with the most severe drought observed since 1900, have caused the biggest regional water reservoirs—Lake Powell and Lake Mead—to decline from nearly full in 1999 to about 50% full in 2004; there has been no substantial recovery since. All of these changes, as well as dramatic warming and drying elsewhere in the region and deep into Mexico, are consistent with projected anthropogenic climate change, but seem to be occurring faster than projected by the most recent national (*2*) and international (*3*) climate change assessments; this could indicate that substantially more severe warming and drying lies ahead.

The land surface of the West is also changing at a rate that is unprecedented since systematic monitoring began in the 20th century. Background tree mortality rates in western U.S. forests have increased rapidly in recent decades (*4*), and more than a million hectares of piñon pine mortality in the

Southwest has been
of record warm ter
not seen previously
Moreover, the bac
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change (*4*). Even
western deserts are
spread drought-ind
A clear link with r
again implicates gl
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drought" (*5*) and u
impacts. Similarly,
and associated snow
an accelerating inc
large wildfires (*7*).

The warming a
can be confidently
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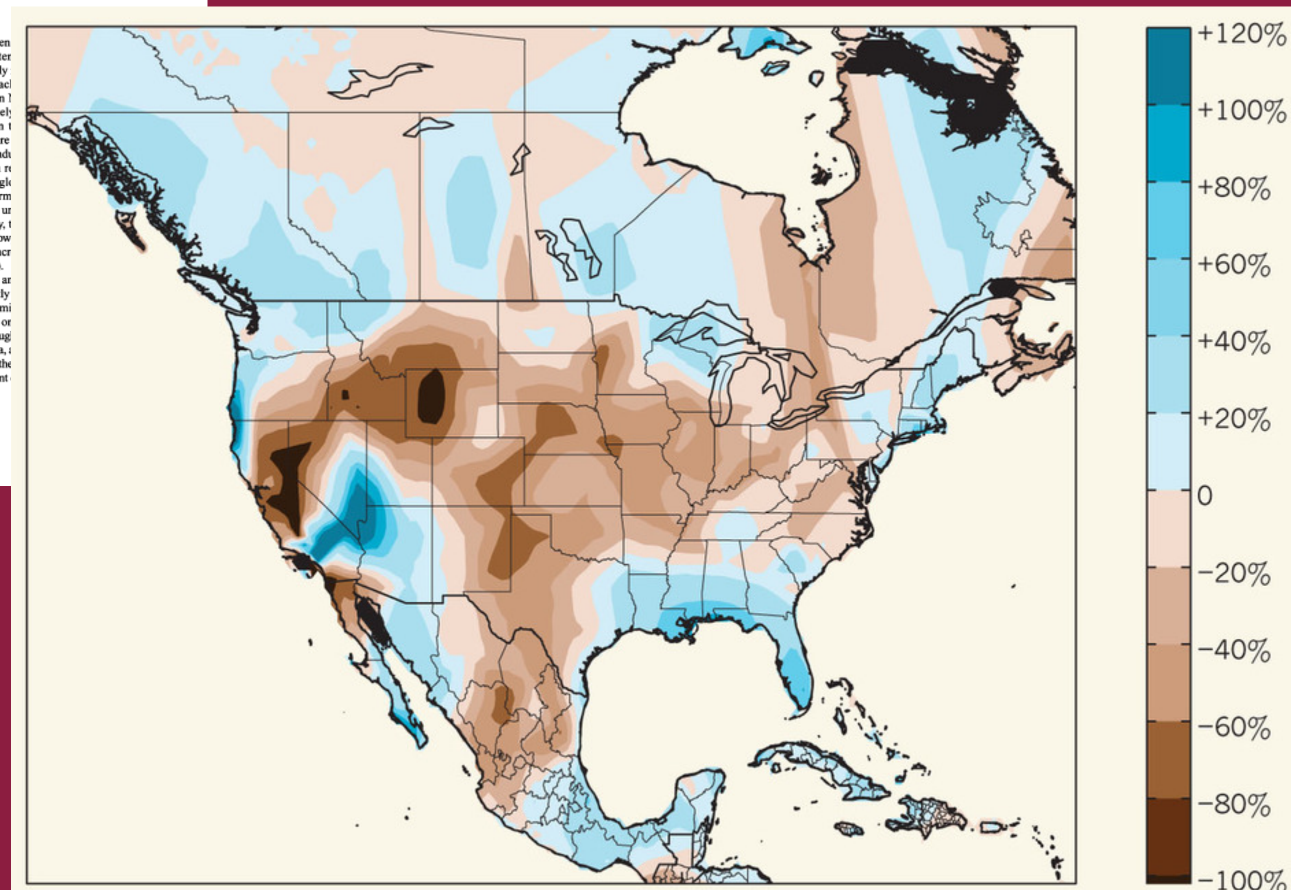
ern North America,
occurred prior to the
cause of the current

[1]Climate Assessment of the Southwest, University of Arizona, 845 N. Park Avenue, Suite 532, Tucson, AZ 85721, USA. [2]Western Water Assessment, University of Colorado, 325 Broadway R/PSD, Boulder, CO 80305, USA. E-mail: jto@email.arizona.edu; bradley.udall@colorado.edu



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Overpeck, J. T. (2013). Climate science: The challenge of hot drought. *Nature*, *503*(7476), 350-351.

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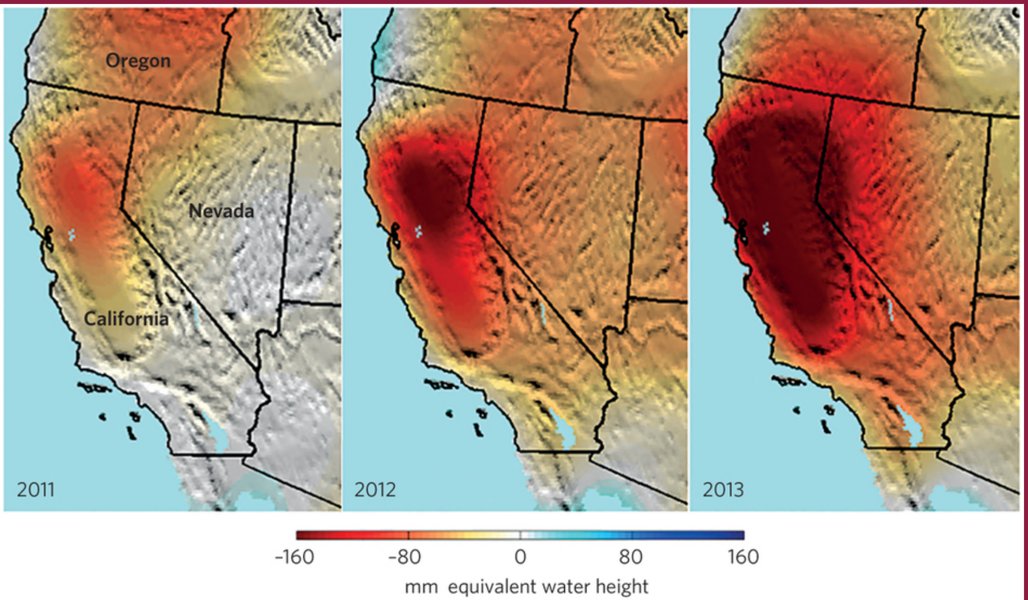
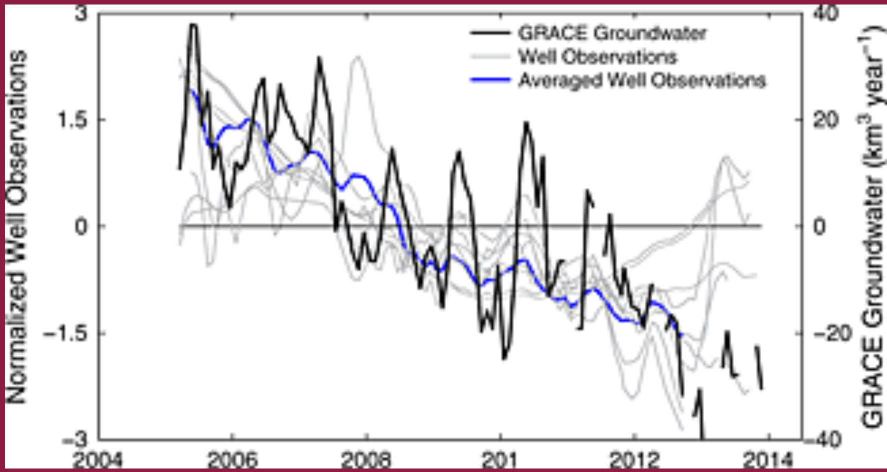
The present drought in the West is the most extreme in over a century (Cayan et al. 2010), affecting not only surface-water storage but also groundwater reserves (Castle et al. 2014).



Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change*, *4*(11), 945-948.



