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Managing Water in the West

Stochastic Nonparametric Framework for Basin Wide Streamflow and Salinity Modeling

Application to Colorado River basin

Boulder Dendro Workshop
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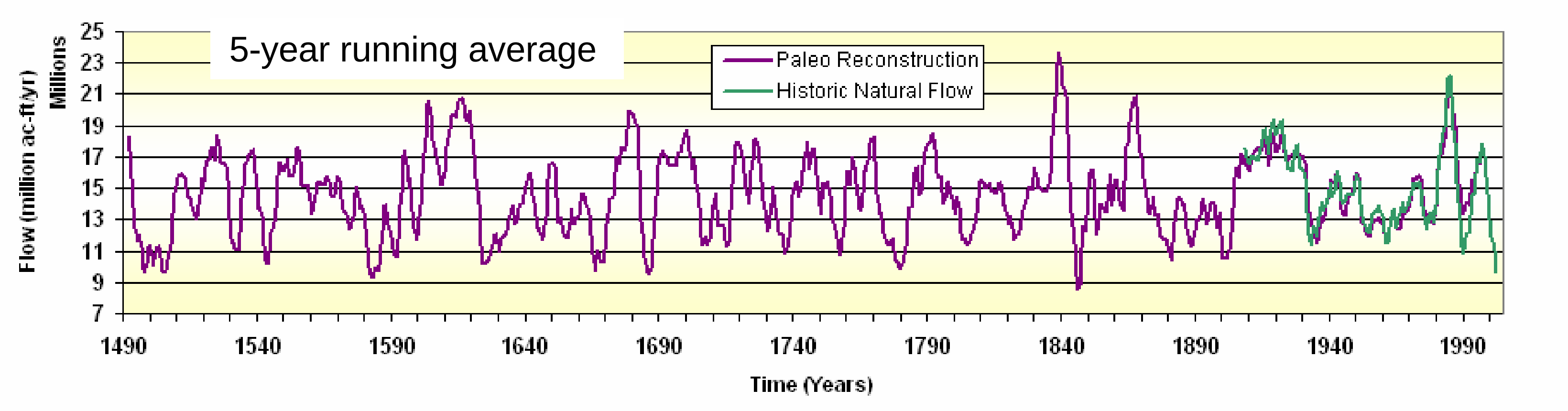
May 14, 2007

U.S. Department of the Interior
Bureau of Reclamation

Recent conditions in the Colorado River Basin

- **Below normal flows into Lake Powell 2000-2004**
  - **62%, 59%, 25%, 51%, 51%, respectively**
    - **2002 at 25% lowest inflow recorded since completion of Glen Canyon Dam**
- **Some relief in 2005**
  - **105% of normal inflows**
- **Not in 2006 !**
  - **73% of normal inflows**
- **Current 2007 forecast**
  - **50% of normal inflows**

Colorado River at Lees Ferry, AZ



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Continuing pressures in the basin

- Evidence of shift in annual cycle of precipitation
  - Regonda et al. 2005; Cayan et al. 2001
  - Mote, 2003
- Links with large-scale climate
  - Hoerling and Kumar, 2003
- Trends indicated increased drought conditioned
  - Andreadis and Lettenmaier, 2006
- Increasing population growth
  - Growing water demand by M&I
- Further development of allocated water supply

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Motivation

- How unusual is the current dry spell?
- How can we simulate stream flow scenarios that are consistent with the current dry spell and other realistic conditions?

- Key question for this research is how to plan for effective and sustainable management of water resources in the basin?
  - a robust framework to generate realistic basin-wide streamflow scenarios
  - a decision support model to evaluate operating policy alternatives for efficient management and sustainability of water resources in the basin.

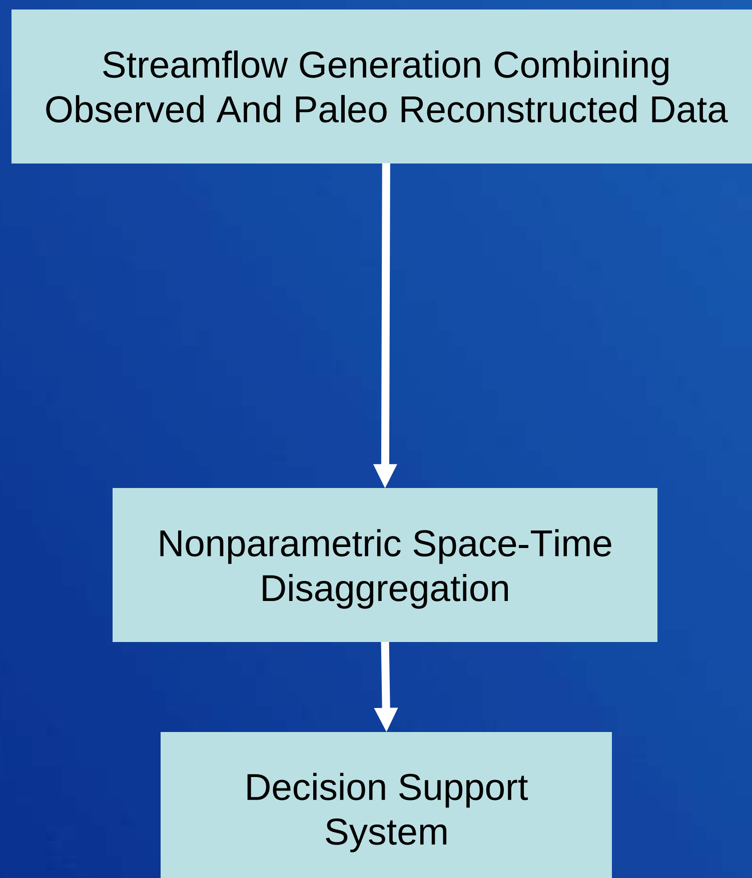
Can we provide answers?

- What is currently possible
  - ISM : captures natural variability of streamflow
    - Only resamples the observed record
    - Limited dataset
- How can we improve ?
  - Improve stochastic hydrology scenarios
  - Incorporate Paleoclimate information

How do we accomplish this?

- Proposed framework
  - Robust space-time disaggregation model
    - central component of all these sections.
  - Incorporating Paleoclimate Information
    - Combine observed and paleostreamflow data
  - Colorado River decision support system
    - Colorado River Simulation System (CRSS)
    - Provides means policy analysis

Flowchart of study



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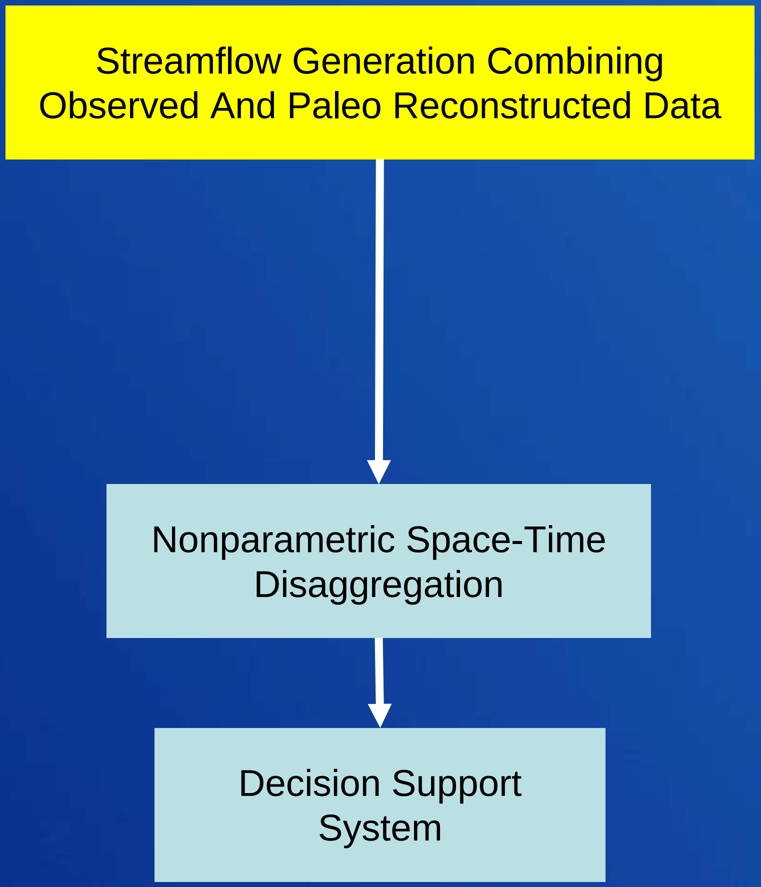
Flowchart of study



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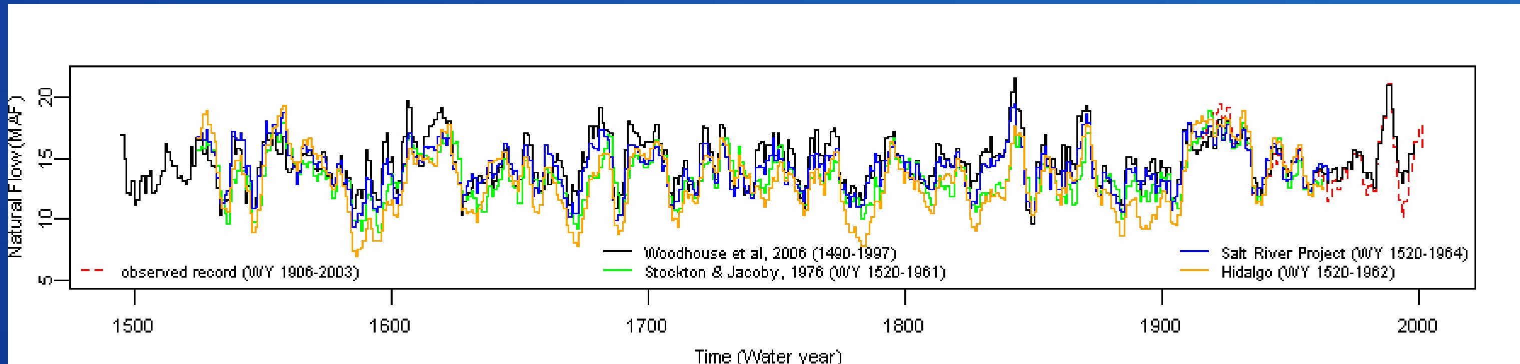


