Exploring beyond the historical sequence to understand how multi-year drought characteristics affect Winter Run salmon in California

James Gilbert[1,2], Miles Daniels[1,2], Ann-Marie Osterback[1,2], Rob Sherrick[3]

[1]University of California, Santa Cruz

[2]NOAA Fisheries Southwest Fisheries Science Center (affiliate)

[3]California Department of Fish and Wildlife

UC SANTA CRUZ

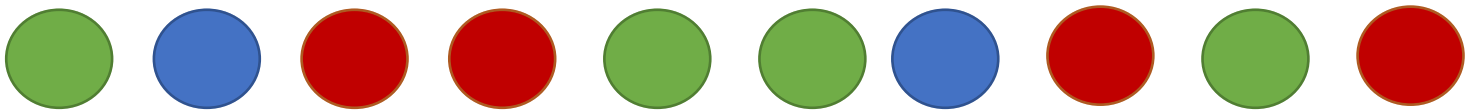
NOAA FISHERIES

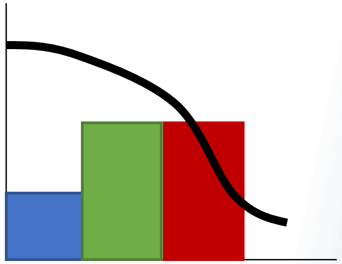
Does the sequence of wet and dry years matter?

If the hydrologic record can (generally) be represented as a sequence of independent year types – we can think of sequences like the following:

*Example: 10 years might have **4 dry** + **4 "normal"** + **2 wet** years (could be inflows, reservoir storage, deliveries, some other hydrologically-driven outcome)*

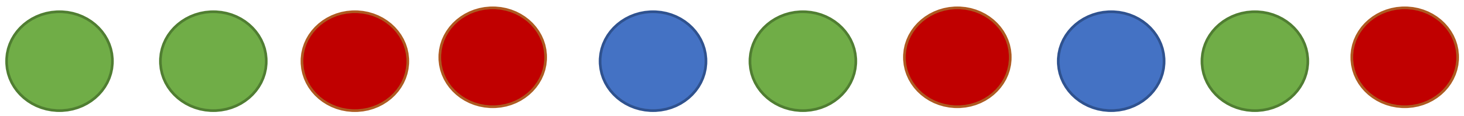
"Historical"

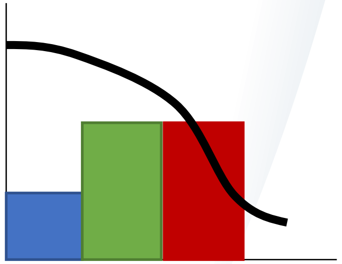




Storage or Delivery

Another plausible realization



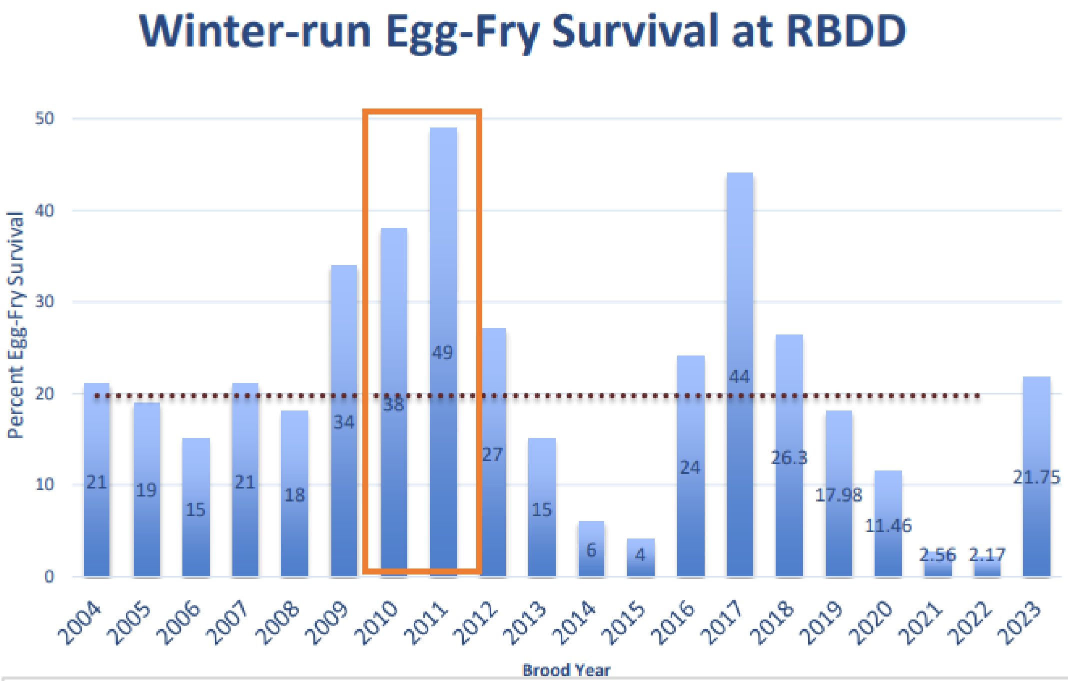


Storage or Delivery

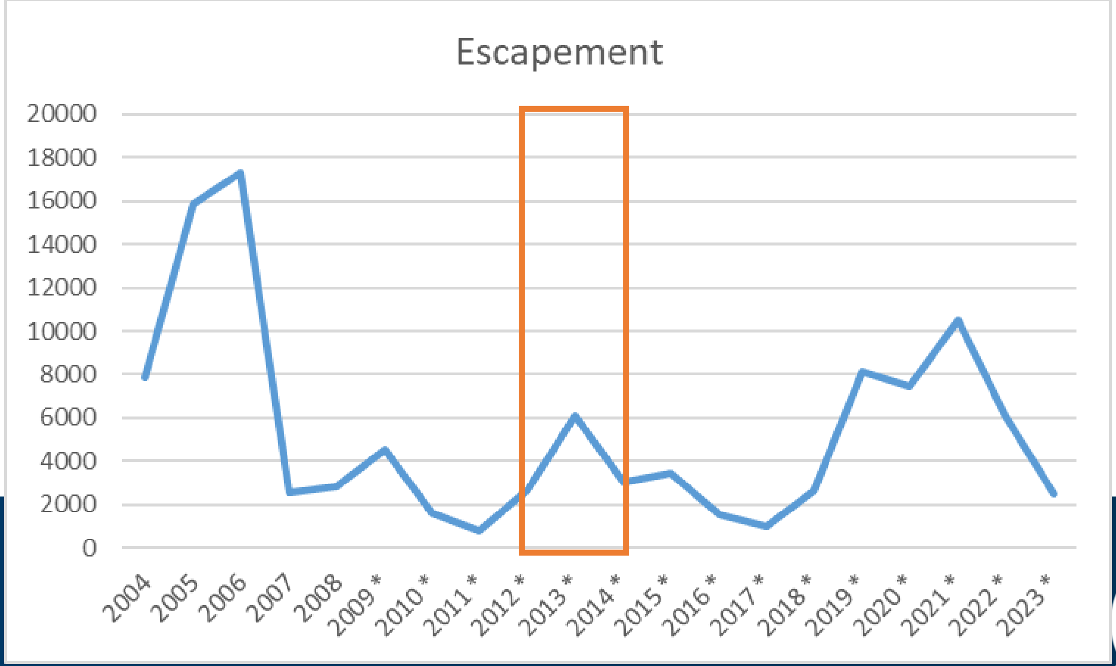
Might expect a very similar outcome for a system with little "memory" – significant multi-year autocorrelation in hydroclimate signal, storage capacity much greater than annual runoff

Winter-run Chinook salmon have a ~3-year life cycle

Wetter years tend to lead to higher than average early life stage survival, and an increase in escapement (number of adults returning) three years later



Plot from 2023 juvenile production estimate letter (https://www.fisheries.noaa.gov/s3/2024-01/jpe-letter-2023.pdf)



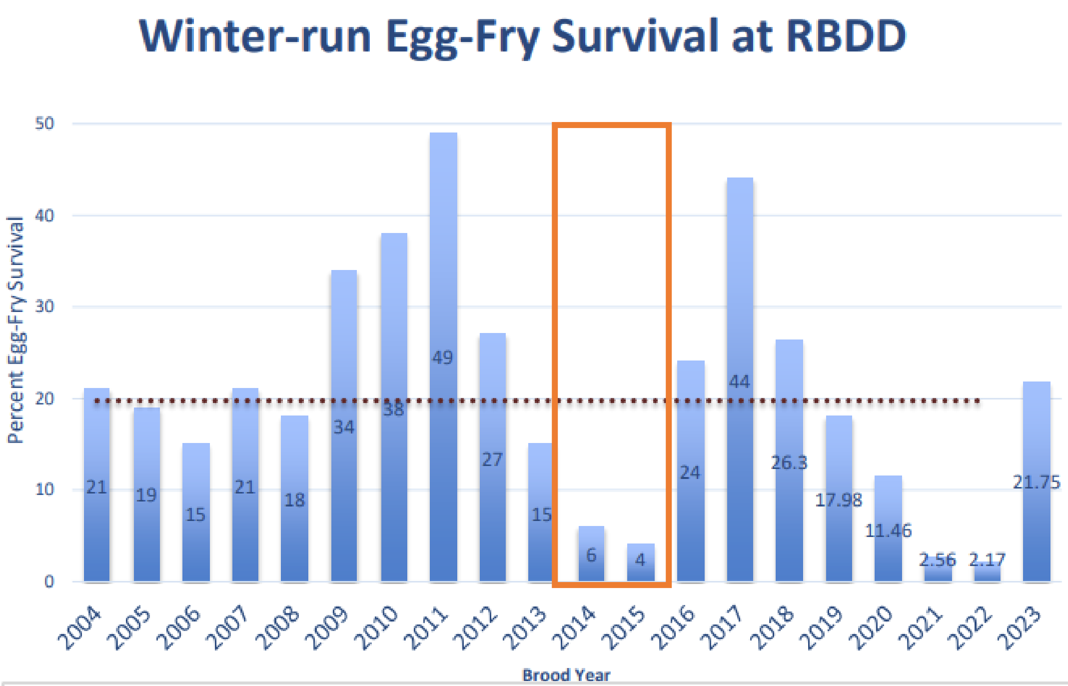
Data from GrandTab via SacPas (https://www.cbr.washington.edu/sacramento/data/query_adult_grandtab.html)