Geophysical Research Letters
Volume 41, Issue 16, pages 5904-5911, 29 AUG 2014
DOI: 10.1002/2014GL061055

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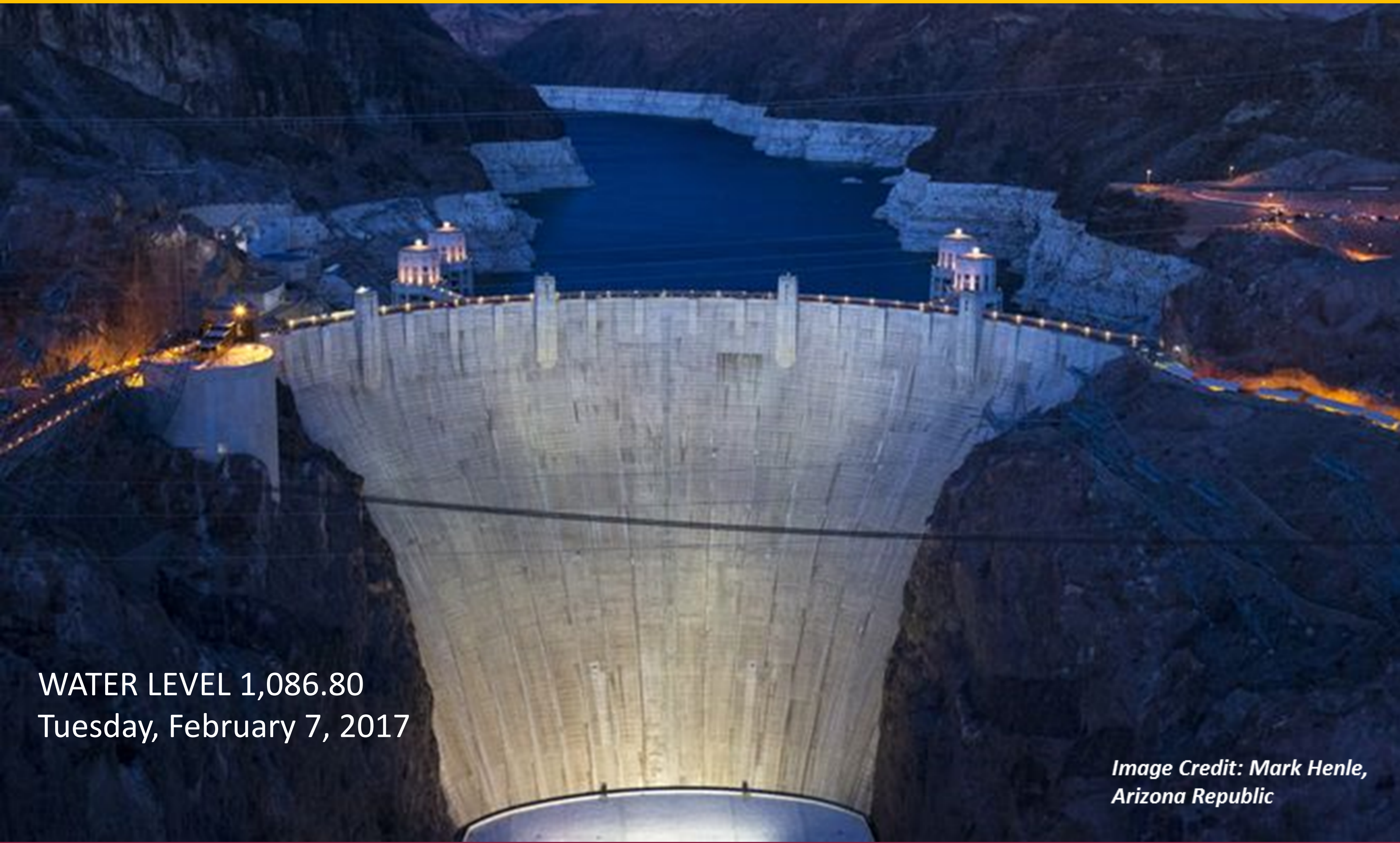
Water levels in the major Colorado River reservoirs are at historic lows



WATER LEVEL 1,086.80
Tuesday, February 7, 2017

Image Credit: Mark Henle, Arizona Republic

Future drought may exceed even the driest centuries of the Medieval Climate Anomaly, leading to unprecedented drought conditions (Cook et al., 2015)

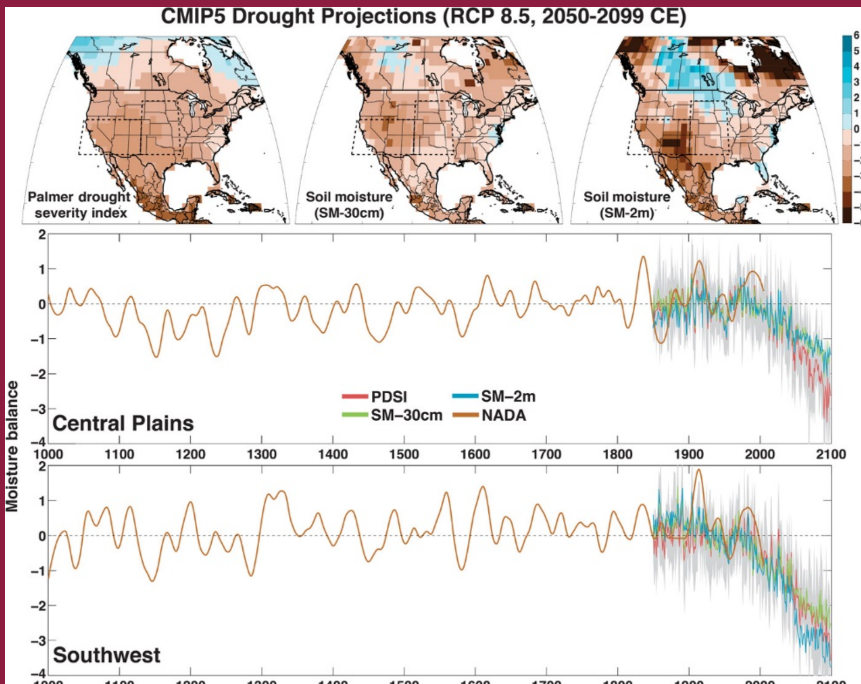


Fig. 1 Top: Multimodel mean summer (JJA) PDSI and standardized soil moisture (SM-30cm and SM-2m) over North America for 2050–2099 from 17 CMIP5 model projections using the RCP 8.5 emissions scenario.

Given environmental and societal uncertainties, how can cities dependent on the CRB develop transformational solutions to implement water sustainability transitions?

Decision making under uncertainty

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Article

Decision-Making under Uncertainty for Water Sustainability and Urban Climate Change Adaptation

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Abstract: Complexities and uncertainties surrounding urbanization and climate change complicate water resource sustainability. Although research has examined various aspects of complex water systems, including uncertainties, relatively few attempts have been made to synthesize research findings in particular contexts. We fill this gap by examining the complexities, uncertainties, and decision processes for water sustainability and urban adaptation to climate change in the case study region of Phoenix, Arizona. In doing so, we integrate over a decade of research conducted by Arizona State University's Decision Center for a Desert City (DCDC). DCDC is a boundary organization that conducts research in collaboration with policy makers, with the goal of informing decision-making under uncertainty. Our results highlight: the counterintuitive, non-linear, and competing relationships in human–environment dynamics; the myriad uncertainties in climatic, scientific, political, and other domains of knowledge and practice; and, the social learning that has occurred across science and policy spheres. Finally, we reflect on how our interdisciplinary research and boundary organization has evolved over time to enhance adaptive and sustainable governance in the face of complex system dynamics.

"Second, there is a need for more research that is not only *place-based* but also *comparative* (e.g., cross-site, cross-ecosystem, cross-cultural) to advance sustainability science. Such research will be essential in identifying both context-specific and generalizable patterns and relationships.

Third, we should increase our focus on understanding and informing sustainability transitions in ways that are anticipatory, adaptive, and responsive to stakeholder needs and interests."

DCDC III: Transformational Solutions for Urban Water Sustainability Transitions

asu news [science & tech]

August 21, 2015

NSF award will expand scope, impact of ASU water research

Posted: August 21, 2015

In the grips of long-term drought, the Colorado River Basin and the cities that rely on its water face unprecedented challenges and significant uncertainty with a warming climate and large-scale land-use change. They are developing new water-resource policies for a future of increasing uncertainty.

Now, water managers and decision makers of cities of the Colorado River Basin will be able to take greater advantage of Arizona State University's Decision Center for a Desert City (DCDC) thanks to a new $4.5 million National Science Foundation award.

The four-year award, the third made to DCDC in

A new National Science Foundation grant will allow ASU to expand the geographic scope of Decision Center for a Desert City's work beyond Phoenix to include other cities dependent on Colorado River water sources, such as Lake Mead.

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Urban Sustainability Transitions

- Traditional water governance regimes are ill-equipped to respond to these challenges
  - expert-driven, overly bureaucratic, and rely on technocratic and hard-path engineering solutions
  - suffer from path dependence and lack institutional incentives to consider transformational changes
- While managing transitions requires understanding biophysical drivers and constraints on systems, our focus is on decision making, institutional dynamics, governance, and multi-sector coordination
  - managing transitions toward urban water sustainability in an era of climate change requires innovative approaches to governance that are anticipatory, adaptable, just, and evidence-supported

Table 1. Contrasting elements of adaptation and transformation.