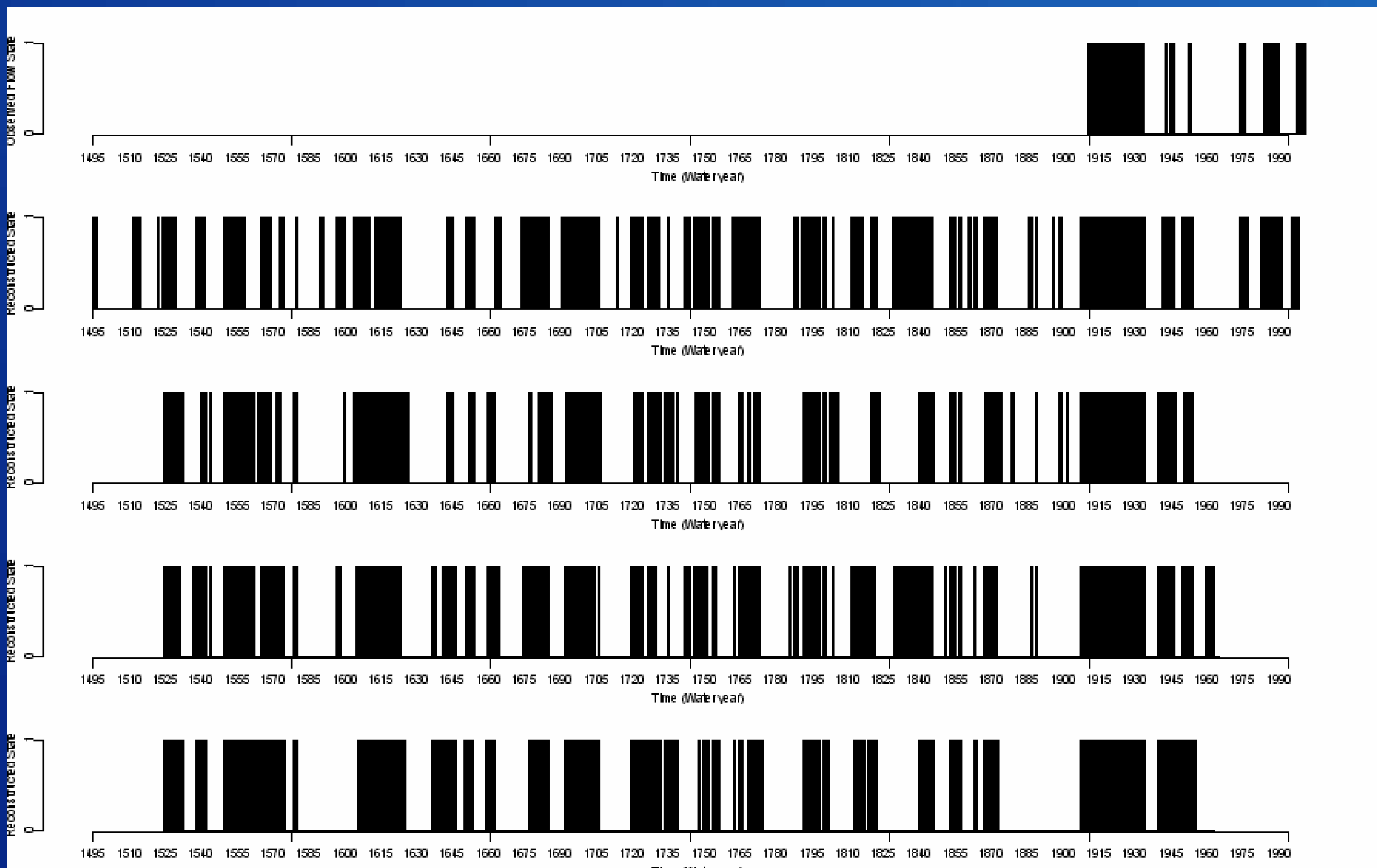
observed record

Woodhouse et al. 2006

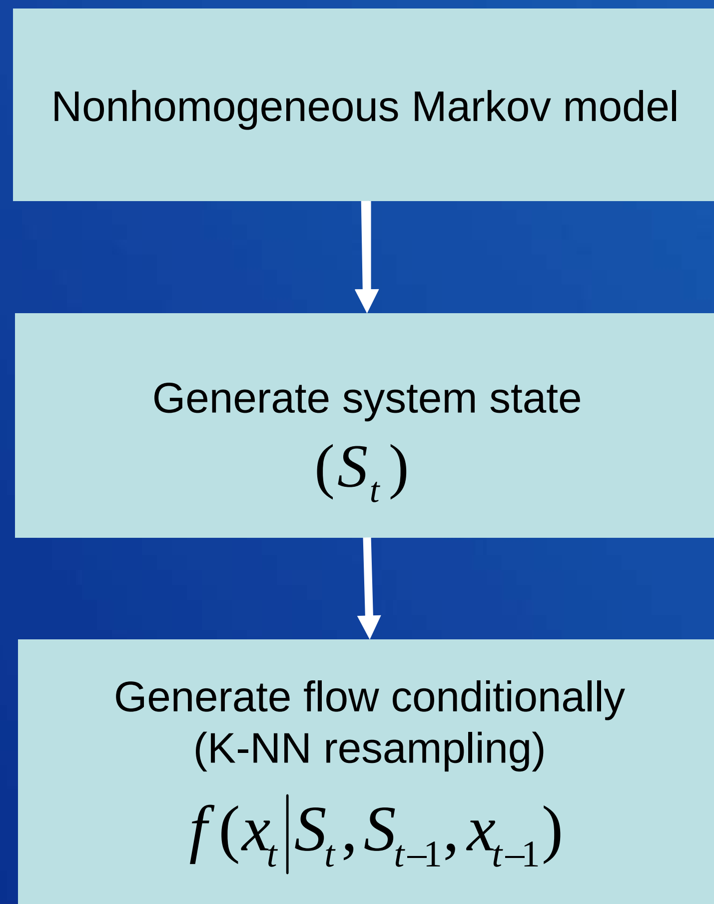
Stockton and Jacoby, 1976

Hirschboeck and Meko, 2005

Hildalgo et al. 2002



Simulation flowchart



Discrete kernal function

$$K(x) = \frac{3h}{(1-4h^2)}(1-x^2) \quad \text{for } |x| \leq 1$$

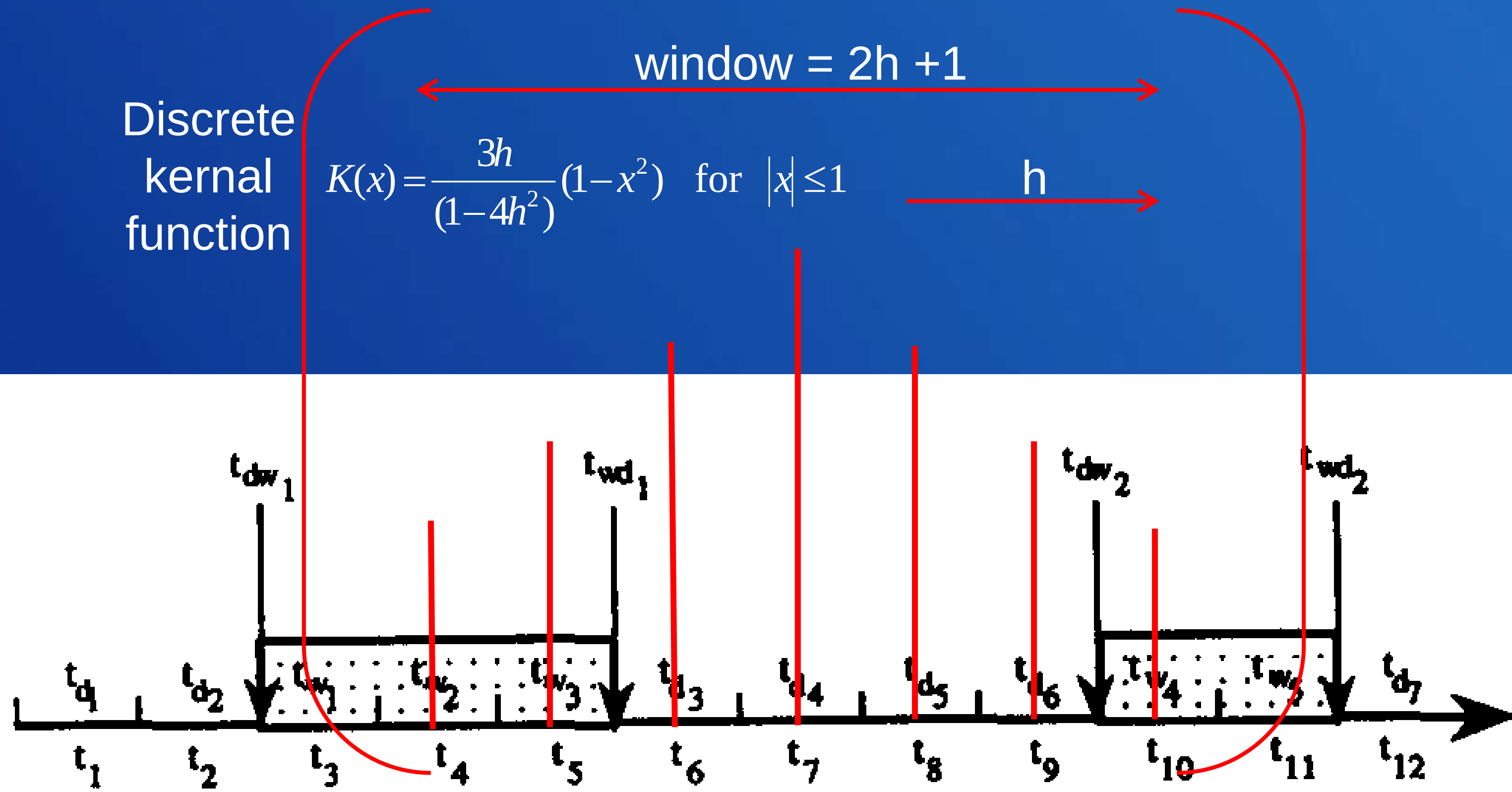


FIG. 1. Precipitation-Occurrence Process (t_1, t_2, . . . = Day Indices; t_{w_1}, t_{w_2}, . . . = Wet-Day Indices; t_{d_1}, t_{d_2}, . . . = Dry-Day Indices; t_{dw_1}, t_{dw_2}, . . . = Day Indices of Transition from Dry Day to Wet Day; and t_{wd1}, t_{wd2}, . . . = Day Indices of Transition from Wet Day to Dry Day)

Source: Rajagopalan et al., 1996

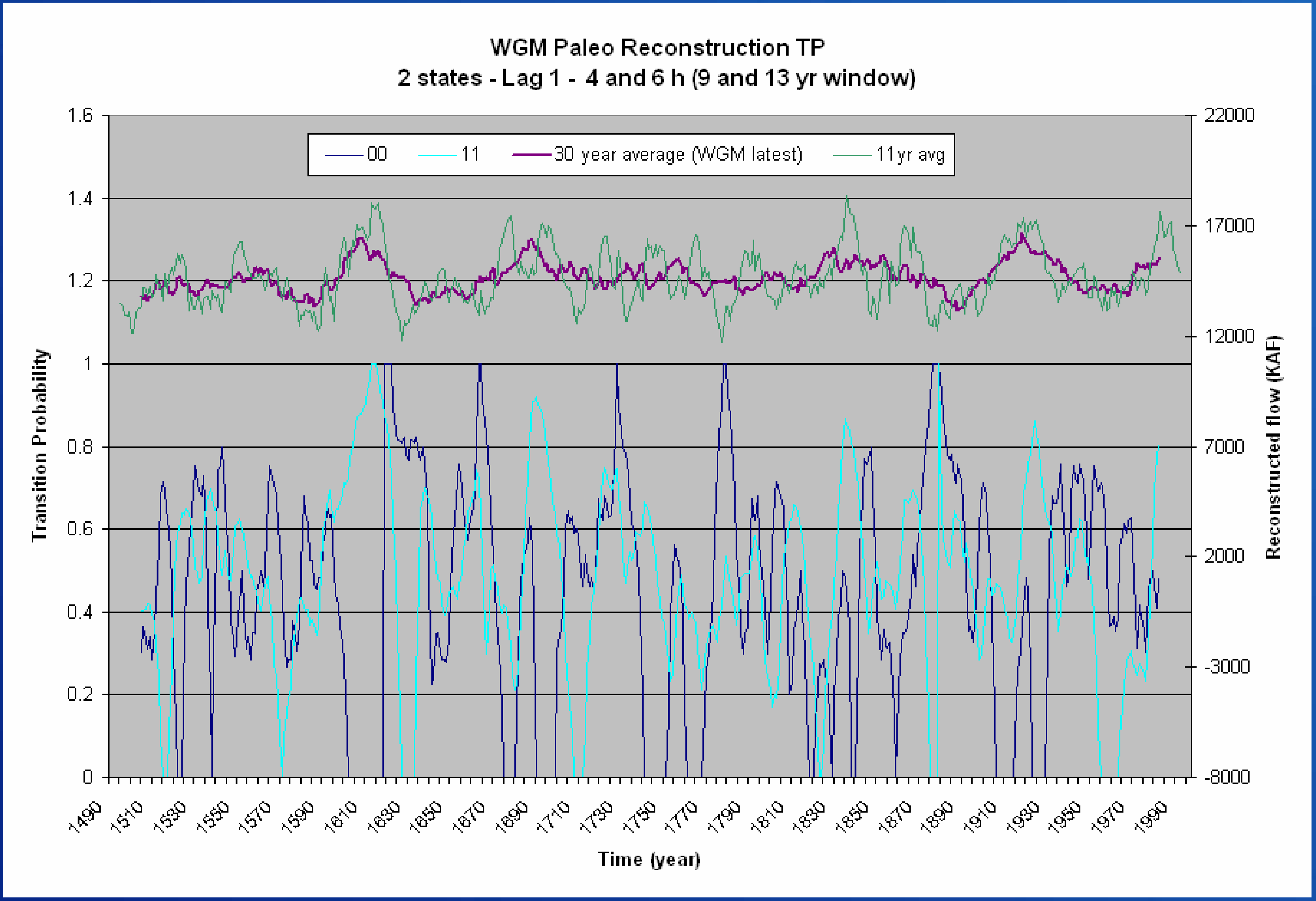
Nonhomogenous Markov model with Kernel smoothing (Rajagopalan et al., 1996)

- TP for each year are obtained using the Kernel Estimator

$$P_{dw}(t) = \frac{\sum_{i=1}^{ndw} K\left(\frac{t - t_{dw_i}}{h_{dw}}\right)}{\sum_{i=1}^{nd} K\left(\frac{t - t_{d_i}}{h_{dw}}\right)} \qquad P_{dd}(t) = 1 - P_{dw}(t)$$

- *h* determined with LSCV
- 2 state, lag 1 model was chosen
  - ‘wet (1)’ if flow above annual median of observed record; ‘dry (0)’ otherwise.
  - AIC used for order selection (order 1 chosen)

