WATER AVAILABILITY ANALYSIS in Regional Hydrologic Systems with CLIMATE CHANGE Using Climate-In-The-Box Linked to Physically–Based Hydrologic Models

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Work Performed by the U.S.G.S. Global Climate Change Program
&
California Application Project (CAP)
(a NOAA/OGP Regional Integrated Sciences and Assessments (RISA) member)

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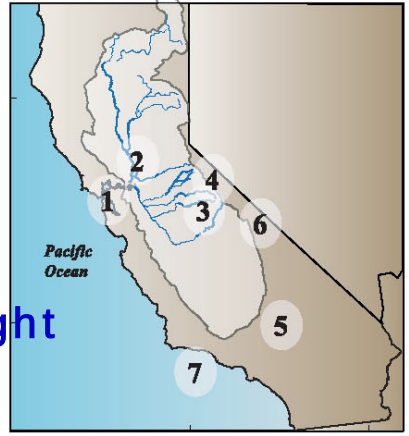
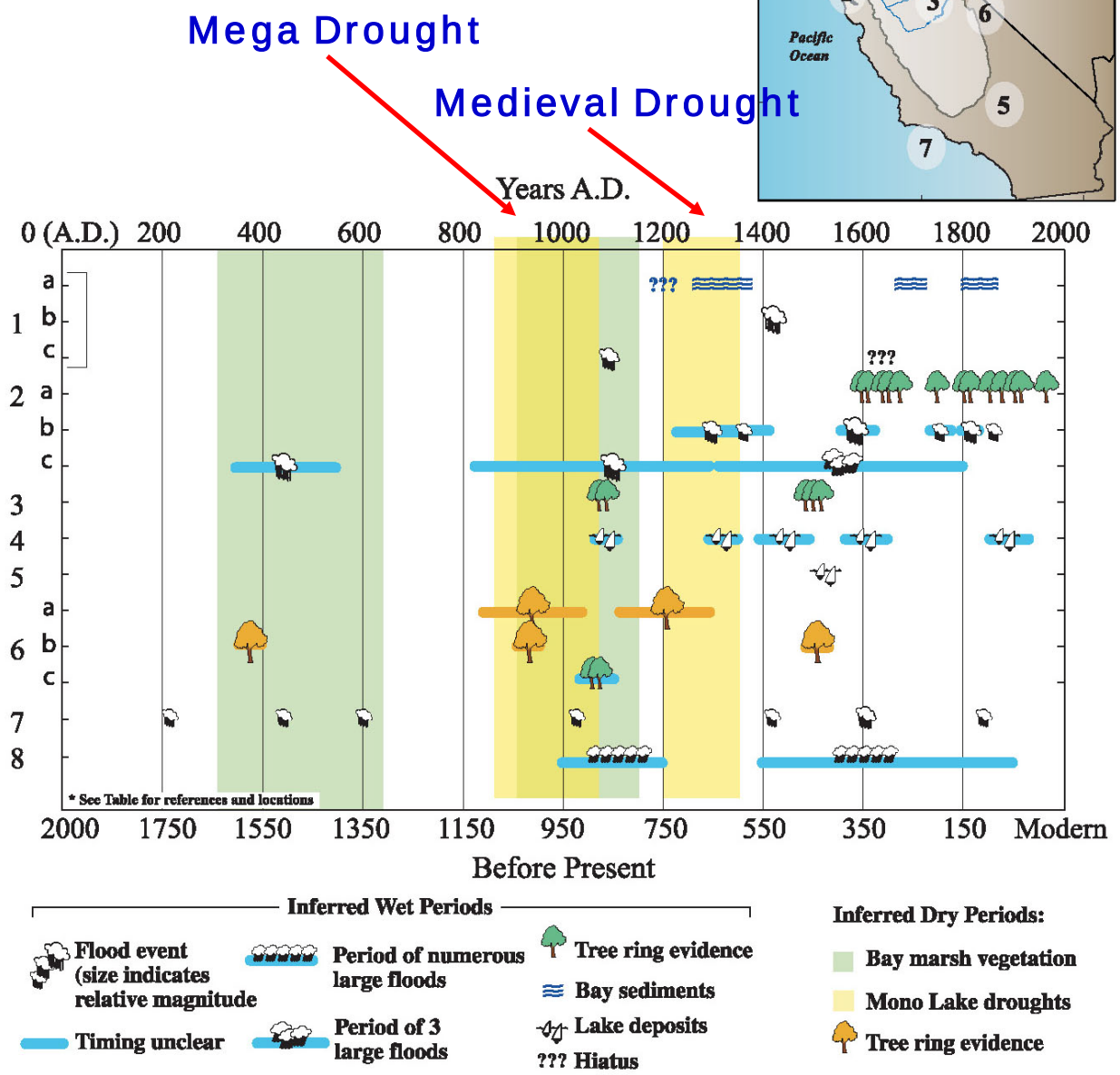
Paleo-Extreme Climate Events Central Valley, California

Mega-Droughts > 100 years long





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Research & Applied Scientists

- Computational and Data-Management Barriers?
  - Input & Through-Put of data streams for Coupled Models
  - Parallel Processing of Coupled Physically-Based Models
  - Synthesis and Visualization for Analysis and QA/QC
- Benefits from High-Performance Computing?
  - Multiple components processed in lagged parallel sequence
  - Accelerates numerical experimentation & analysis
- Current Architecture? ➔ Small DELL Multi-Blade clusters/ single machines
  - Windows/Linux ➔ 64-bit (Visual Studio/Cluster Toolkit)
- Current Needs for Regional Climate Modeling & App's?
  - More variables downscaled ➔ Analysis of more Secondary Effects and Marginal Changes to hydrologic system
- Integrated ESM for impact assessment? Wider USGS involvement linkage to coupled modeling systems under current development
- Sufficient Data Storage Capabilities? ➔ 90 TB per HPC????
- Benefits from access to Datasets, Integrated modeling codes, standardized formatting? ➔ Accelerate Processing, Collaboration, Communication of Research Results to Stakeholders
- Data visualization and analysis tools for research or Stakeholder engagements? ➔ Essential for "good story telling" to public and water managers. Analysis of temporal and spatial indicators needed for management thresholds.

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, 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 "Index" metrics not a real hard number. Hard to make decisions on normalized indices or use in physical models.

- Manage uncertainties in climate vulnerabilities? Estimation of skill and carry uncertainties through coupled models if possible ➔ coupled-hydrologic models are calibrated (mass-balanced and mass constrained)

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

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Model and Data

What Models and Data should be available on CIB?

1) Primary Models➔ GCMs, RCMs➔dynamic downscaling, Statistical Models ➔statistical downscaling, etc

2) Secondary Models➔ Physically-Based Hydrologic Models, Remote-Sensing Analysis (land use, vegetation, deformation, etc), Biological Models?, Economic Models?, Chemical Models?, Ecological?, Land-Use?

What are tests required for inclusion of data, research products and model codes within CIB?

1) QA/QC ➔ Chain of Custody for standard datastreams, confidential data security, etc

2) Skill ➔ Key climate primary and secondary indicators from hindcast analysis?

3) Model Performance ➔ (Intercomparison Standards ex. IPCC & NRC-Hydrocoin) especially key components that impact primary data feeds precipitation, temperature, relative humidity, wind speed, etc.

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Workflow, Scenarios, Datasets, & Tools

- What Workflows would be beneficial?

  Object-oriented Workflows that allow users & researchers to step through preparation, simulation & analysis and edit/build custom workflows for their application

  Integrated Workflows that combine CGIS, Models, Downscaling, Coupling, Analysis, Visualization, & Synthesis/Summary

- What are the scenarios, tools, and datasets that should be included?

  Scenarios ➔ Global and Regional, Inclusion of Urban Heat Islands

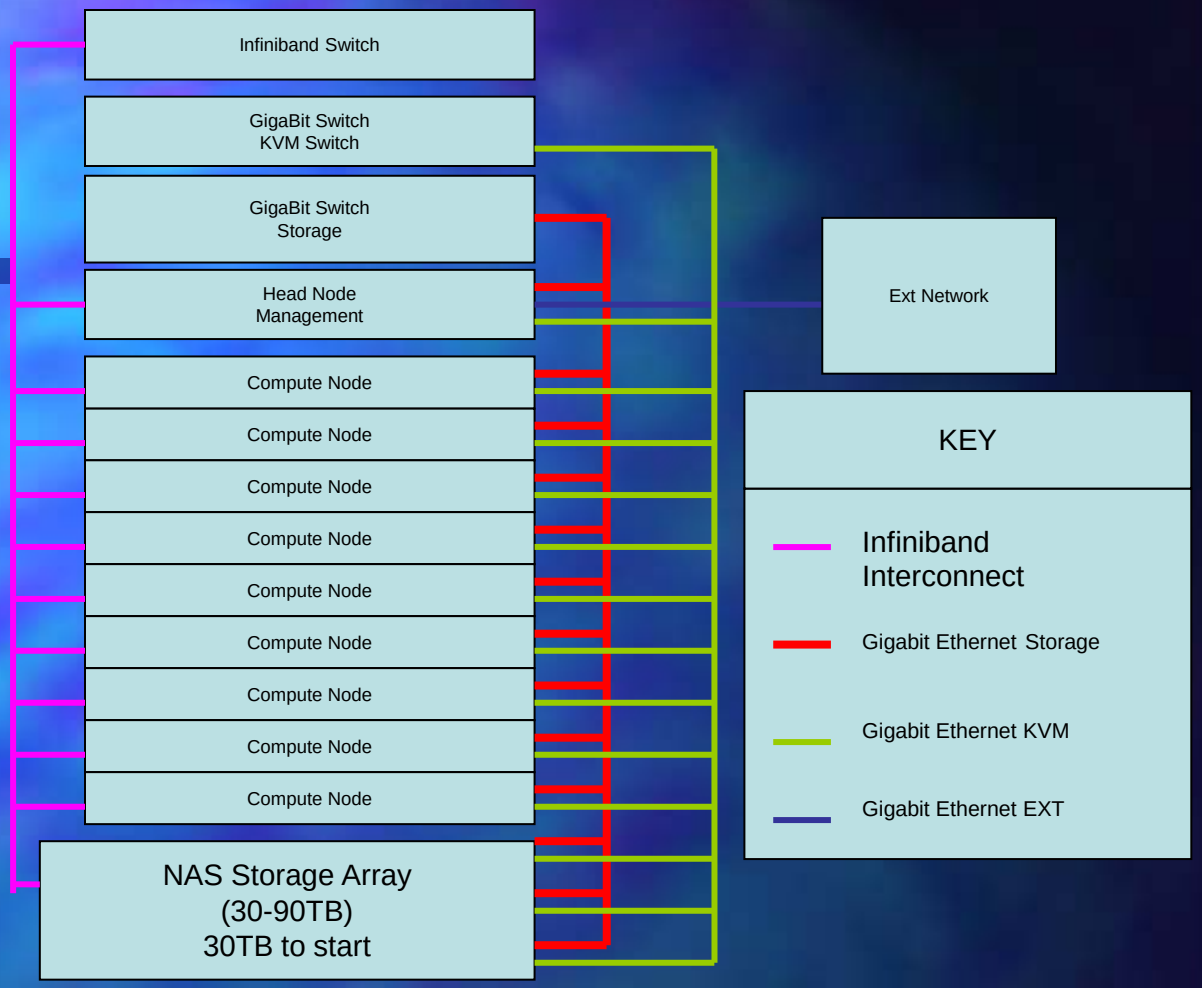
  Tools ➔ Remote Sensing (ex. TOPS, InSAR, Landsat), Mapping (ex. ARC-GIS), Code Development (ex. Fortran/C Compilers), Database (ex. Access), Downscaling/Coupling Programs, Analysis Tools, Visualization, other index-summary visualizations?