Adaptation	Transformation
Incremental change	Major, potentially fundamental, change
Respond to shock	Action in anticipation of major stresses
Maintain previous order	Create new order, open ended
Build adaptive capacity	Reorder system dynamics
Emergent properties guide trajectory	Build agency, leadership, change agents

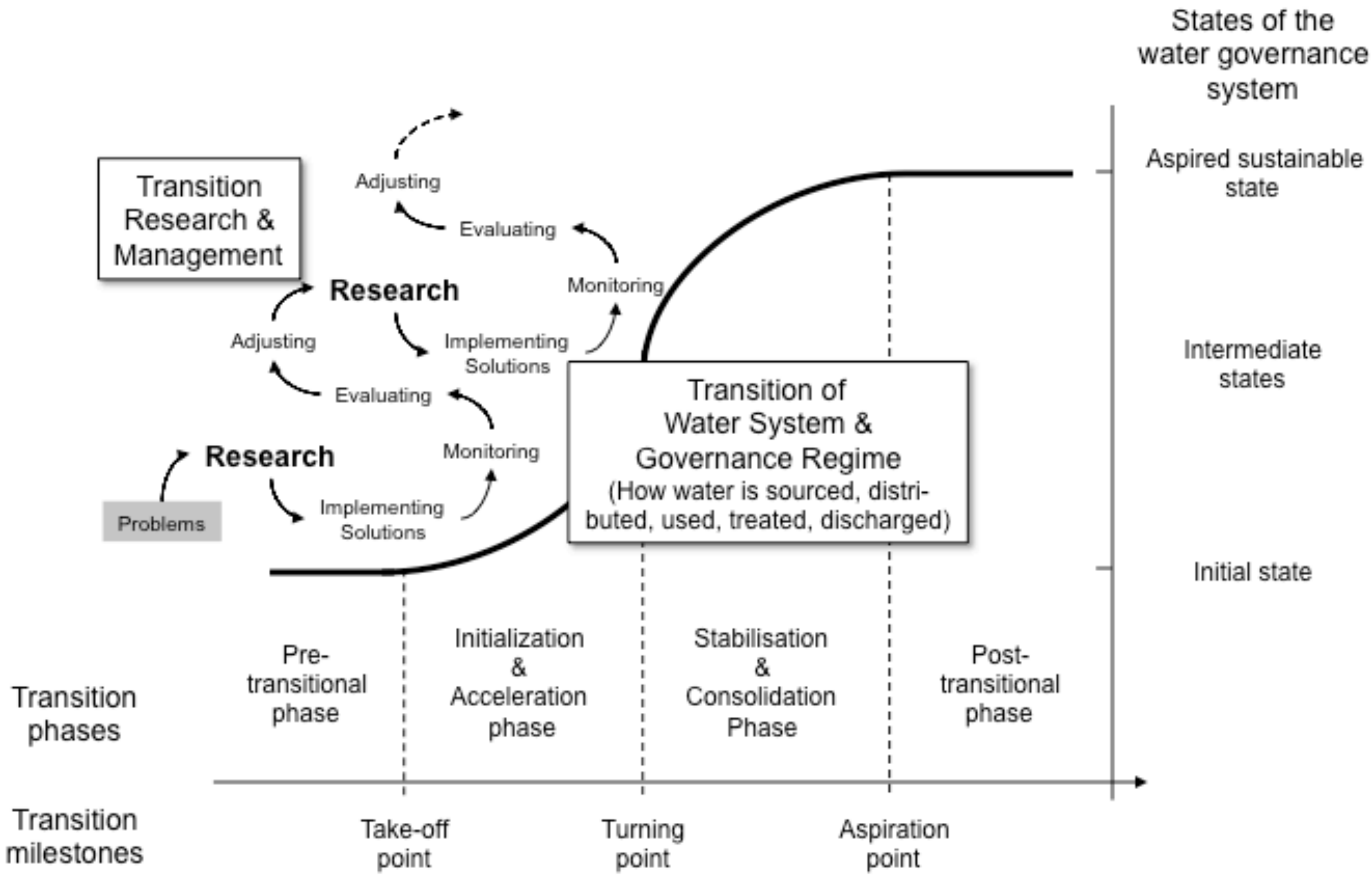
Table 2. Contrasting elements of resilience and sustainability.

Resilience Theory Approach	Sustainability Science Approach
Change is normal, multiple stable states	Envision the future, act to make it happen
Experience adaptive cycle gracefully	Utilize transition management approach
Origin in ecology, maintain ecosystem services	Origin in social sciences, society is flawed
Result of change is open ended, emergent	Desired results of change are specified in advance
Concerned with maintaining system dynamics	Focus is on interventions that lead to sustainability
Stakeholder input focused on desirable dynamics	Stakeholder input focused on desirable outcomes

Redman, C. (2014). Should sustainability and resilience be combined or remain distinct pursuits?. *Ecology and Society, 19(2*).

Solutions Framework for Transitions

- We use the term *solution* to refer to both substantive changes made to socio-ecological-technical systems (*outcomes*) and the path that led to the changes (*process*)
- The framework enables specific knowledge to be constructed about individual potential water solutions consisting of three distinct knowledge areas:
  - a. What is the *effectiveness and efficiency* of a water solution?
  - b. What is the *cause* of a water solution?
  - c. What is the *scalability and transferability* of a water solution?
- The framework supports generalization of knowledge on water solutions through meta-analyses based direct comparison of water solutions without losing important context information
- Framework is structured into four modules with goal to guide *inventorying, analyzing, evaluating, and extrapolating solutions*


States of the water governance system
Aspired sustainable state
Intermediate states
Initial state
Transition Research & Management
Adjusting
Evaluating
Monitoring
Research
Implementing Solutions
Adjusting
Evaluating
Monitoring
Research
Implementing Solutions
Problems
Transition of Water System & Governance Regime
(How water is sourced, distri-buted, used, treated, discharged)
Transition phases
Pre-transitional phase
Initialization & Acceleration phase
Stabilisation & Consolidation Phase
Post-transitional phase
Transition milestones
Take-off point
Turning point
Aspiration point

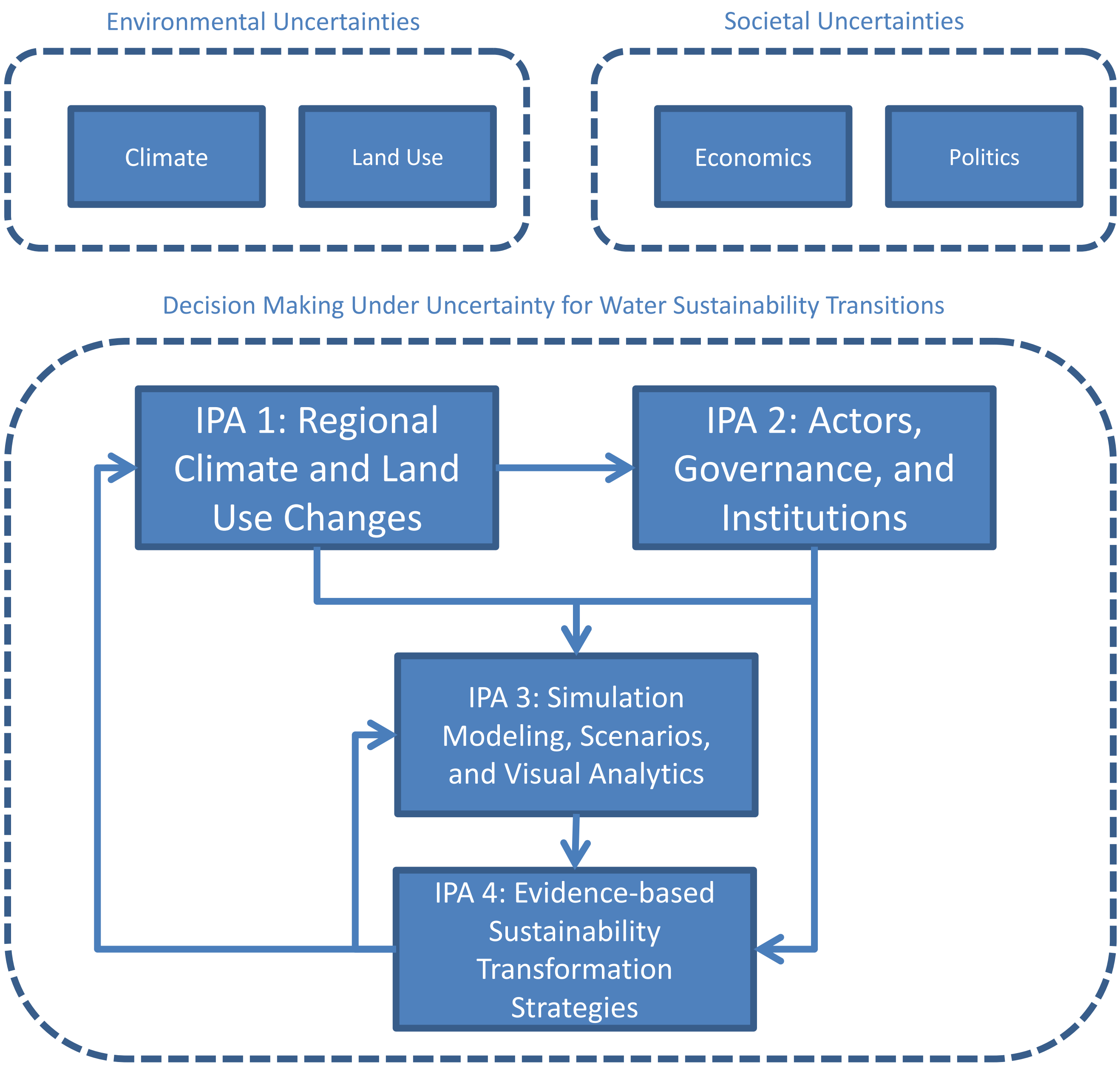


Figure 3. Integrated analytical framework for theory of decision making under multiple uncertainties to inform water sustainability transitions in the CRB.