Window length chosen with LSCV



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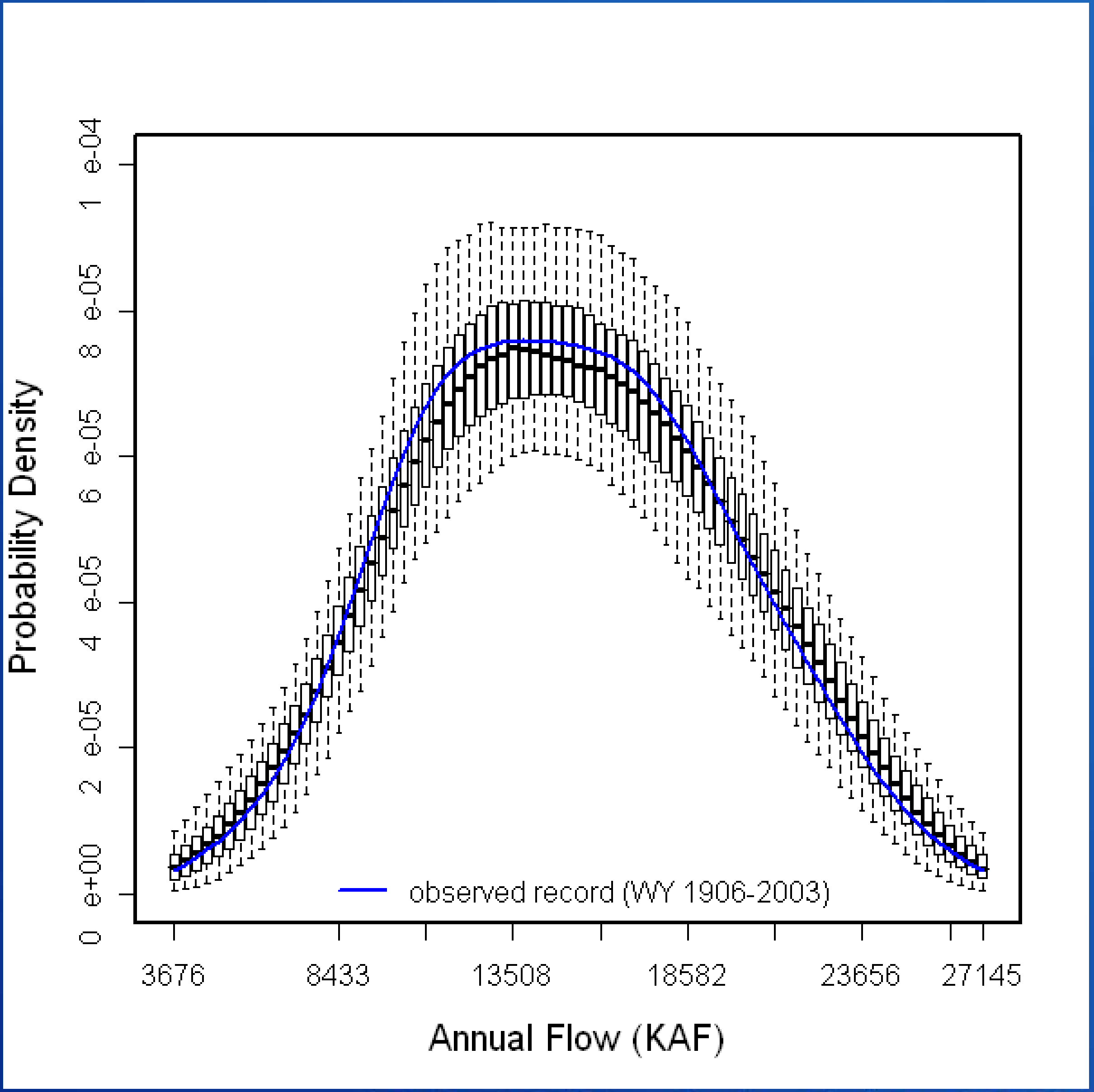
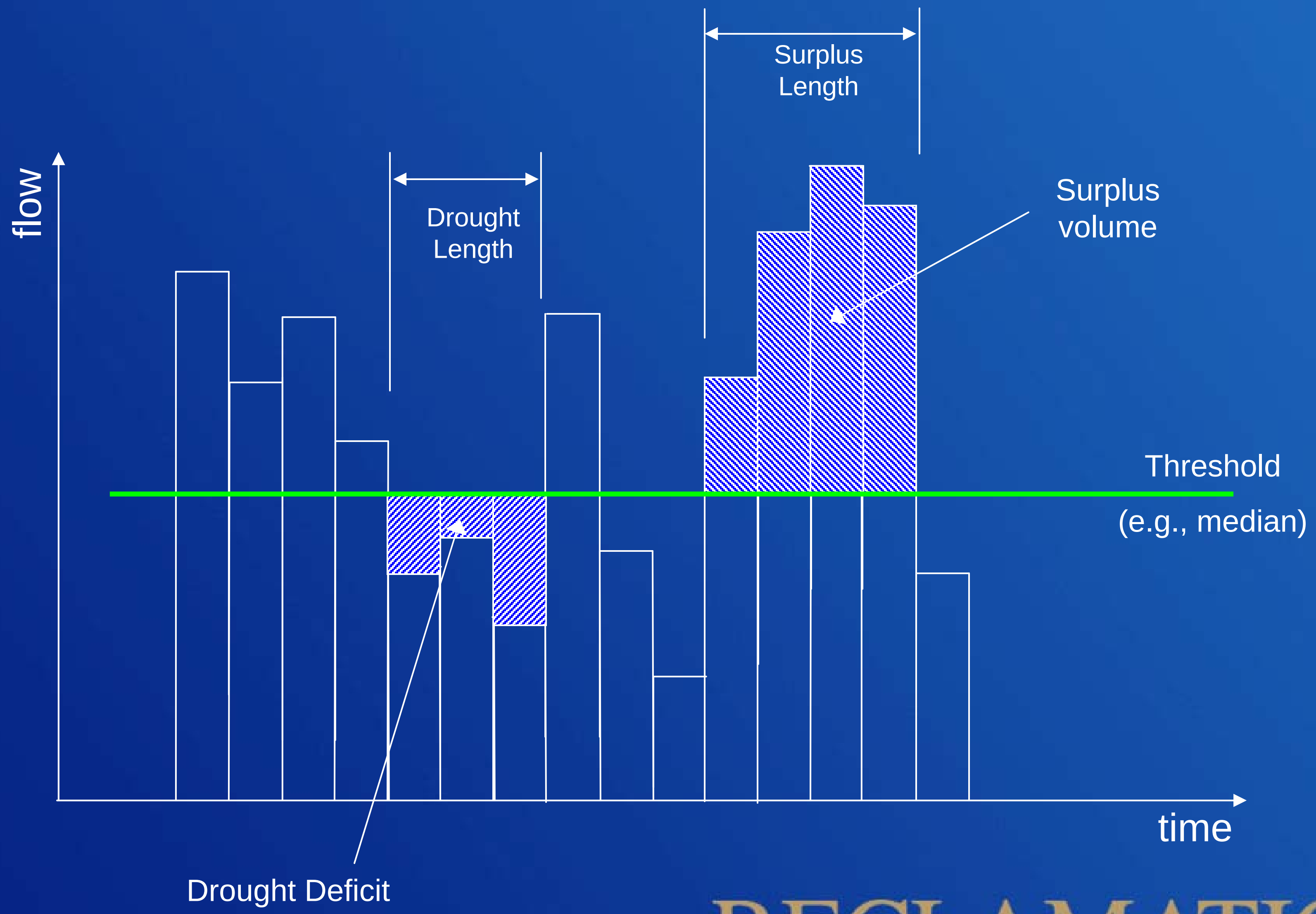
Paleo Conditioned

- NHMC with smoothing
- 500 simulations
- 60 year length

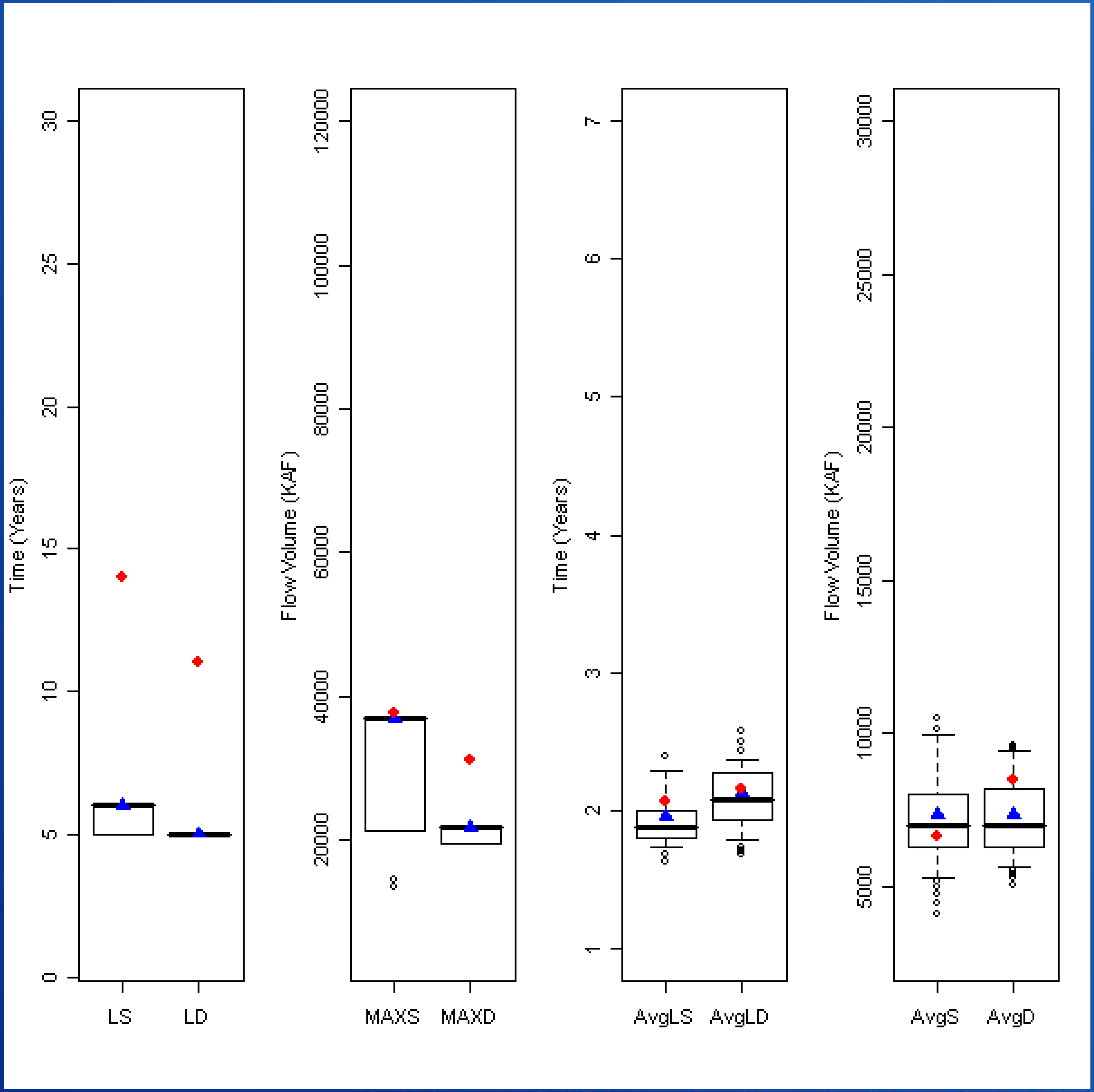


Drought and Surplus Statistics



No Conditioning

- ISM
- 98 simulations
- 60 year length



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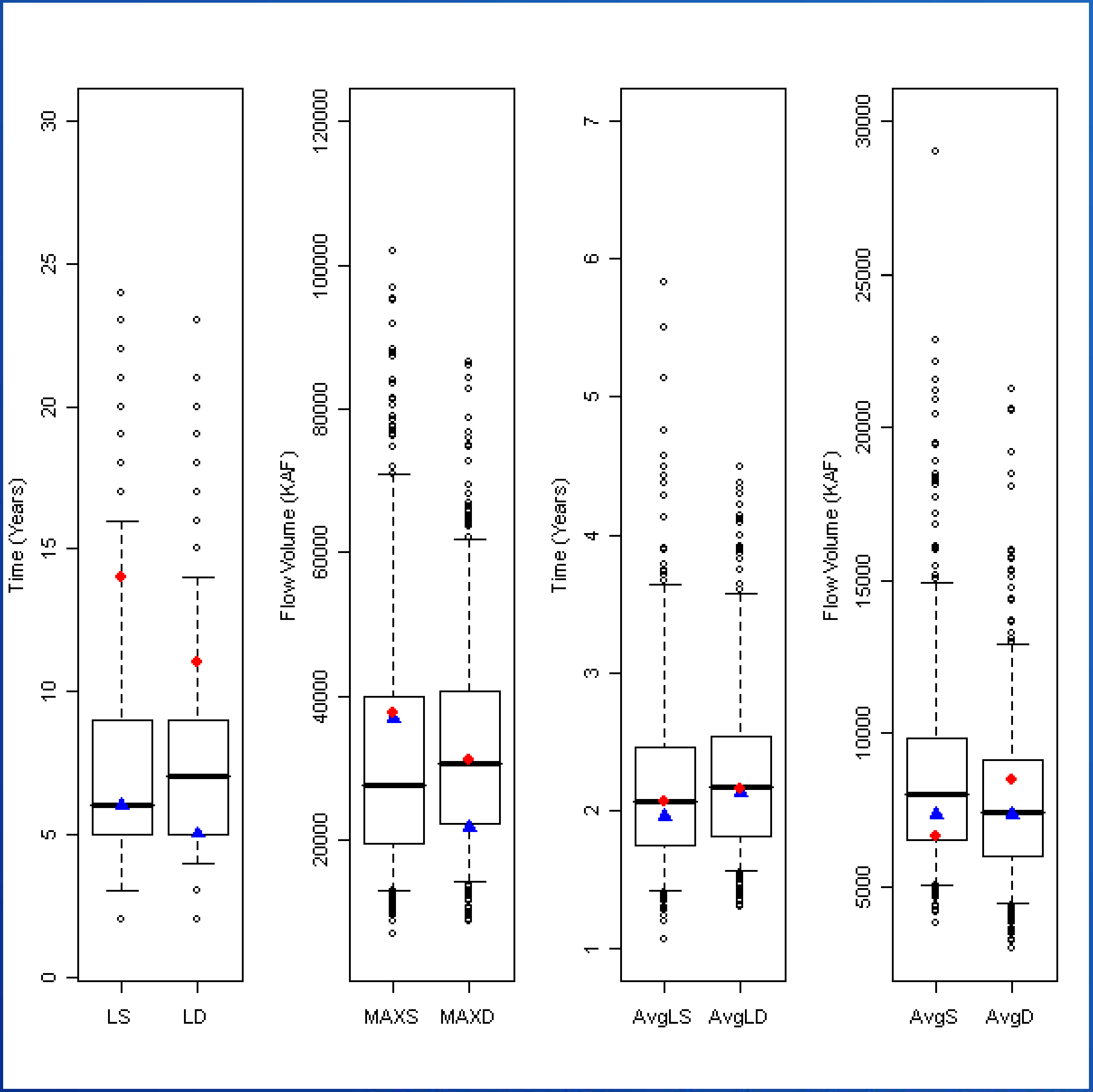
Paleo Conditioned

