Using Climate and Hydrological Models to Assess Potential Future Conjunctive Use -- The Central Valley Example

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U.S.G.S. Global Climate-Change Program
(Science Applications & Decision Support --SADS)
California Application Project (CAP)
(a NOAA/OGP Regional Integrated Sciences and Assessments (RISA) member)
&
NASA Climate-In-A-Box Research Program
USGS Cooperative Water Program
USGS-OGW Groundwater Availability Program

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Sustainable Water Resources Roundtable
University of California, Davis, CA
December 6 - 8, 2011

Today's Presentation

State of the Science

Hydrologic Tools

Conjunctive Use Analysis –Central Valley Example

Outlook

Sustainability: Development and use of water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.

Conjunctive Use: Joint use and management of surface-water and groundwater resources to maximize reliable supply and minimize damage to the quantity or quality of the resource.

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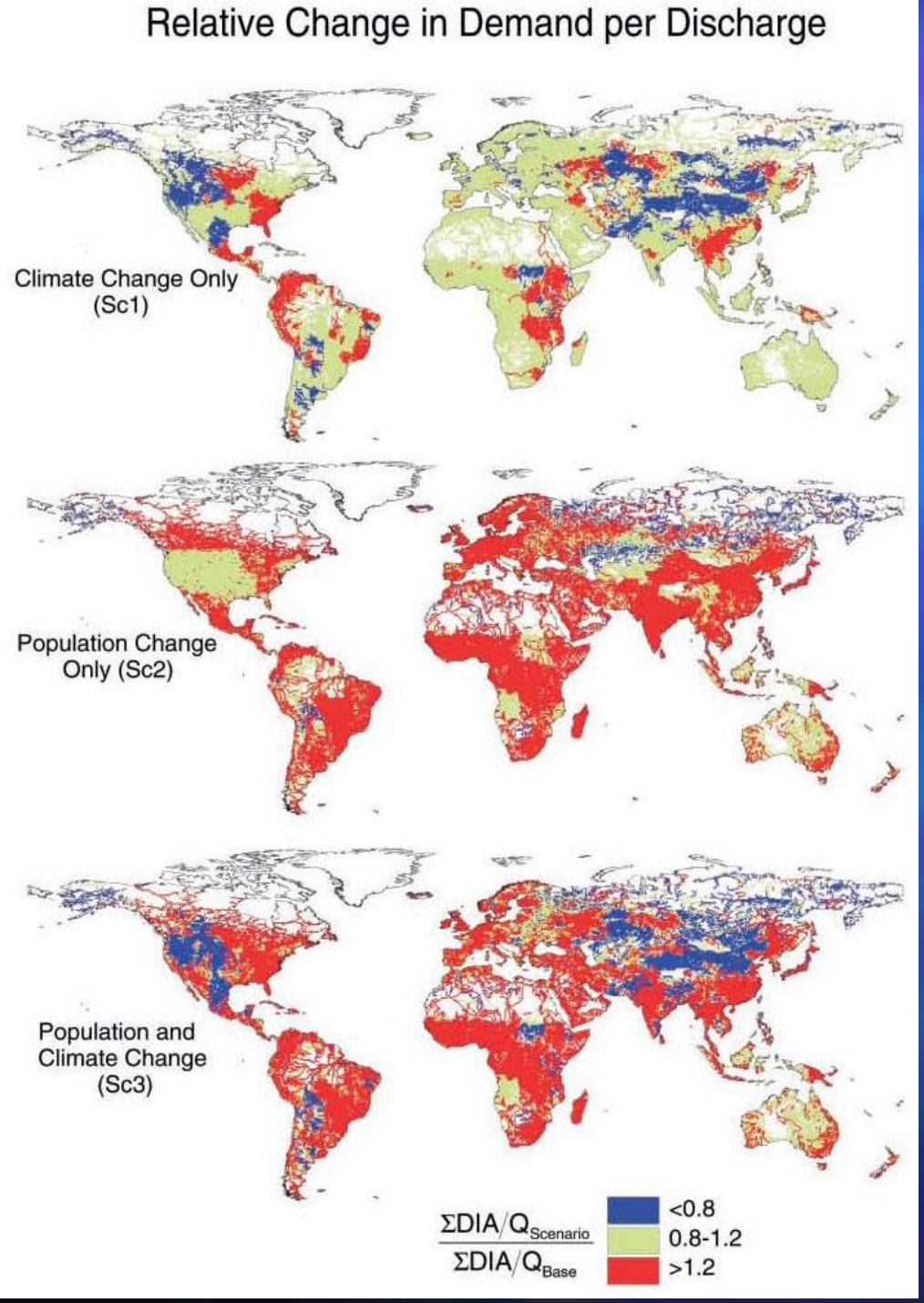
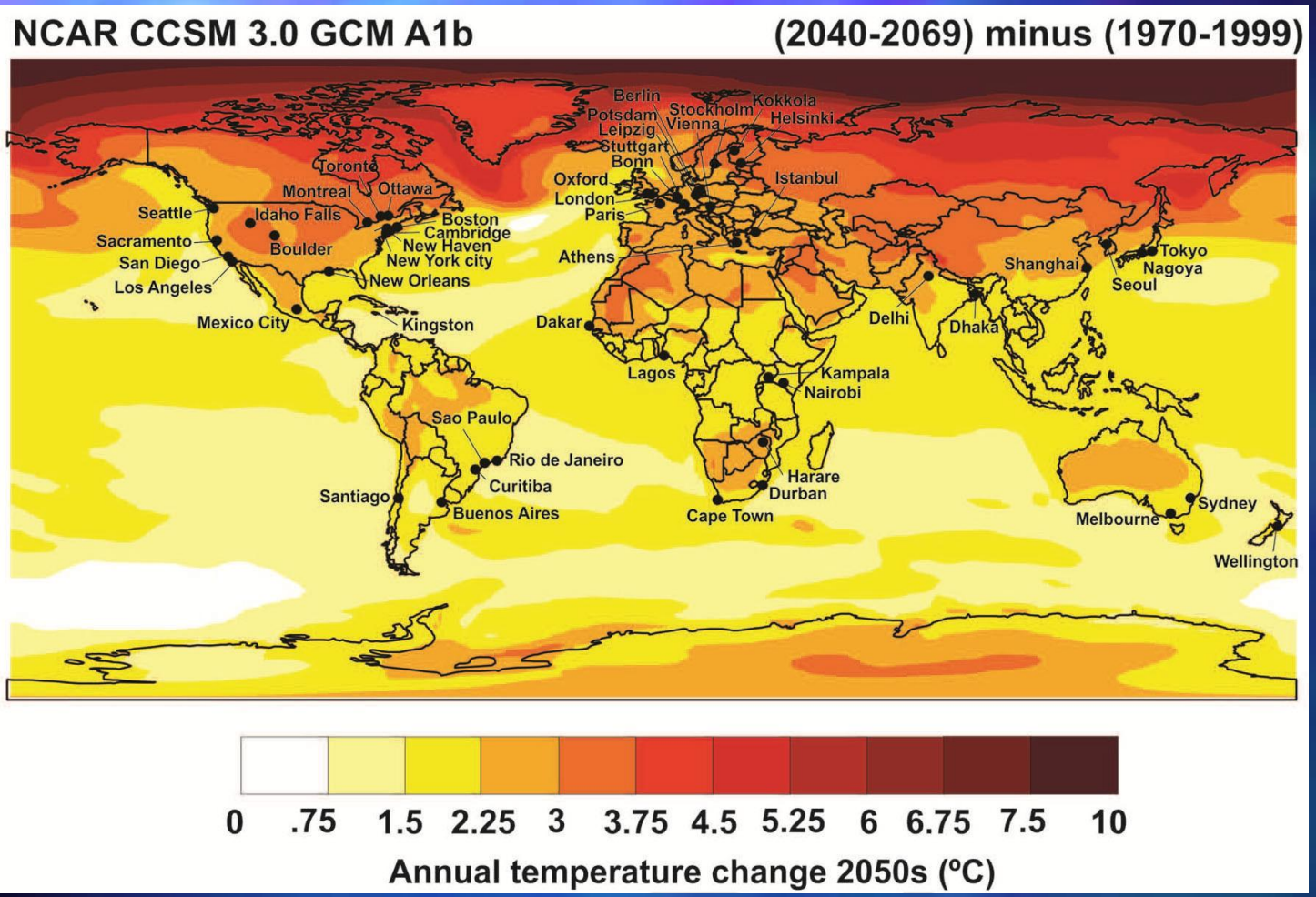


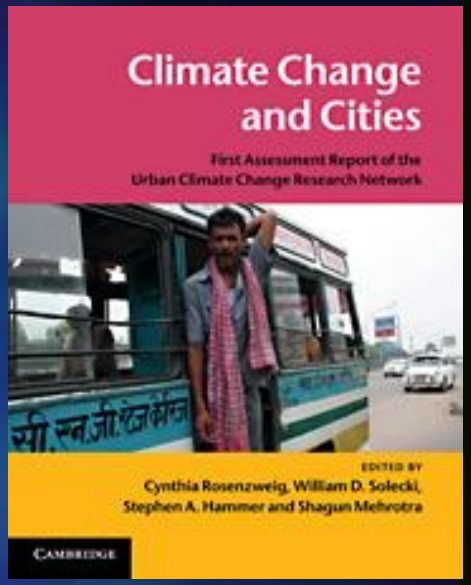
Global Analysis of Water Stress from Major Surface-water Drainages

- Large part of World's Population with Water Stress
- Rising Water Demands outweigh effects of greenhouse warming-climate change through 2025
- Direct human impacts on global water supply poorly articulated but important to larger global change question

(Vorosmarty et al., April, 2010, Science)

Additional Urban-Demand and Climate-Change Issues





Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network (Cambridge University Press) **http://www.cambridge.org/us/catalogue**

Risk Framework

- **Climate Hazards**
- **Vulnerabilities**
- **Adaptive Capacity**
- **Sustainability**

Urban Climate → ***Urban Heat Islands, Air pollution & Climate extremes***

Governance/Management → ***Transboundary, Capture of Unappropriated Runoff & Environmental Flows 1st***

Managed Resources → ***Agriculture to Urban, Water-Energy Nexus, & Formal vs Informal Supply***

RELATION TO USGS MISSIONS SUSTAINABILITY/CONJUNCTIVE USE CENTRAL VALLEY

- **One Water → Single resource (Precipitation, surface water and groundwater)**
- **Competition for Water → Demand for water resources People, Agriculture Environment (Entire Central Valley not just Sacramento and San Joaquin)**
- **Sustainable development → Complex system requires integrated water-management approach → Linked models used to support this analysis**
- **Availability/Sustainability→ Changes in streamflow, groundwater storage, regions suitable for agriculture, and dynamics between natural and societal water-supply demands**
- **Groundwater effects → Significant changes in Flows, Storage, & Secondary effects on multiple time scales (Flow-centric & Storage-centric Indicators?)**
- **Climate variability/change Analysis → Management provided with observationally informed modeling and resource analyses**
- **Climate change → Important influences on management strategies for conjunctive/sustainable use on periods of 100 years or more (ENSO, NAMS/PineappleExp, PDO, AMO, + Change)**