  Datasets ➔ Global and Regional Reanalysis: Precipitation, Temperatures, Plus other attributes such as relative humidity, wind speeds, cloudiness,

High-Performance Cluster for Climate-In-The-Box Project

SGI Octane-3

IBM DS3512



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Plan for DSS with Self-Updating Models

1) Maintain Skill
   ➔Update Historical
2) Automated Updates of historical Inputs & Analysis
3) Integrate Updated Past with Future
4) Automated Updates of future Inputs & Analysis

Integrated System Solution

Using TOPS in Basin Characteristic Model (BCM)/ MODFLOW(MF-FMP) Decision Support System (DSS)

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Earth-Sun System & Planetary Models

Terrestial Observation and Prediction System (TOPS)
250 m,
1 km,
8 km Grids
Historical Data
(1989 to present)
Nowcasts
Futurecasts

DATA

Earth-Sun Observations

Terra-MODIS
Aqua-MODIS
AVHRR, GOES
RUCs, Snotel
Nexrad, GCIP
Landsat
InSAR

PREDICTIONS/ FORECASTS

INTEGRATED SYSTEM SOLUTION

Web User Interface

GIS grid generation Applications Server

GIS gridded data Storage Server

OGC Services for Web Mapping and Data Distribution

OBSERVATIONS

Decision Support Tools

MODFLOW-FMP/BCM TOOLS

Create input data for "self-updating" models

Large Basin/Macro Agriculture CVHM(Central Valley) Model

Small Basin/Micro Agriculture PVHM(Pajaro Valley) Model

SIMULATION RESULTS

Implement FMP & BCM analysis using simulations for analysis linked with:

1) TOPS data for ET, runoff, and landuse
2) InSAR data to assess land subsidence
3) Local data for water levels and streamflow

Monitoring results of FMP/BCM-based water management decisions with updated models using TOPS/Model DSS Nowcast

Planning water use and allocations with TOPS/Model DSS Futurecasts

Value and Benefits

Using NASA TOPS inputs to DSS process improves output results and helps to maintain a current model

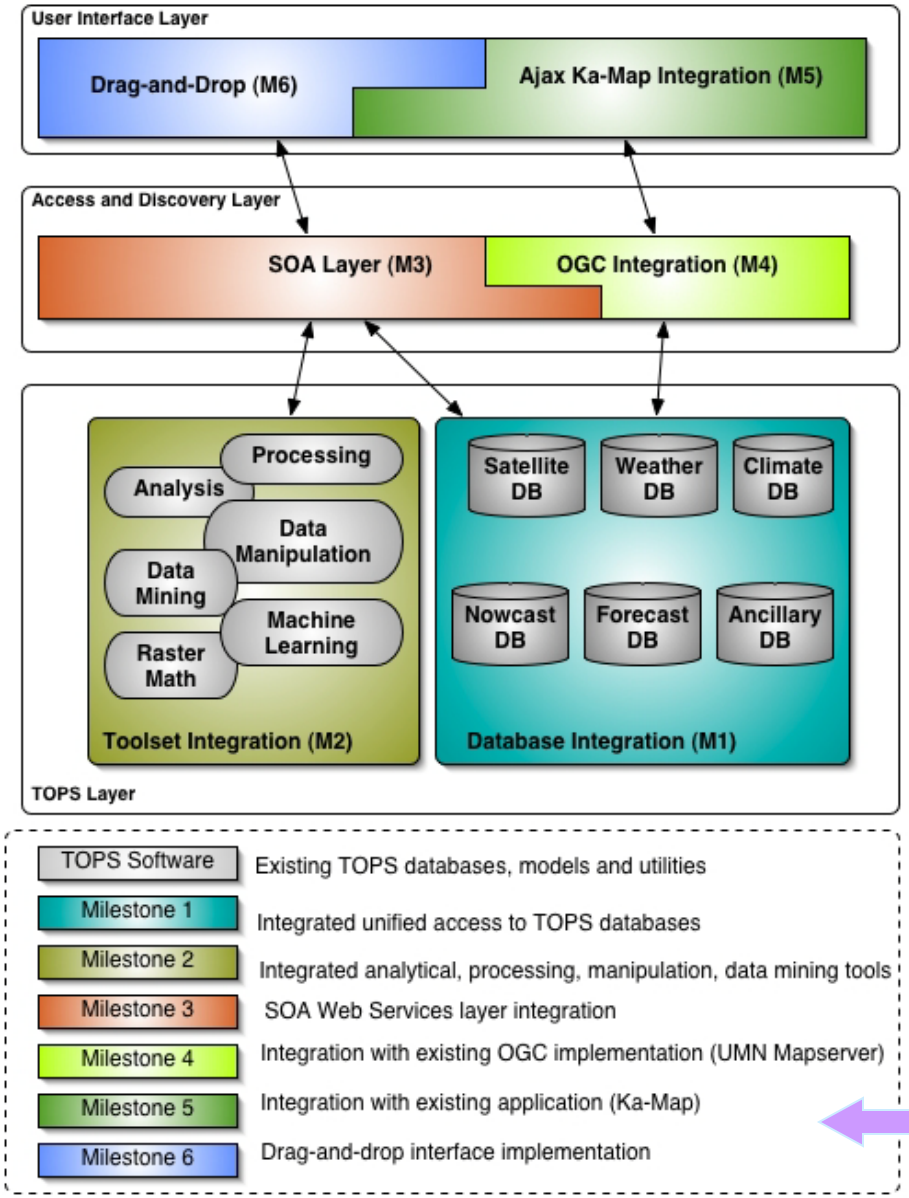
Making NASA TOPS readily available through web-based and DSS model application server improves access and reduces time to process high-quality input data for MF-FMP/BCM simulations

Improved output results means more time for model analysis with more current information

Improved model reporting leads to better water-resource management decisions at the basin scale which results in more sustainable water supply, healthy ecosystems and communities

Healthy communities are more economically viable, and as such are stewards of water resources

Example of NASA--TOPS architecture and development strategy. Linkage to USGS models part of Milestone 5 and 6 (Nemani and Votava, personal commun., 2008).



Historical Input Data, OBS Data, & Downscaling Reference Data for Land-Use & Hydrologic Models

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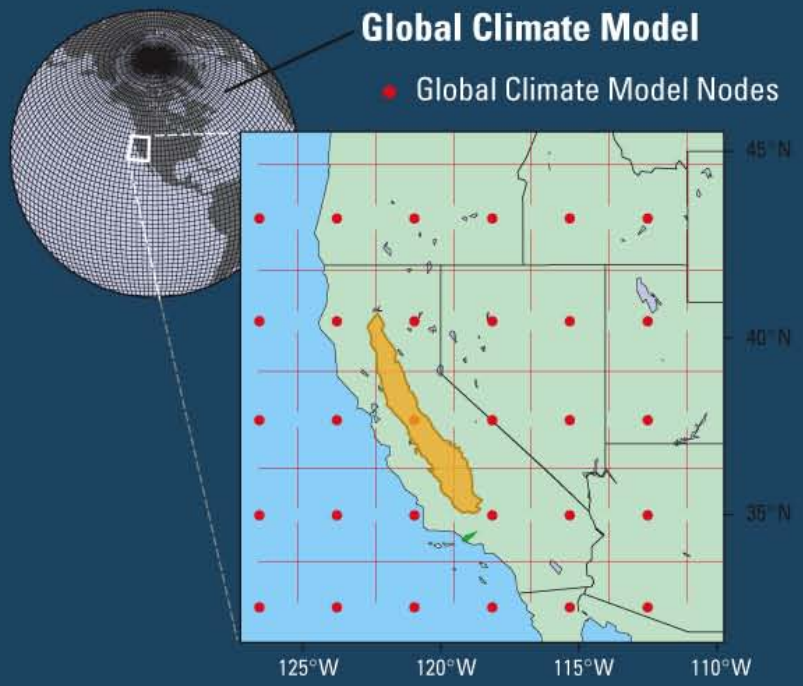
Linkage of Global Climate Model to Regional Hydrologic Models



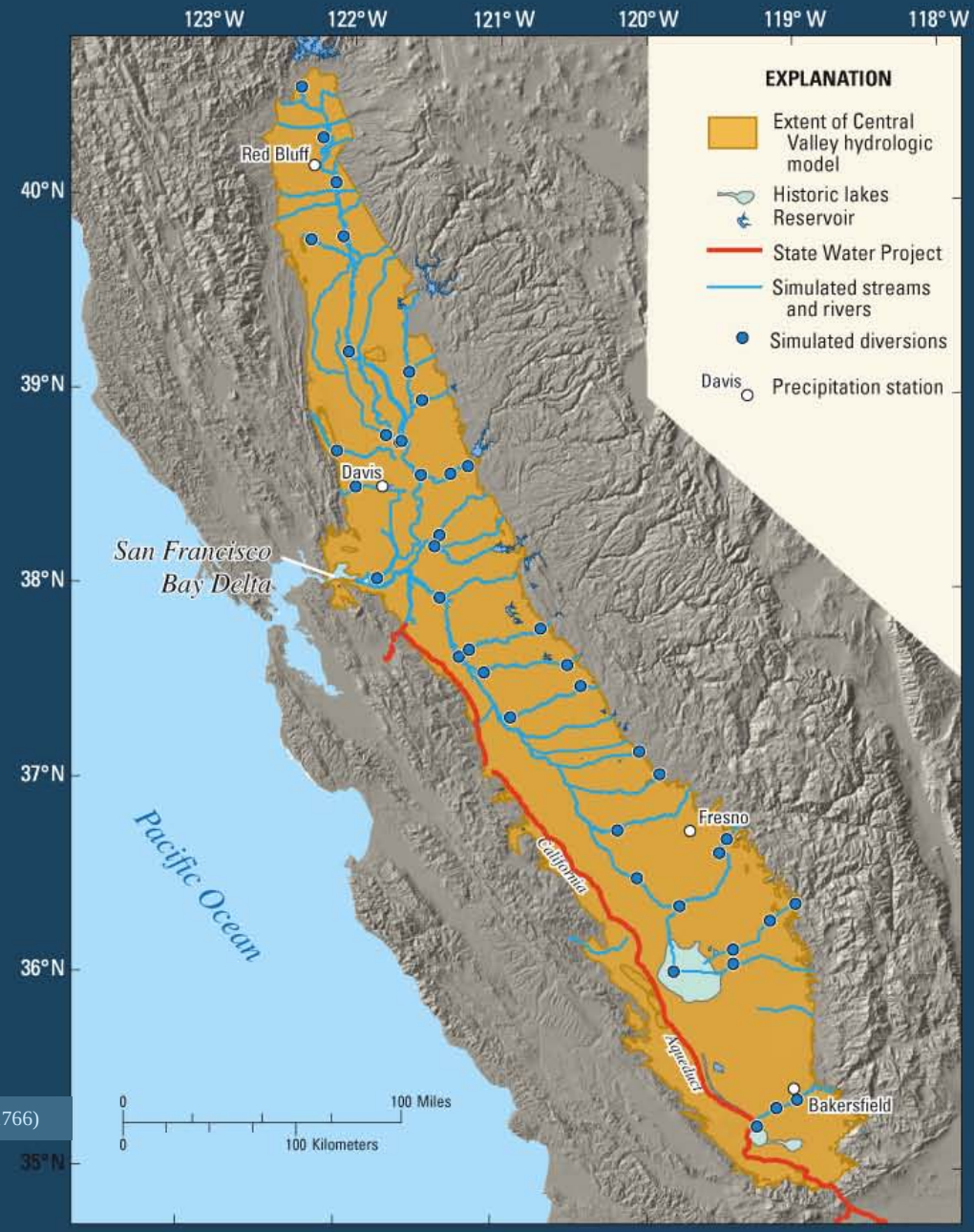


Figure 1. Map of Central Valley Hydrologic Model illustrating relation to the rivers, diversions, and San Francisco Bay Delta