- NHMC with smoothing
- 2 states
- 500 simulations
- 60 year length



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Conclusions

- Combines strength of
  - Reconstructed paleo streamflows: system state
  - Observed streamflows: flows magnitude
- Develops a rich variety of streamflow sequences
  - Generates sequences not in the observed record
  - Generates drought and surplus characteristic of paleo period
- TPM provide flexibility
  - Nonhomogenous Markov chains
    - Nonstationary TPMs
  - Use TPM to mimic climate signal (e.g., PDO)
  - Generate drier or wetter than average flows

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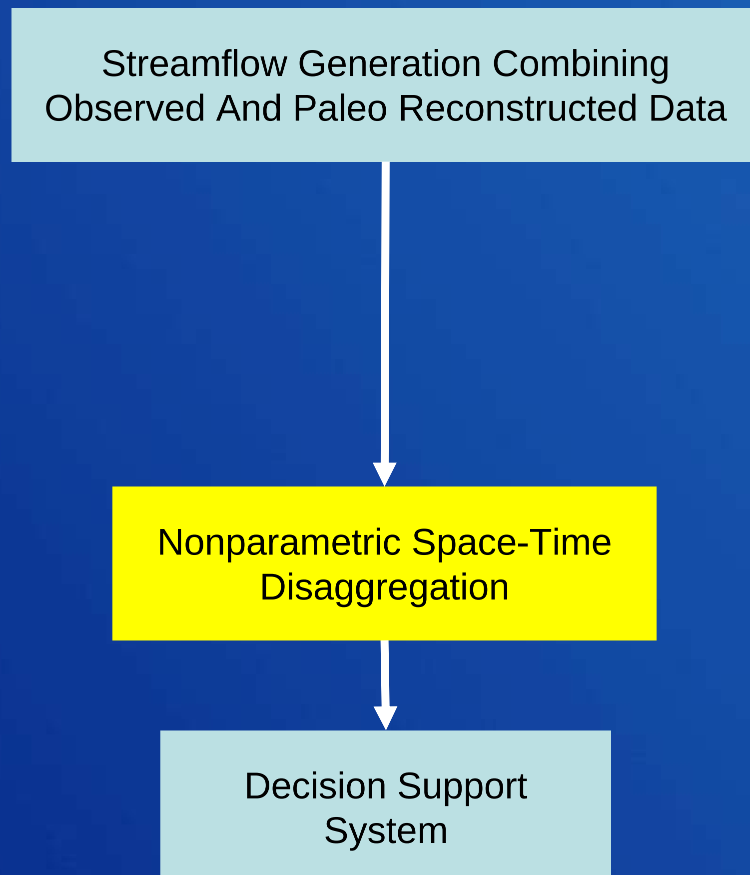
Flowchart of study



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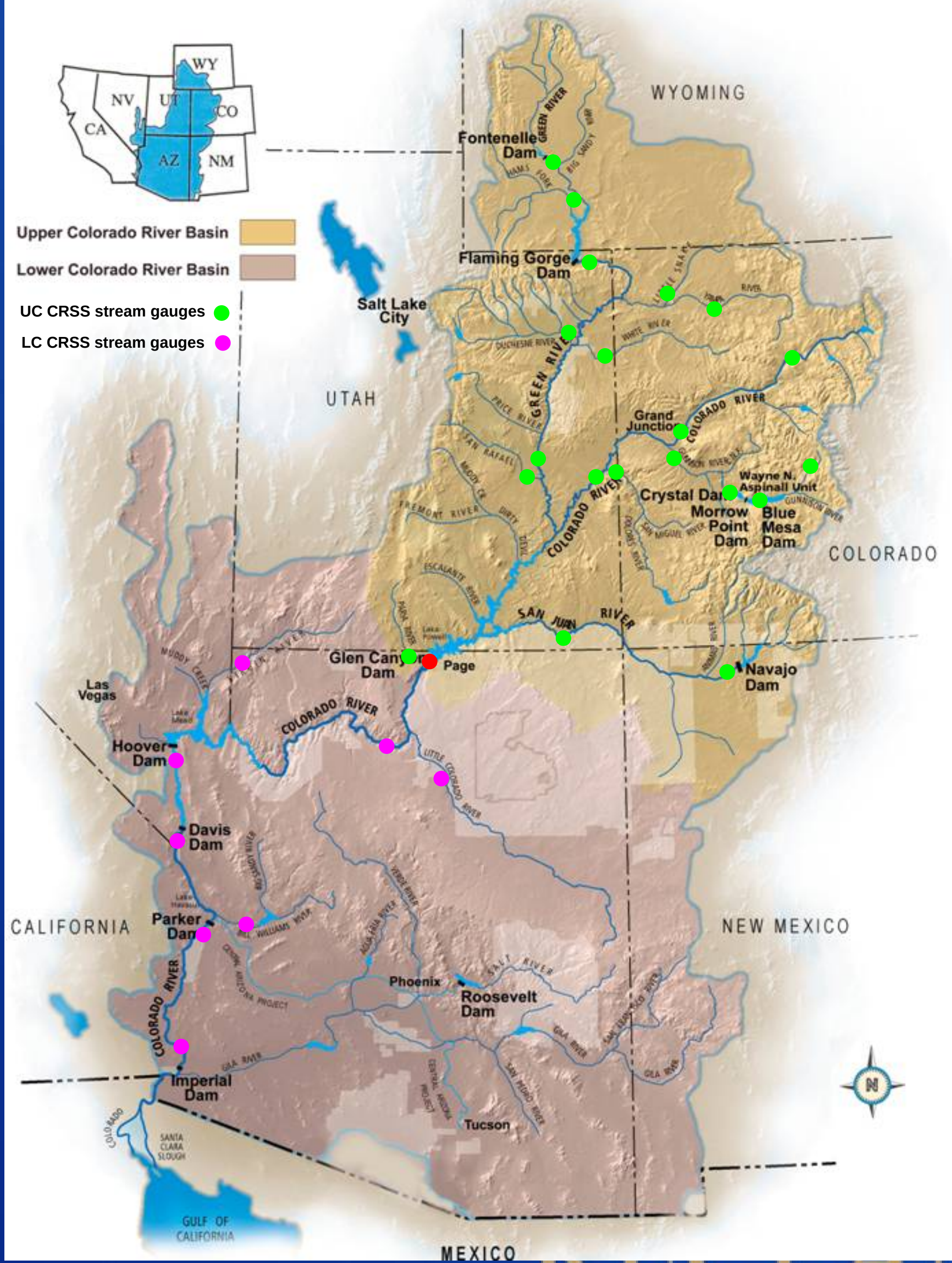
Colorado River Basin



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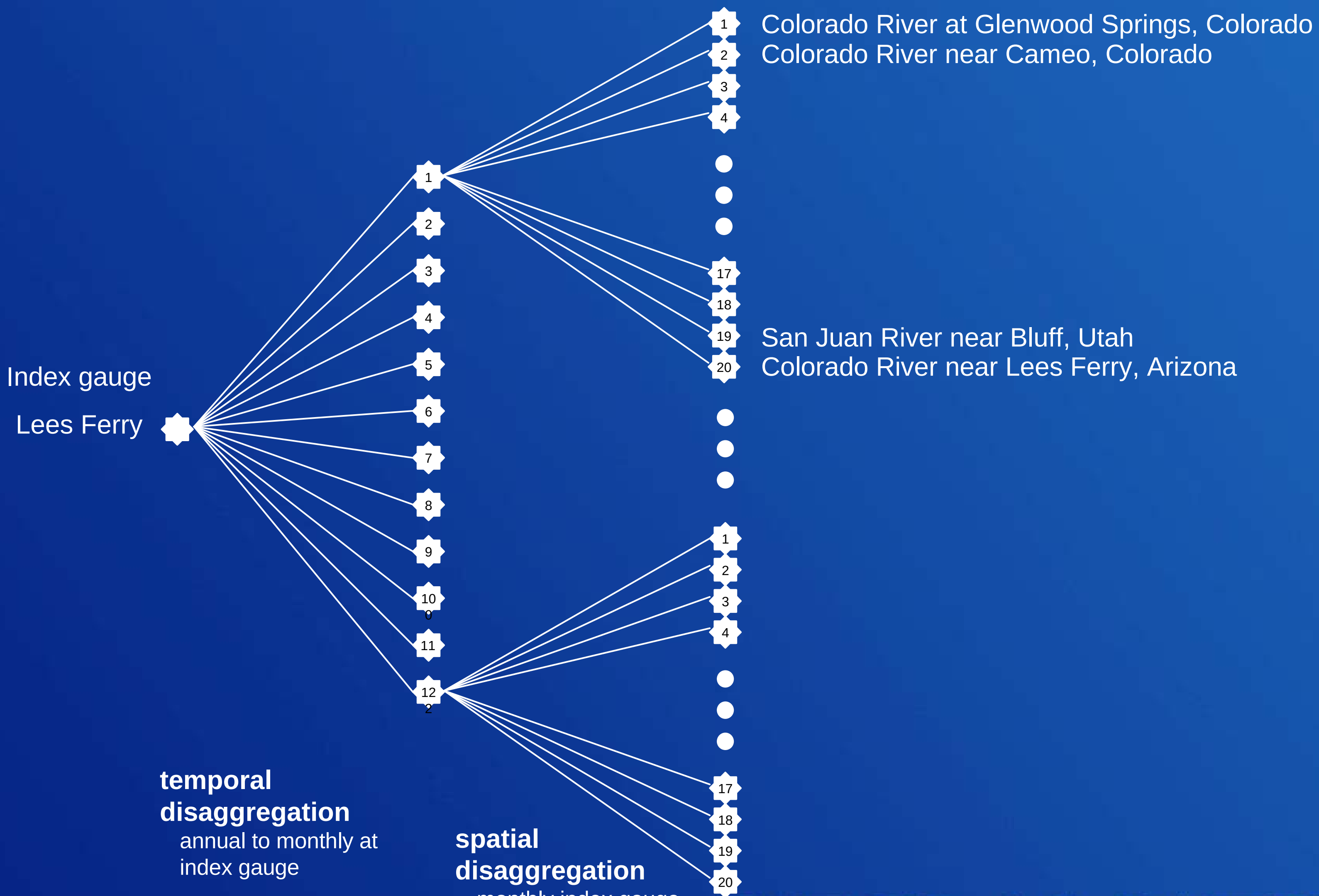
Disaggregation scheme



temporal disaggregation
annual to monthly at index gauge

spatial disaggregation
monthly index gauge to monthly gauge

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Proposed Methodology

- **Resampling from a conditional PDF**

$$f(X|Z)=\frac{f(X,Z)}{\int f(X,Z)dX}$$

Joint probability

Marginal probability

- **With the "additivity" constraint**
- **Where *Z* is the annual flow**

  X are the monthly flows
- **Or this can be viewed as a spatial problem**
  - **Where *Z* is the sum of d locations of monthly flows**

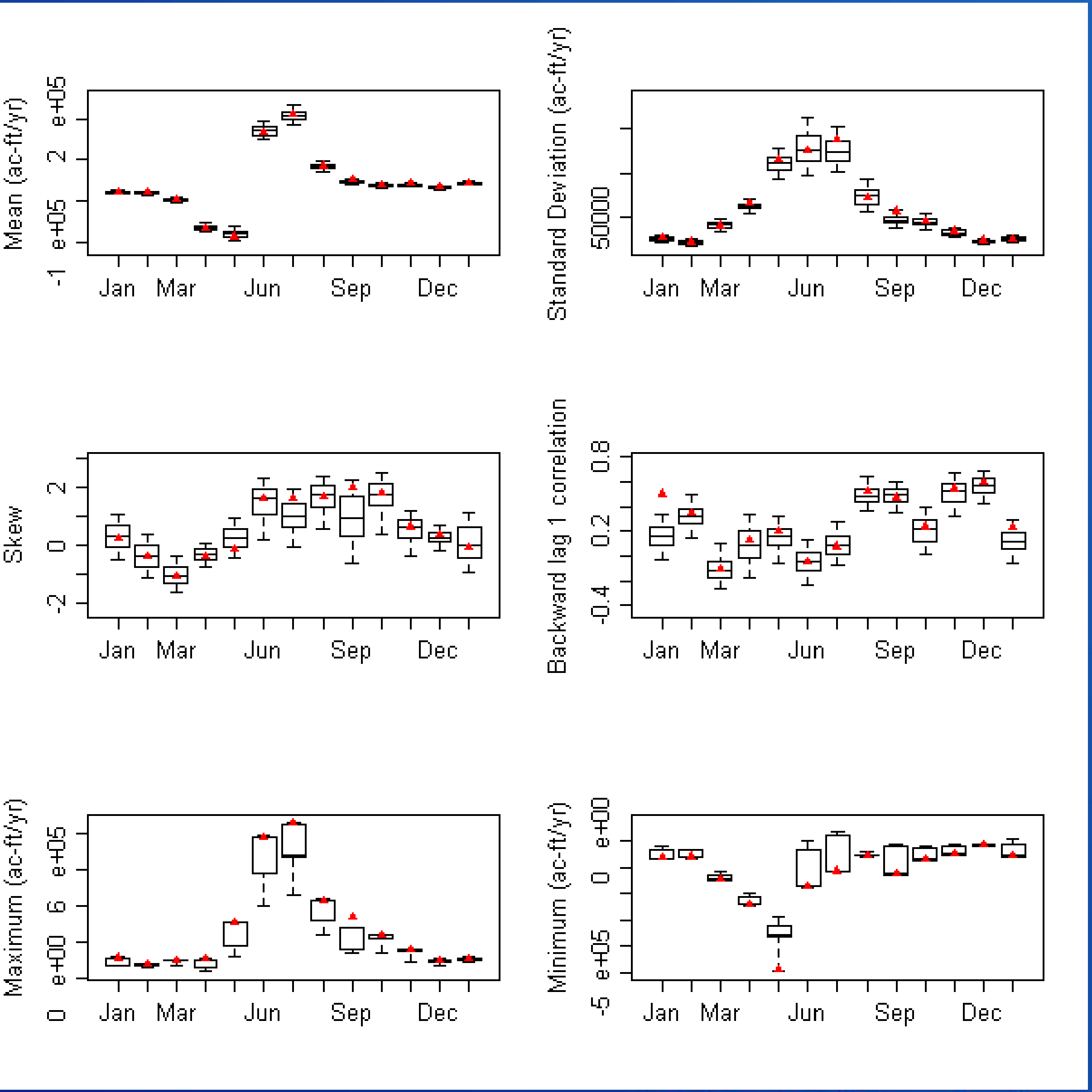
    X are the d locations of monthly flow