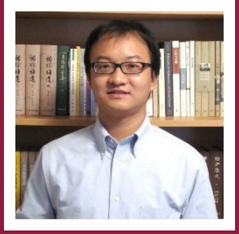
Regional Climate and Land-Use Changes as Biophysical Drivers of Urban Water Systems Decision Making Under Uncertainty

IPA 1

IPA 2

IPA 3

IPA 4



Enrique Vivoni

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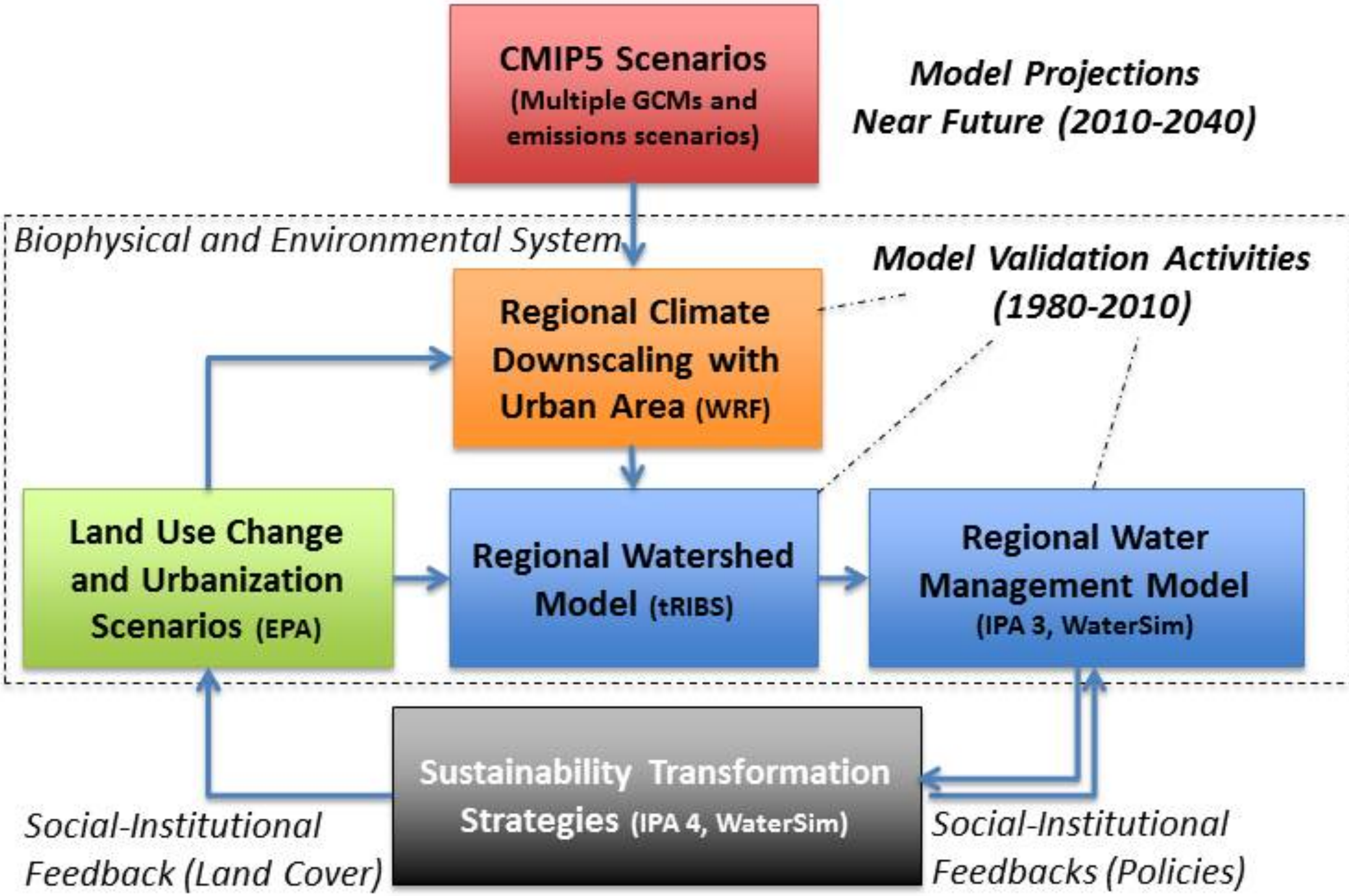
CMIP5 Scenarios
(Multiple GCMs and emissions scenarios)
Model Projections
Near Future (2010-2040)
Biophysical and Environmental System
Model Validation Activities
(1980-2010)
Regional Climate Downscaling with Urban Area (WRF)
Land Use Change and Urbanization Scenarios (EPA)
Regional Watershed Model (tRIBS)
Regional Water Management Model
(IPA 3, WaterSim)
Sustainability Transformation Strategies (IPA 4, WaterSim)
Social-Institutional Feedback (Land Cover)
Social-Institutional Feedbacks (Policies)

Actors, Institutions, and Governance as Socioeconomic Drivers of and Constraints on Urban Water Systems Decision Making

IPA 1

IPA 2

IPA 3

IPA 4

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Amber Wutich

Michael Hanemann

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Actors, Institutions, and Governance

- Toward water sensitive cities in the Colorado River basin: A comparative historical analysis to inform future water sustainability transitions
- Climate adaptation framing and discourse in Phoenix, Denver, and Las Vegas
- Urban water demand: Sustainability challenges and transformational solutions of academic scientists, water consultants, and utility managers

2016 DCDC Urban Water Demand Roundtable
Denver, Co

1990s

Denver & Colorado

1997 Denver Water issued a new Conservation Master Plan including water conservation strategies. The strategies were informed in part by the Citizens Advisory Committee

Las Vegas & Nevada

1991 The Southern Nevada Water Authority was established, with responsibility for addressing long term water needs and concerns

1993 The Las Vegas Valley Water District officially became the manager of the Southern Nevada Water Authority

1995 The first conservation plan for the Las Vegas region was developed by the Las Vegas Valley Water District, the Southern Nevada Water Authority, and other agencies

Phoenix & Arizona

1993 The Central Arizona Groundwater Replenishment District was established

1994 The Salt River Project began a water banking project as part of Arizona's efforts to maximize its allocation of Colorado River water

1995 The Arizona Department of Water Resources' rules requiring water users to establish their water use "is from an assured or adequate water supply" became active

1996 The Arizona Water Banking Authority was created in an effort to allow Arizona to maximize its use of its water from the CAP

1996 The height of the Theodore Roosevelt Dam was increased for safety and to prepare for greater water demand in the Phoenix metro area

1999 The Secretary of the Interior issued regulations that allowed interstate water banking among the lower basin Colorado River states

2000 The Colorado River Interim Surplus Guidelines were adopted by the U.S. Bureau of Reclamation, detailing what constitutes surplus conditions in the Colorado River's lower basin

2000s

Denver & Colorado

2002 A severe drought hit Colorado, one the worst in the state's history, and Denver Water enforced mandatory water restrictions

2004 Denver Water opened a recycled water treatment plant to provide recycled wastewater to industrial and agricultural parties

2006 Denver Water began a new water conservation advertising campaign, entitled "Use Only What You Need"

Las Vegas & Nevada

2002 More than a million people were officially served by the Las Vegas Valley Water District

2007 The official preservation site for the Las Vegas Springs, the Springs Preserve, was opened

Phoenix & Arizona

2003 The Governor's Drought Task Force was established

2005 The Arizona legislature enacted the Community Water System planning and reporting requirements

2007 The Arizona legislature issued mandatory water adequacy regulations

2007 The Seven Basin States' Affirmation Agreement for Colorado River management was finalized. The U.S. Bureau of Reclamation implemented guidelines (through 2026) for management of lakes Mead and Powell