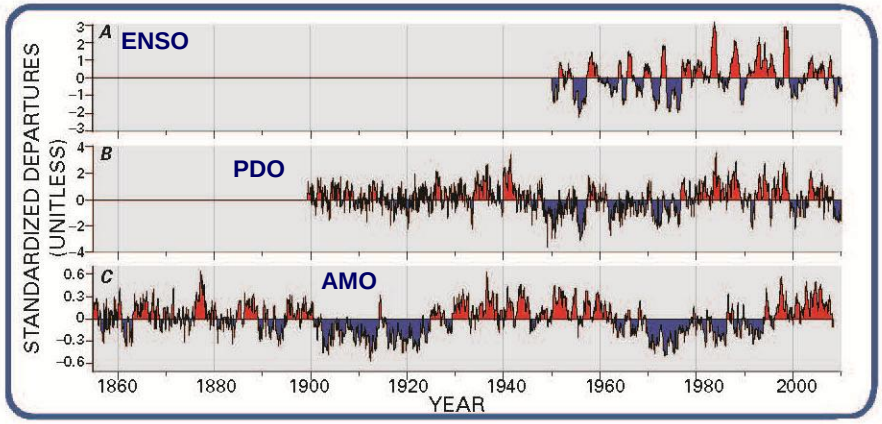


Figure 1. Interactions between the positive (red) and negative (blue) phases of the (*A*) multivariate El Niño/Southern Oscillation (ENSO) index (Wolter and Timlin, 1993, 1998), (*B*) Pacific Decadal Oscillation (PDO) index (Mantua and Hare, 2002), and (*C*) Atlantic Multidecadal Oscillation (AMO) index (Enfield and others, 2001) cumulatively affect U.S. climate and, in turn, surface and groundwater resources.

USGS Office of Global Change
Effects of Climate Variability and Change on Groundwater Resources of the United States
Fact Sheet FS09-3074 (2009)
By Jason Gurdak, Randall T. Hanson, and Timothy R. Green

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Paleo-Extreme Climate Events Central Valley, California

Is one person's Climate Change another person's Climate Variability??

NO--There are natural & anthropogenic components & competing drivers such as urbanization

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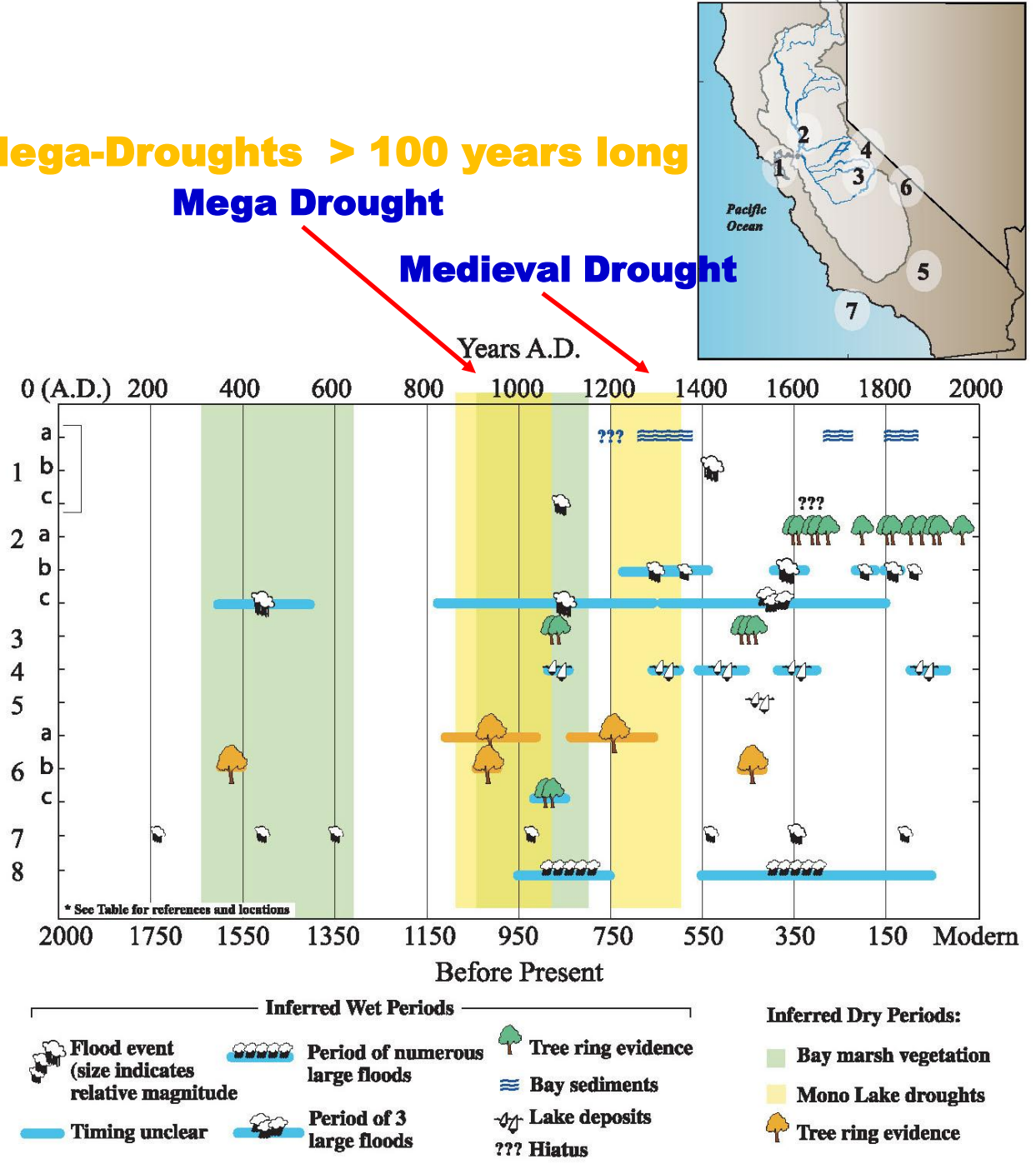
Mega-Droughts > 100 years long



How Conjunctive Use/Sustainability Analysis Help Stakeholders?

- **Climate Vulnerabilities? → Extreme Events, Sustained Events, Permanent changes to system, Unsustainable adaptation**

  Primary Effects → More dry Springs, Higher minimum temperatures, More cloudy/foggy days, More windy days, Amount/timing of snowmelt runoff, Frequency of wet years, Frequency of storms, Length of growing seasons, etc.

  Secondary Effects → Land Subsidence, Seawater intrusion, Decreased streamflow gains/losses, Increased soil salinization, Decreased soil moisture, Land-use adaptation (*esp. urbanization!*)

- **Variables/metrics used for vulnerabilities? Focus of current research and analysis of coupled models -- most "Indicators" only based on data. Need to make decisions on indicators from data and physically-based models.**

- **Ensemble Analysis Adequate? Maybe not -- the traditional statistical and probabilistic approach to synthesis of results may not capture linkages or secondary-limiting factors of conjunctive use. Indicators from ensembes may not catch extremes or tipping points**

- **Current Observational Networks & Assoc Data Adequate? Maintenance of Input Data Streams for regional hydrologic models one of biggest challenges and needs → Part of DSS should include integrated ground and remote-sensing networks in Mountains & Valleys→ Support of SELF-UPDATING MODELS**

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Outlook

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USGS MODLOW with the FARM PROCESS—Features and Capabilities

Supply-and-Demand Modeling Framework Connected to Nature and Humanity

Farm Demand for Irrigation

Non-Routed Deliveries as Water Transfers

Routed Surface-Water Delivery to Farm

Groundwater Pumpage by Well

Streamflow Conveyance and Drain Network

Natural and Artificial Recharge

Water-Use Management

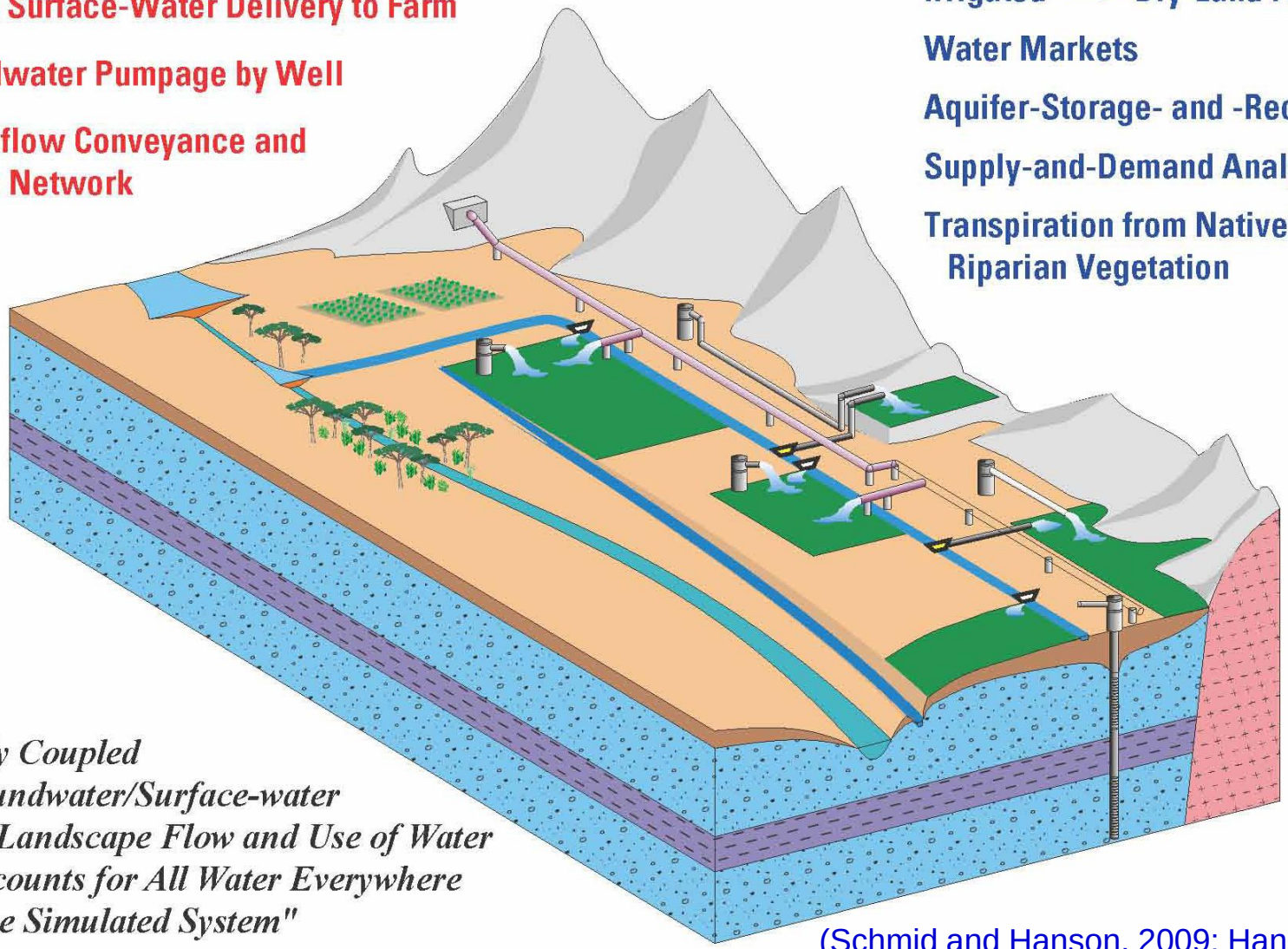
Irrigated ⟹ Dry-Land Farming

Water Markets

Aquifer-Storage- and -Recovery Systems

Supply-and-Demand Analysis

Transpiration from Native and Riparian Vegetation



Fully Coupled Groundwater/Surface-water and Landscape Flow and Use of Water "Accounts for All Water Everywhere in the Simulated System"