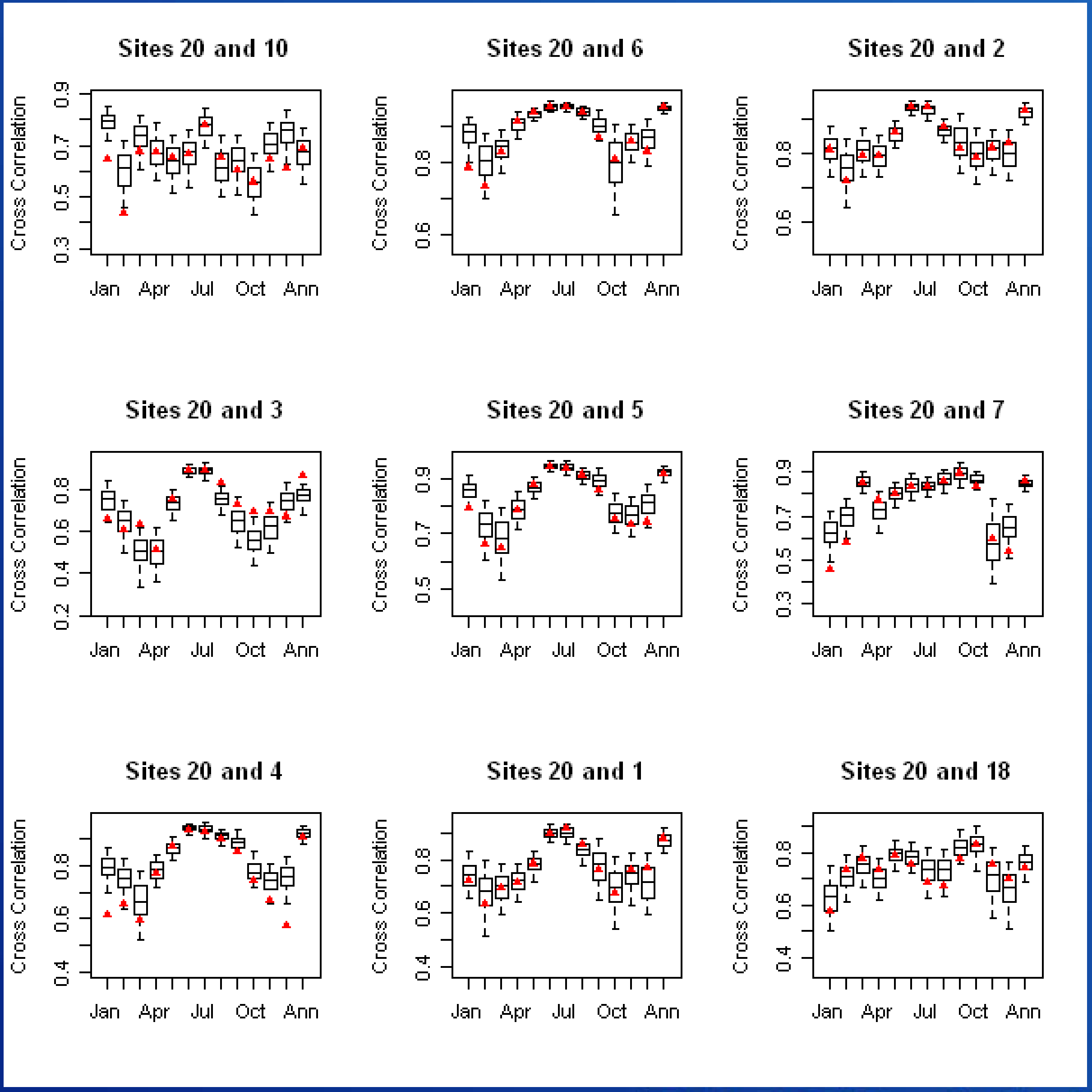
- **Annual stochastic flow**
  - **modified K-NN lag-1 model (Prairie et al., 2006)**
  - **500 annual simulations**

Prairie et al., 2006

Lees Ferry

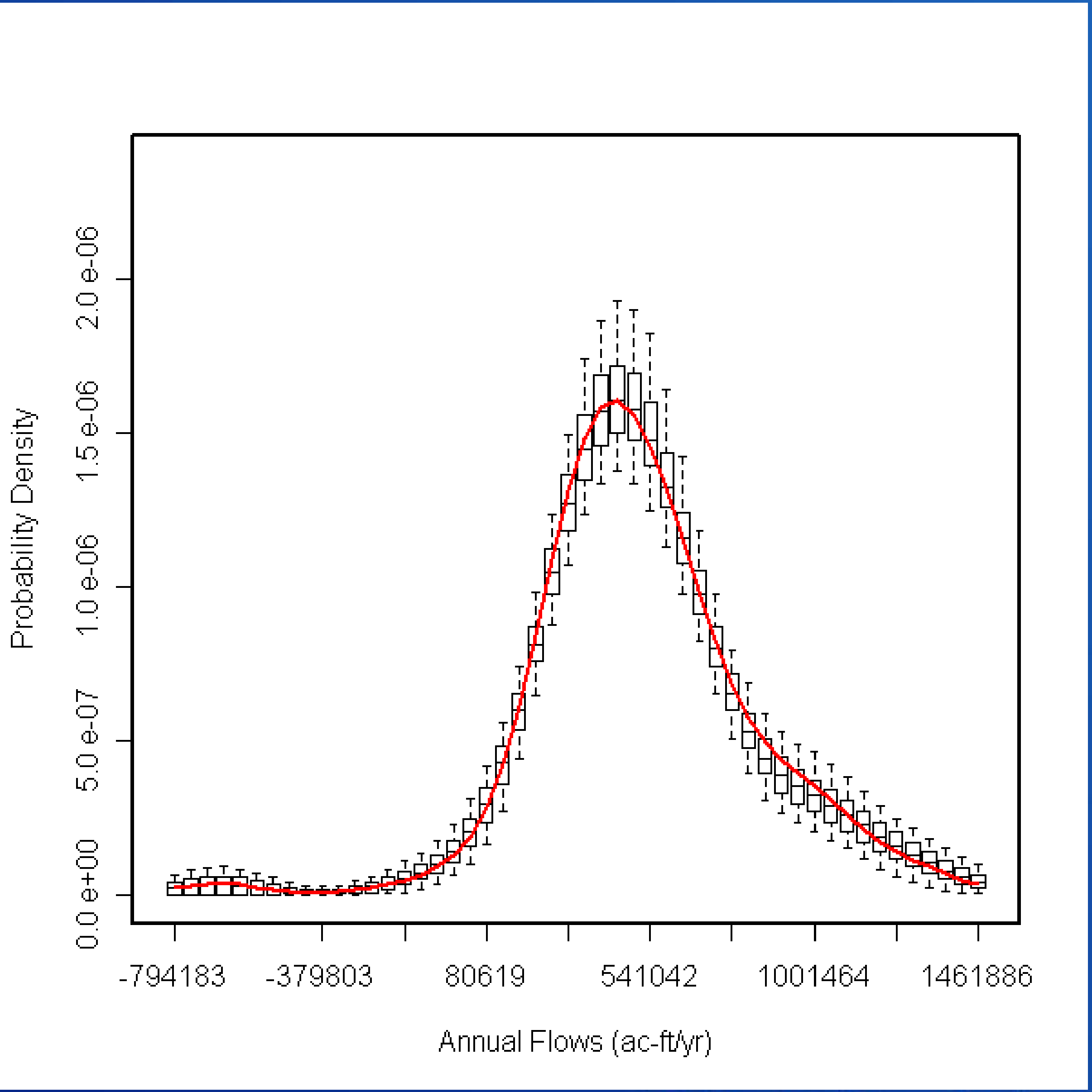
- intervening





Cross Correlation

- **Total sum of intervening**



Probability Density Function

- Lees Ferry
- Intervening

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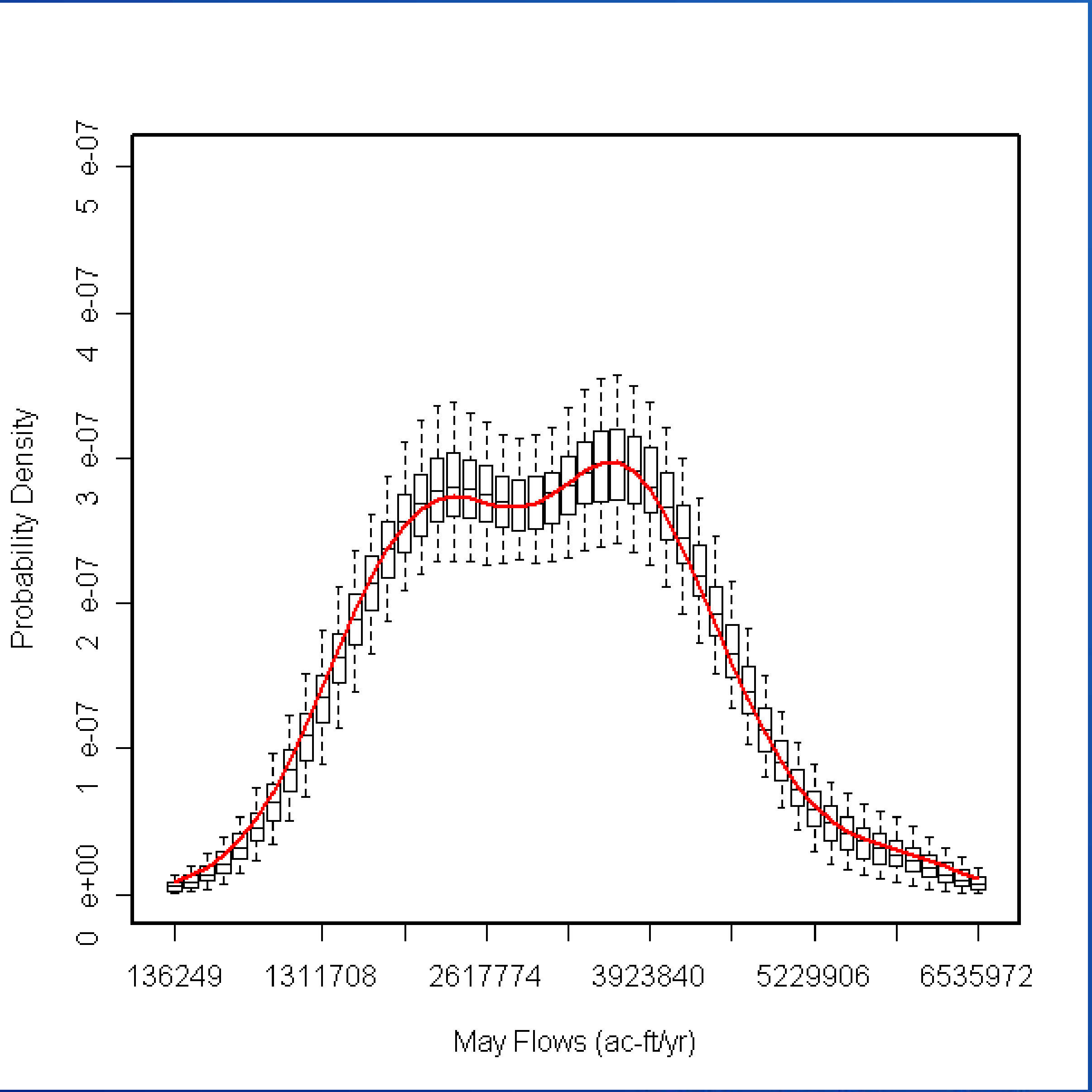