UC SANTA CRUZ

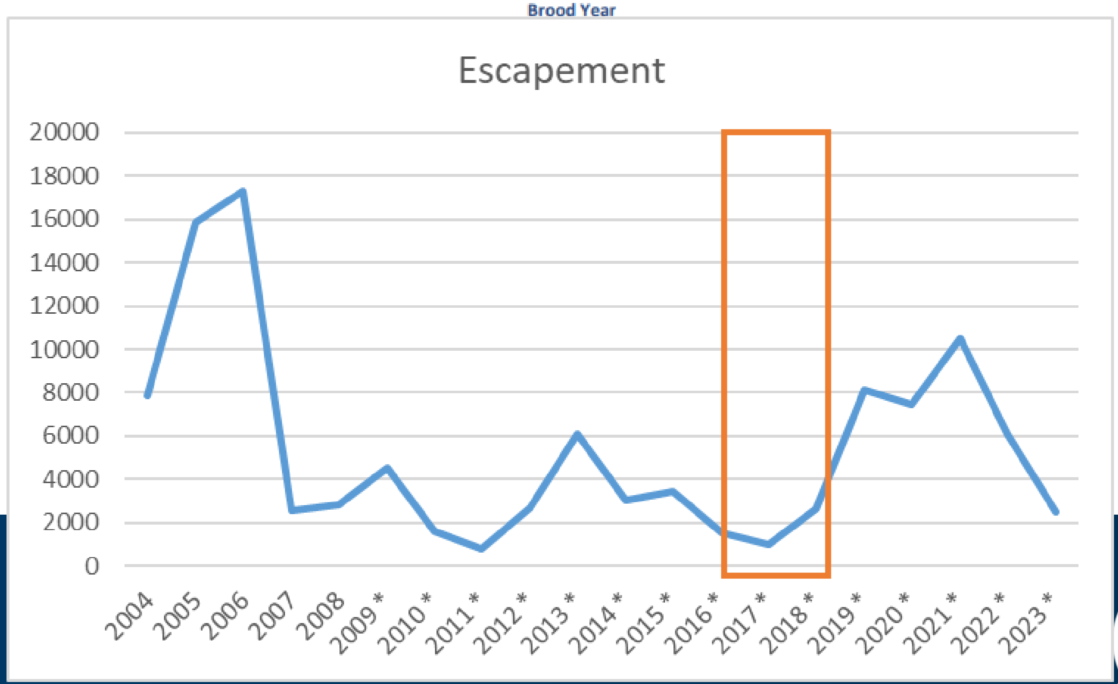
NOAA FISHERIES

Winter-run Chinook salmon have a ~3-year life cycle

Drier years tend to lead to lower than average early life stage survival, and a decrease in escapement (number of adults returning) three years later



Plot from 2023 juvenile production estimate letter (https://www.fisheries.noaa.gov/s3/2024-01/jpe-letter-2023.pdf)



Data from GrandTab via SacPas (https://www.cbr.washington.edu/sacramento/data/query_adult_grandtab.html)

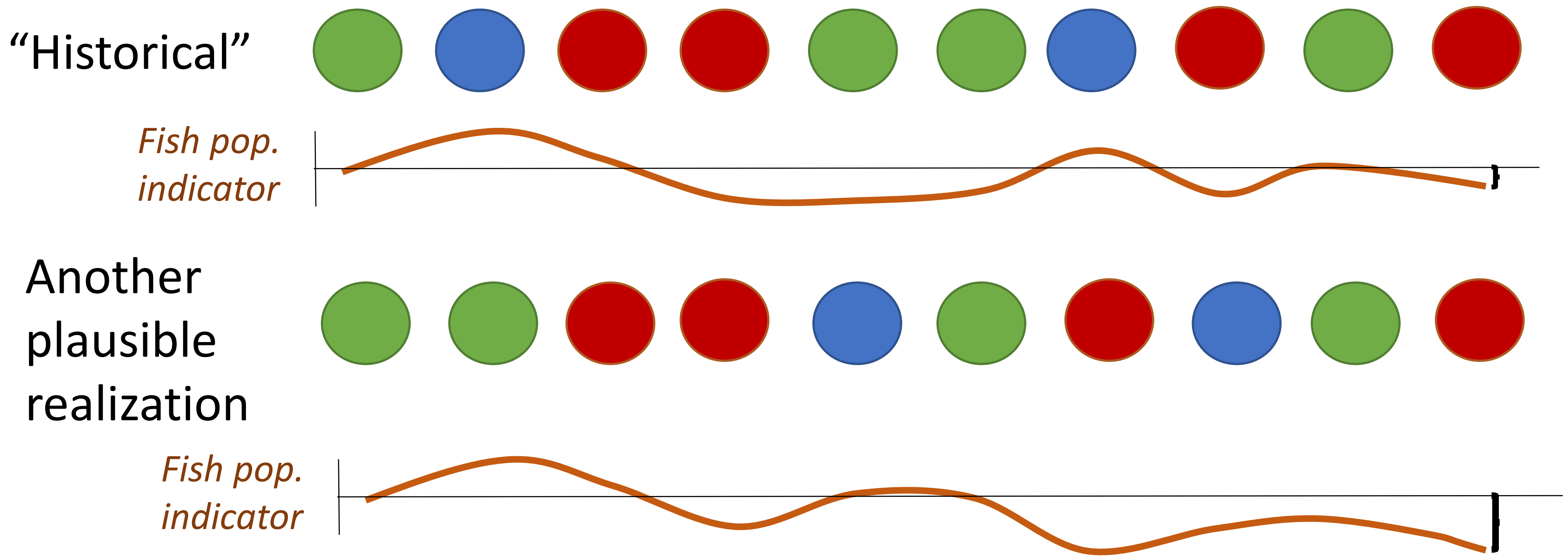
UC SANTA CRUZ

NOAA FISHERIES

Does the sequence of wet and dry years matter?
Might it matter more for fish with a 3-year life cycle?

If the hydrologic record can (generally) be represented as a sequence of independent year types – we can think of sequences like the following:

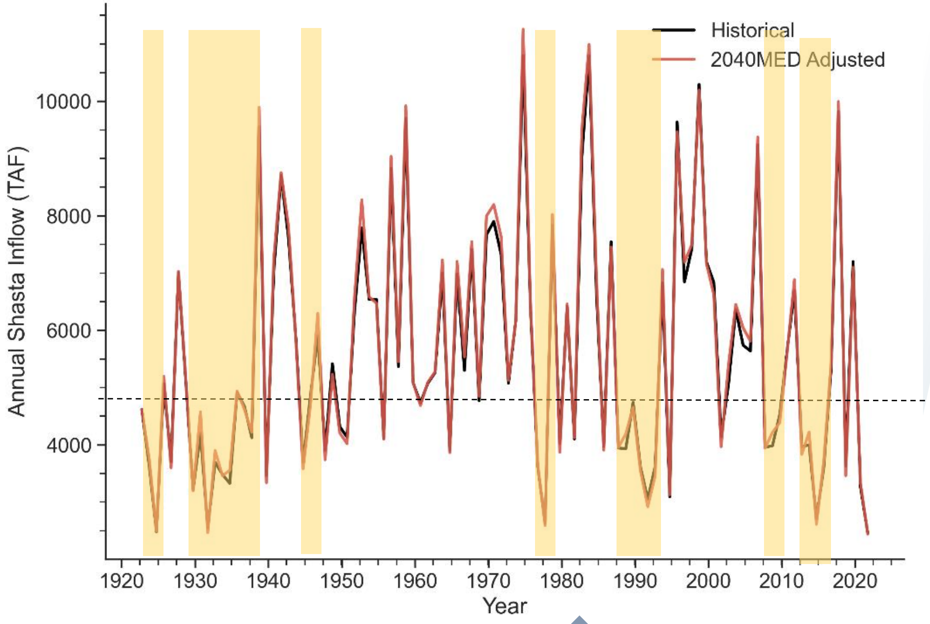
*Example: 10 years might have **4 dry** + **4 "normal"** + **2 wet** years (could be inflows, reservoir storage, deliveries, some other hydrologically-driven outcome)*