2009 The draft Environmental Impact Statement for Denver Water's proposal to raise Gross Dam by 125 feet was released

Simulation Modeling, Visual Analytics, and Scenarios for Integrating & Exchanging Knowledge

IPA 1

IPA 2

IPA 3

IPA 4

Ross Maciejewski

Ray Quay

David Sampson

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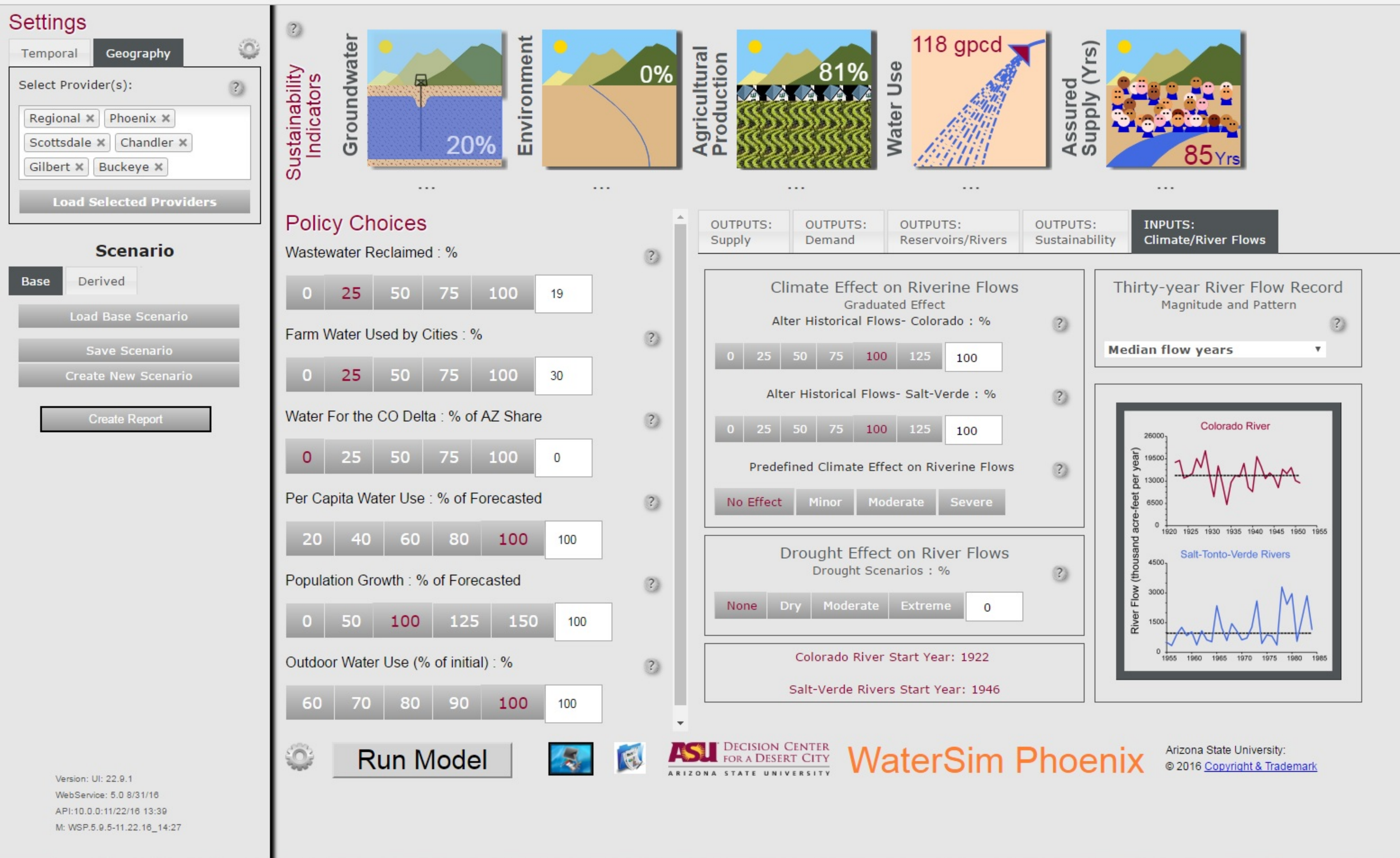

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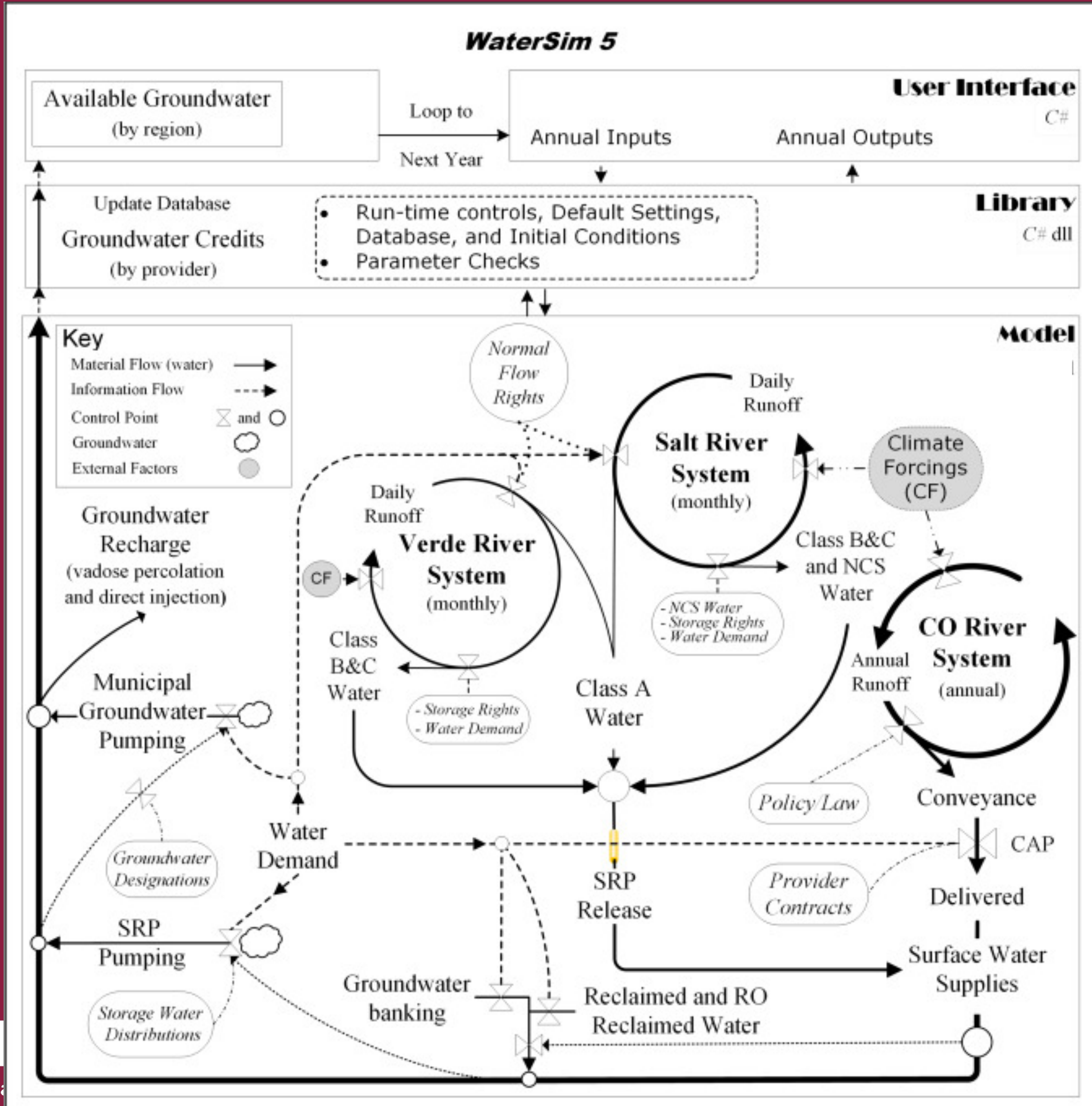
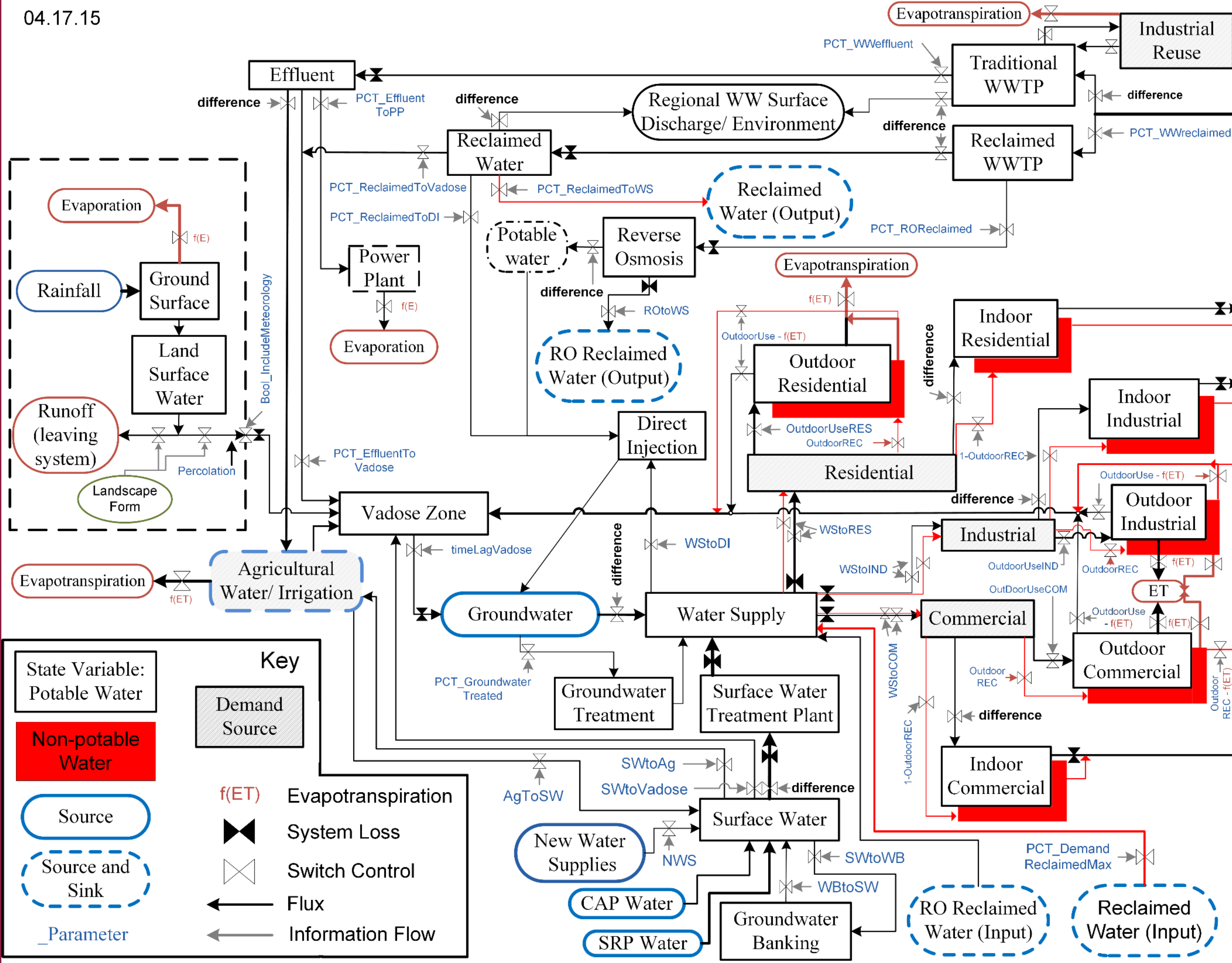