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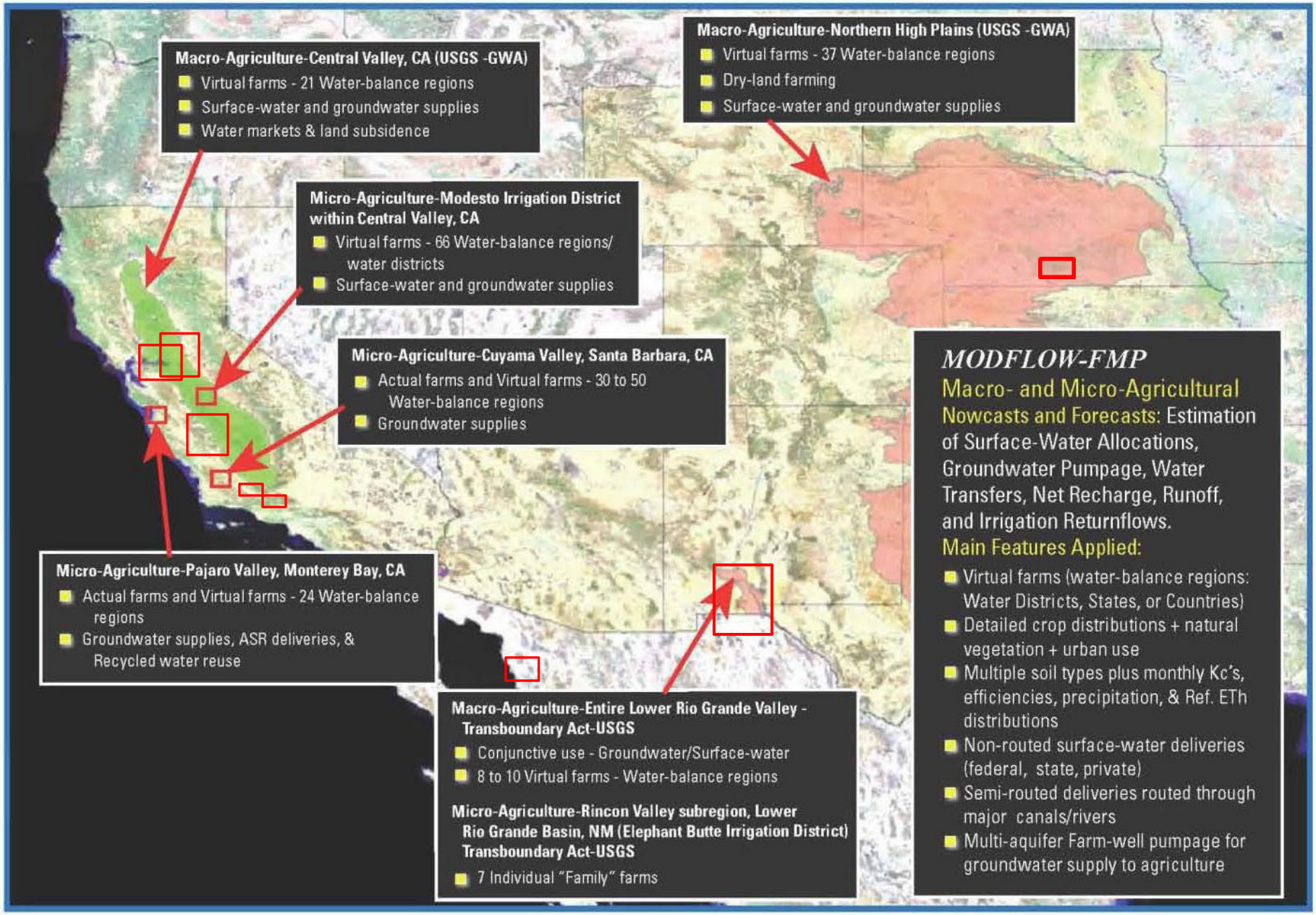
(Schmid and Hanson, 2009; Hanson et al., 2010)

Recent Applications of MF-FMP in USA & Mexico



Decision Support System (DSS) & LINKAGE BETWEEN GCM and BCM & CVHM → Supply-Constrained/Demand-Based Hydrologic Model System

Run GCM Model (CM2/PCM)

Statistical Downscaling
12km →4km Bias Corrected → 270m
Precipitation,
Temperature, & Ref-ET
(Constructed Analogs Method)

Run Basin Characteristic Model(BCM) of all Central Valley Watersheds
Estimate Mountain Runoff/Recharge to Rivers & Reservoirs

Farm Process (FMP) Input of Monthly Precipitation & Reference ET
Resampling onto Valley-Wide (CVHM) MODFLOW-FMP Grid→Simulate Agricultural Supply & Demand

Build Stream Routing/Deliveries
41 River Inflows, 66 Diversions,
42 Nonrouted deliveries
(Reservoir Releases,
Unregulated Streamflows &
Project Water Deliveries)

Run Central Valley Hydrologic Model (CVHM) (MODFLOW-FMP)

DSS →Analyze Flows
Groundwater,
Surface-water, &
Landscape Budgets

DSS → Analyze Levels
Groundwater Levels,
Streamflow,
& Land Subsidence

DSS → Analyze Supply/Demand
Drought Response
& Adaptation

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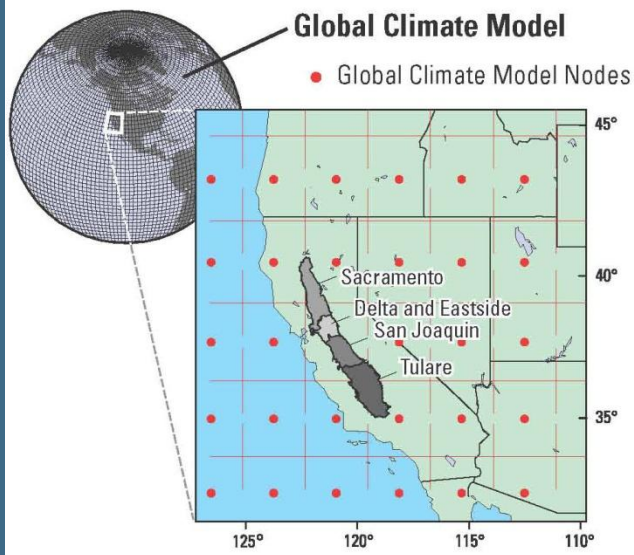
Basin Characteristics Model (BCM) Simulates Precipitation-Runoff/Recharge from downscaled climatology in the mountain watersheds surrounding the Central Valley (Sierra Nevada and Coast Ranges Mountains)

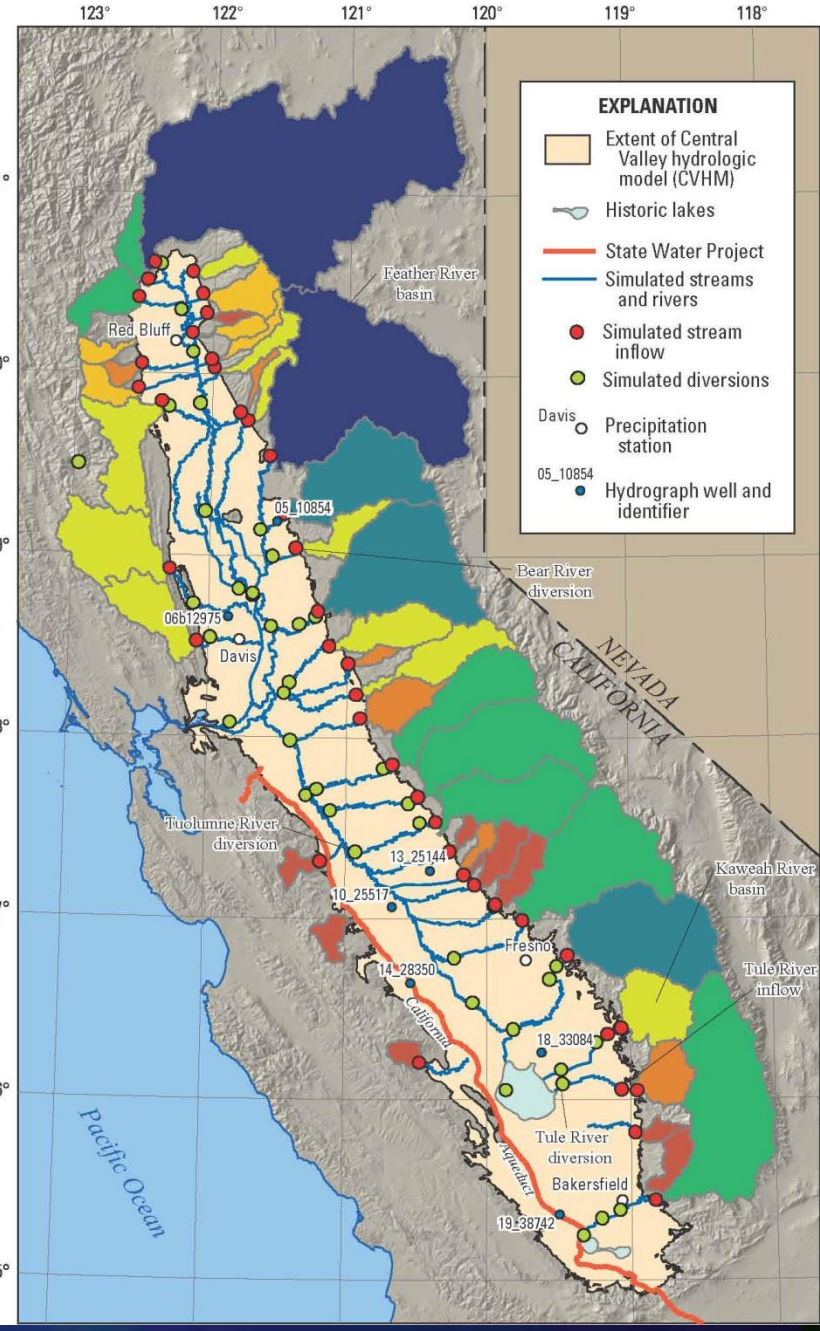
Also Developing Linkage with VIC Model



Mountain Hydroligic Watershed Model (MHWM) using the Basin Characteristics Model (BCM)

Average runoff, in millions of cubic meters per year

- 5.7 to 100
- 100 to 200
- 200 to 400
- 400 to 750
- 750 to 1,000
- 1,000 to 2,000
- 2,000 to 4,000
- 4,000 to 9,250



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Modified from Hanson and Dettinger, 2005; Faunt *et al.*, 2009a.