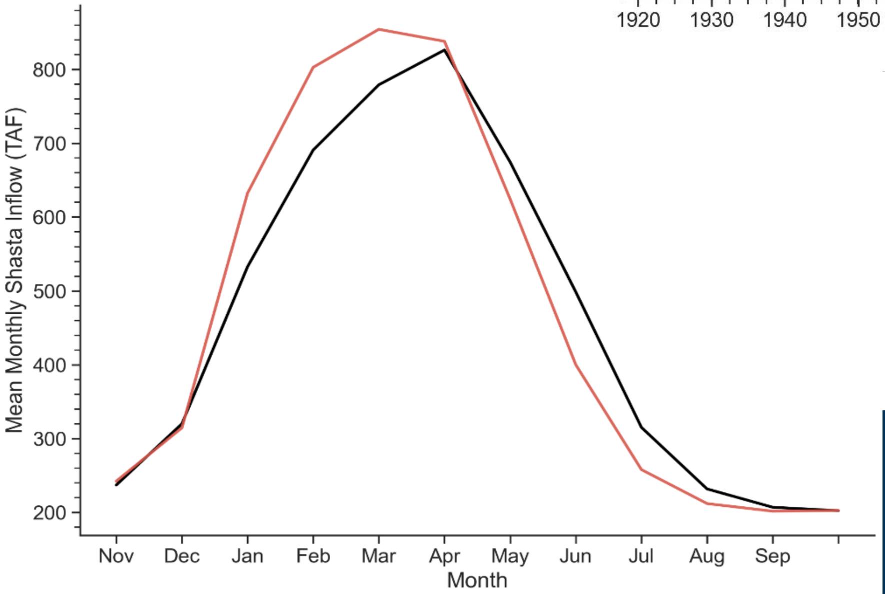
Hypothesis: The timing and order of wet (population recovery) and dry (low survival) years has an important effect on projections of winter-run Chinook salmon populations

How do we commonly represent hydrologic sequences and variability in Central Valley planning models?

- Planning analysis uses the historical hydrology trace 1921 - 2021
- Hydrologic change applied as perturbations to monthly pattern, but keeping same annual sequence



What about other sequences of droughts? Different durations and severities?



UC SANTA CRUZ

NOAA FISHERIES

Objective

- Better understand how the sequence and characteristics of dry and wet years affects winter-run Chinook salmon population projections
- Additional motivation comes from Governor's Executive Order N-10-21:

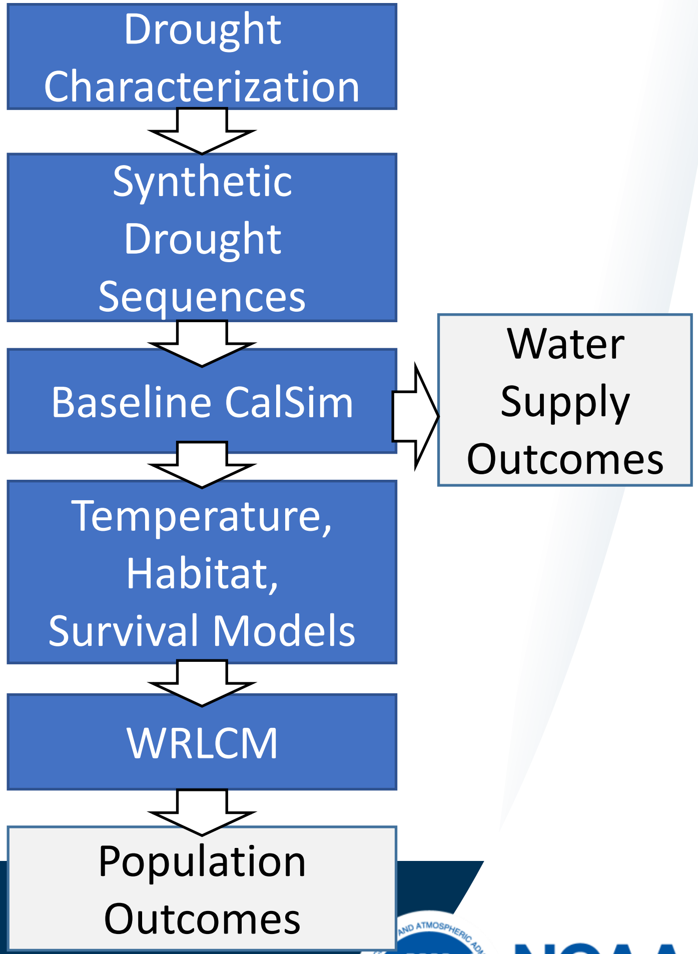
  "..develop strategies to protect communities and fish and wildlife in the event of drought lasting at least six years.."

- Funding support provided by California Department of Fish and Wildlife to help address questions that arise from this Executive Order

Analytical Framework: CalSim3 and the Winter-Run Lifecycle Model (WRLCM)

- **Phase I: Drought Synthesis & Assessment**
  - Characterize historical droughts
  - Generate drought sequences
  - Create corresponding CalSim3 input datasets
  - Run Baseline CalSim for each sequence

  - Run "downstream" component models
  - Run WRLCM
  - Evaluate baseline salmon response to drought

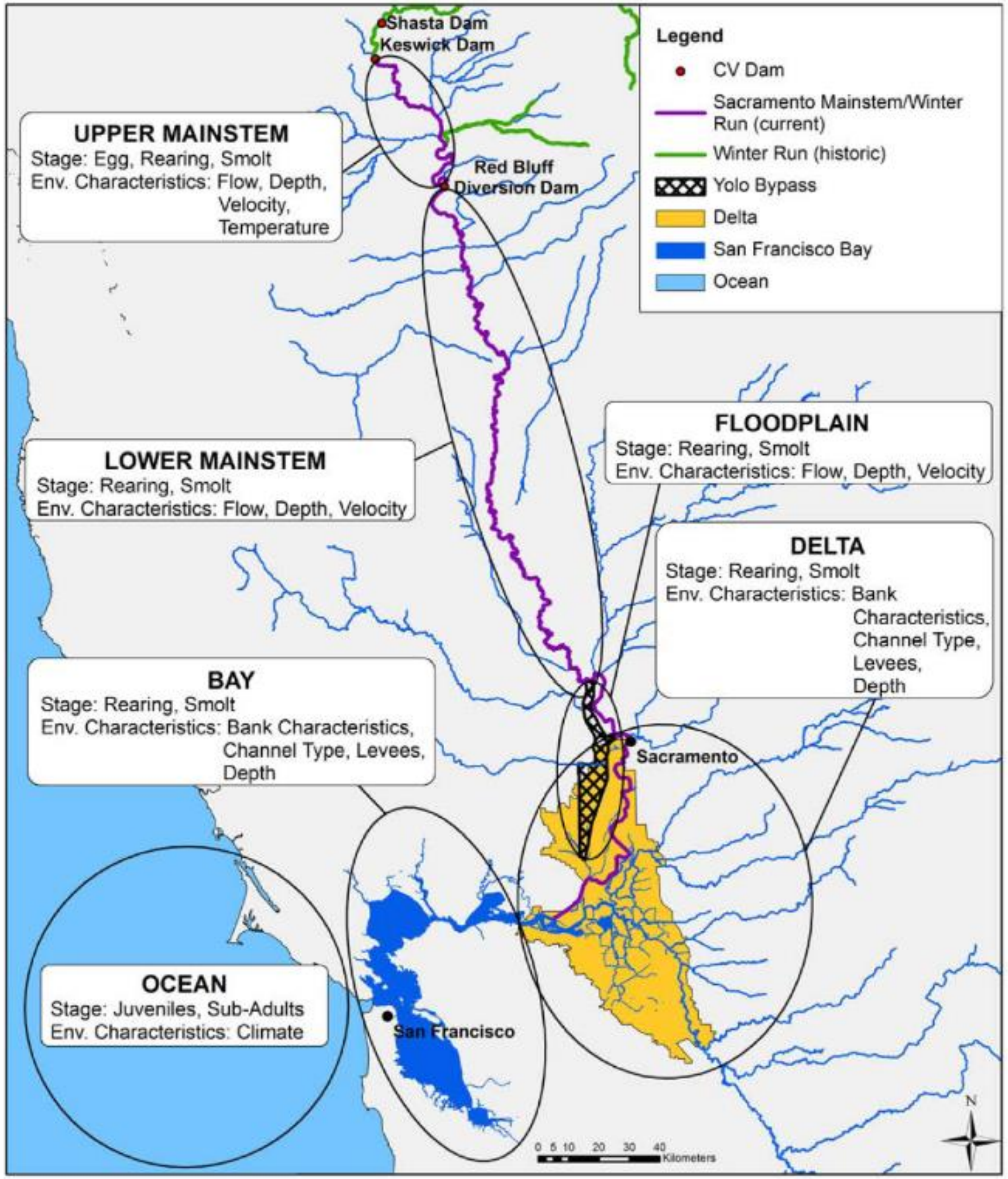


The CalSim3 planning model translates hydrologic inputs to managed water resource outcomes across the Central Valley