Modified from Hanson and Dettinger, 2005; Faunt and others, 2009 (USGS Prof. Paper 1766)

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A2- Scenario & Model Linkages

- A GCM linked to a regional basin characterization model (BCM) that defines all upper and flow boundary conditions to a regional hydrologic model (RHM) of the Central Valley, California that represents groundwater, surface water, and agricultural components ➔ Series of Linked physically-based hydrologic models

- The future projection (A2) potentially extreme conditions that is 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

- The General Fluid Dynamics Laboratory (GFDL) climate model used with the simulated atmospheric circulation and attendant conditions from 2000 to 2100. The A2 climate projection used to explore response of the linked regional hydrologic models with:
  (1) Agricultural land use held constant at 2006 distribution.
  (2) Historical urban water use 1961-2003 ~4% & future urban water use projected to increase at 1.2% per year through at least 2040.
  (3) One meter rise in sea level at Delta outflow over 21st Century.

- GCM ➔ BCM & CVHM used to evaluate potential effects of extreme climate change on conjunctive use of water in one of the largest food producing regions of the world. Future use and movement of water includes assessment of runoff and mountain-front recharge from surrounding mountains, irrigation supply & demand, and response of groundwater and streamflow to climate change and increased urbanization.

- Simulation Response metrics of Conjunctive Use ➔ Diversions of surface water for irrigation, streamflow and streamflow infiltration, changes in groundwater storage, and related effects ➔ potential land subsidence and groundwater/surface-water relations in the Sacramento Delta, as well as Economic/Environmental adaptation of agriculture to changing climate.

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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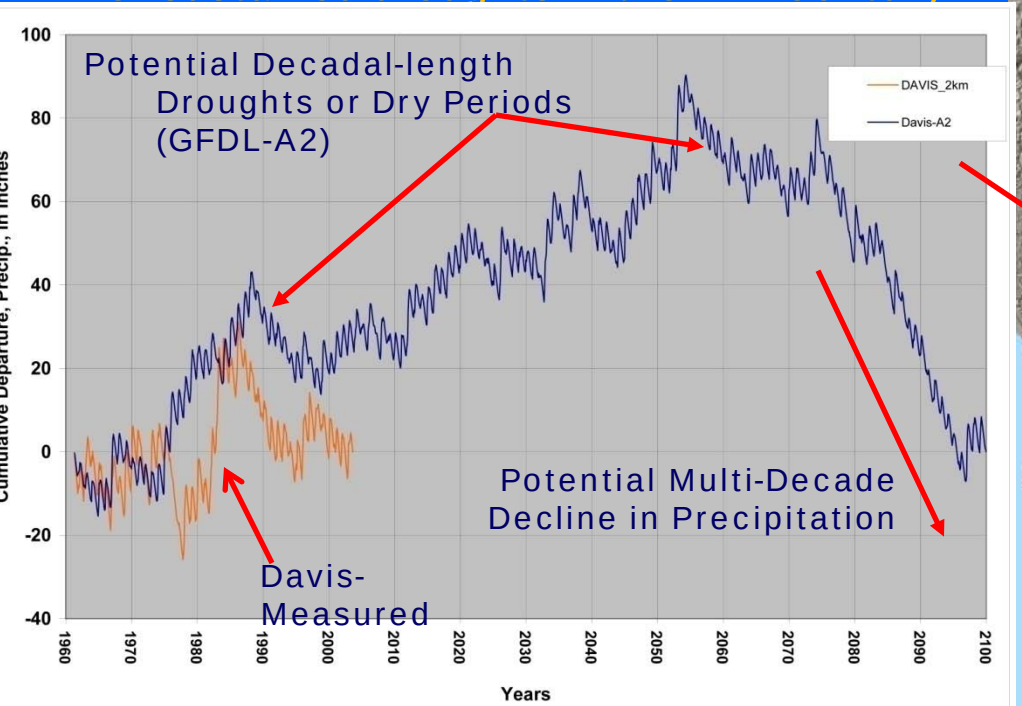
Precipitation Stationarity and Weak-Stationarity ?

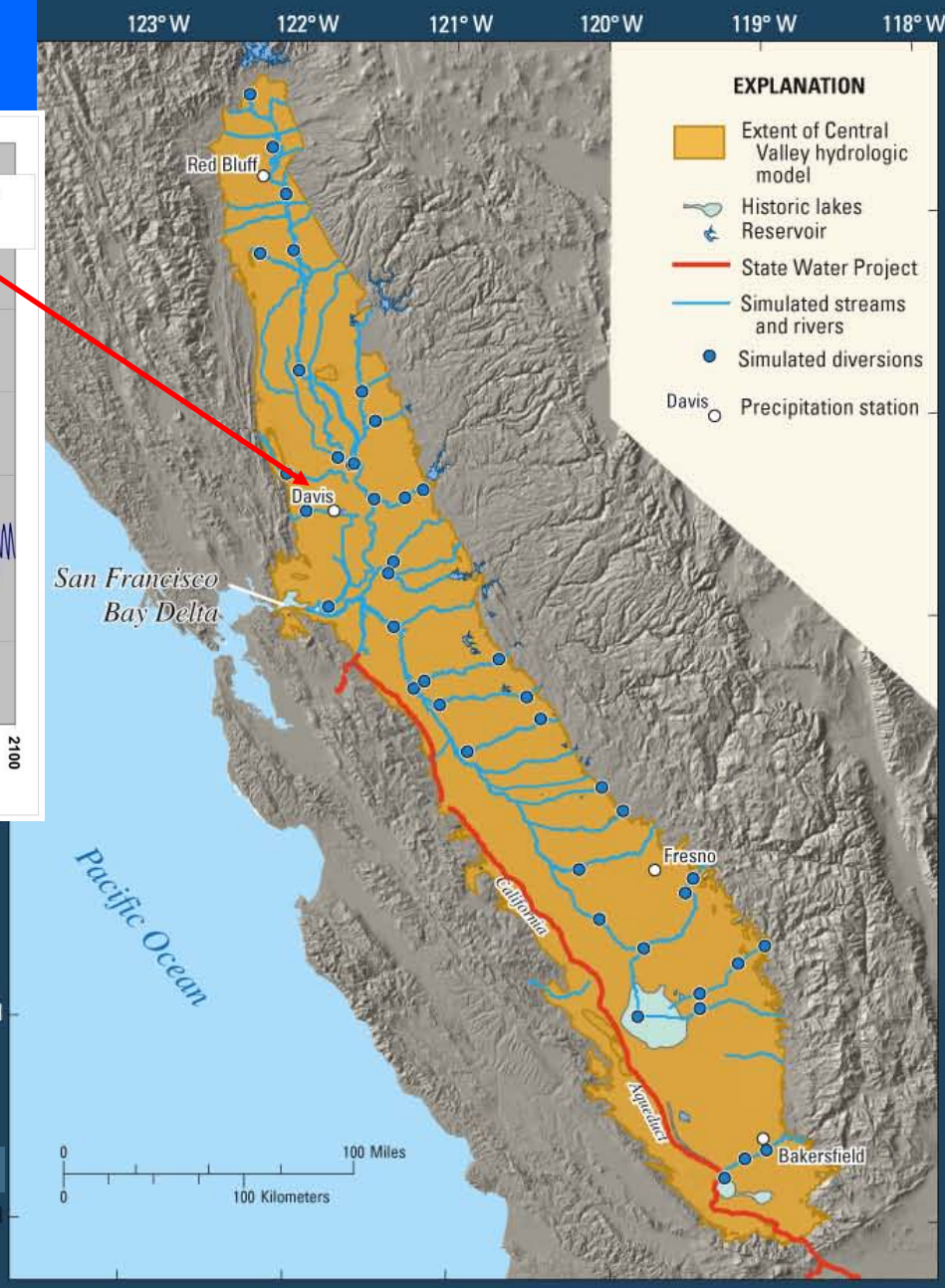
Cumulative Precipitation Downscaled

Shows A2 Scenario at Davis with the potential for sustained droughts in the 21st Century