Probability Density Function

- Lees Ferry
- Total sum of intervening

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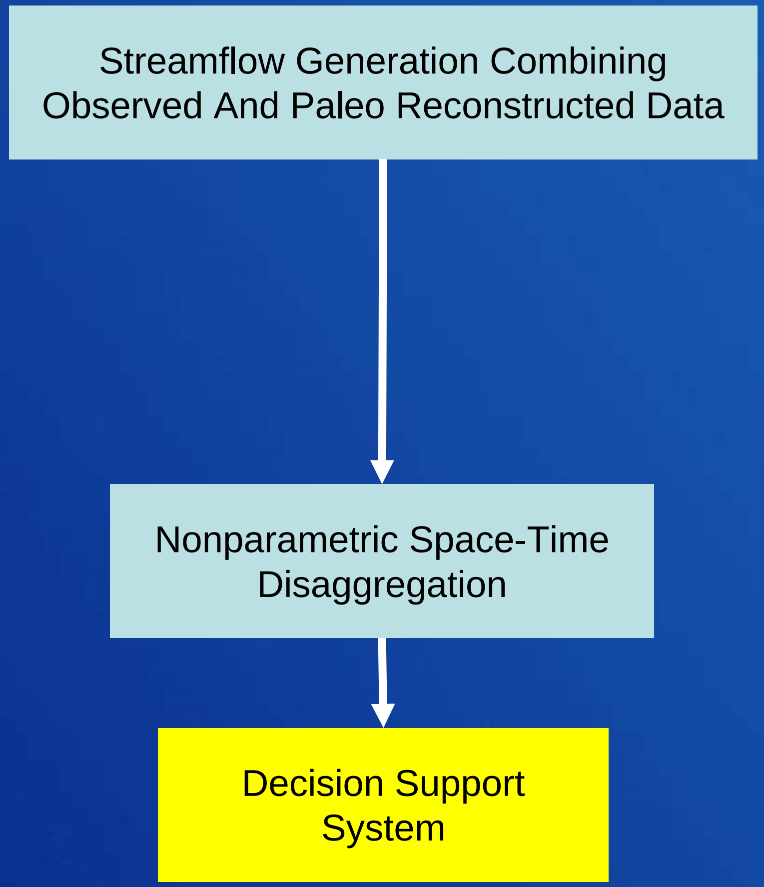
Conclusions

- A flexible, simple, framework for space-time disaggregation is presented
    - Eliminates data transformation
    - Parsimonious
    - Ability to capture any arbitrary PDF structure
    - Preserves all the required statistics and additivity
- Easily be conditioned on large-scale climate information
- Can be developed in various scheme to fit needs
- View nonparametric methods as an additional stochastic view of data set
    - Adds to ISM and parametric methods

Flowchart of study



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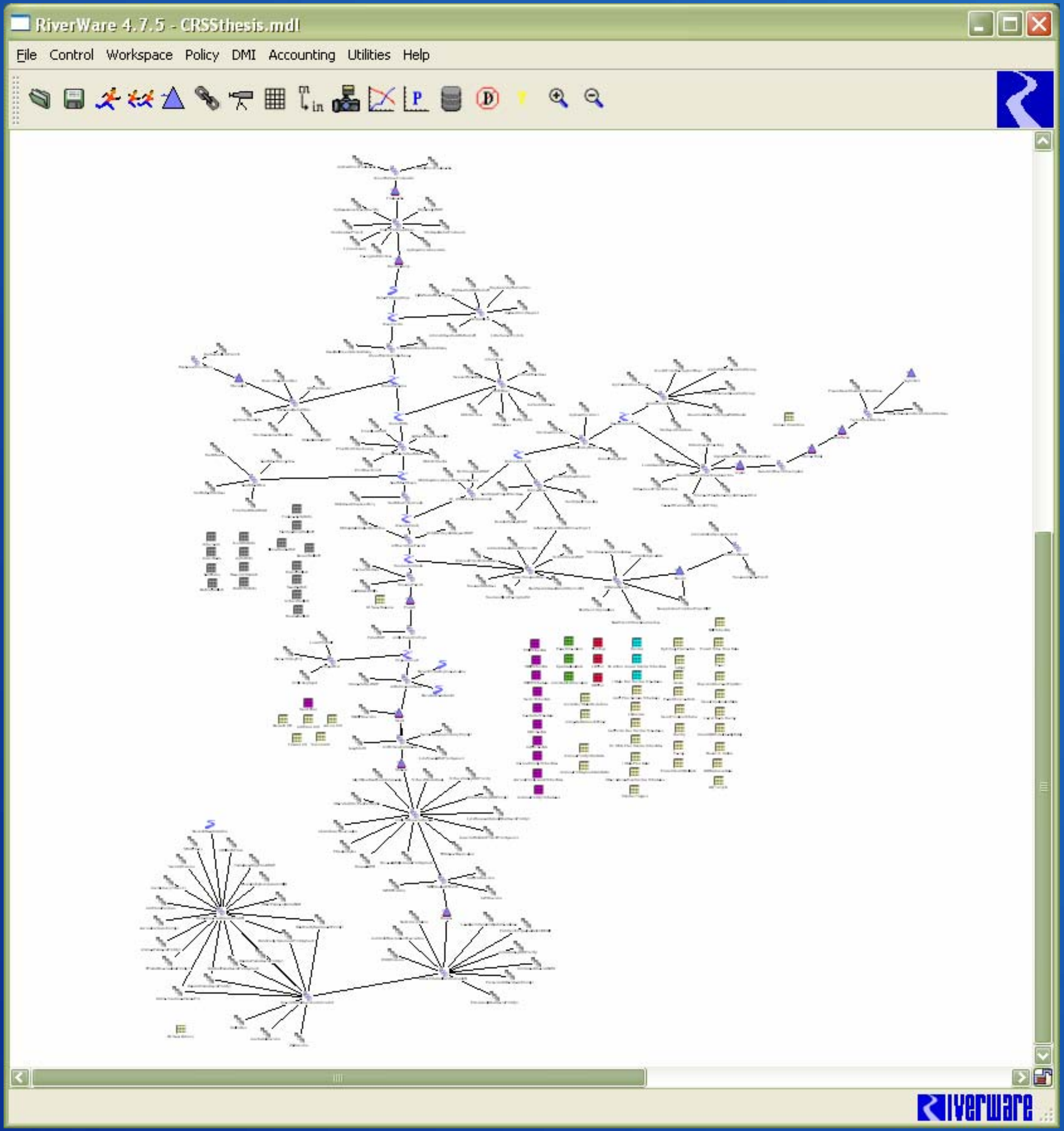
Colorado River Simulation System (CRSS)

- Requires realistic inflow scenarios
- Captures basin policy
- Long-term basin planning model
- Developed in RiverWare (Zagona et al. 2001)
- Run on a monthly time step



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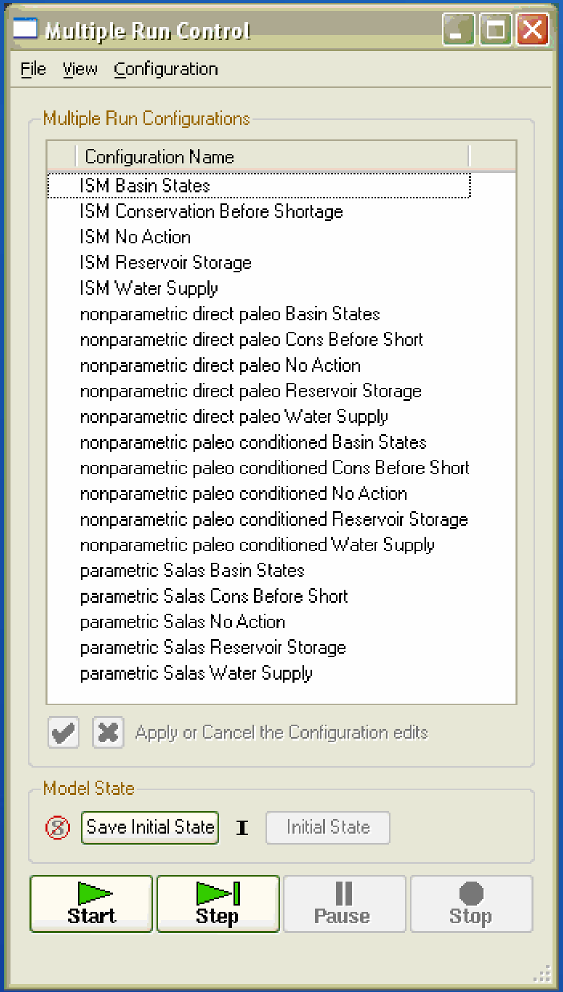
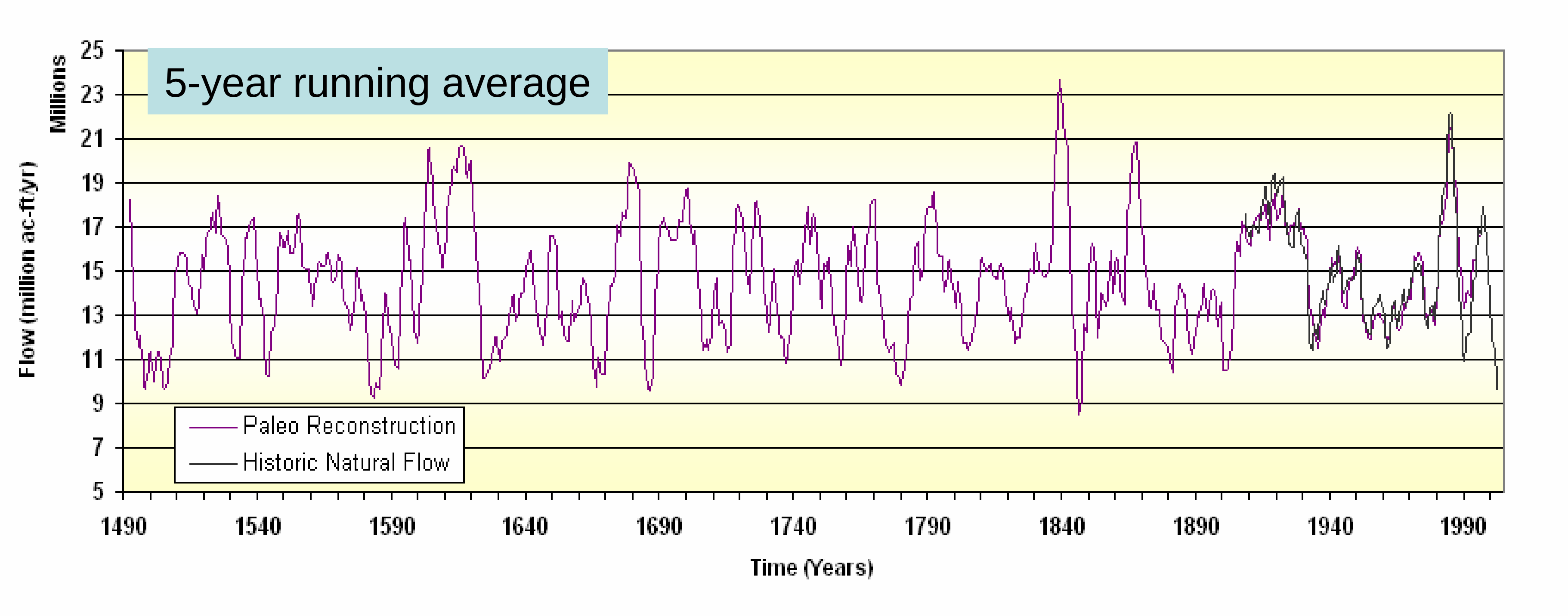
Hydrologic Sensitivity Runs

- **4 hydrologic inflow scenarios**
  - Records sampled from a dataset using ISM
    - Observed flow (1906-2004)
      - 99 traces
    - Paleo flow (1490-1997) (Woodhouse et al., 2006)
      - 508 traces
  - Other
    - Paleo conditioned (Prairie, 2006)
      - 125 traces
    - Parametric stochastic (Lee et al., 2006)
      - 100 traces
- **All 4 inflow scenarios were run for each alternative**



ISM-Based Flows

- Historic natural flow (1906-2004) : averages 15.0 MAF
- Paleo reconstruction (1490-1997) : averages 14.6 MAF
  - Lees B from Woodhouse et al., 2006