- Model used by state and federal government to represent long-term operations of facilities
  - Current operations provide a useful baseline for comparison
- Monthly time step, logic defining conveyance network, demands, regulations, and priorities in a linear programming framework
- Results feed into other models and WRLCM for population analysis

Winter Run Lifecycle Model (WRLCM)

- Represents movement & survival across Winter Run salmon life stages
- Spatial structure to evaluate conditions for different life stages
- Built around CalSimII and CalSim3, relies on intermediate “downstream” models to translate managed flows into habitat and survival



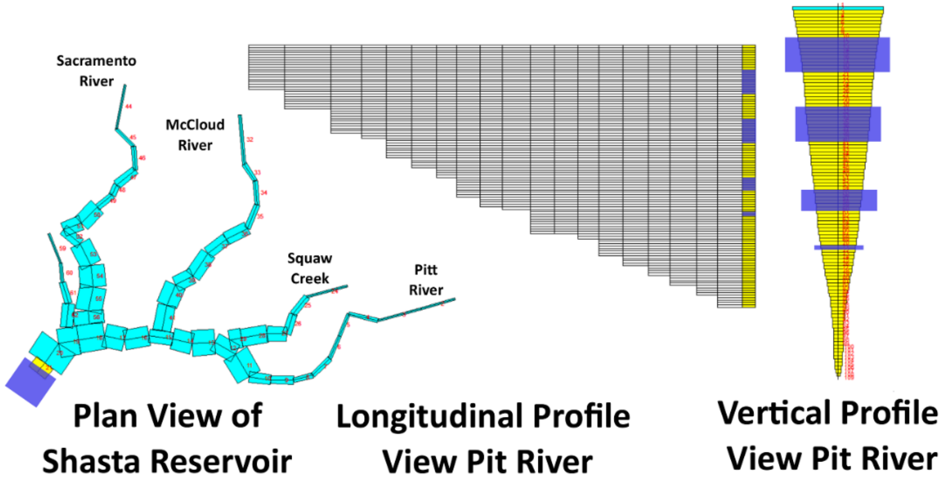
UC SANTA CRUZ

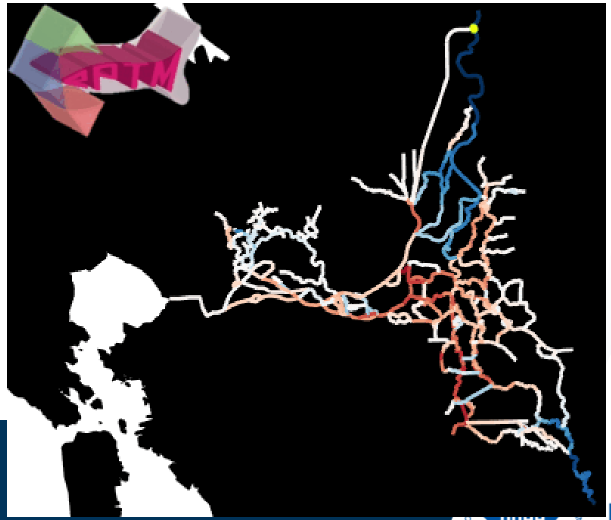
Hendrix, N., Jennings, E., Criss, A., Danner, E., Sridharan, V., Greene, C. M., et al. (2017, January 6). Model Description for the Sacramento River Winter-run Chinook Salmon Life Cycle Model. National Marine Fisheries

NOAA FISHERIES

CalSim-WRLCM Process: “Downstream” Models

- Upper Sacramento River Water temperature
  - Determine temperature effects on early life stage survival
  - Models: CE-QUAL-W2 & RAFT, Rapid Reservoir-River Assessment Models
- River, Delta, & Bay habitat
  - Determine capacity for outmigrating juveniles
- Delta Survival
  - DSM2 hydro -> ePTM
  - Computational bottleneck:
    - Concurrent effort to speed up ePTM through emulation, simplified simulation





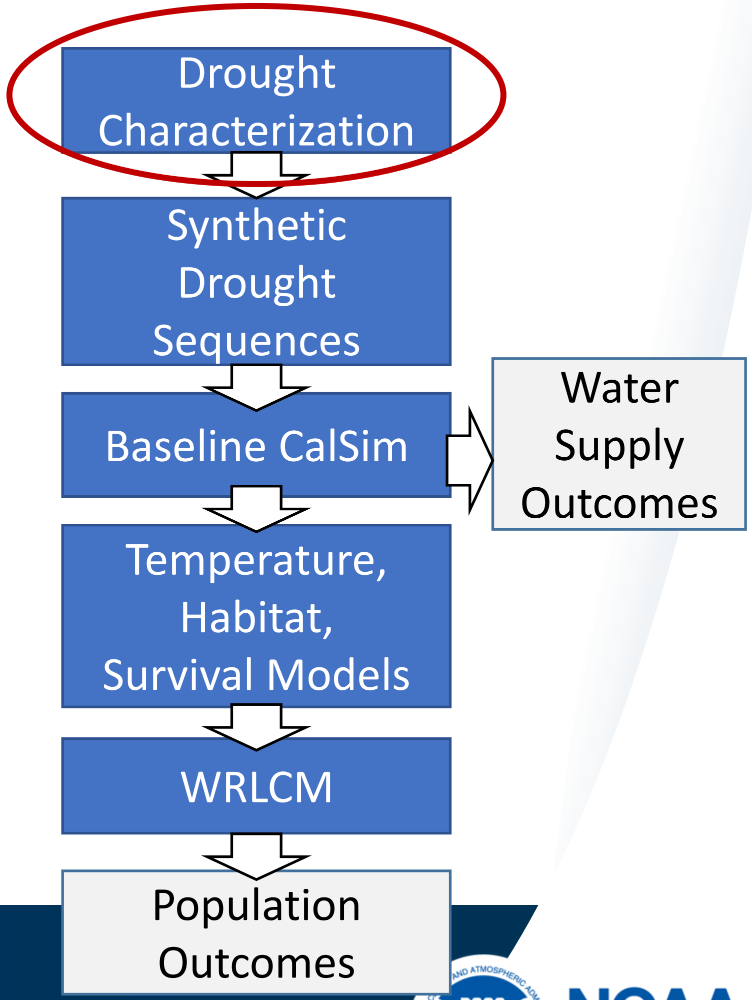
UC SANTA CRUZ

NOAA FISHERIES

Analytical Framework: CalSim3 and the Winter-Run Lifecycle Model (WRLCM)

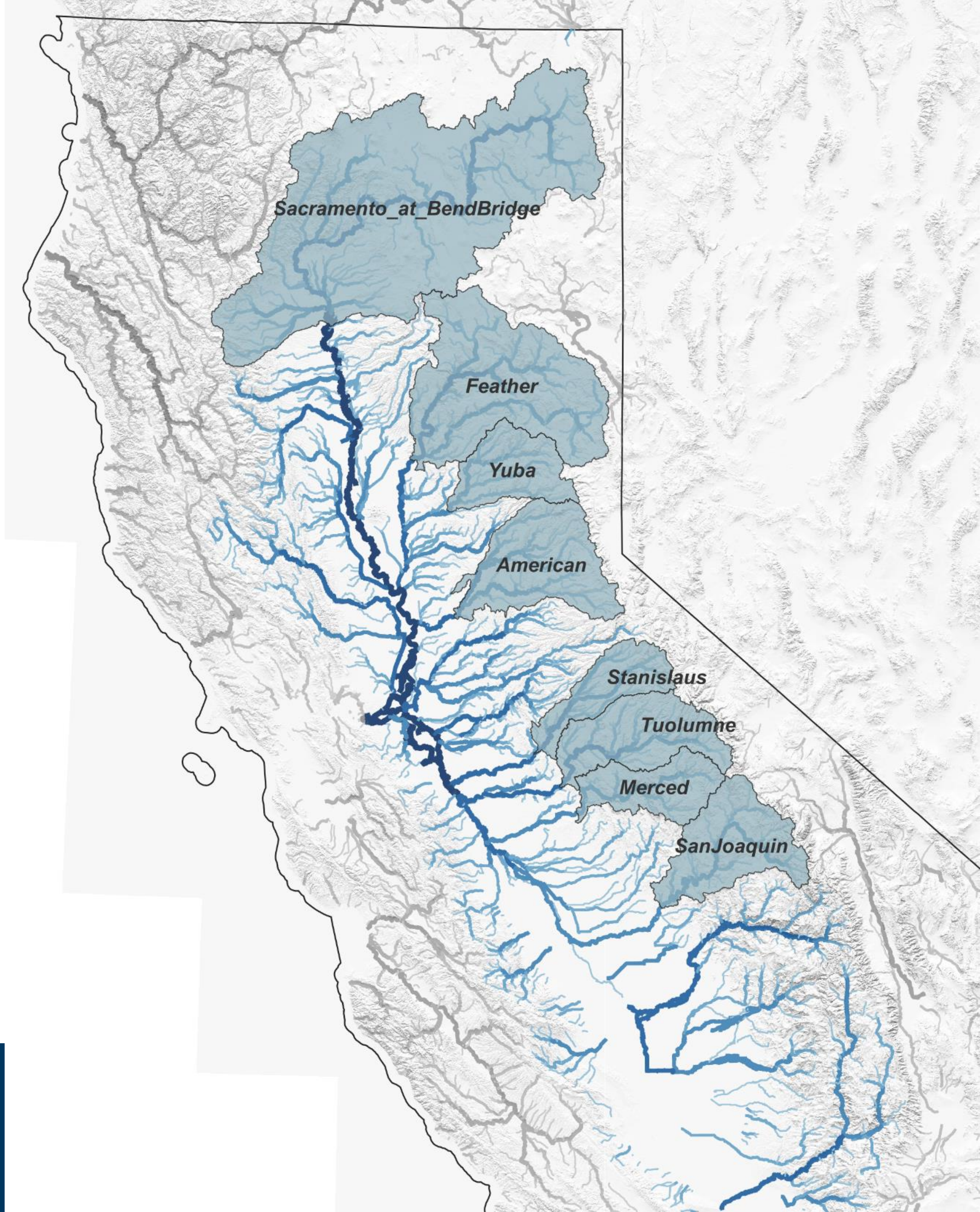
- **Phase I: Drought Synthesis & Assessment**
  - Characterize historical droughts
  - Generate drought sequences
  - Create corresponding CalSim3 input datasets
  - Run Baseline CalSim for each sequence