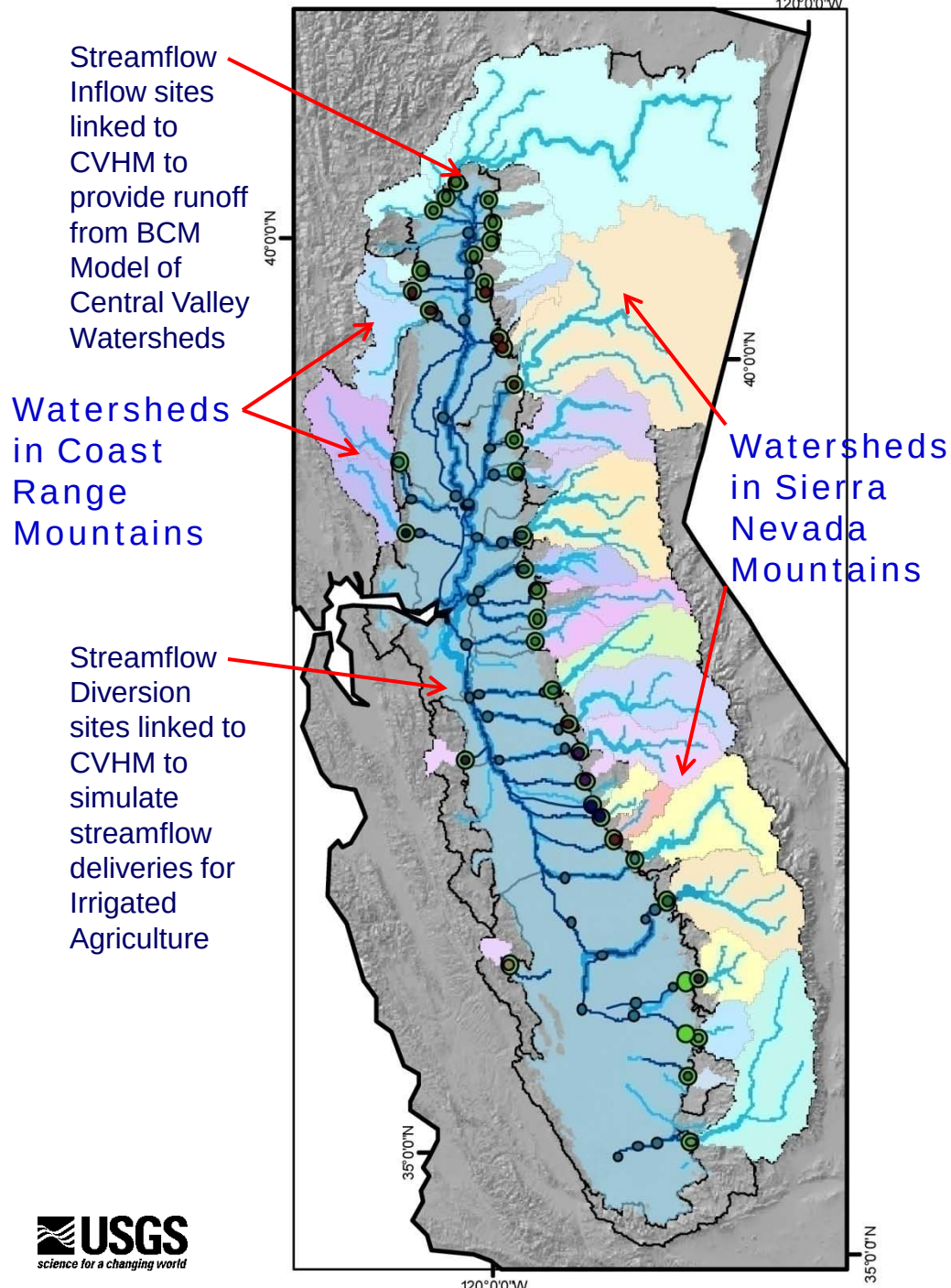


	Davis-Measured 1917-2005 (89 yrs)	Davis-GFDL/A2 2006-2099 (94 yrs)
Mean	17.3 in	13.7 in
Variance	37.8 in^2	19.4 in^2
>PDO-AMO	43 yr (79%)	52 yr (87%)
PDO	18 yr (14%)	19 yr (10%)
MON-PE	9 yr (3%)	9 yr (2%)
ENSO	2 – 6 yr (4%)	2 – 6 yr (1%)

Modified from Hanson and Dettinger, 2005; Faunt and others 2009 (USGS Prof. Paper 1766)



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)



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Preliminary Results Subject to USGS approval and modification

Runoff from BCM Model (1970-2000)

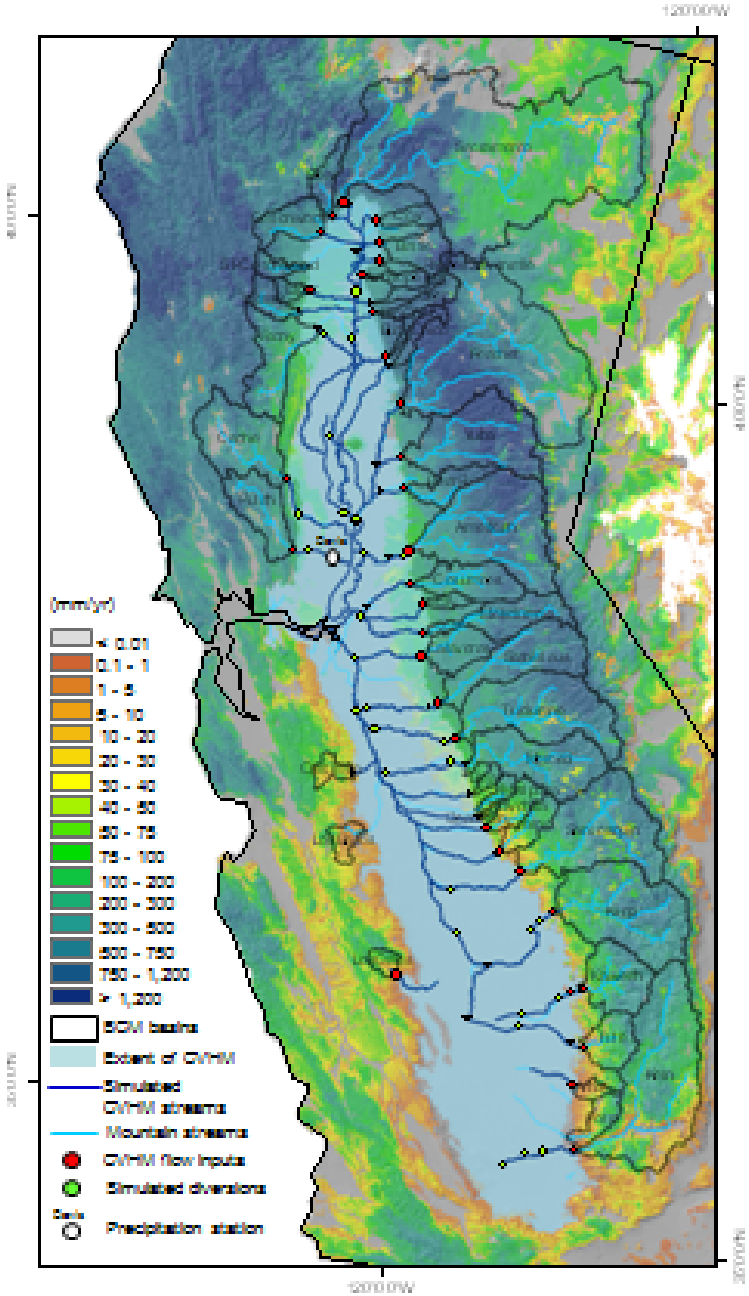
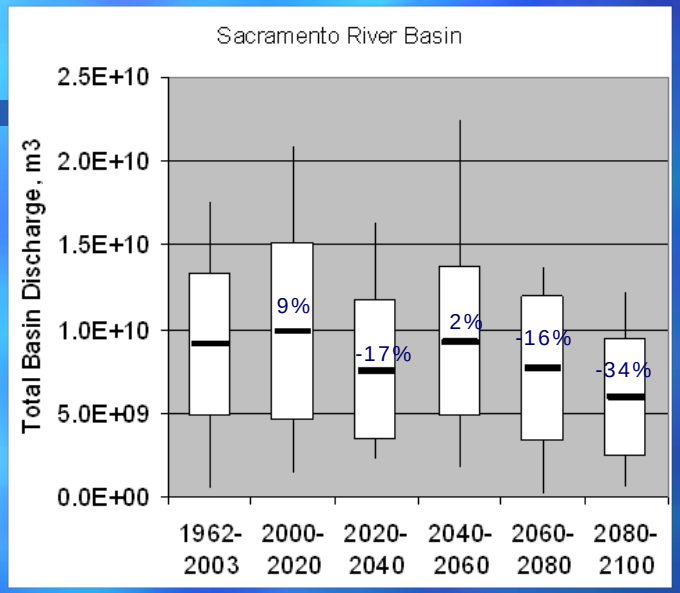


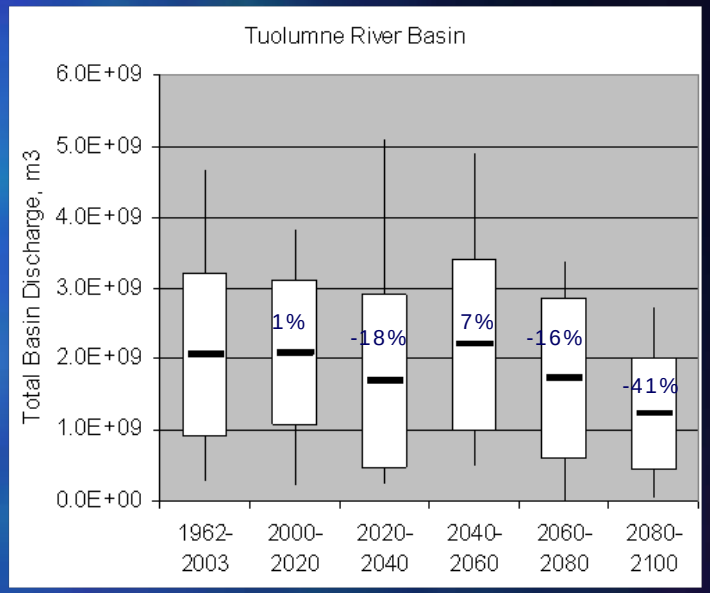
Figure 1. Map showing study area with the model grid area of the Central Valley Hydrologic Model (CVHM), basins modeled using the Basin Characterization Model (BCM), and current (1970-2000) spatially distributed runoff calculated using the BCM.

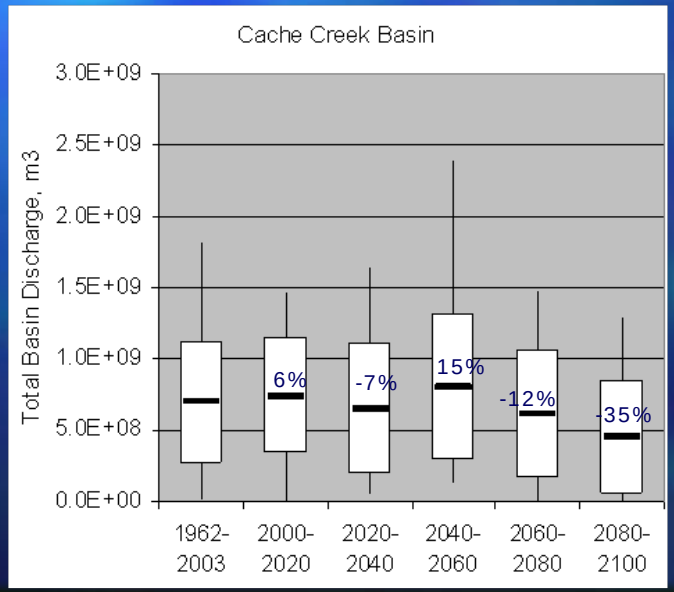
Preliminary Results Subject to USGS approval and modification

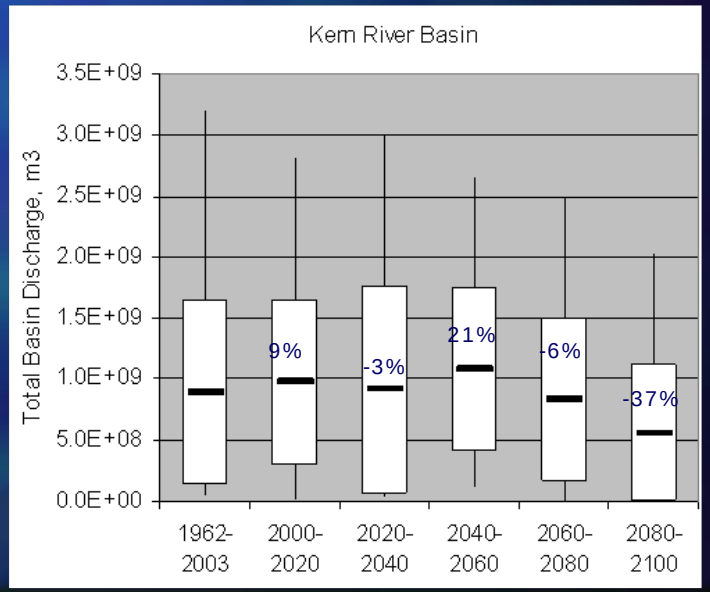
Current (1962-2003) modeled and future 20-year projections of total basin discharge for 4 basins in the study area, depicted as mean (black bar), standard deviation (white box), and range (vertical lines). Percent change in future mean discharge from current mean is indicated for each 20-yr period.