Linkage of Global Climate Model to Regional Hydrologic Models

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Outlook

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A2- Scenario & Model Linkages

- **Future projection (A2)** → Extreme conditions - generally characterized as climatically quite, warm, substantially drier, assumes high growth in population, regionally based economic growth, and slow technological changes that represents “heavy emissions" and "business as usual" increase in future greenhouse emissions (Cayan et al., 2009). → Reduced Snowfall, reduced Precipitation, Increased Temperature and ET

- **Model Assumptions**:
  (1) No Adaptation → Land use (Agriculture, Urban, & Native) held constant at 2006.
  (2) Future urban water use → Increase 1.2% per year through at least 2040.
  (3) Sea-Level rise GW only → One meter rise with monthly variation in sea level at Delta controls groundwater outflow.

- **GCM → MHWM (BCM) & CVHM (MF-FMP) used to evaluate potential effects of extreme climate change on conjunctive use of water** → Runoff & recharge from mountains, irrigation supply & demand, and groundwater, surface water, and agricultural components

- **Simulation Response metrics of Conjunctive Use** → SW Diversions, streamflow and infiltration/base-flow, groundwater storage, and related effects → potential land subsidence and groundwater/surface-water relations in the Sacramento Delta.

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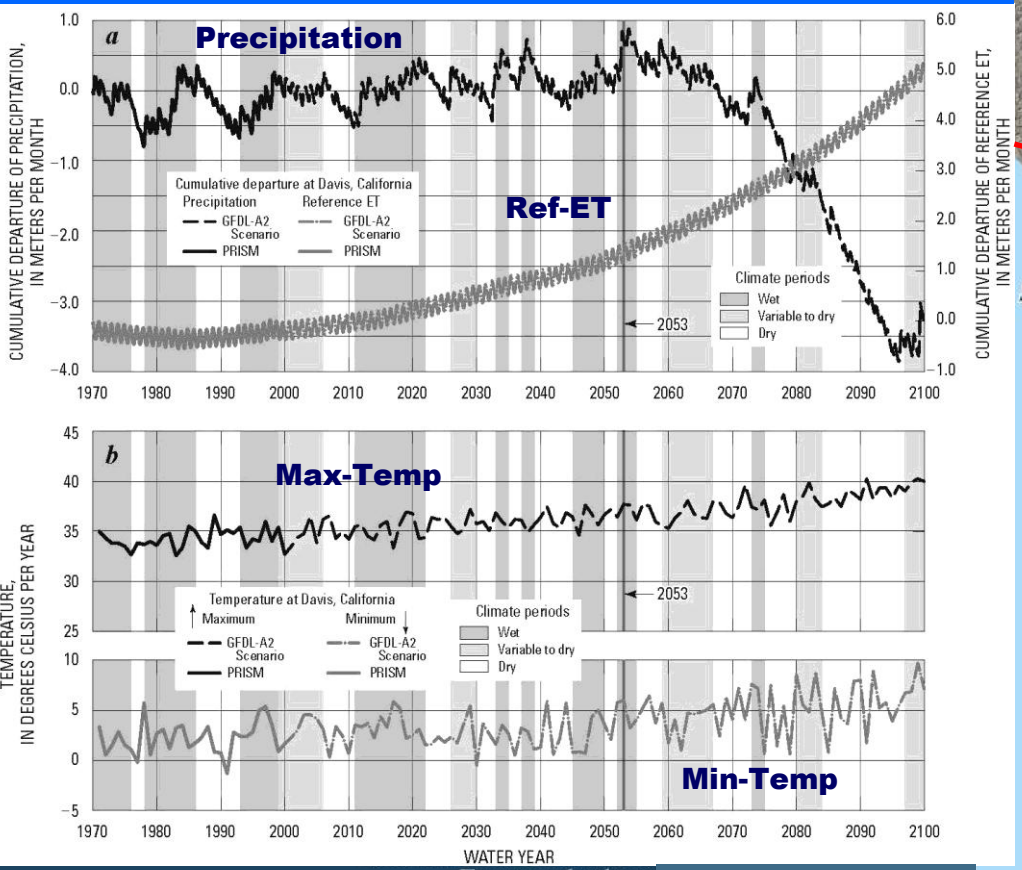
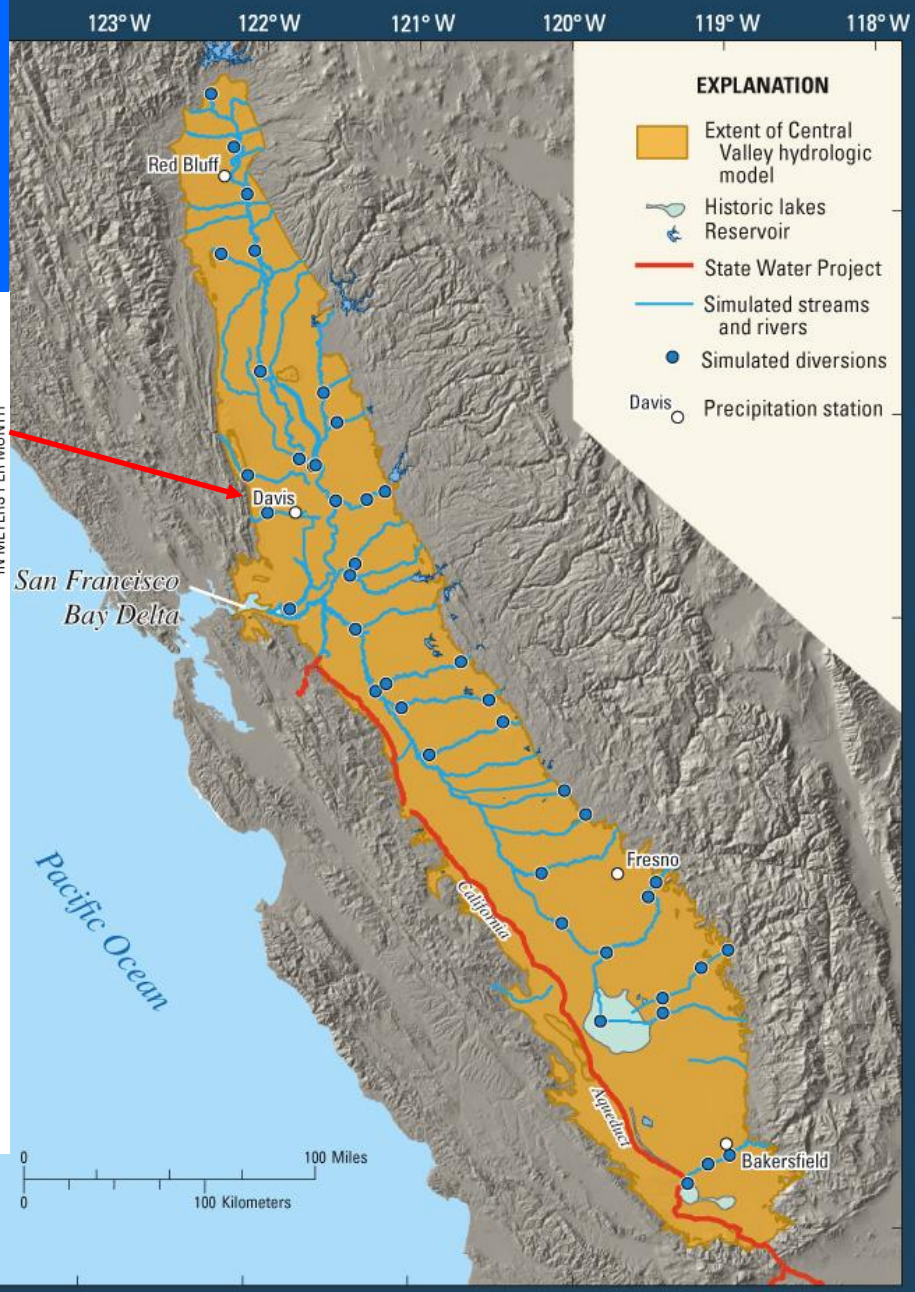
Cumulative Precipitation & Temperature Downscaled

Shows A2 Scenario at Davis with the potential for

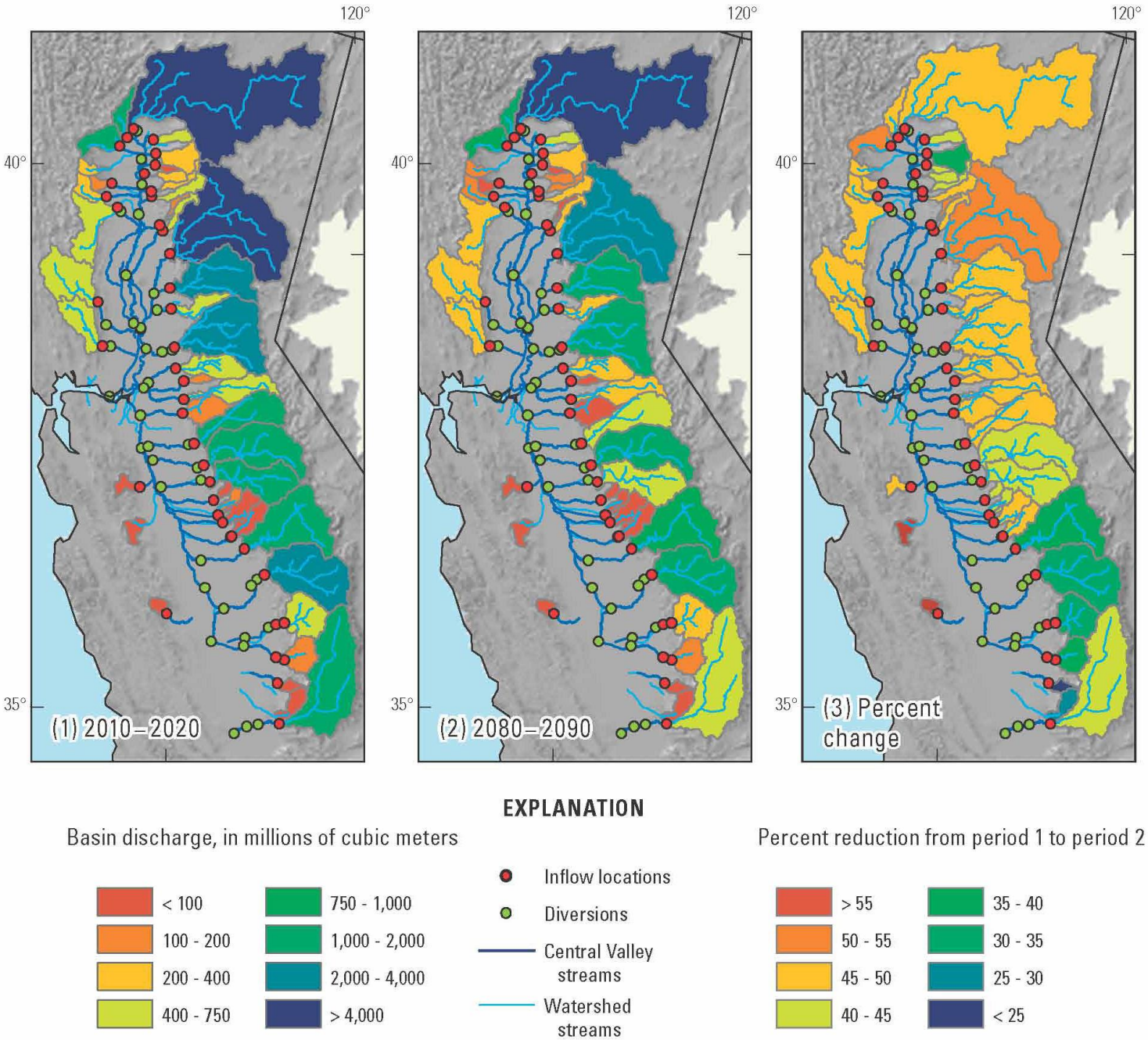
- **Decreased Precipitation**
- **Increases in Temperature of +2 to+4°C & ET**
- **Sustained droughts in the 21st Century (10-15% Drier)**