  - Run “downstream” component models
  - Run WRLCM
  - Evaluate baseline salmon response to drought



Drought Characterization & Synthesis: Data

- **Use 8-river annual flow as index for Central Valley hydrology**
- **Gage record**
  - Natural flow at 8 gage locations
  - ~100 years
- Paleohydrology record
  - Estimated from tree rings – growth correlated with precipitation and runoff
  - ~1000 years
  - May be less sensitive to extreme wet conditions



UC SANTA CRUZ

Drought Characterization & Synthesis: Method Selection

- Reviewed methods in literature, considering criteria:
  - *Appropriate for streamflow*
  - *Suitable for multi-year sequences*
  - *Generate sequence with specified properties*
  - *Quantifiable probabilities or risks*
  - *Can be based on observed or projected hydrology data*

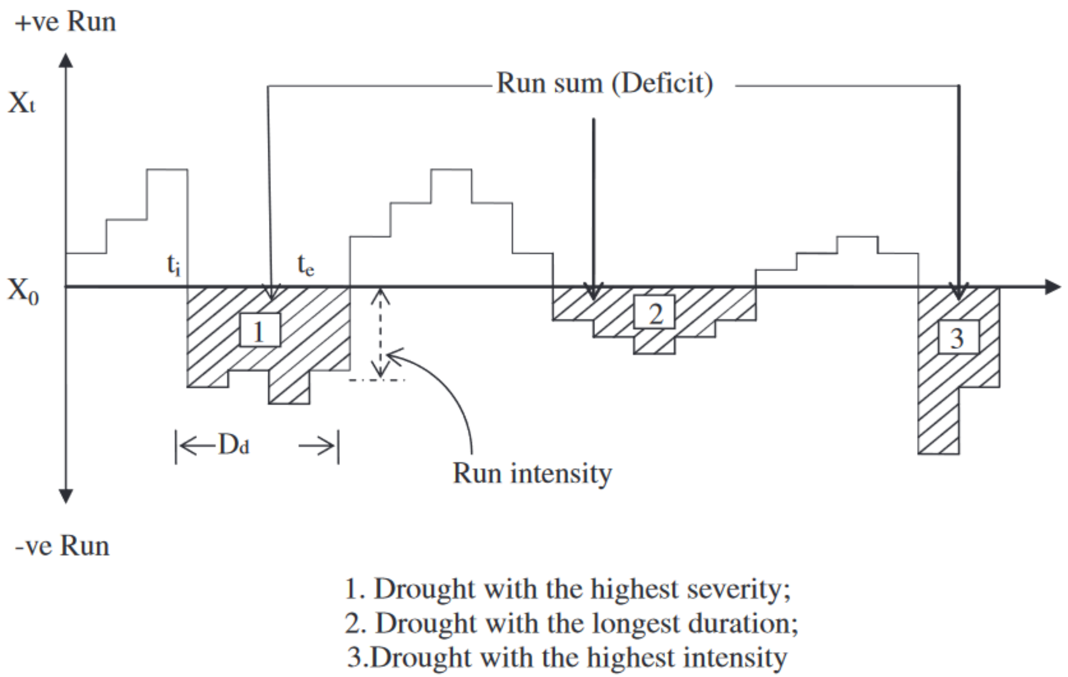


Fig. 1. Drought characteristics using the run theory for a given threshold level.

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(1), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Drought Characterization & Synthesis: Applying Method

- Assign a drought "threshold"
  - *Threshold,* X_0 = *MeanQ – 0.5*StdDev*
- Process time series to quantify:
  - Drought incidence ($Q_i < X_0$)
  - Drought duration *(# contiguous years* $Q_i < X_0$*)*
  - Deficit ($X_0 - Q_i$)
  - Drought severity ($\sum(X_0 - Q_i)$)
- Same measures for wet intervals between drought ("pluvials")

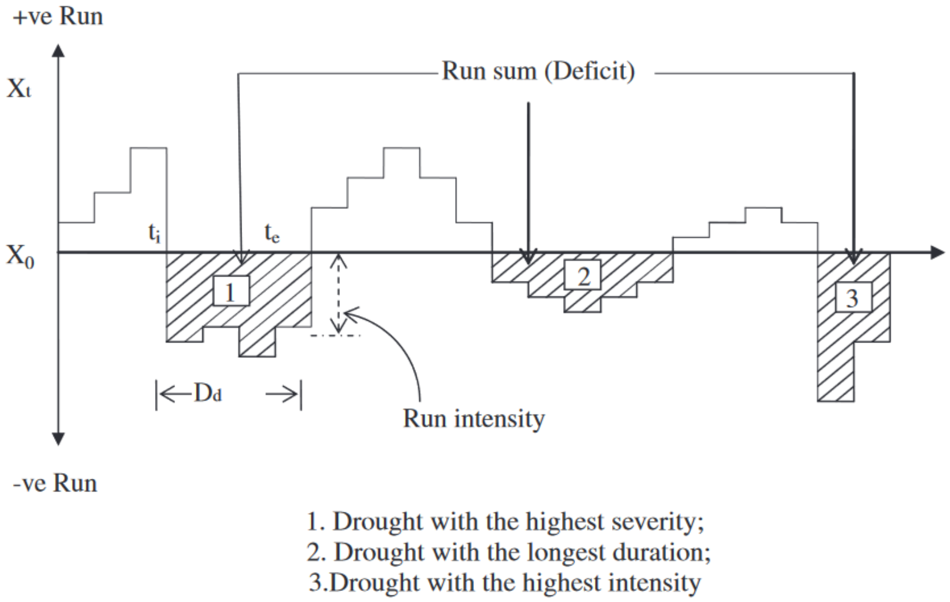
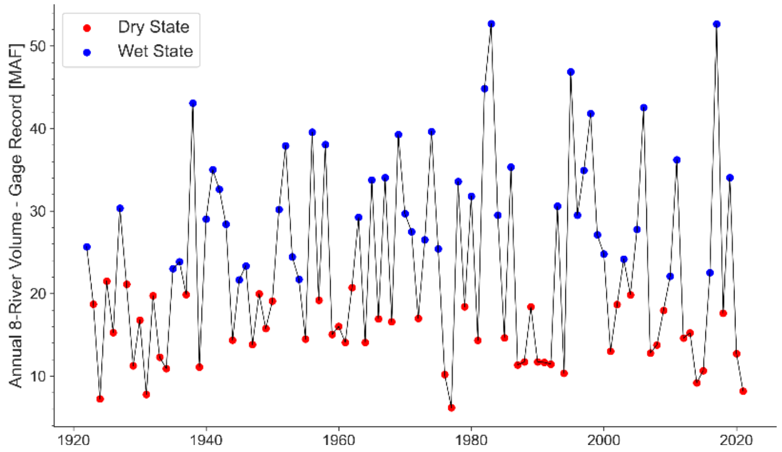
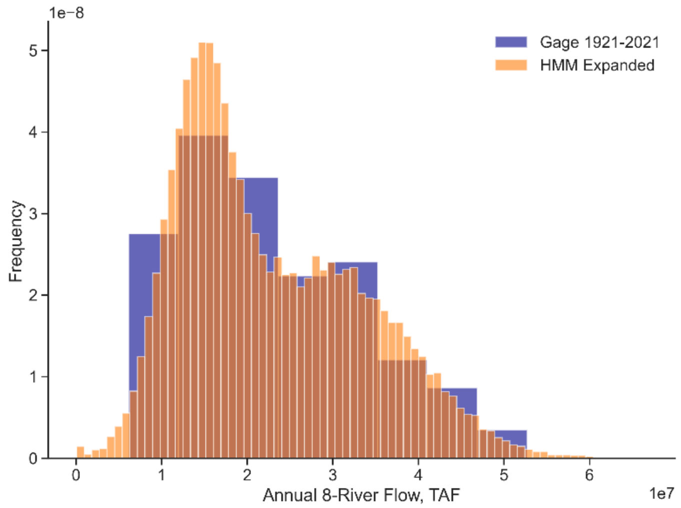


Fig. 1. Drought characteristics using the run theory for a given threshold level.