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

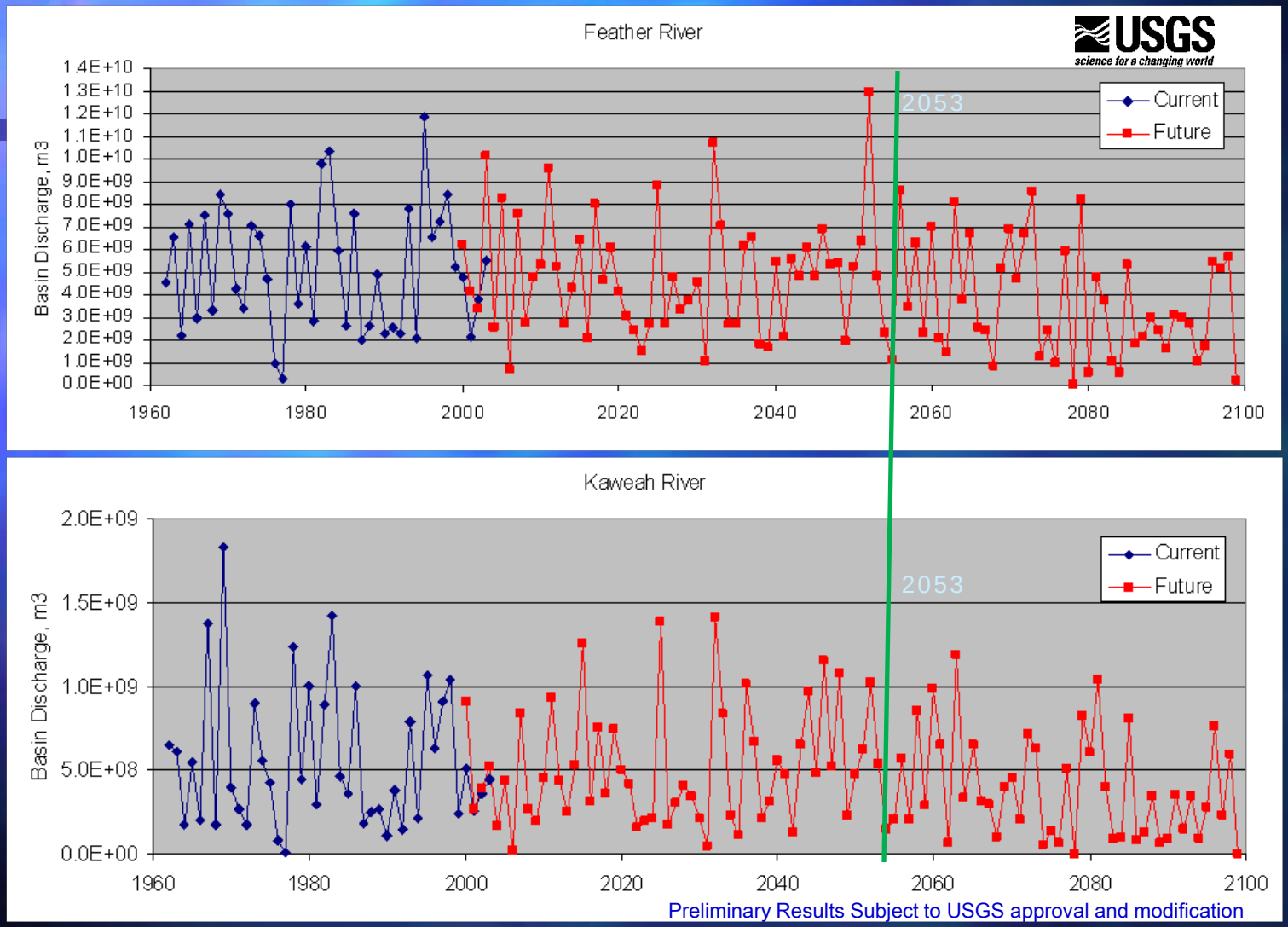




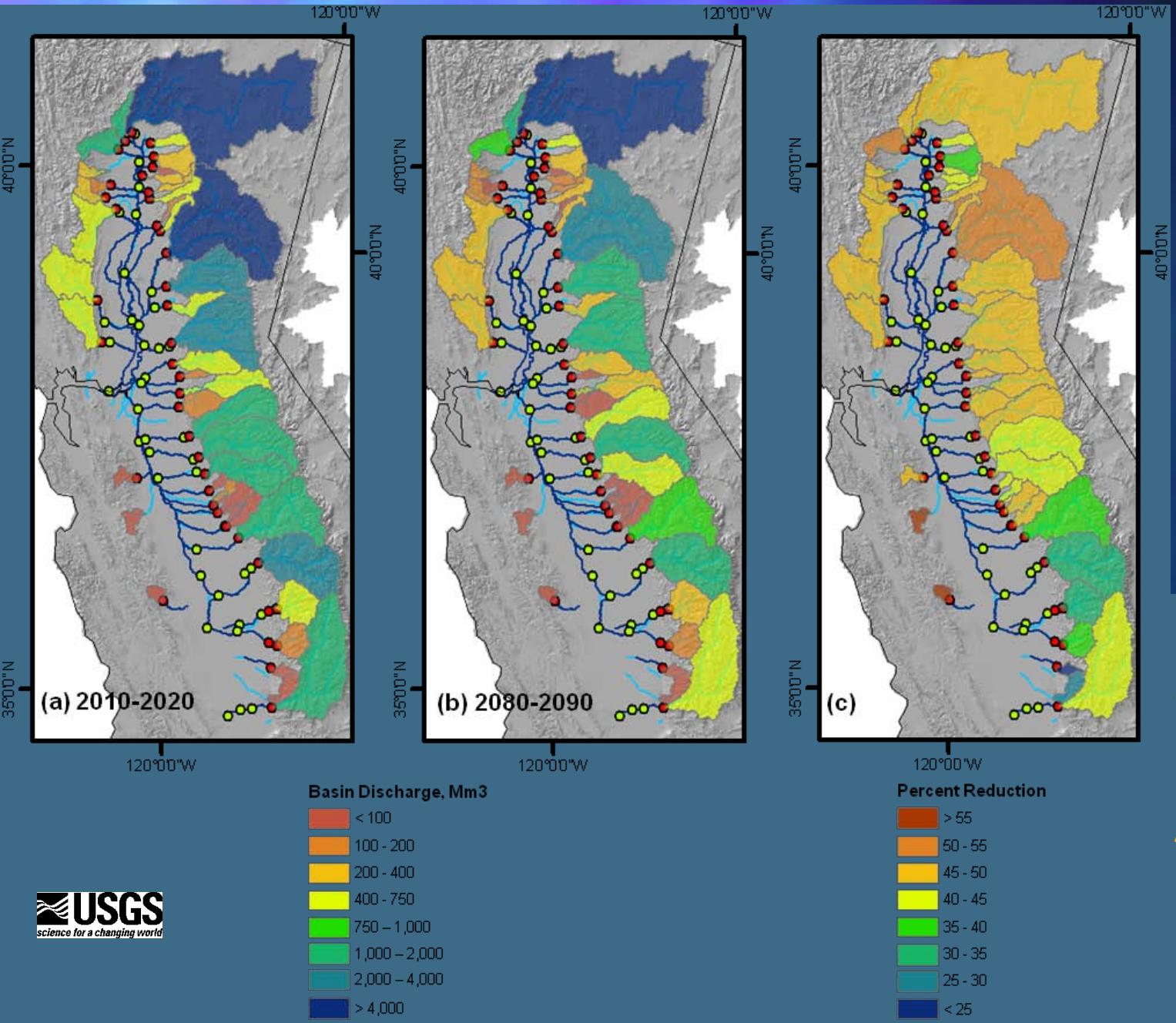




Examples of transition from current (1962-2003) modeled and future (2000-2100) projections of total basin discharge for the North (Feather River) and South (Kaweah River) basins, Central Valley California.



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



Mean total basin discharge for (a) 2010-2020, and (b) 2080-2090, in millions of cubic meters, and (c) percent reduction in discharge between the 2 decades, for each of the 43 basins in the study area.

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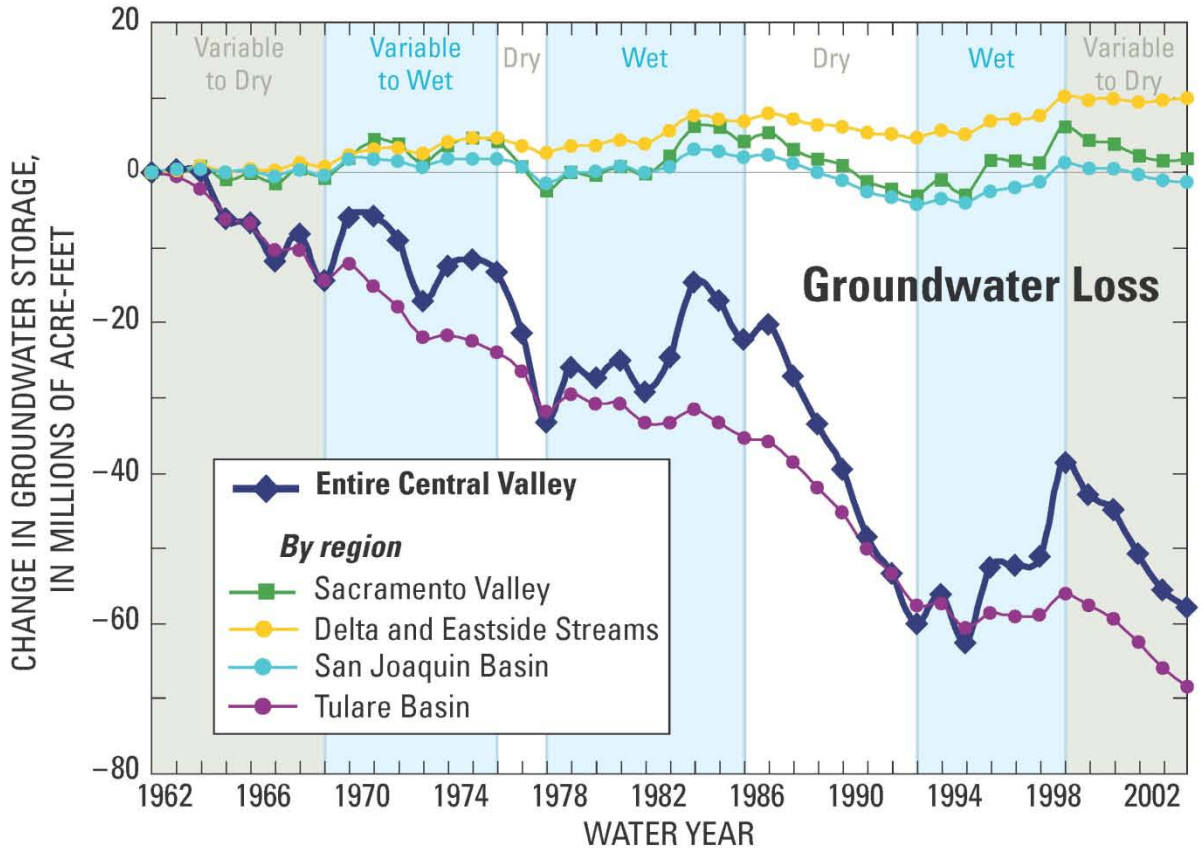
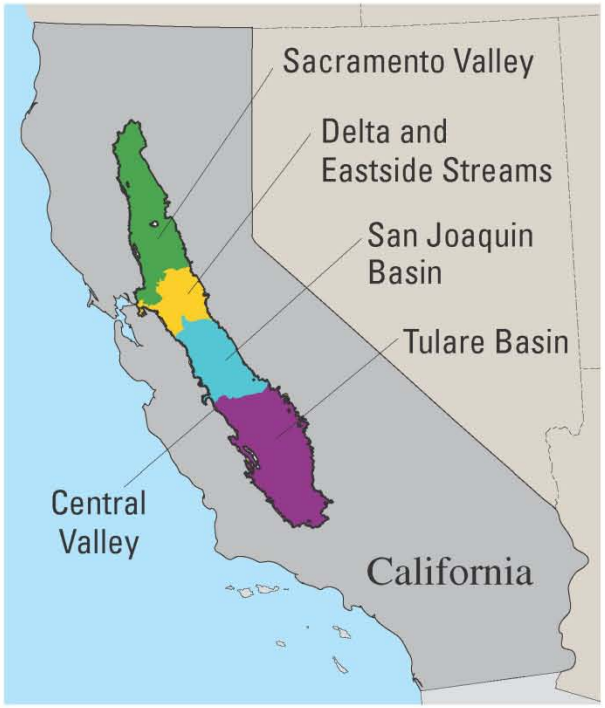
Simulated Historical Change in Groundwater Storage (Water Years 1961 – 2003)