Faunt and others, 2009 (USGS Prof. Paper 1766)



Discharge Reduced by 20 – 65%→Largest in North & Central



Mean total basin discharge for

(1) 2010-2020,

(2) 2080-2090,

(3) Percent reduction in discharge between the 2 decades, for each of the 43 basins in the study area.

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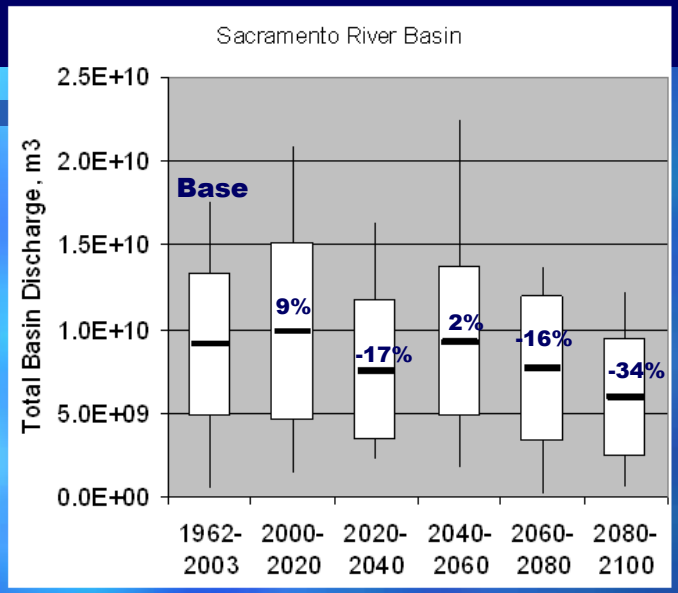
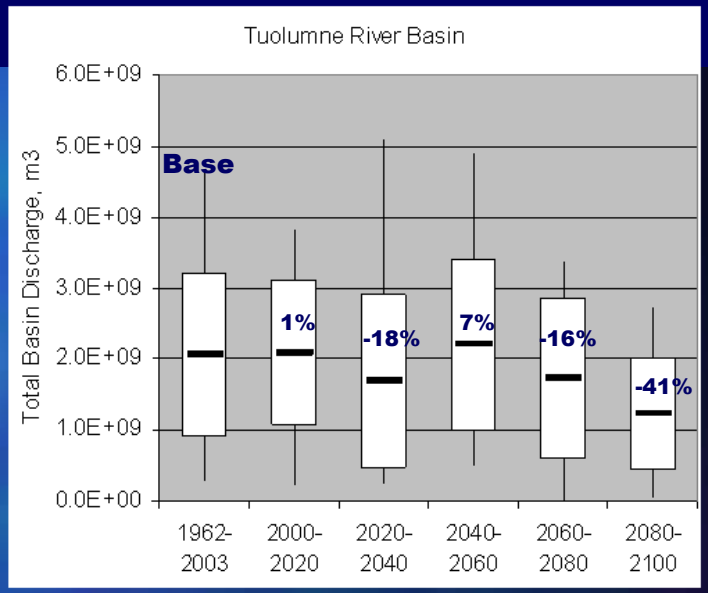
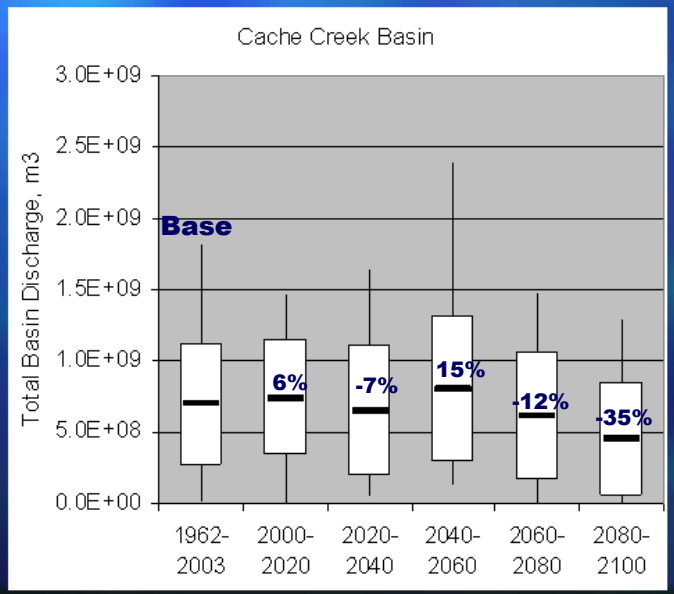
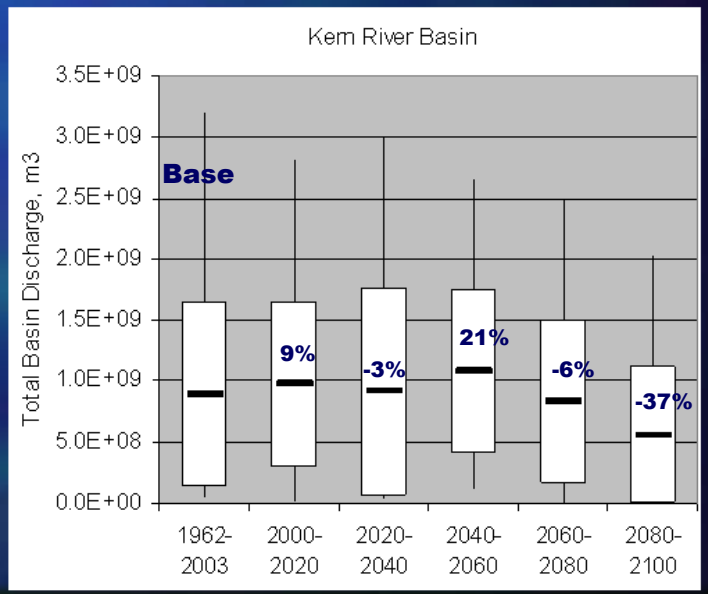
Current (1962-2003) modeled and future 20-year projections of total basin discharge for 4 basins in the study area, depicted as mean (black bar), standard deviation (white box), and range (vertical lines). Percent change in future mean discharge from current mean is indicated for each 20-yr period.

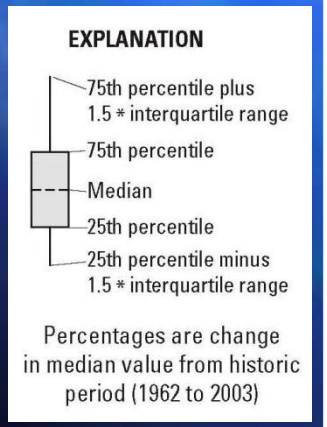
Streamflow Reductions of ~30 – 40% from major Rivers flowing from Sierra's to Central Valley in later decades of 21st Century











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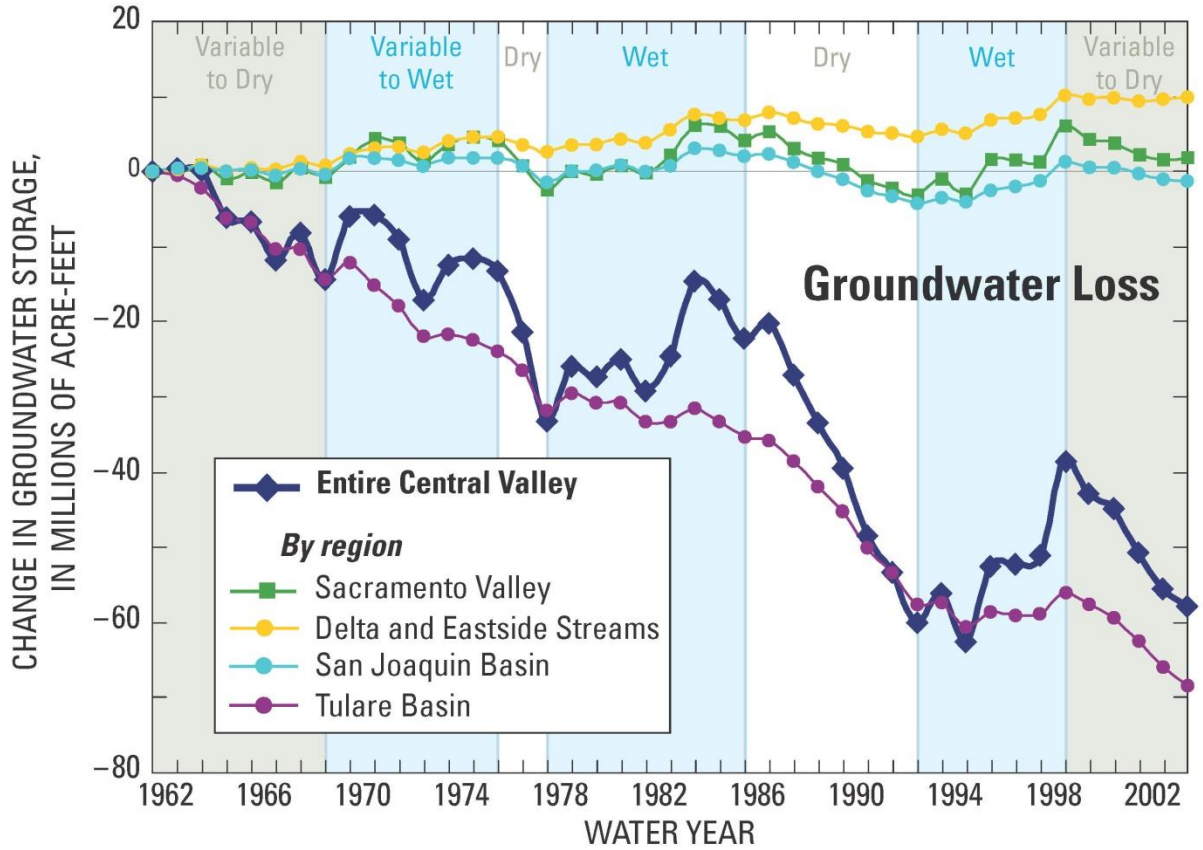
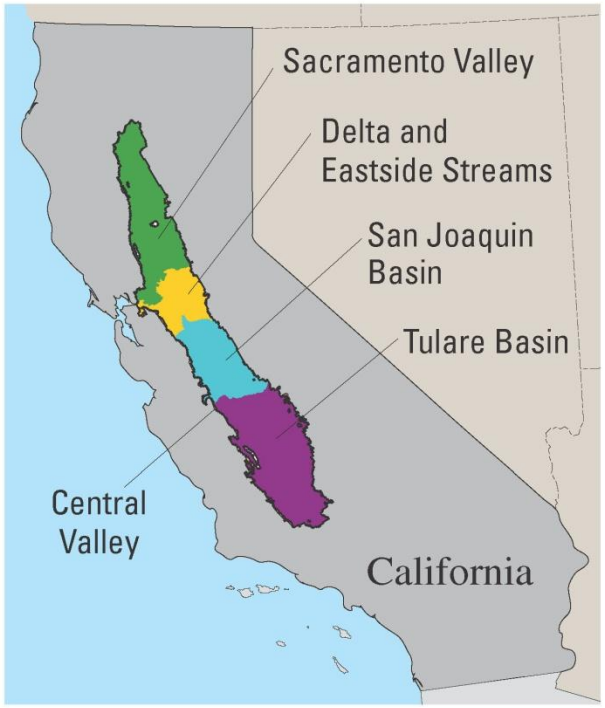
Historical Change in Groundwater Storage (Water Years 1961 – 2003)