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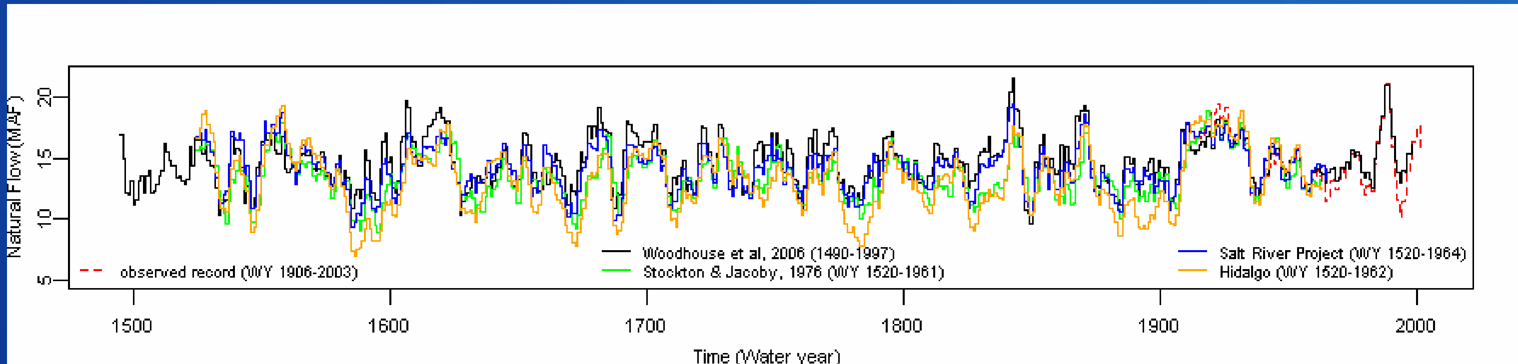
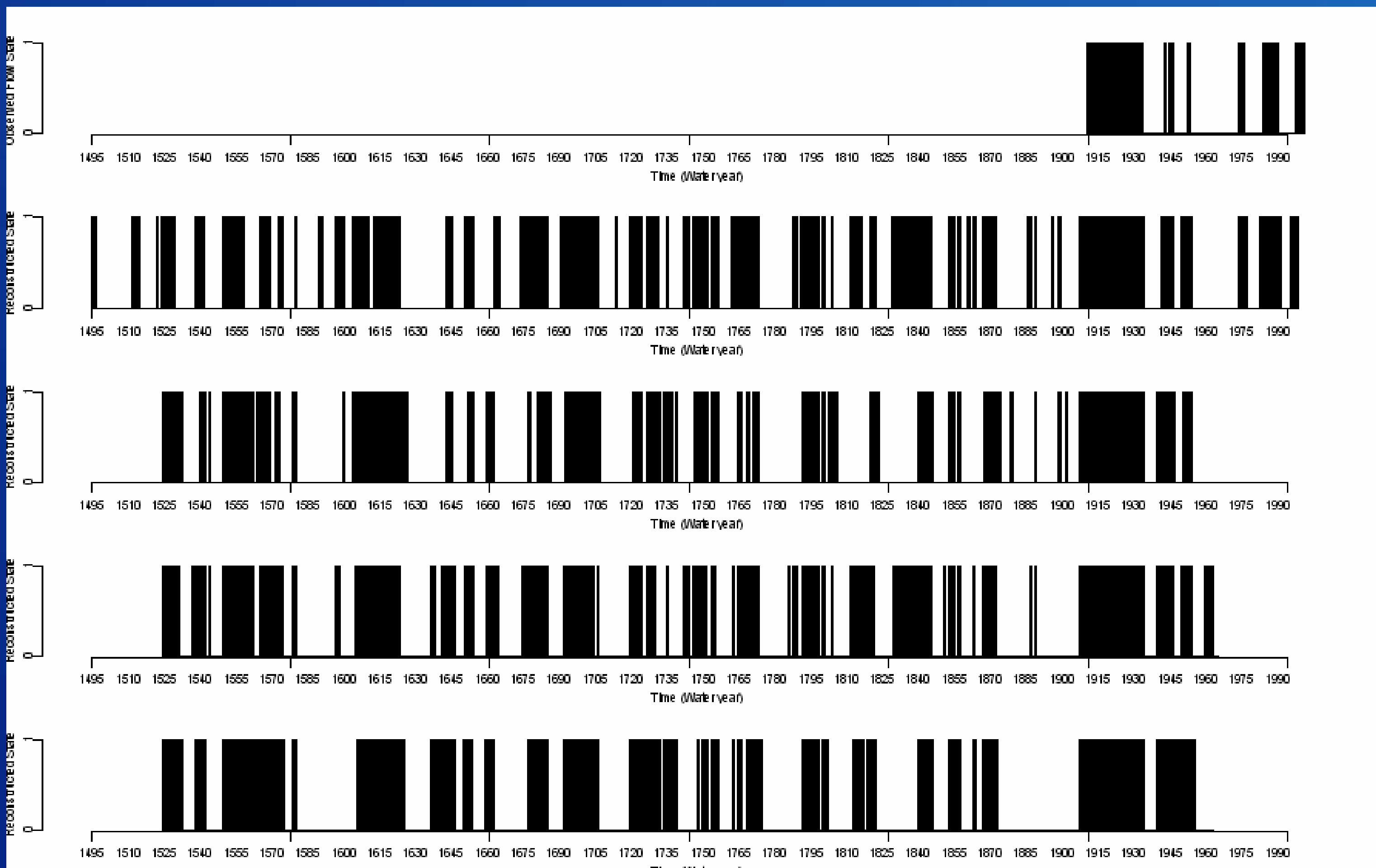




observed record

Woodhouse et al. 2006

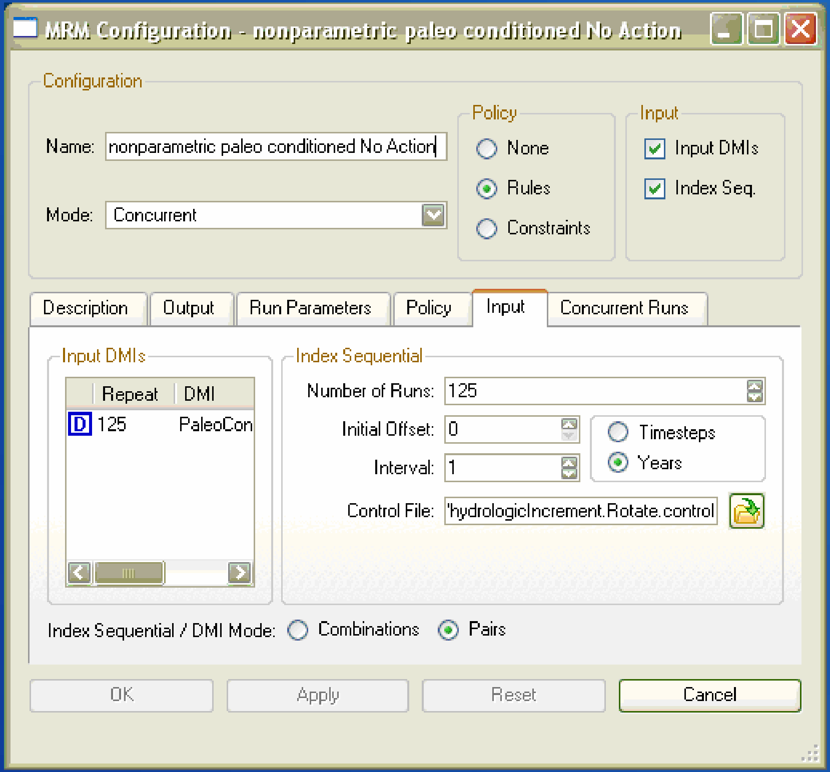
Stockton and Jacoby, 1976

Hirschboeck and Meko, 2005

Hildalgo et al. 2002

Alternate Stochastic Techniques

- Paleo conditioned
  - Combines observed and paleo streamflows
  - Generates
    - Observed flow magnitudes
    - Flow sequences similar to paleo record
- Parametric
  - Fit observed data to appropriate model (i.e., CAR)
  - Generates
    - Flow magnitudes not observed
    - Flow sequences similar to observed record



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CRSS Modeling Assumptions –
Alternate Hydrologic Sequences

- Index Sequential Method & Alternate Stochastic Techniques
- Alternate Hydrologic Sequences & Results

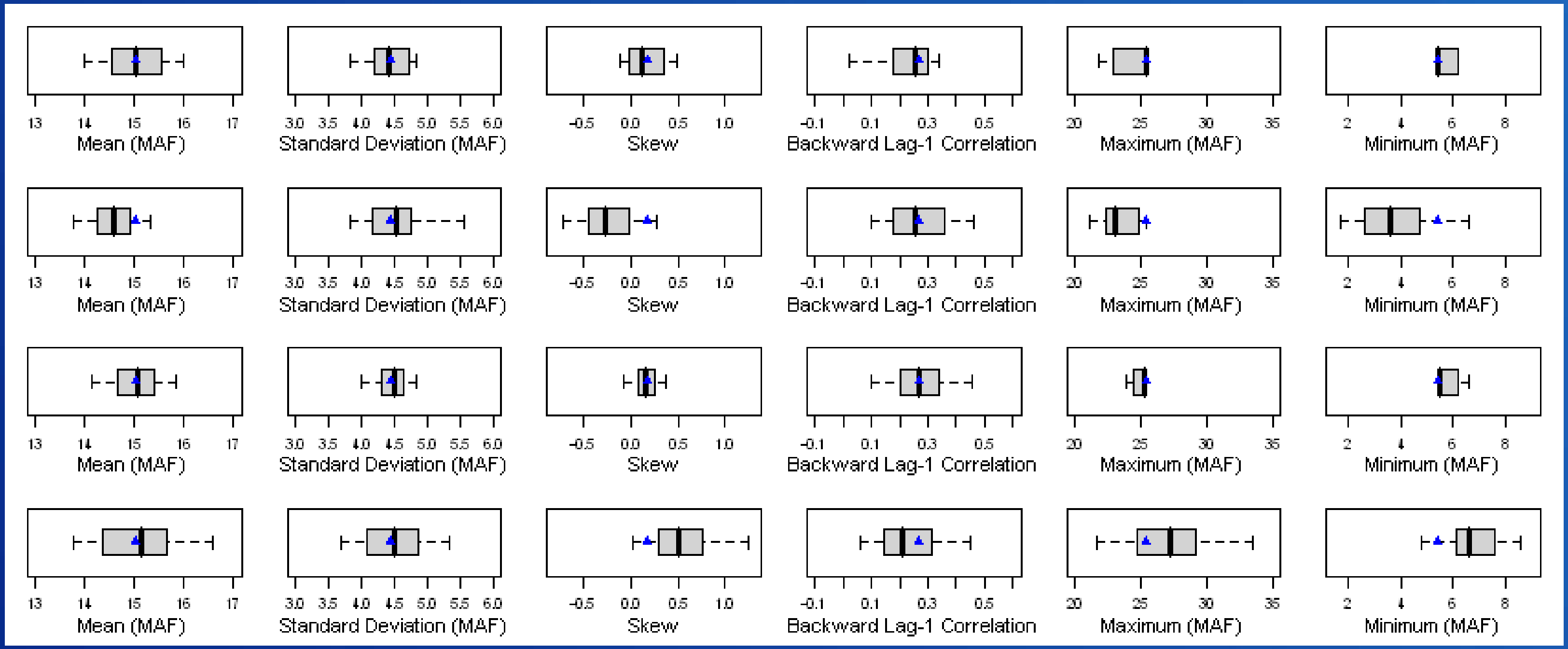
Boxplots of Basic Statistics

Observed

Direct Paleo

Paleo Conditioned

Parametric



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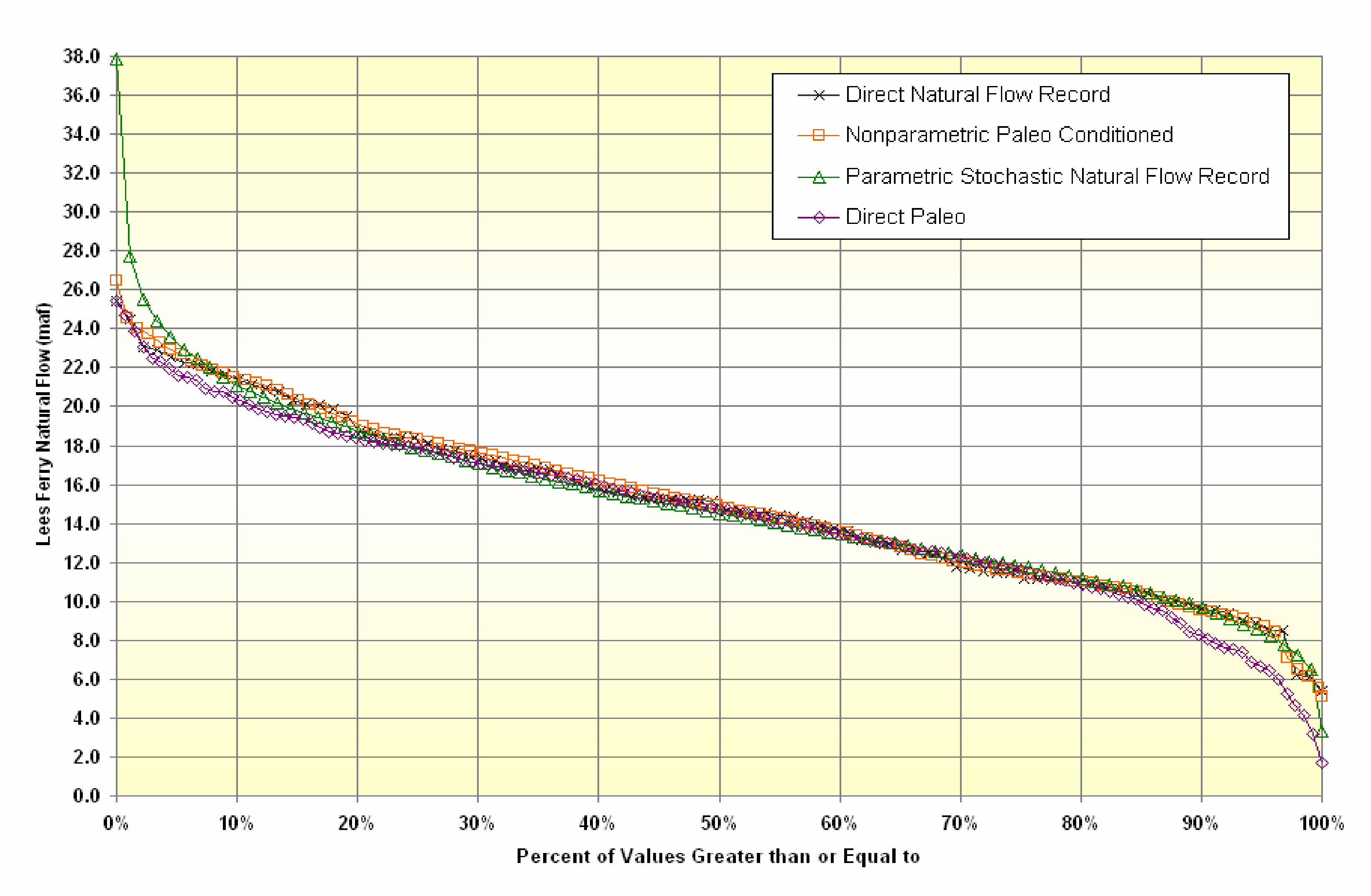
Annual Natural Flow at Lees Ferry
No Action Alternative
Years 2008-2060