WaterSim 5
Available Groundwater
(by region)
Loop to
Next Year
User Interface
C#
Annual Inputs
Annual Outputs
Update Database
Groundwater Credits
(by provider)
Run-time controls, Default Settings, Database, and Initial Conditions
Parameter Checks
Library
C# dll
Model
Key
Material Flow (water)
Information Flow
Control Point and
Groundwater
External Factors
Normal Flow Rights
Daily Runoff
Salt River System
(monthly)
Climate Forcings (CF)
Daily Runoff
Verde River System
(monthly)
CF
Class B&C and NCS Water
- NCS Water
- Storage Rights
- Water Demand
Groundwater Recharge
(vadose percolation and direct injection)
Class B&C Water
- Storage Rights
- Water Demand
Class A Water
CO River System
(annual)
Annual Runoff
Municipal Groundwater Pumping
Policy/Law
Conveyance
Water Demand
SRP Release
CAP
Groundwater Designations
Provider Contracts
Delivered
SRP Pumping
Surface Water Supplies
Groundwater banking
Reclaimed and RO Reclaimed Water
Storage Water Distributions


04.17.15
Evapotranspiration
Industrial Reuse
PCT_WWeffluent
Traditional WWTP
Effluent
difference
PCT_Effluent ToPP
difference
Regional WW Surface Discharge/ Environment
difference
difference
Reclaimed WWTP
PCT_WWreclaimed
Reclaimed Water
PCT_ReclaimedToVadose
PCT_ReclaimedToWS
Reclaimed Water (Output)
PCT_ReclaimedToDI
Potable water
Reverse Osmosis
PCT_ROReclaimed
Evaporation
f(E)
Rainfall
Ground Surface
Land Surface Water
Runoff (leaving system)
Percolation
Landscape Form
Bool_IncludeMeteorology
Power Plant
f(E)
Evaporation
difference
ROtoWS
RO Reclaimed Water (Output)
Evapotranspiration
f(ET)
OutdoorUse - f(ET)
Outdoor Residential
Indoor Residential
difference
OutdoorUseRES
OutdoorREC
Residential
1-OutdoorREC
Indoor Industrial
Direct Injection
PCT_EffluentTo Vadose
Vadose Zone
difference
OutdoorUse - f(ET)
Outdoor Industrial
WStoRES
Industrial
WStoDI
timeLagVadose
Evapotranspiration
f(ET)
Agricultural Water/ Irrigation
difference
WStoIND
OutdoorUseIND
OutdoorREC
f(ET)
OutDoorUseCOM
ET
Groundwater
Water Supply
Commercial
OutdoorUse - f(ET)
f(ET)
Outdoor Commercial
PCT_Groundwater Treated
Groundwater Treatment
Surface Water Treatment Plant
WStoCOM
Outdoor REC
Outdoor REC - f(ET)
difference
1-OutdoorREC
Indoor Commercial
Key
State Variable: Potable Water
Demand Source
Non-potable Water
Source
Source and Sink
_Parameter
f(ET) Evapotranspiration
System Loss
Switch Control
Flux
Information Flow
SWtoAg
AgToSW
SWtoVadose
difference
Surface Water
New Water Supplies
NWS
SWtoWB
PCT_Demand ReclaimedMax
CAP Water
WBtoSW
SRP Water
Groundwater Banking
RO Reclaimed Water (Input)
Reclaimed Water (Input)

Anticipatory Modelling

- Model developed in participatory process with stakeholders to explore uncertainty
- Simulated business-as usual (BAU) and mega-drought (MD) conditions in modern Phoenix from 2000 to 2060
- Metrics focused on groundwater
- Policy, planning, and management interventions (i.e., solutions) derived from stakeholder engagement and research focused including historical analysis, narrative analysis, sustainability appraisal, survey research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Urban adaptation to mega-drought: Anticipatory water modeling, policy, and planning for the urban Southwest

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Mega-drought
Scenario planning
Water resources management
Sustainable urban development
WaterSim 5

ABSTRACT

This paper uses 'Medieval' drought conditions from the 12th Century to simulate the implications of severe and persistent drought for the future of water resource management in metropolitan Phoenix, one of the largest and fastest growing urban areas in the southwestern USA. WaterSim 5, an anticipatory water policy and planning model, was used to explore groundwater sustainability outcomes for mega-drought conditions across a range of policies, including population growth management, water conservation, water banking, direct reuse of RO reclaimed water, and water augmentation. Results revealed that business-as-usual population growth, per capita use trends, and management strategies are not sustainable over the long term, even without mega-drought conditions as years of available groundwater supply decline over the simulation period from 2000 to 2060. Adding mega-drought increases the decline in aquifer level and increases the variability in flows and uncertainty about future groundwater supplies. Simulations that combine drought management policies return the region to levels that are more sustainable. Results demonstrate the value of long-term planning and policy analysis for anticipating and adapting to environmental and societal change. Similar anticipatory exercises can be used to assess different suites of drought management policies in other cities facing uncertainty about future conditions.

1. Introduction

Climate change is expected to increase the frequency, intensity, and duration of drought in the southwestern United States in coming decades, and questions are being raised about the sustainability of the region's water resources (Cook, Ault, & Smerdon, 2015). General Circulation Models (GCMs) have been used as the basis for projecting future climatic and hydrological conditions under varying greenhouse gas concentration scenarios (Vörösmarty, Green, Salisbury, & Lammers, 2000; Kundzewicz et al. 2008; Arnell, 2004). There is, however, low confidence about the severity, seasonality, and spatial patterns of drought conditions and their implications for regional water supply when the GCMs are combined with regional climate and hydrological models (Wilby & Dessai, 2010). Wilby (2005) and Trenberth (2010) have warned that uncertainties associated with the GCMs are unlikely to be resolved in the short- to mid-term future because models vary in the way they treat complex climate processes, and there are trial-and-error effects associated with adding more variables and feedbacks to capture system dynamics.