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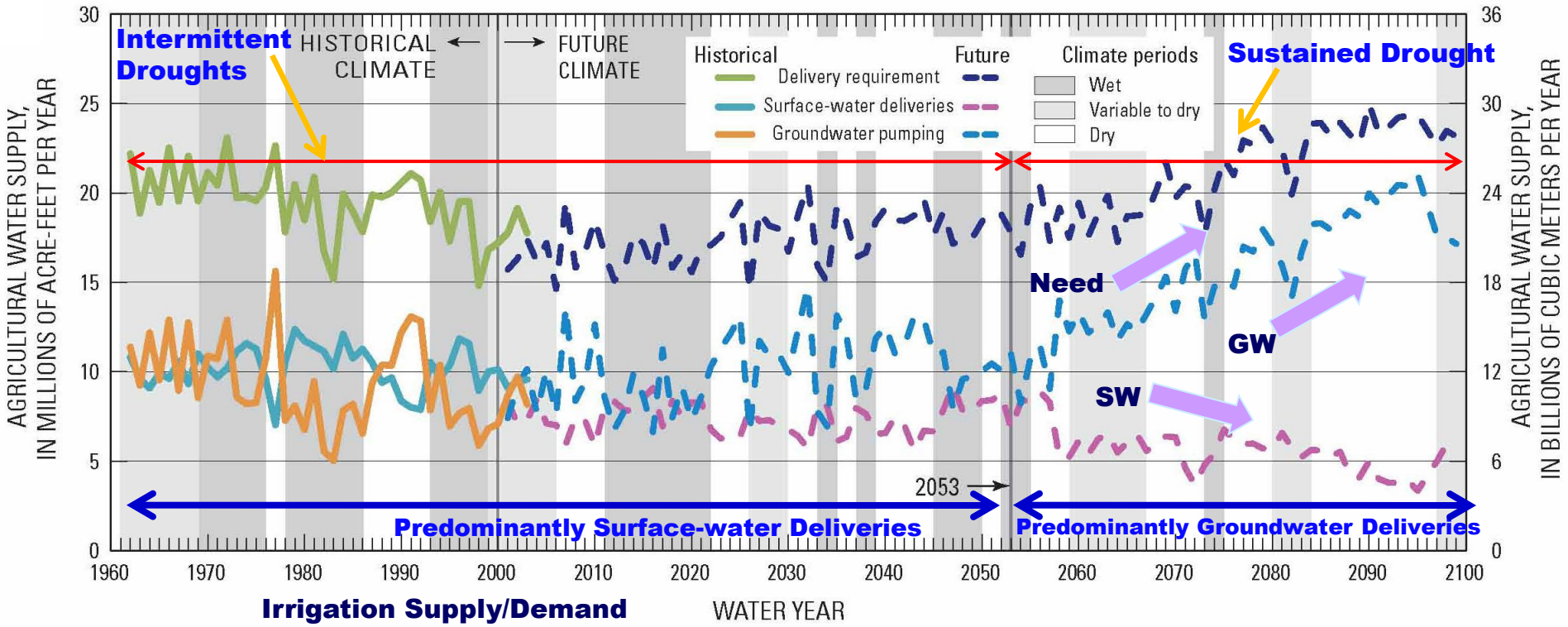
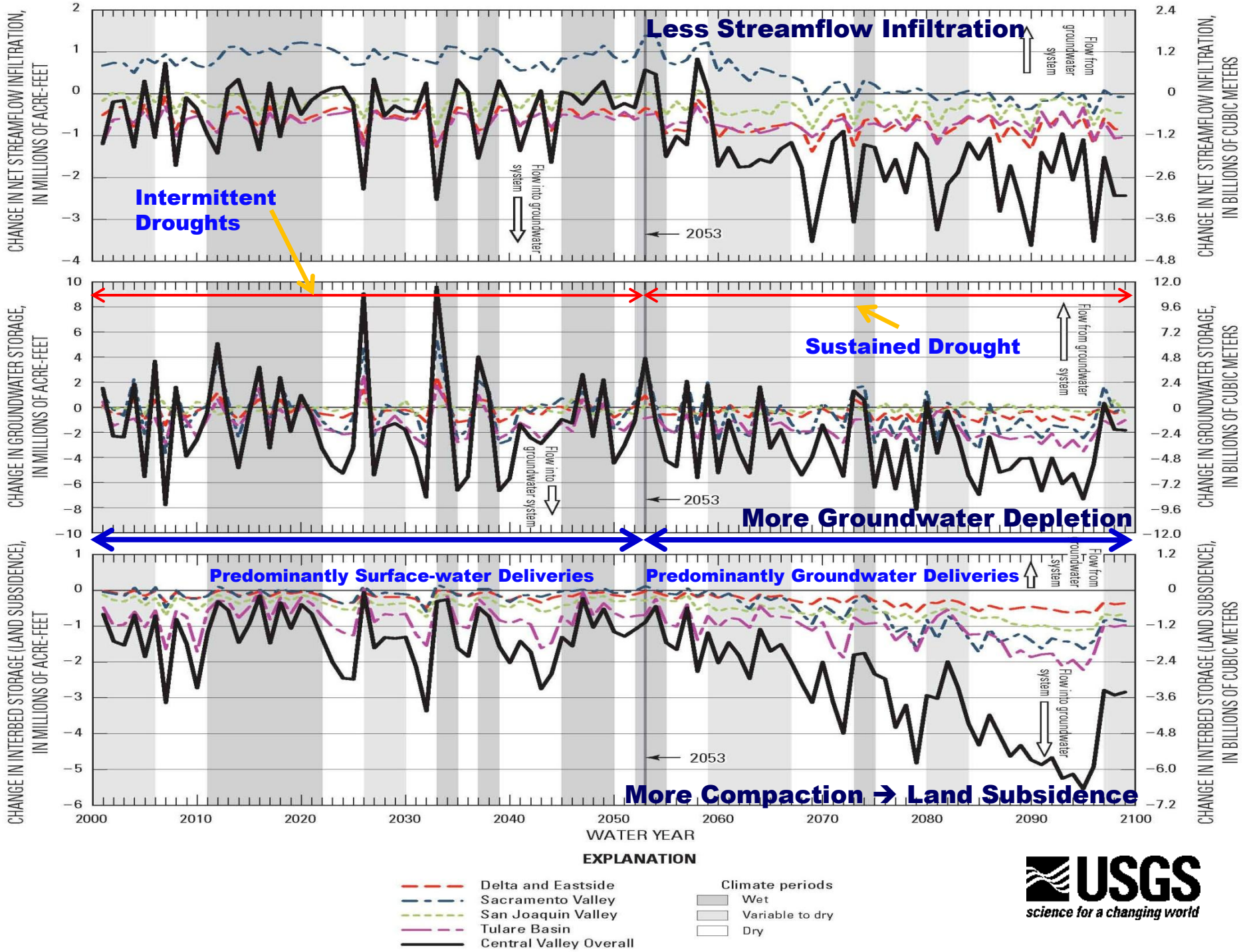
Agricultural and Urban Water Supply → 20% of a groundwater pumped in USA

Faunt, C.C., Hanson, R.T., Belitz, Kenneth, and Rogers, Laurel, 2009, California's Central Valley Groundwater Study: A Powerful New Tool to Assess Water Resources in California's Central Valley: U.S. Geological Survey Fact Sheet 2009-3057, 4 p. (http://pubs.usgs.gov/fs/2009/3057/)

Conjunctive Use Transition from Surface-Water to Groundwater Use



- Historical Surface-water to groundwater deliveries averaged about 1.33-to-1, (ranging from 2-to-1 ➔wet periods to 1-to-3 during persistent dry periods)
- GFDL-A2 scenario yields modeled ratios of surface-water to groundwater deliveries averaged about 1-to-2.75 (ranging from 1-to-1 ➔ wet periods to 1-to-3 during dry epochs)