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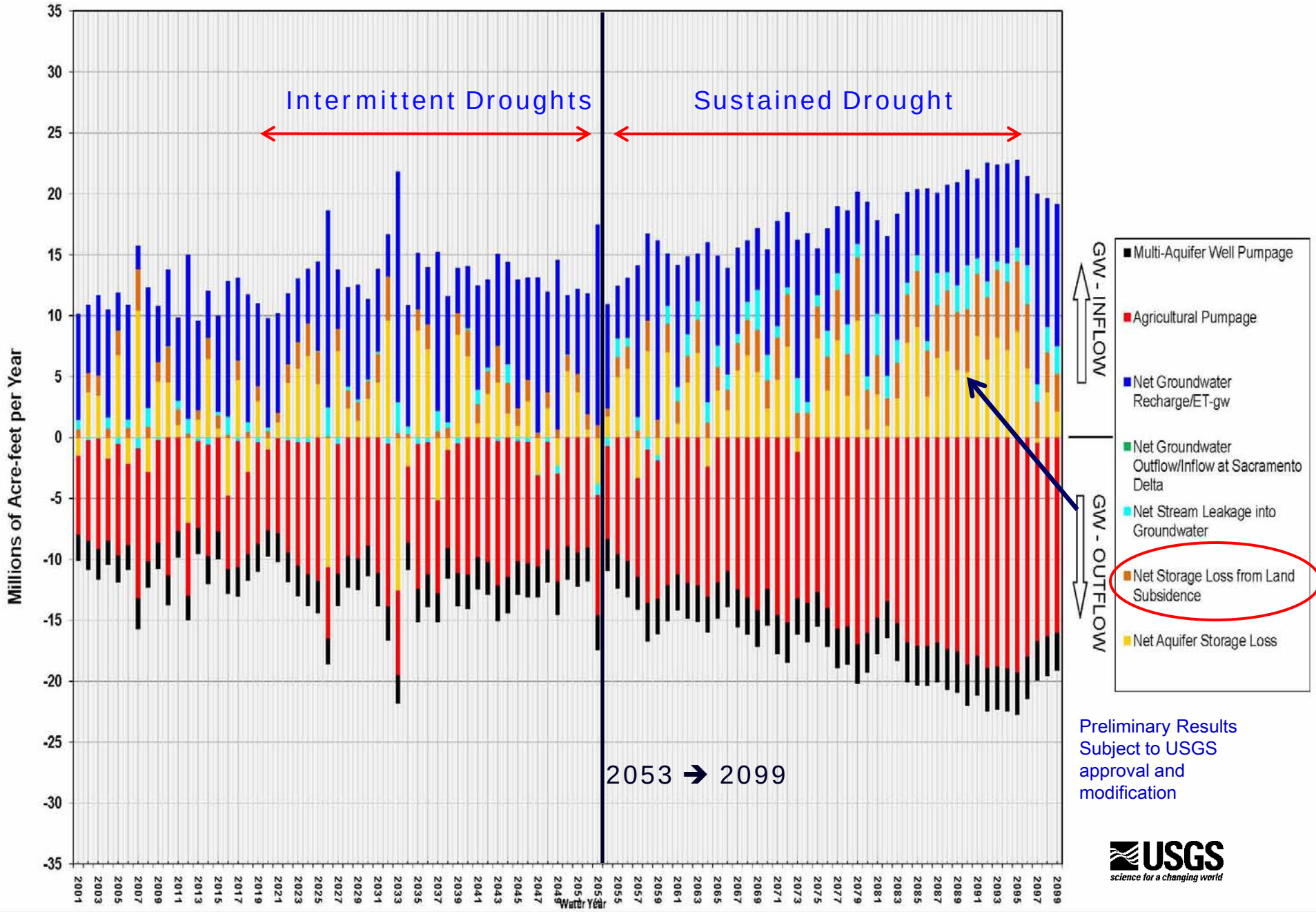
Faunt, C.C., Hanson, R.T., Belitz, Kenneth, and Rogers, Laurel, 2009, California's Central Valley Groundwater Study: A Powerful New Tool to Assess Water Resources in California's Central Valley: U.S. Geological Survey Fact Sheet 2009-3057, 4 p. (http://pubs.usgs.gov/fs/2009/3057/)

Net Groundwater Hydrologic Budget for GFDL-A2 Scenario, Central Valley, California



Preliminary Results Subject to USGS approval and modification

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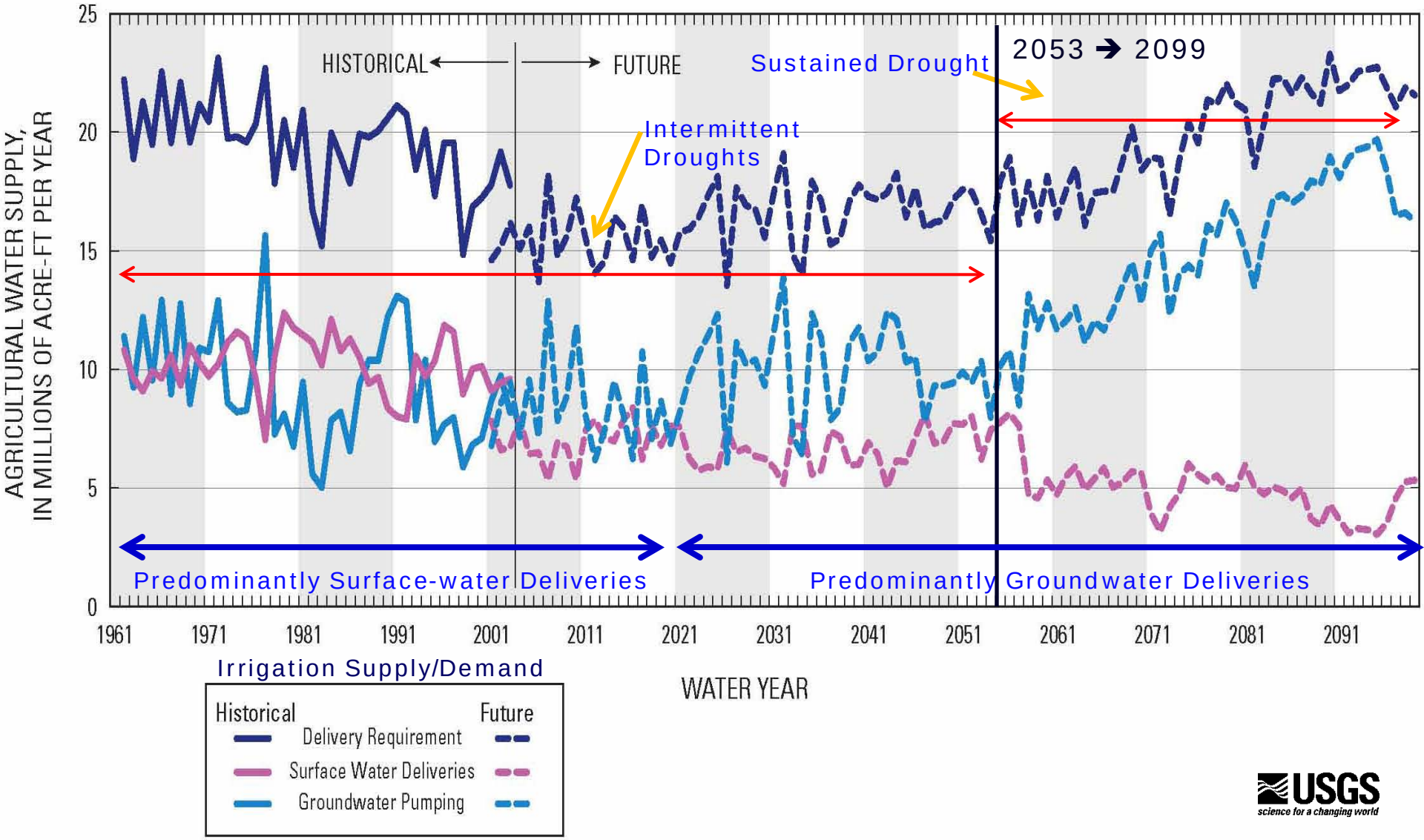
AGRICULTURAL WATER-SUPPLY AND DEMAND FOR GFDL-A2 SCENARIO, CENTRAL VALLEY, CALIFORNIA