A note on record length & distribution fitting:

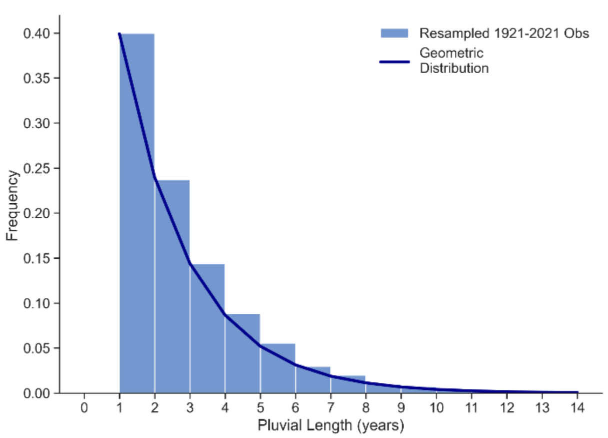
- **Problem:** Very small sample size for long duration (rare) droughts in gage and paleo records – difficulty fitting deficit & severity distributions (and uncertainty in duration distributions)
- **Solution:** expand existing records with a hidden Markov model (HMM), improve sample size

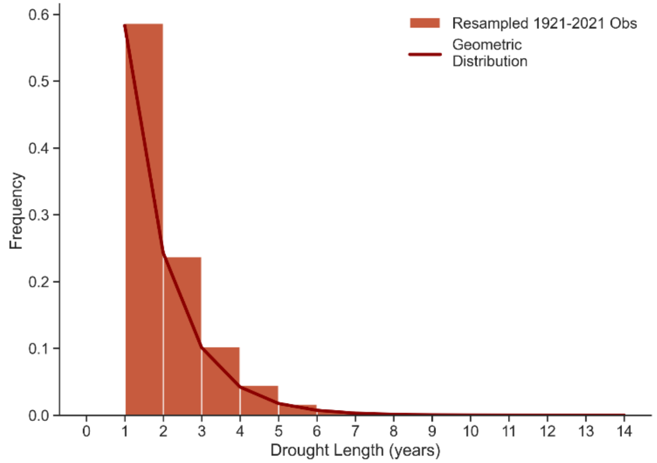


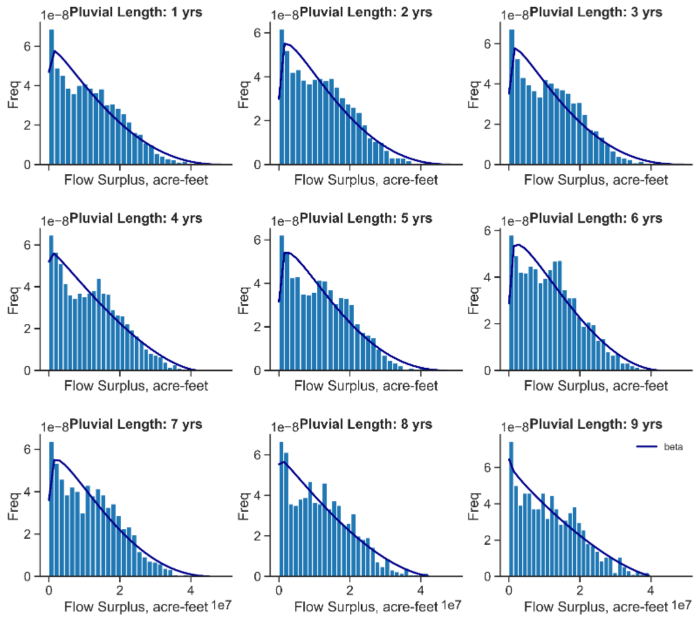


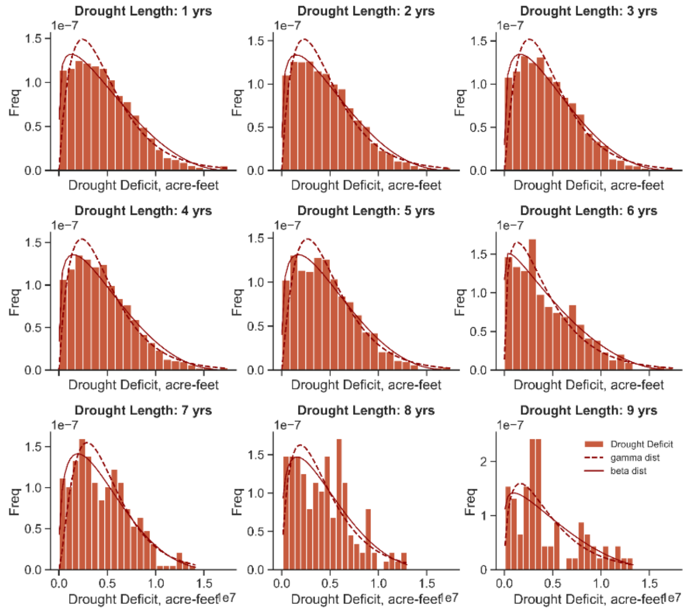
Fit distributions to drought duration & severity data

- Drought & pluvial durations: Geometric distribution
- Individual deficits (surpluses) during a drought (pluvial) of length 1 – 9 years: Beta distribution





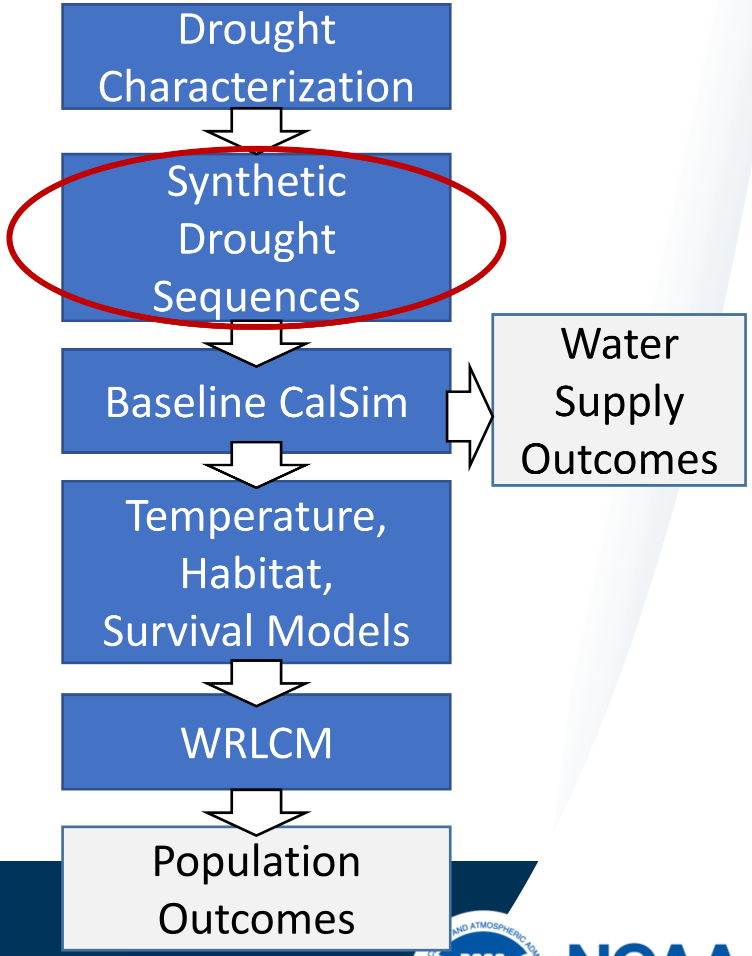




UC SANTA CRUZ

Analytical Framework: CalSim3 and the Winter-Run Lifecycle Model (WRLCM)

- **Phase I: Drought Synthesis & Assessment**
  - Characterize historical droughts
  - **Generate drought sequences**
  - Create corresponding CalSim3 input datasets
  - Run Baseline CalSim for each sequence
  - Run "downstream" component models
  - Run WRLCM
  - Evaluate baseline salmon response to drought



Drought Characterization & Synthesis

- Selection: "Alternating renewal" model (and related versions)
  - *Examples: Loáiciga, H. A. (2005). Kendall & Dracup, (1992)*
  - Drought ≈ one or more years below a prescribed threshold
  - Annual flow time series can be characterized using statistical distributions of:
    - Durations
    - Intensities
    - Total deficits (surpluses)