Less Streamflow Infiltration
Intermittent Droughts
Sustained Drought
More Groundwater Depletion
Predominantly Surface-water Deliveries
Predominantly Groundwater Deliveries
More Compaction → Land Subsidence
Flow from groundwater system
Flow into groundwater system
2053
CHANGE IN NET STREAMFLOW INFILTRATION, IN MILLIONS OF ACRE-FEET
CHANGE IN NET STREAMFLOW INFILTRATION, IN BILLIONS OF CUBIC METERS
CHANGE IN GROUNDWATER STORAGE, IN MILLIONS OF ACRE-FEET
CHANGE IN GROUNDWATER STORAGE, IN BILLIONS OF CUBIC METERS
CHANGE IN INTERBED STORAGE (LAND SUBSIDENCE), IN MILLIONS OF ACRE-FEET
CHANGE IN INTERBED STORAGE (LAND SUBSIDENCE), IN BILLIONS OF CUBIC METERS
WATER YEAR
EXPLANATION
Delta and Eastside
Sacramento Valley
San Joaquin Valley
Tulare Basin
Central Valley Overall
Climate periods
Wet
Variable to dry
Dry
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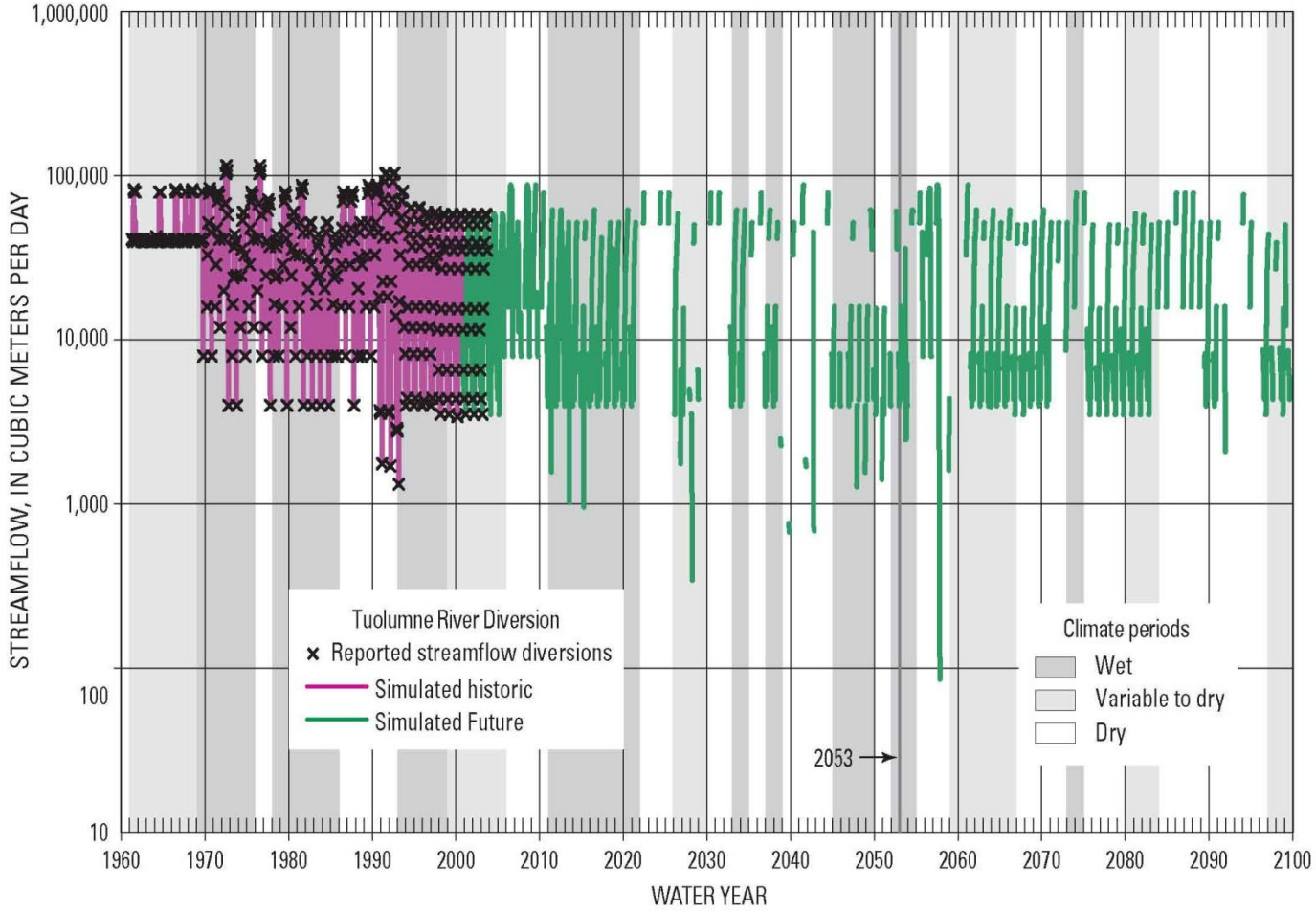
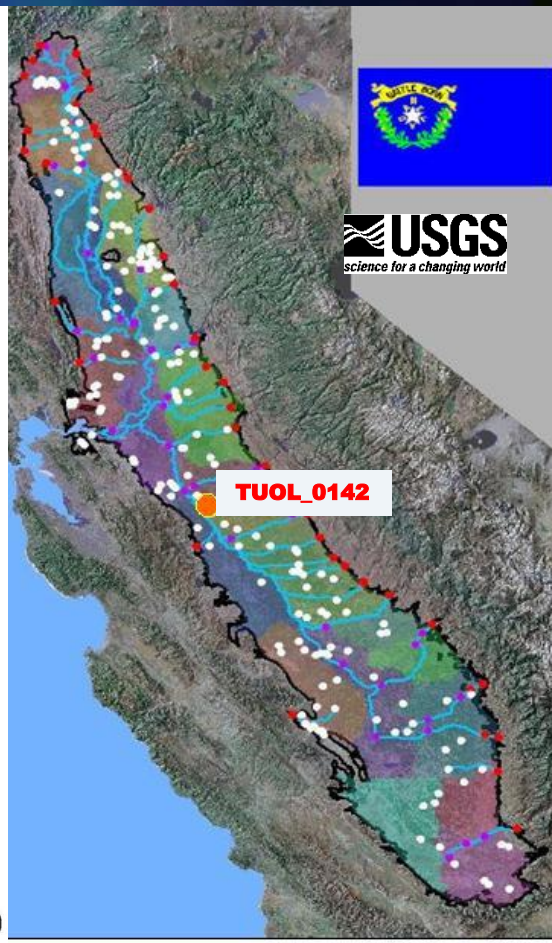
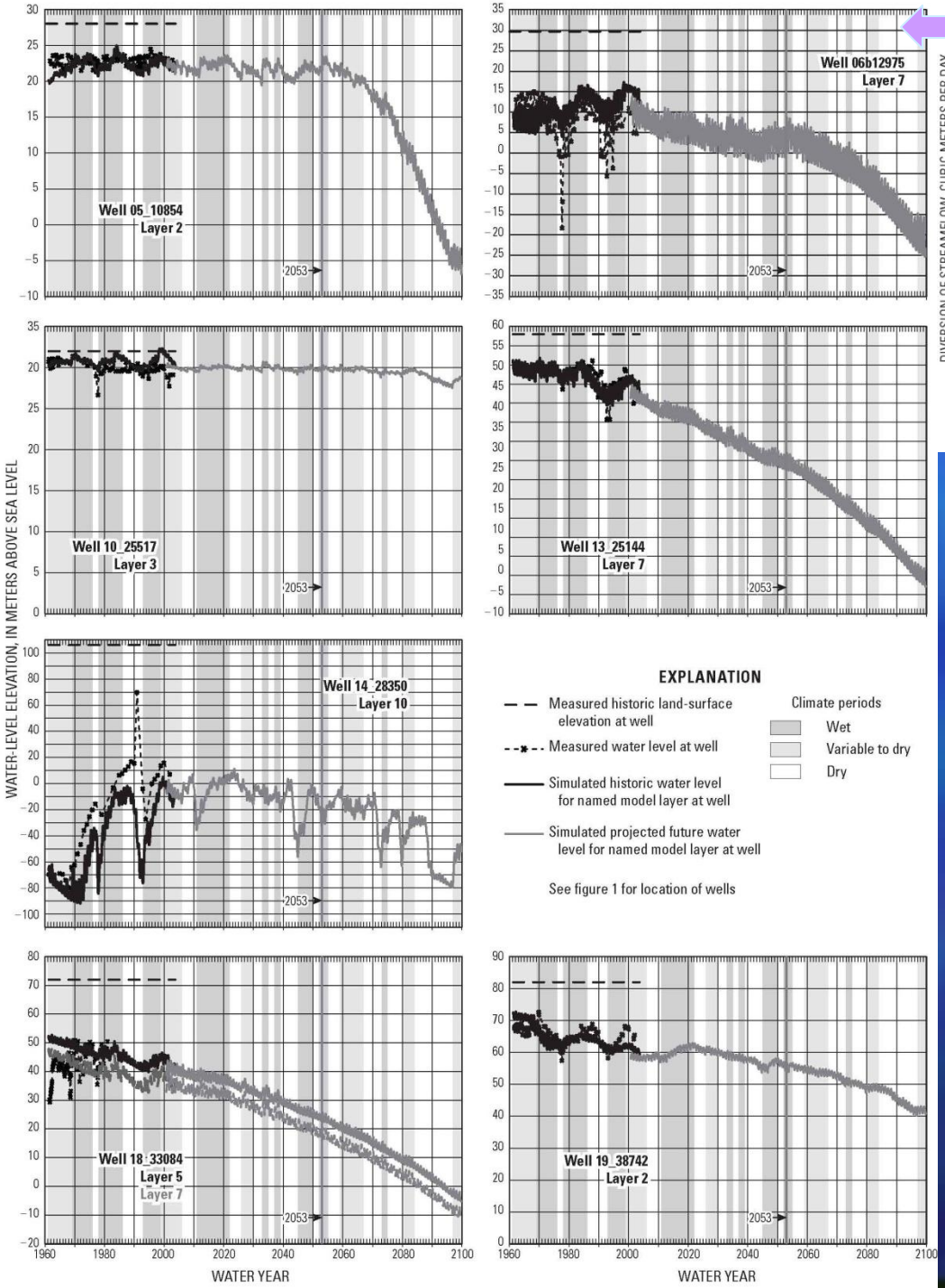
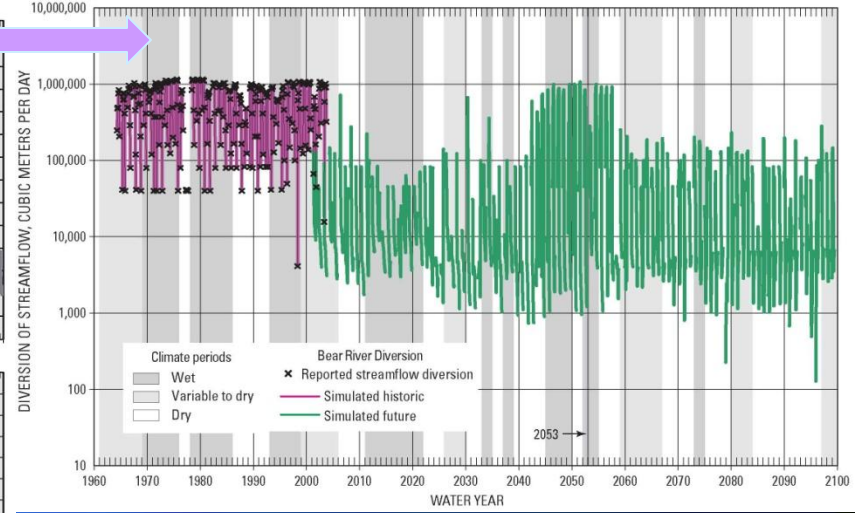
A2-Reduction in Surface-Water Diversions for Riparian Habitat on the Tuolomne River, San Joaquin Valley, Central Valley, California





Water diverted for maintaining Riparian Habitat from the Central Sierras may become intermittently unavailable in 21st Century





Continued Increase in Groundwater Demand → Increased Pumpage → Increased Declines in groundwater Levels