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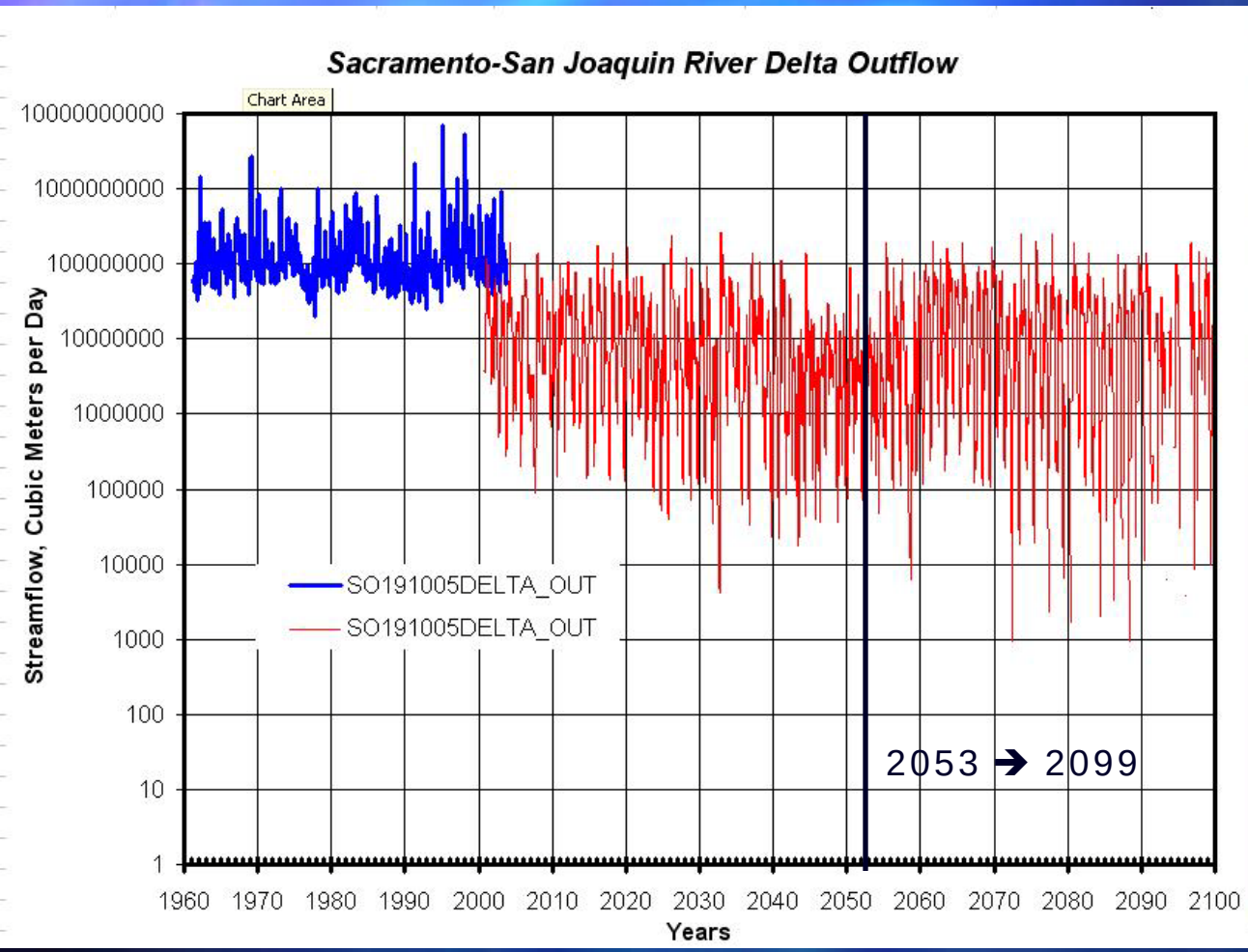
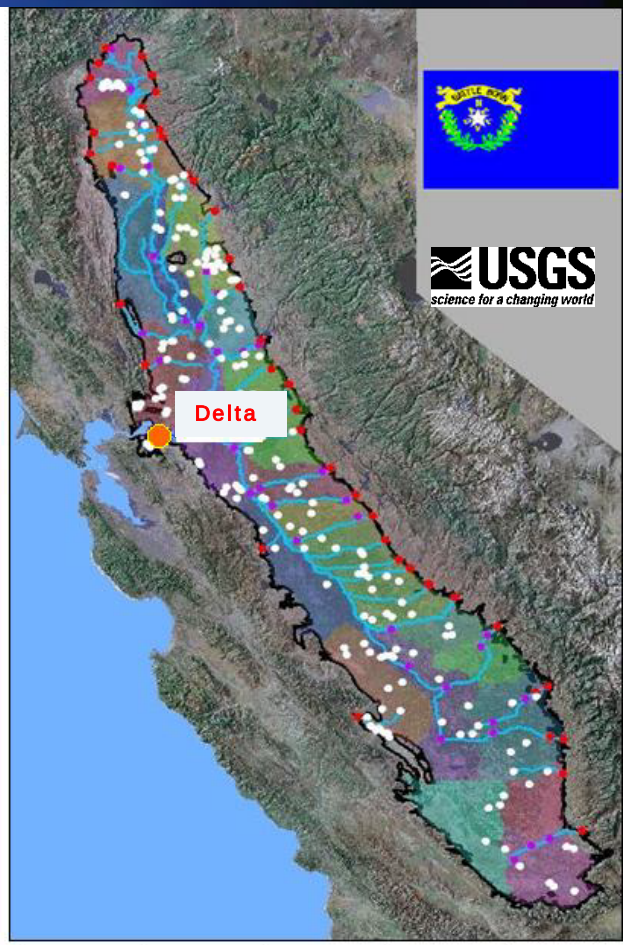
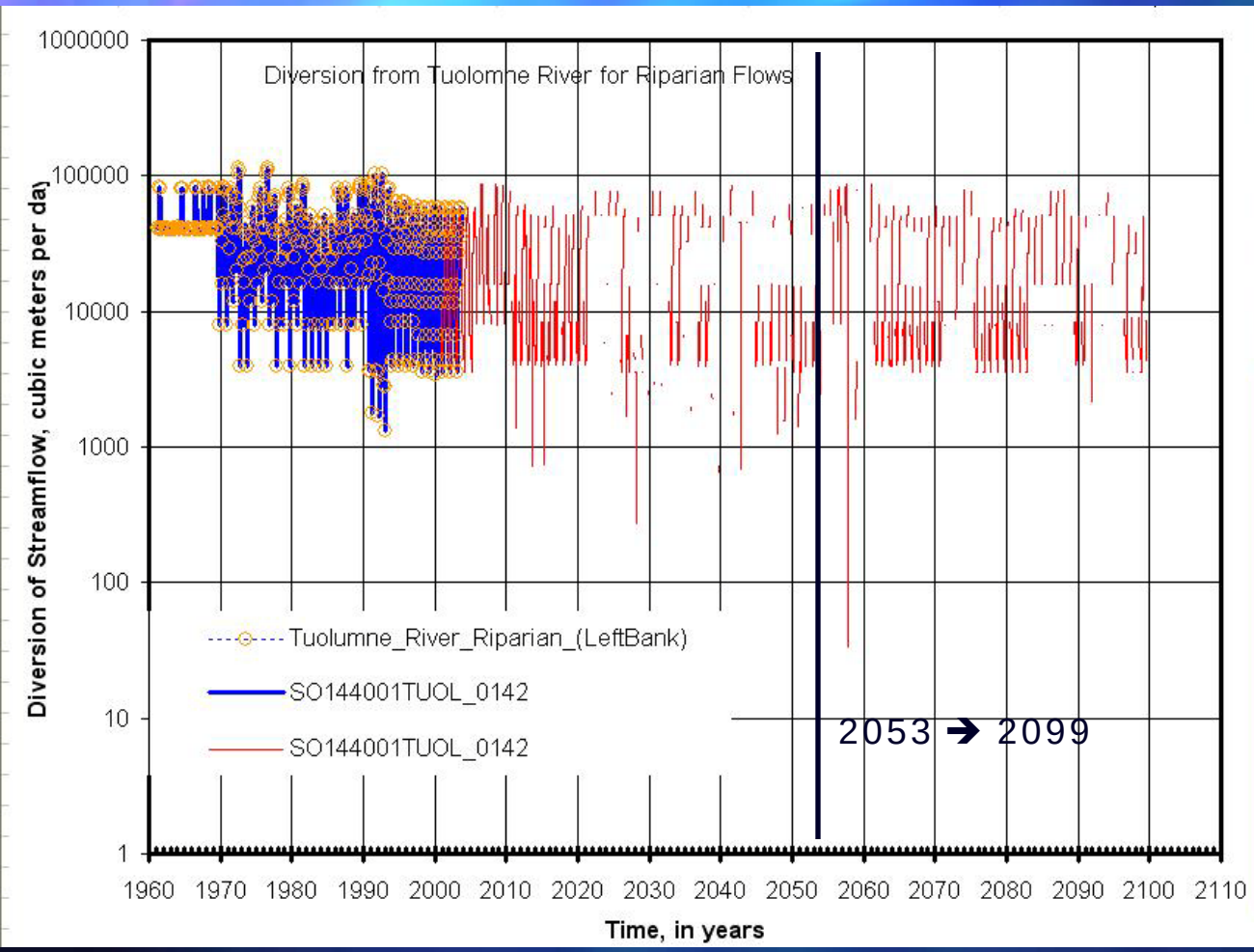
A2-Reduction in Streamflow to San Francisco Bay through the Bay Delta, Sacramento Valley, Central Valley, California

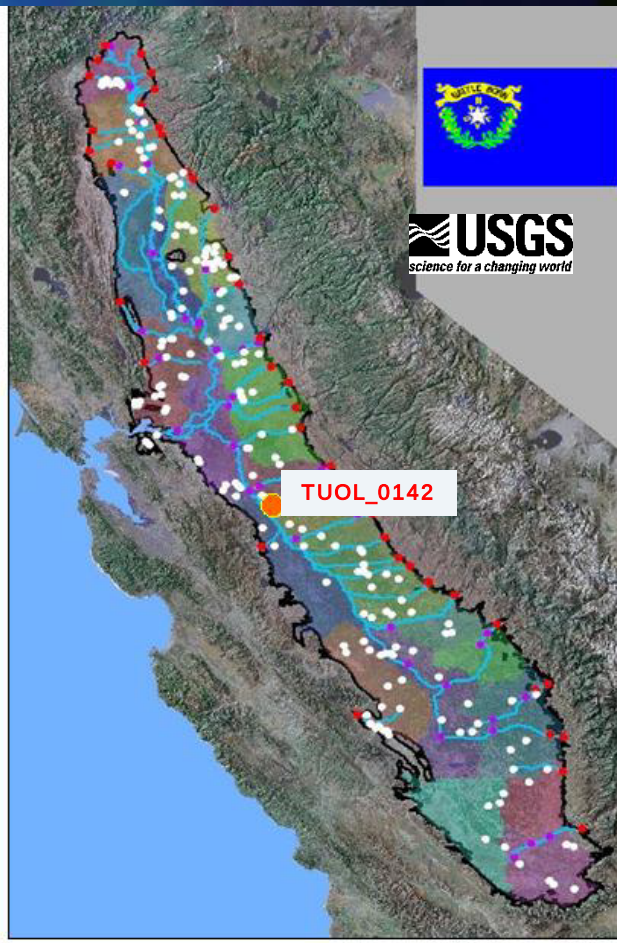




Outflow to the Bay and water available for Southern California and San Joaquin-Tulare Agriculture may decline by a factor of 10 - 100 and become intermittently unavailable during the projected sustained droughts in the second half of the 21st Century

A2-Reduction in Surface-Water Diversions for Riparian Habitat on the Tuolomne River, San Joaquin Valley, Central Valley, California