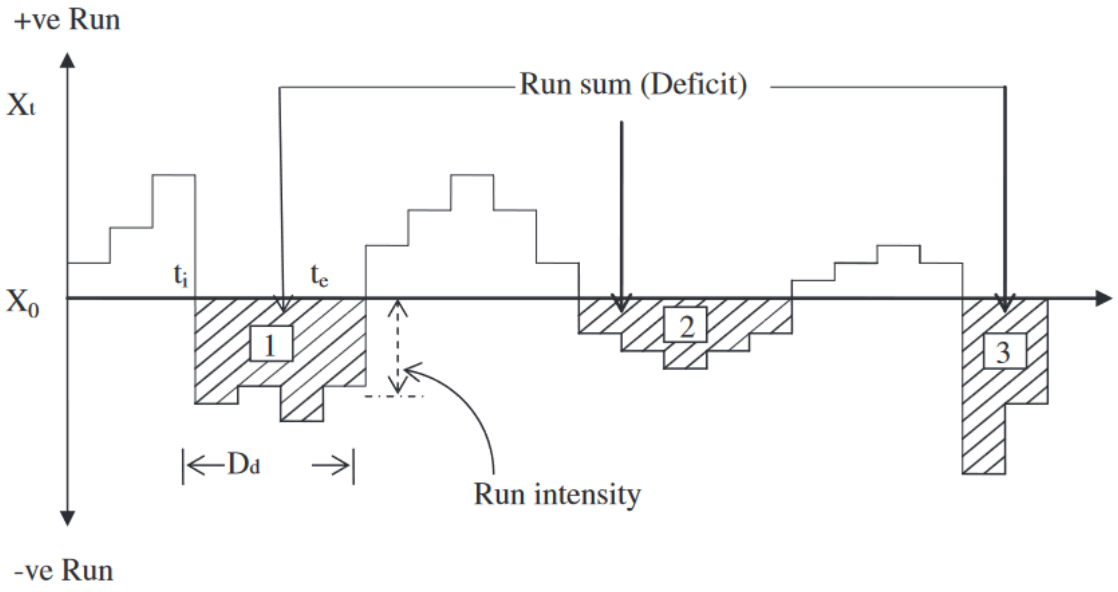
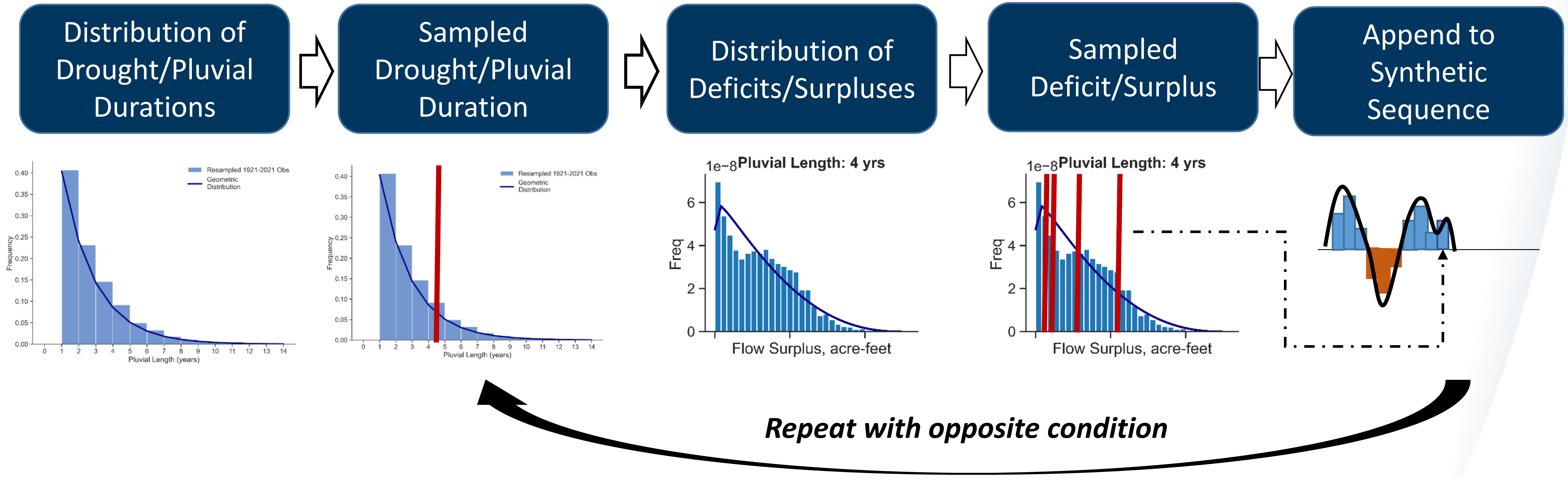


Fig. 1. Drought characteristics using the run theory for a given threshold level.

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(1), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

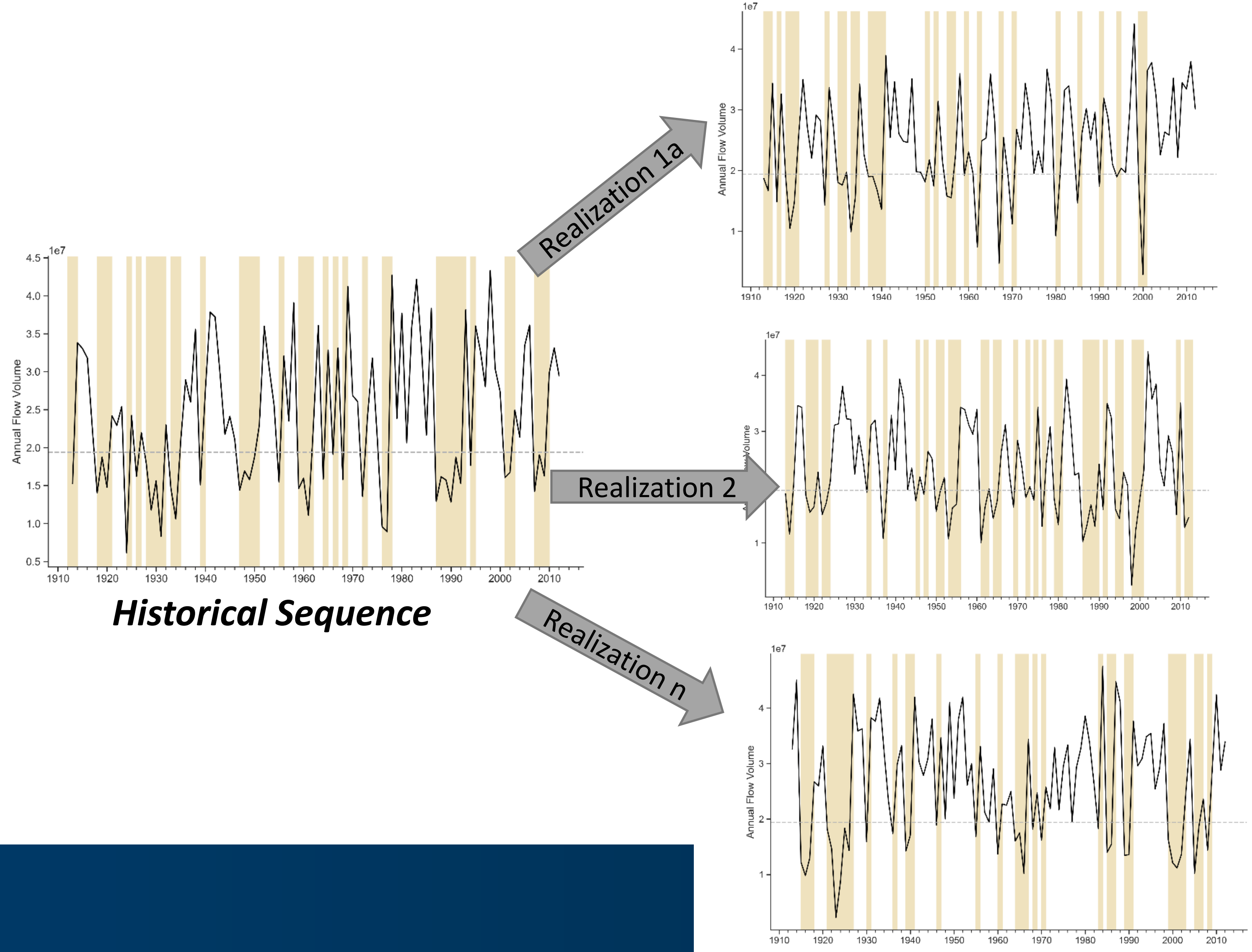
Drought Characterization & Synthesis: Applying Method



Drought Characterization & Synthesis

Result:

- Unique sequence of annual streamflow values
- Wet and dry years no longer occur in same ord
- Each sequence (realization) equally plausible, conditional on the annual historical dataset