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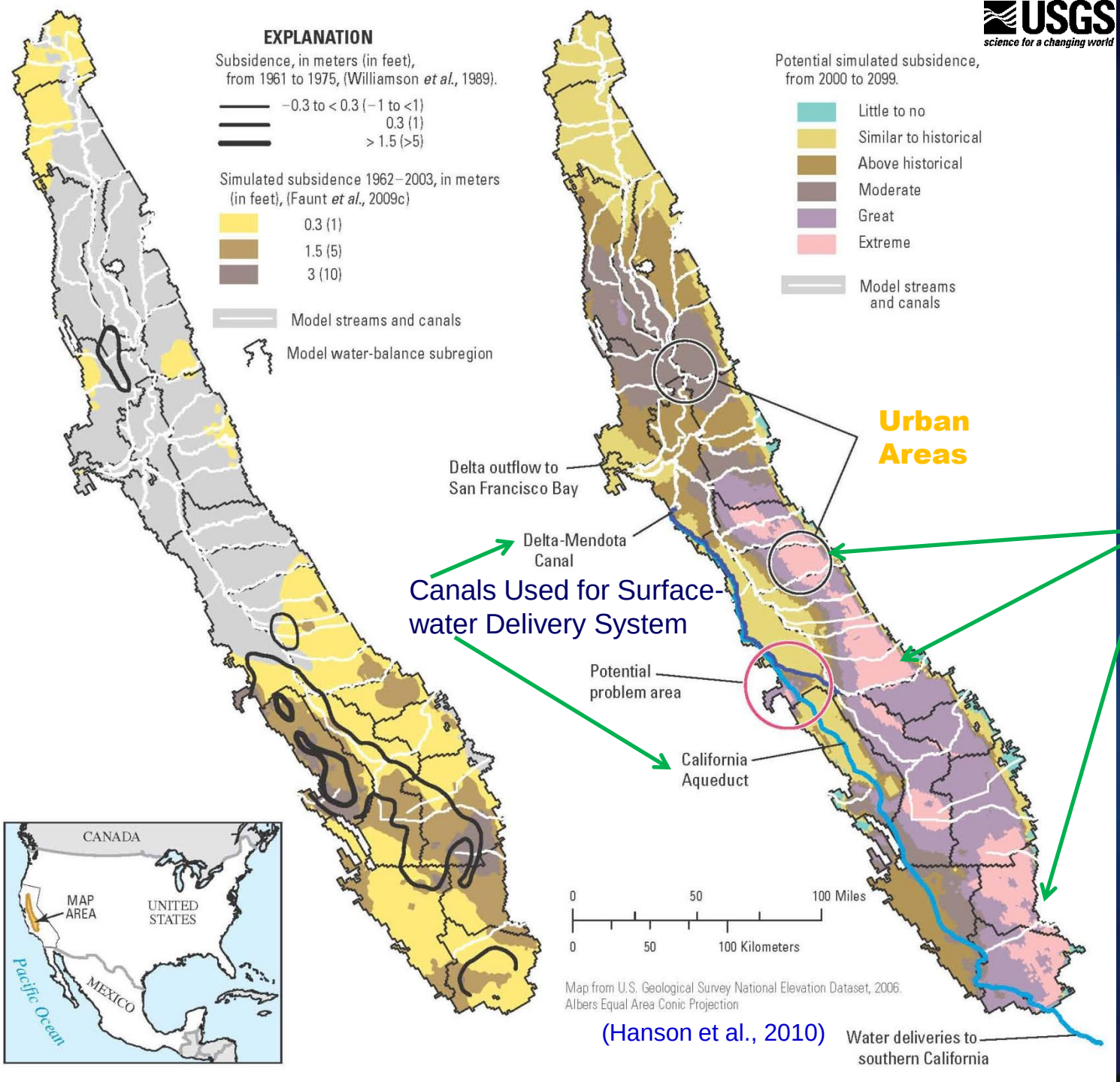
Old and New Subsidence



Renewed Subsidence in Historical Areas

Largest new Subsidence Adjacent to Sierras where Surface-water Deliveries for Irrigation become less

Additional subsidence in growing Urban areas

Summary of A2 Scenario Simulation of 21st Century

- **Increased** Groundwater Storage Depletion under A2 scenario for 21st Century in Central Valley
- **Increased** Land Subsidence throughout Central Valley and especially in the Tulare Basin and areas adjacent to Sierras (southern Central Valley)
- **Increased** streamflow infiltration and decreased groundwater outflow in the Sacramento Delta from 1-meter rise in sea level & 1.2% per year Urban Water Growth (model sensitive to even larger urban-demand growth rates!)
- **Decreased** Precipitation → Intermittent droughts in first half of century followed by sustained drought in 2nd-half of 21st Century
- **Decreased** Outflow at the Delta plus many rivers & diversions
- **Water-Use Transition** Surface-water dominated irrigation supplies to groundwater supplies with sustained drought.
- **No Operational Drought** Simulated capacity of sw/gw supply in system still greater than combined potential demand on conjunctive-use system
- **Climate Change and Increased Urban water use** → Both affect sustainability → land subsidence and reduced outflow at the Sacramento Delta

- **GCM-MHWM-CVHM Linkage Coupled physically-based, supply-constrained, and demand driven models** Basis for a Decision Support System Evaluate Outflow of streamflow at the Delta, Streamflow, Surface-water Diversions, Land Subsidence, & Drought Scenarios, Supply-&-Demand Components

- **Hydrologic projections** of a Century are more reliable in trends and changes than actual outcomes

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Today's Take-Home Messages

One Water

Linked & Integrated Models and Observation networks needed for Physcially-based Resource Analysis (Self-Updating Models → DSS & Indicators)

Sustainability, Conjunctive Use, Adaptation Controlled by Secondary effects

Management horizons may range from years-decades to more than a Century (2050 time frame may be inadequate)

Multiple Stressors on Resource → Climate change, Urbanization, Agricultural, Environmental

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Conjunctive Use Analysis – Central Valley Example

Outlook

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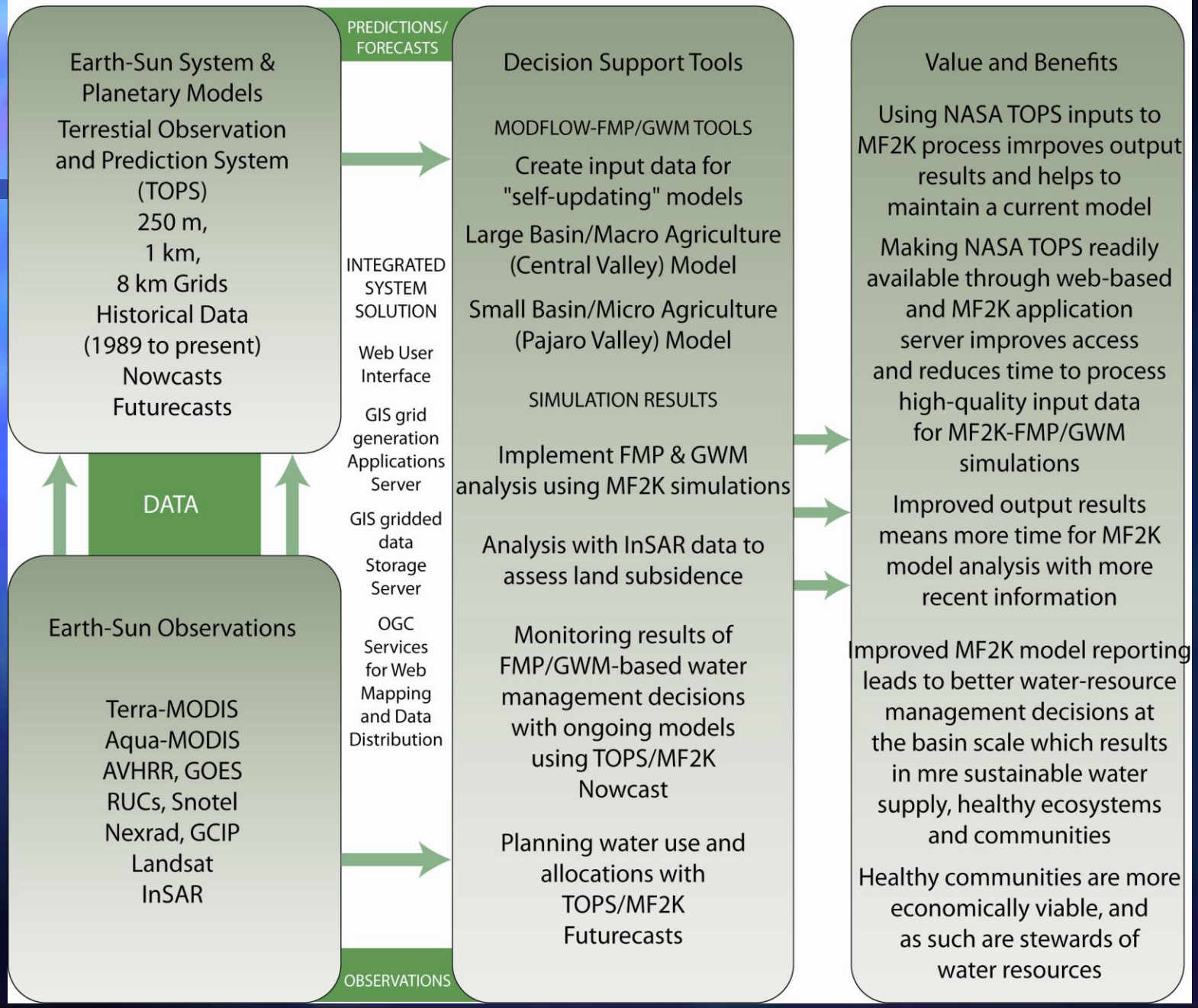
Develop Tools for Integrated Flow/Transport Models & Self-Updating Models → Conjunctive-Use, Adaptation, Sustainability Analysis of Water Resources

- Remote Sensing Data-Stream Linkages → Self-Updating Models & ground-based networks
- Regional Climate Modeling → Coastal and intermontane Agricultural Regions
- Linkages to Climate Models & Analysis - Visualization Tools → Climate-In-A-Box
- Automated Analysis/Synthesis of Remote Sensing Data (ex TOPS)
- Develop Decision Support Systems

Integrated System Solution - Using TOPS in MODFLOW(MF2K) DSS



USGS Integrated Hydrologic Models

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For more information refer to ➔
USGS Office of Groundwater Software:
http://water.usgs.gov/nrp/gwsoftware/fmp/fmp.html/
USGS WEBINAR CLIMATE-CHANGE (*Hanson et al.* 3/17/2011)
(http://wwwrcamnl.wr.usgs.gov/wrdseminar/playwrd.htm?id=17mar2011)

California-Nevada Applications Program (CNAP) & The California Climate Change Center (CCCC) : http://meteora.ucsd.edu/cap/

NASA's Climate-In-A-Box: http://climateinabox.nasa.gov/

NASA's Modeling GURU: https://modelingguru.nasa.gov/index.jspa

Supply-Constrained & Demand-Driven Conjunctive Use Analysis

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