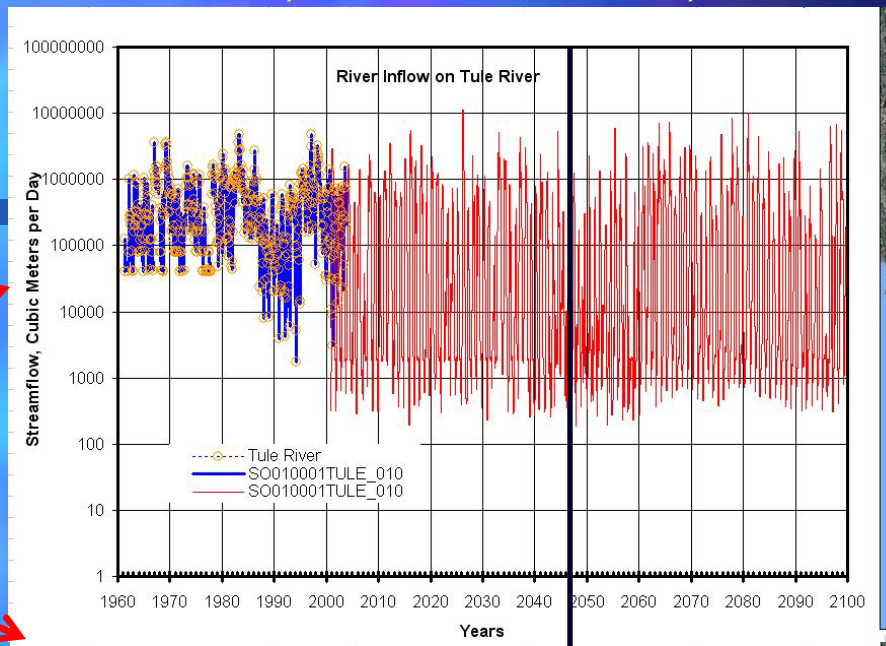


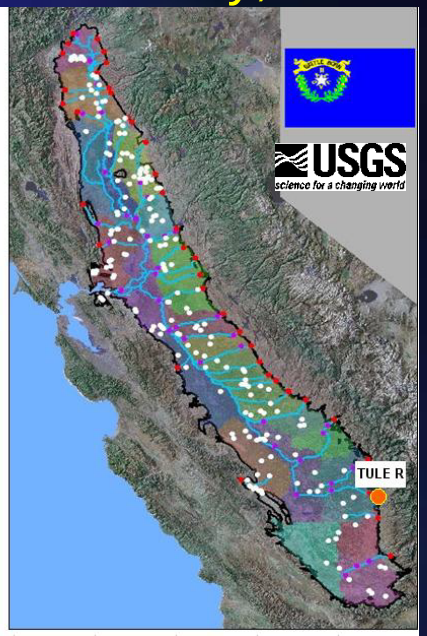


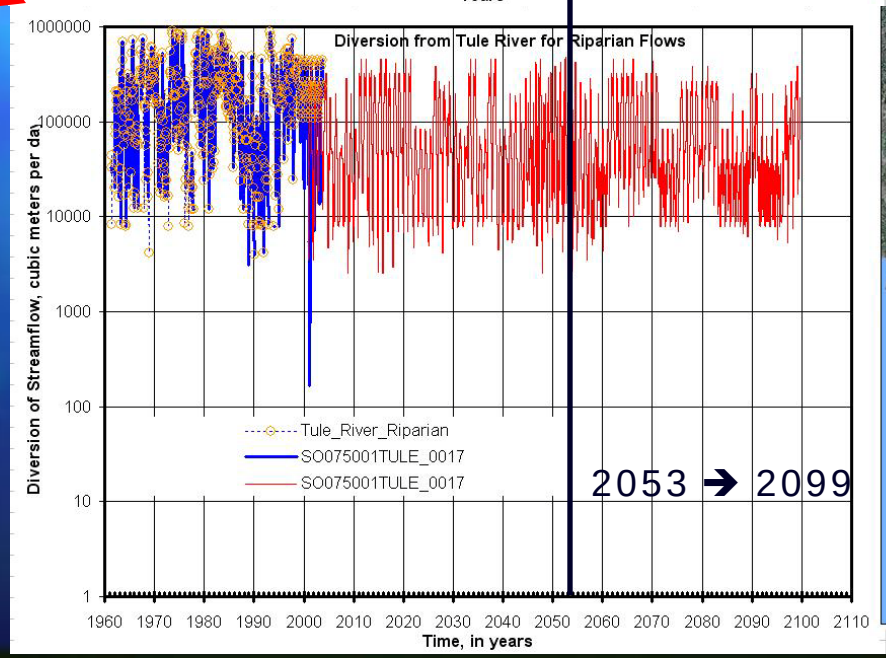
Water diverted for maintaining Riparian Habitat from the Central Sierras may become intermittently unavailable in 21st Century

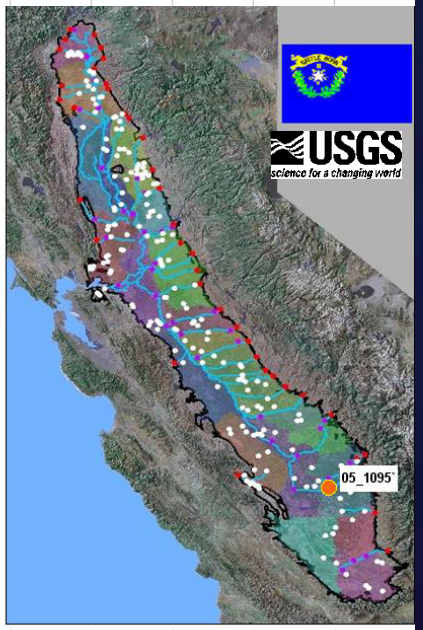
A2-Reduction in Surface-Water Streamflow & Diversions for Irrigation on the Tule River, Tulare Basin, Central Valley, California

Streamflows & Diversions for Irrigation from Southern Sierras may become 10 -100 times lower than hisorical flows at end of 21st Century

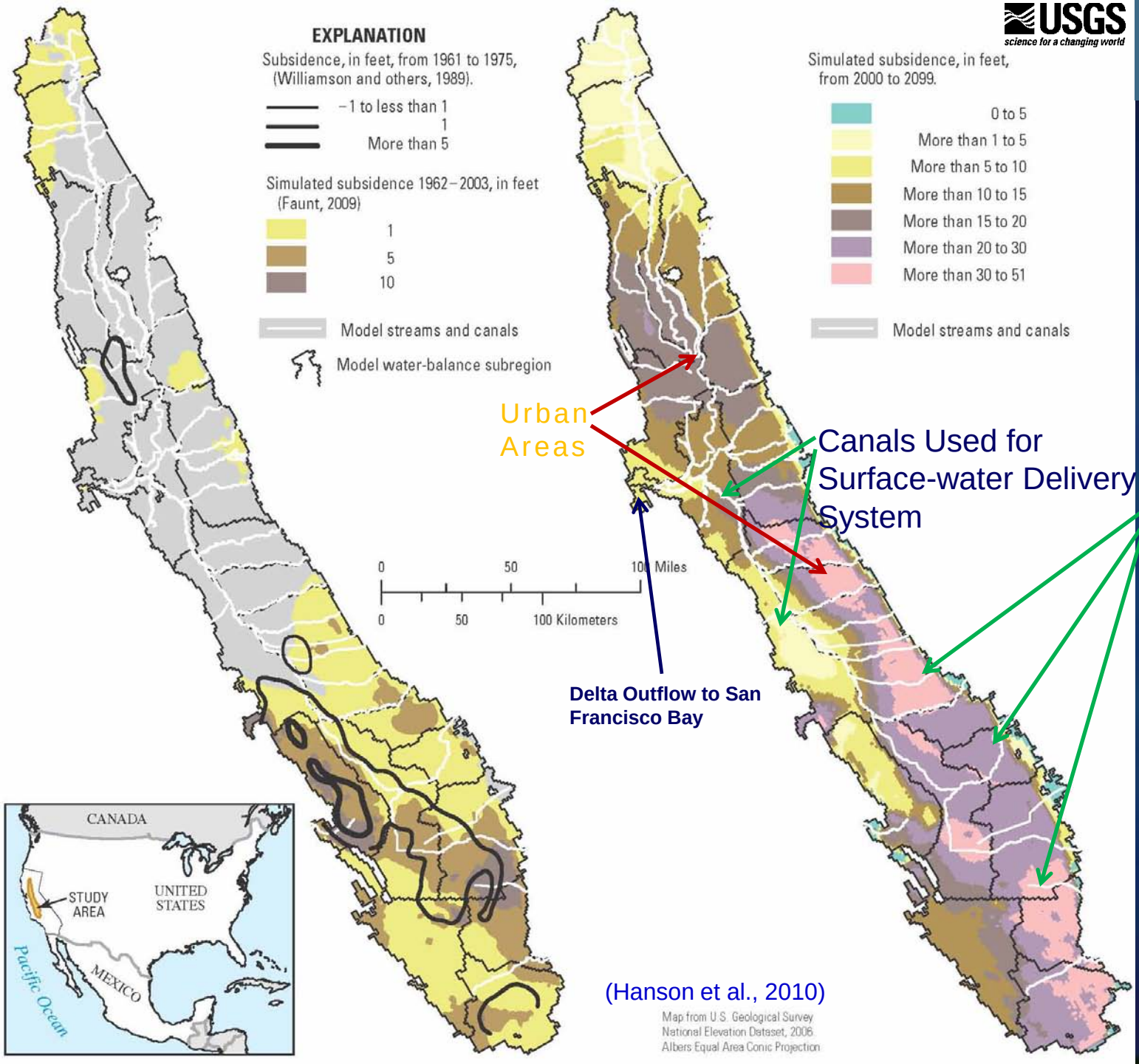








Old and New Subsidence



Renewed Subsidence in Historical Areas

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

Additional subsidence in growing Urban areas

Up to 70,800 hm^3 from fine-grained sediments in 21st Century

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 and 4% per year Urban Growth
- Decreased Precipitation ➔Intermittent droughts in first half of century followed by sustained drought in 2nd-half of 21st Century
- Decreased outflow at the Delta and for many rivers ad diversions
- Transition from surface-water dominated irrigation supplies to groundwater supplies with sustained drought.
- Simulated capacity of system still may not trigger an operational drought because of the large combined potential capacity of the conjunctive-use system
- Climate Change and Increased Urban water use are comparable contributors to bad effects on sustainability ➔ land subsidence and reduced outflow at the Sacramento Delta

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Conclusions for Water Resourses, Central Valley, California

- Natural Climate Change/Variability present from glacial periods
- Extreme Climate Variability Events in past 2000 years including Pluvial (Wet) Periods and Mega-Droughts
- Climate Variability and some Climate Change Present in all Supply and Demand Components Historically and Future Scenarios (A2) show possibility of sustained Droughts in latter part of 21st Century
- Climate Variability and Change Implicitly Embedded in CV Models➔ BCM and MF-FMP on monthly periods facilitates bi-modal annual recharge pattern and climate driven runoff and streamflow
- Precipitation is an important component to recharge even though on an annual basis ET>>P Reduction in precipitation and increased ET ultimately drive decreased runoff and surface-water and increased pumpage/subsidence
- Climate Change with GCMs evaluated with BCM-CVHM linkage Facilitated by MODFLOW Simulation Features (FMP, SFR and Well Packages)
- GCM-BCM-CVHM Linkage Coupled physically-based, supply-constrained, and demand driven models as a basis for a Decision Support System Evaluated of Outflow of streamflow at the Delta, Streamflow, Surface-water Diversions, Land Subsidence, & Drought Scenarios, Supply-&-Demand Components
- A2 Scenario suggests potential changes in climate variability, increased reliance on groundwater for irrigation, & increased land subsidence
- Hydrologic projections of a Century are more reliable in trends than actual outcomes

USGS Climate-Change Research

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For more information refer to ➔ USGS Office of Global Climate Change: http://www.usgs.gov/global_change/

And refer to ➔California Applications Program (CAP) & The California Climate Change Center (CCCC) : http://meteora.ucsd.edu/cap/

Supply-Constrained/Demand-Driven Conjunctive Use Analysis

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