Water managers need to make decisions about how to adapt to climate change before the scientific uncertainties of climate modeling and hydrological impact assessment are resolved. They face classic decision making under uncertainty (DMUU) conditions where stakeholders disagree about problem definition and the probability distributions that describe critical components of the system (e.g., future streamflow and climate, per capita water use, behavioral response to policy instruments). Traditional predict-and-plan efforts in water resources management using optimization models are ill-suited to DMUU problems (Gober, Kirkwood, Ellis, & Deitrick, 2010; Quay, 2010). DMUU strategies favor scenario building, exploration of a wide range of policy options, the search for robust policies that work well across a range of climate conditions, and efforts to preserve the flexibility to respond when the unexpected occurs (Lempert, Popper, & Bankes, 2003). Such strategies often use exploratory simulation models to

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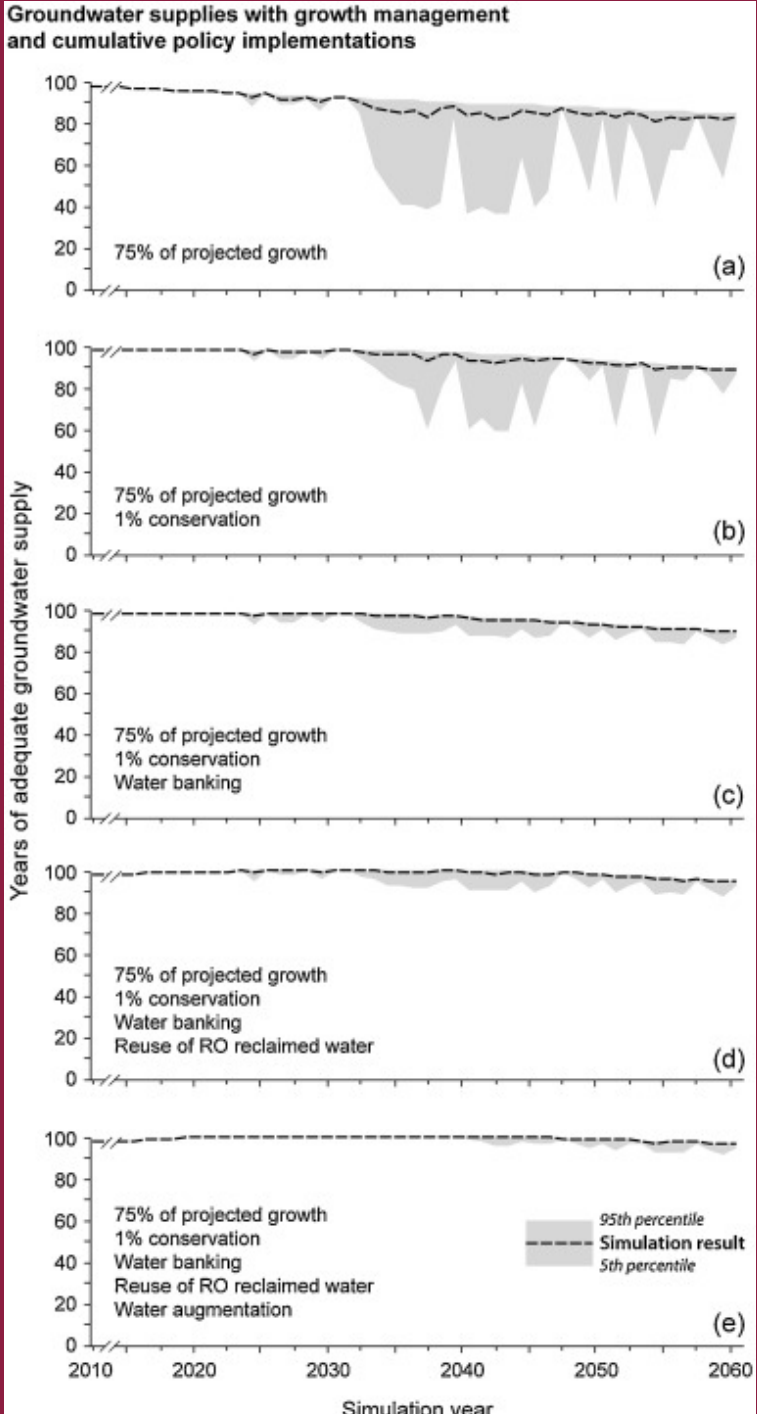
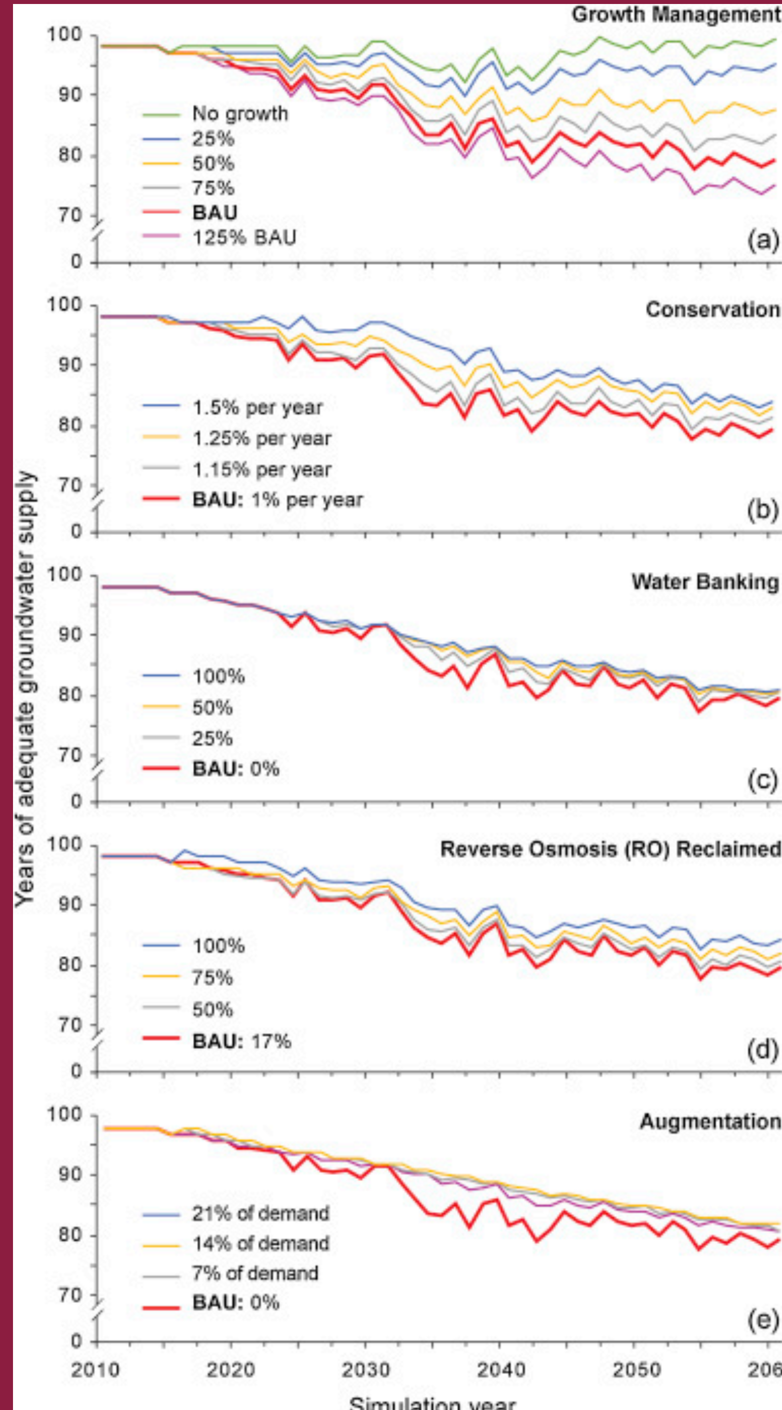
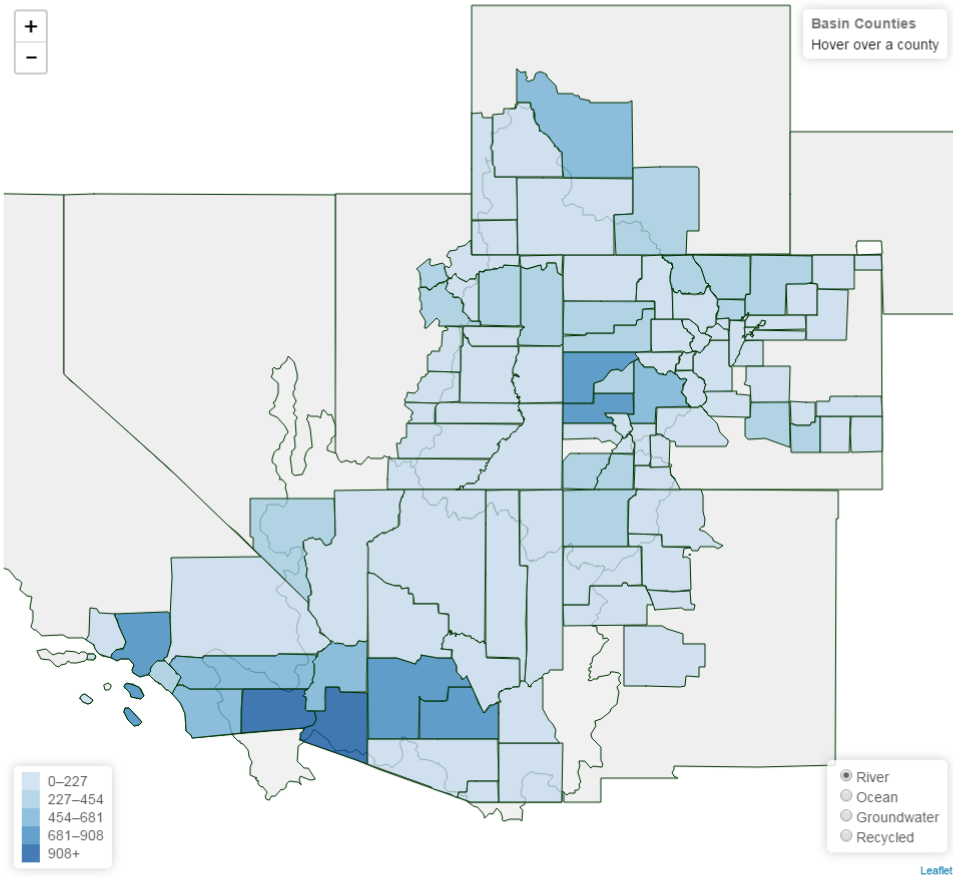