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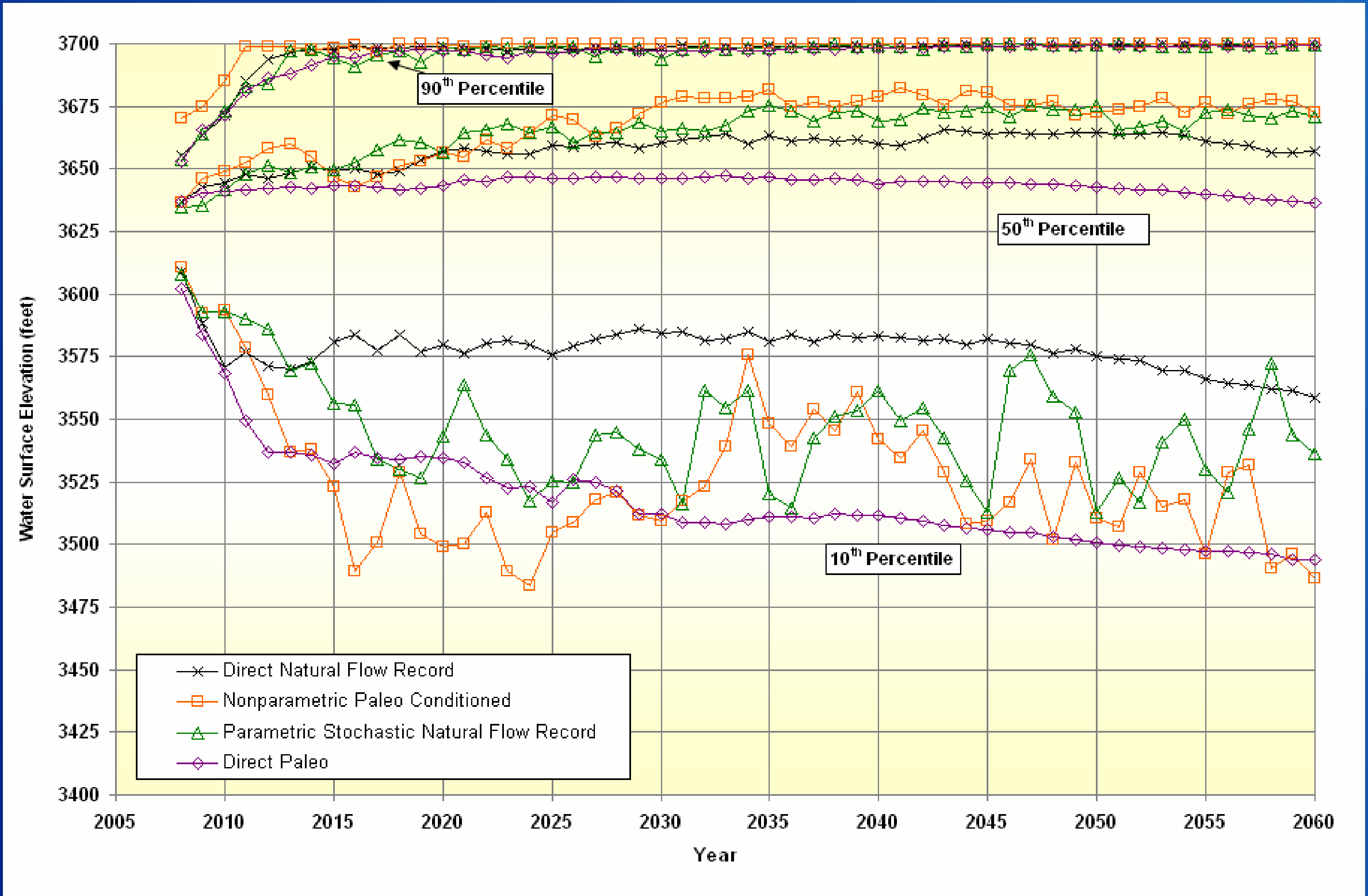
Lake Powell End of July Elevations

No Action Alternative

10th, 50th and 90th Percentile Values



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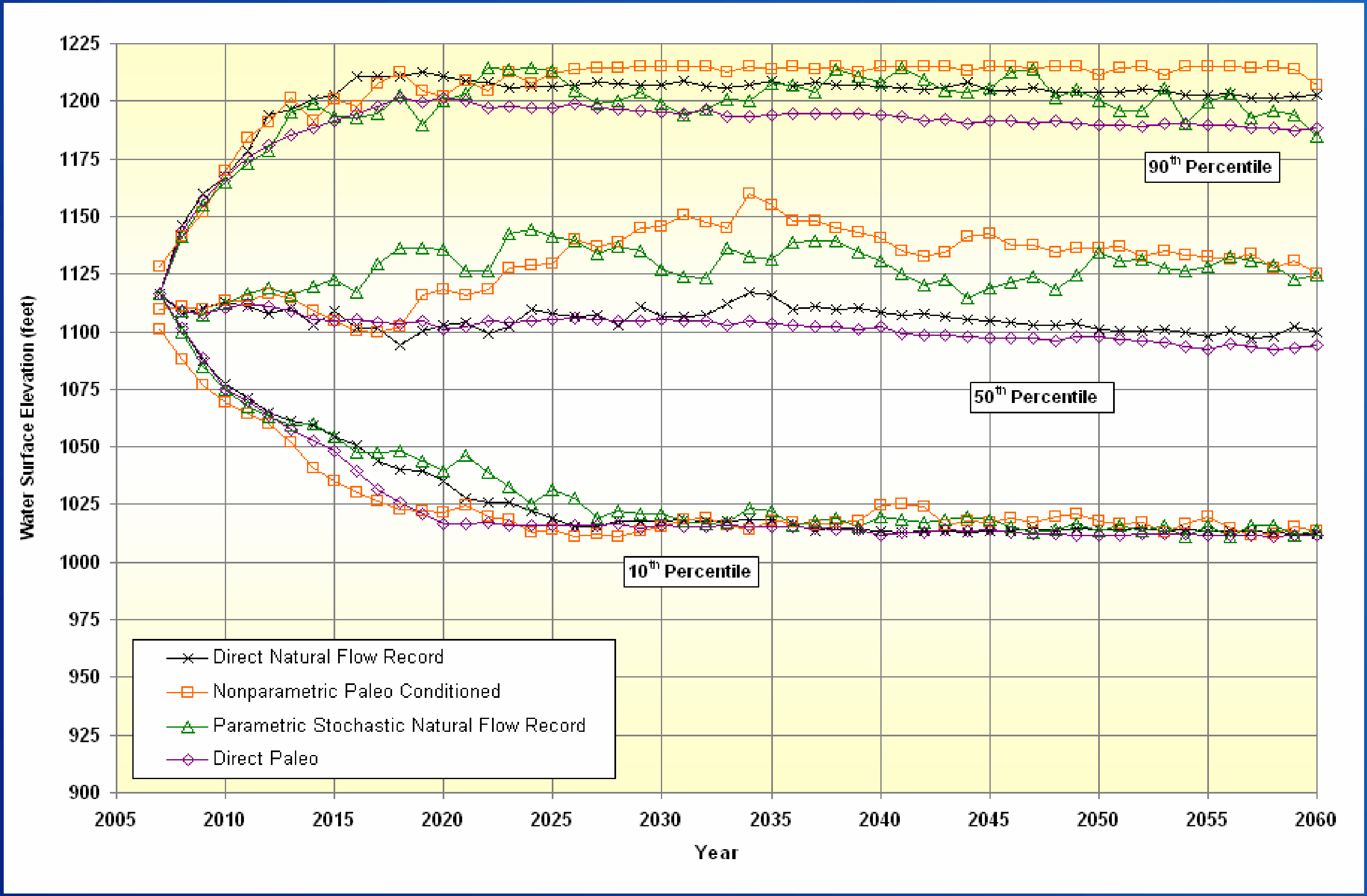
Lake Mead End of December Elevations

No Action Alternative

10th, 50th and 90th Percentile Values



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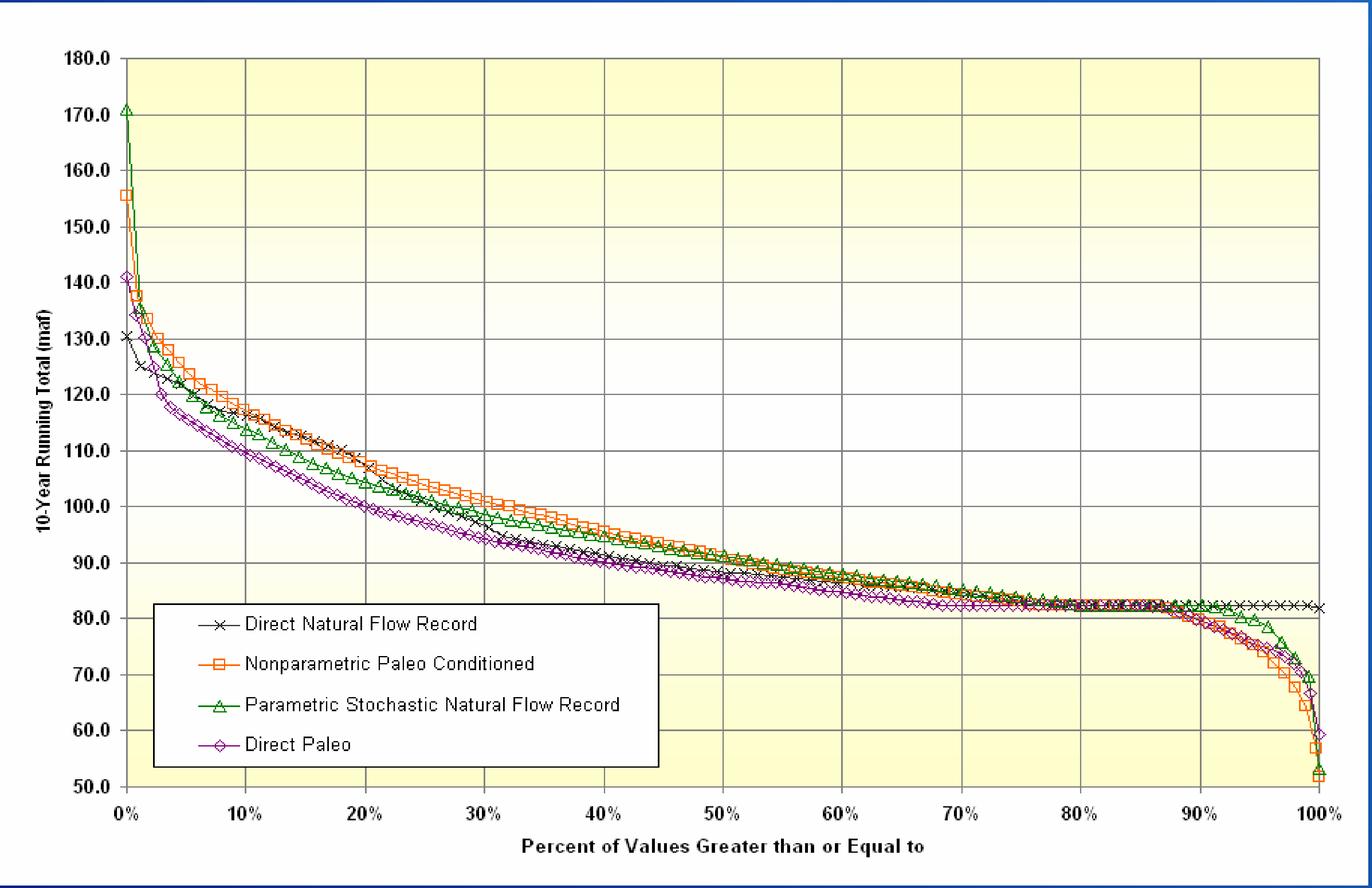
Glen Canyon 10-Year Release Volume
No Action Alternative
Years 2008-2060



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Final statements

- Integrated flexible framework
  - Simple
  - Robust
  - Parsimonious
- Easily represents nonlinear relationship
- Effective policy analysis requires use of stochastic methods other than ISM
- Presented framework allows an improved understanding for operation risks and reliability
- Allows an understanding of climate variability risks based on paleo hydrologic state information

Future direction

- Alternate annual simulation models (parametric, semi parametric) Include correlation from first month and last month
- Apply hidden Markov model
- Explore additional policy choice. Optimization framework to include economic benefits

- Can easily consider climate change scenarios using climate projections to simulate annual flow

Major Contributions

- Prairie, J.R., B. Rajagopalan, U. Lall, T. Fulp (2006) A stochastic nonparametric technique for space-time disaggregation of streamflows, Water Resources Research, (in press).

- Prairie, J.R., B. Rajagopalan, U. Lall, T. Fulp (2006), A stochastic nonparametric approach for streamflow generation combining observational and paleo reconstructed data, Water Resources Research, (under review).

- Prairie, J.R., et al. (2006) Comparative policy analysis with various streamflow scenarios, (anticipated).

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Additional Publications

- Prairie, J.R., B. Rajagopalan, T.J. Fulp, and E.A. Zagona (2006), Modified K-NN Model for Stochastic Streamflow Simulation, ASCE Journal of Hydrologic Engineering, 11(4) 371-378.

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