Groundwater supplies with growth management
and cumulative policy implementations
Years of adequate groundwater supply
75% of projected growth
(a)
75% of projected growth
1% conservation
(b)
75% of projected growth
1% conservation
Water banking
(c)
75% of projected growth
1% conservation
Water banking
Reuse of RO reclaimed water
(d)
75% of projected growth
1% conservation
Water banking
Reuse of RO reclaimed water
Water augmentation
(e)
95th percentile
Simulation result
5th percentile
0
20
40
60
80
100
2010
2020
2030
2040
2050
2060
Simulation year

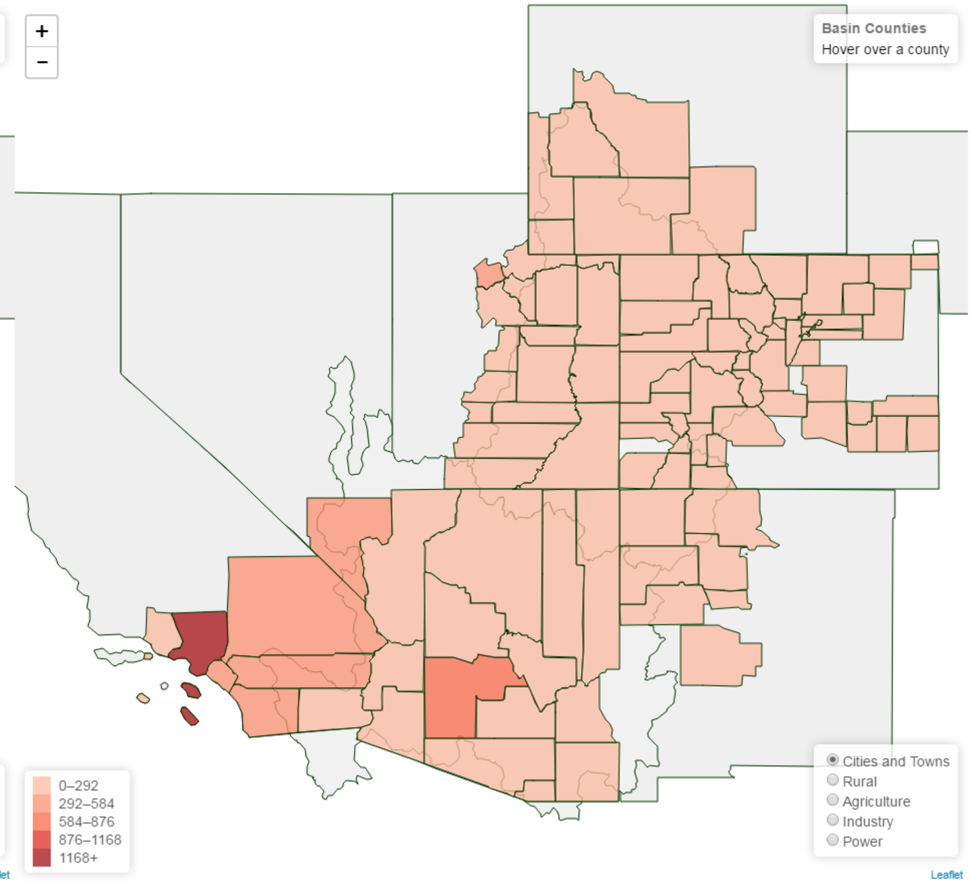

Years of adequate groundwater supply
Growth Management
No growth
25%
50%
75%
BAU
125% BAU
(a)
Conservation
1.5% per year
1.25% per year
1.15% per year
BAU: 1% per year
(b)
Water Banking
100%
50%
25%
BAU: 0%
(c)
Reverse Osmosis (RO) Reclaimed
100%
75%
50%
BAU: 17%
(d)
Augmentation
21% of demand
14% of demand
7% of demand
BAU: 0%
(e)
0
70
80
90
100
2010
2020
2030
2040
2050
2060
Simulation year

Sources



Show Layers: ☑ State ☑ Basin ☑ County
Boundaries: ☑ State ☑ Basin ☑ County

Consumers



[Link]

Evidence-Supported Transition Strategies towards Sustainable Water Governance

IPA 1

IPA 2

IPA 3

IPA 4

Arnim Wiek

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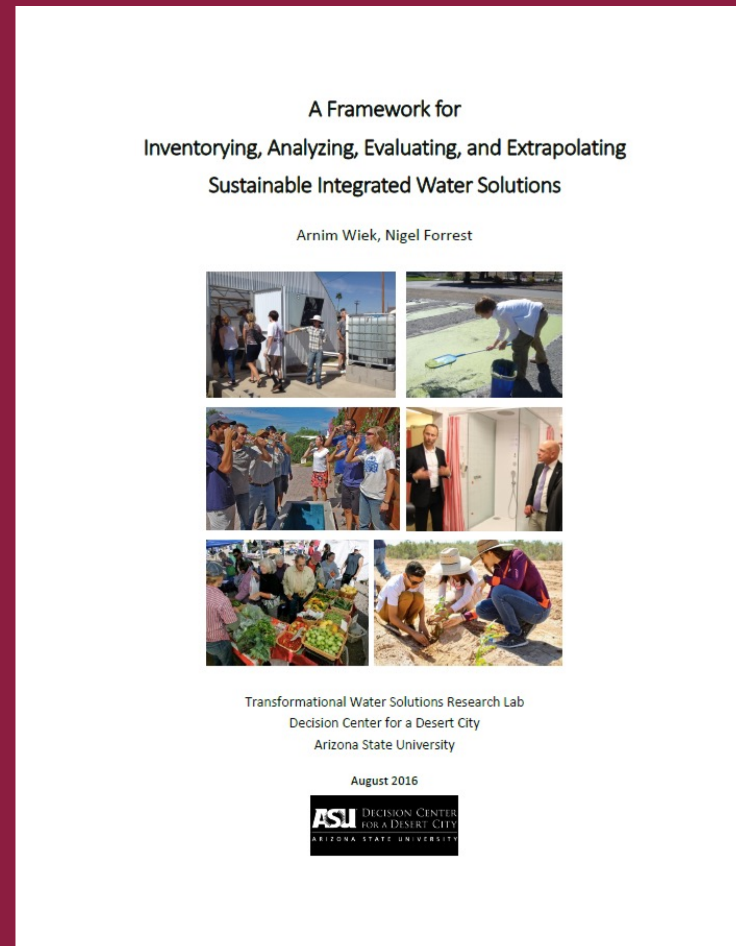
Evidence-supported Transition Strategies

- Inventory of 150+ water solutions (*outcomes and processes* including technologies, infrastructure, governance arrangements, behavior, etc.)
- 17 water solution case studies completed
- Studying transfer and scaling water-sensitive housing in Phoenix, Denver, Las Vegas (interviews and modeling)
- Collaborating with stakeholders in Phoenix and Denver for pilot projects


A Framework for
Inventorying, Analyzing, Evaluating, and Extrapolating
Sustainable Integrated Water Solutions

Arnim Wiek, Nigel Forrest

Transformational Water Solutions Research Lab
Decision Center for a Desert City
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August 2016

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Conclusions and Discussion

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Conclusions and Discussion

- Hydro-climate risks require incremental *and* transformational solutions to inform transitions for CRB-dependent cities
- Managing sustainability transitions requires understanding of historical, social, and political processes to
- Understanding the circumstances surrounding takeoff in past transitions is critical to learning how to catalyze and influence the breakthrough of future transitions
- Transition management relies on understanding, identifying, and taking advantage of “policy windows”
- The transition process requires more effective integration of multiple systems of knowledge and action

CAP System Use Agreement

Transformational Solutions for Climate Change Adaptation and Water Sustainability in the Colorado River Basin

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