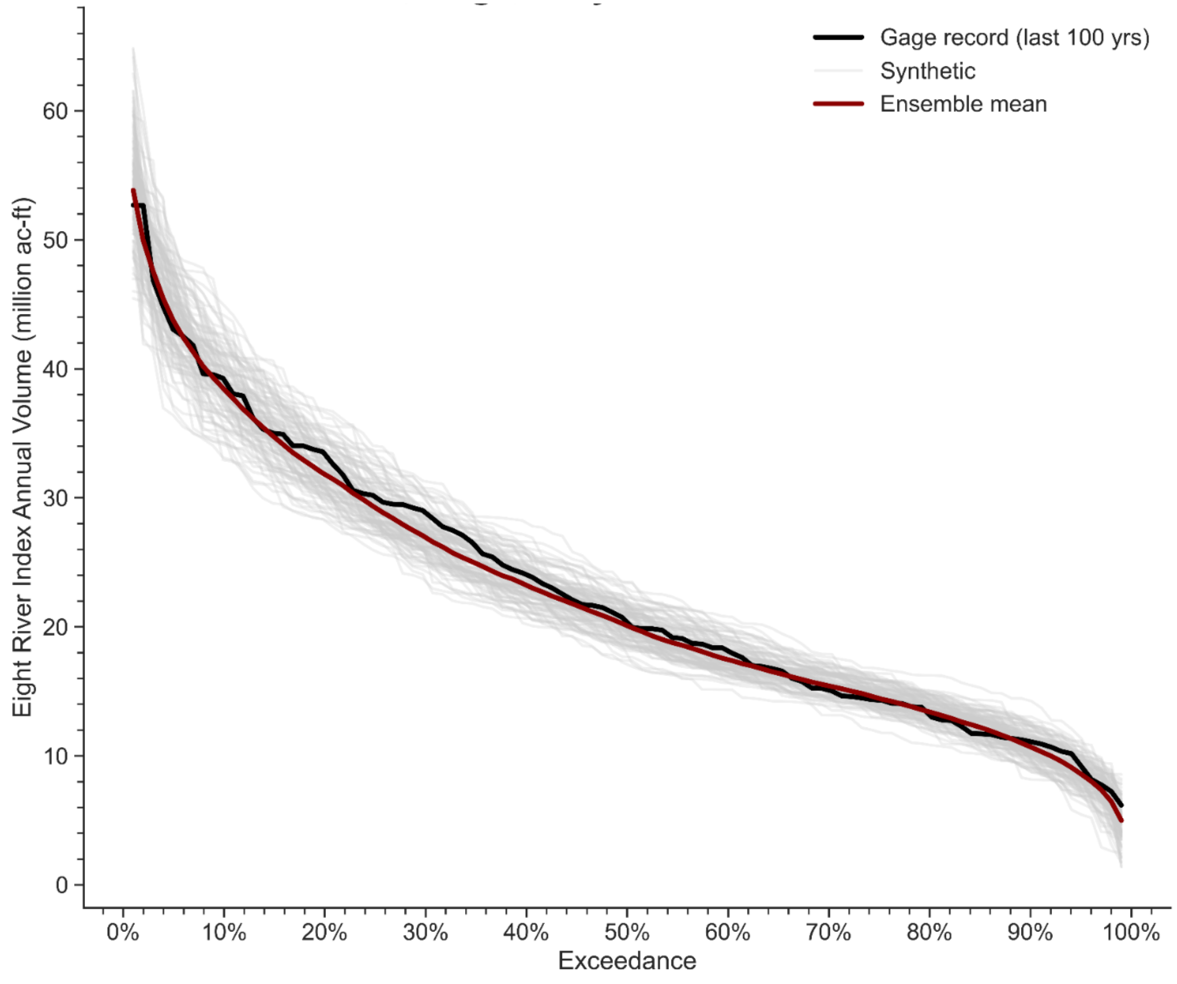
UC SANTA CRUZ

Drought Characterization & Synthesis

Result:

- Generating 100-realization ensemble of annual 8-river flow volume
- Synthetic ensemble mean converges toward source data (**gage record shown**)
- Ensemble includes variation at all exceedance levels

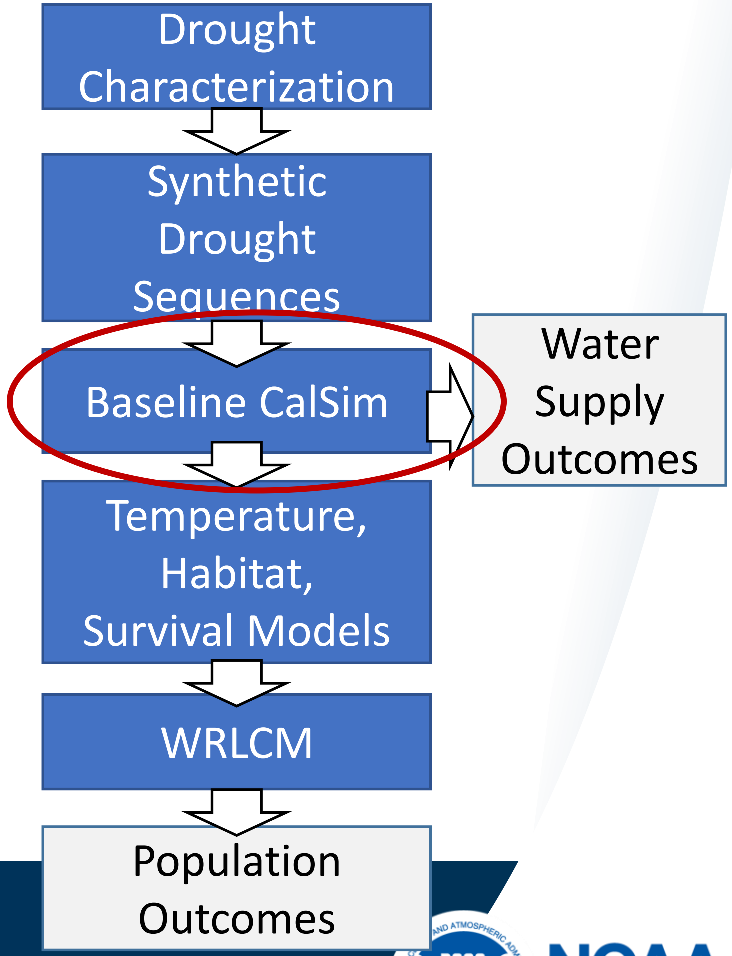
Annual 8-River Volume Exceedance: Gage & Synthetic Realizations



Analytical Framework: CalSim3 and the Winter-Run Lifecycle Model (WRLCM)

- **Phase I: Drought Synthesis & Assessment**
  - Characterize historical droughts
  - Generate drought sequences
  - **Create corresponding CalSim3 input datasets**
  - **Run Baseline CalSim for each sequence**

  - Run “downstream” component models
  - Run WRLCM
  - Evaluate baseline salmon response to drought



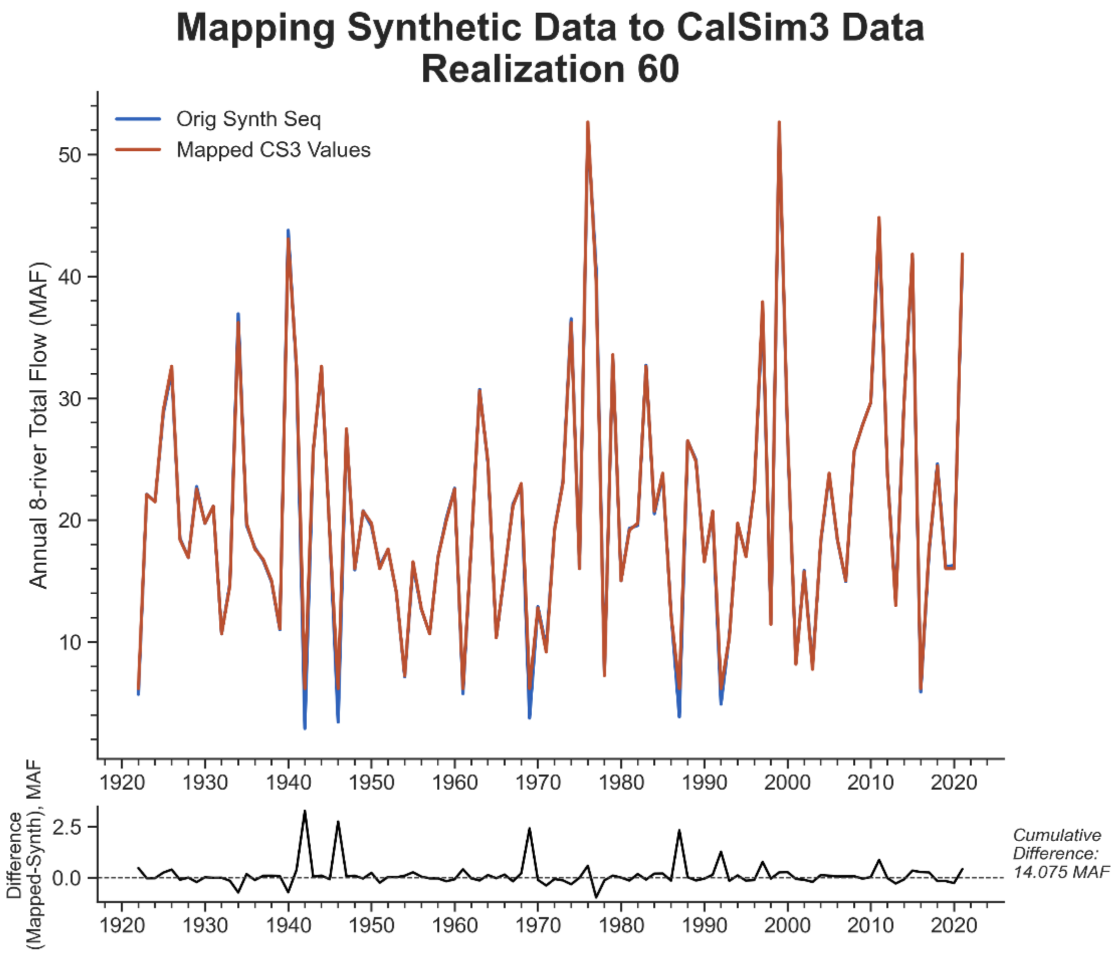
UC SANTA CRUZ

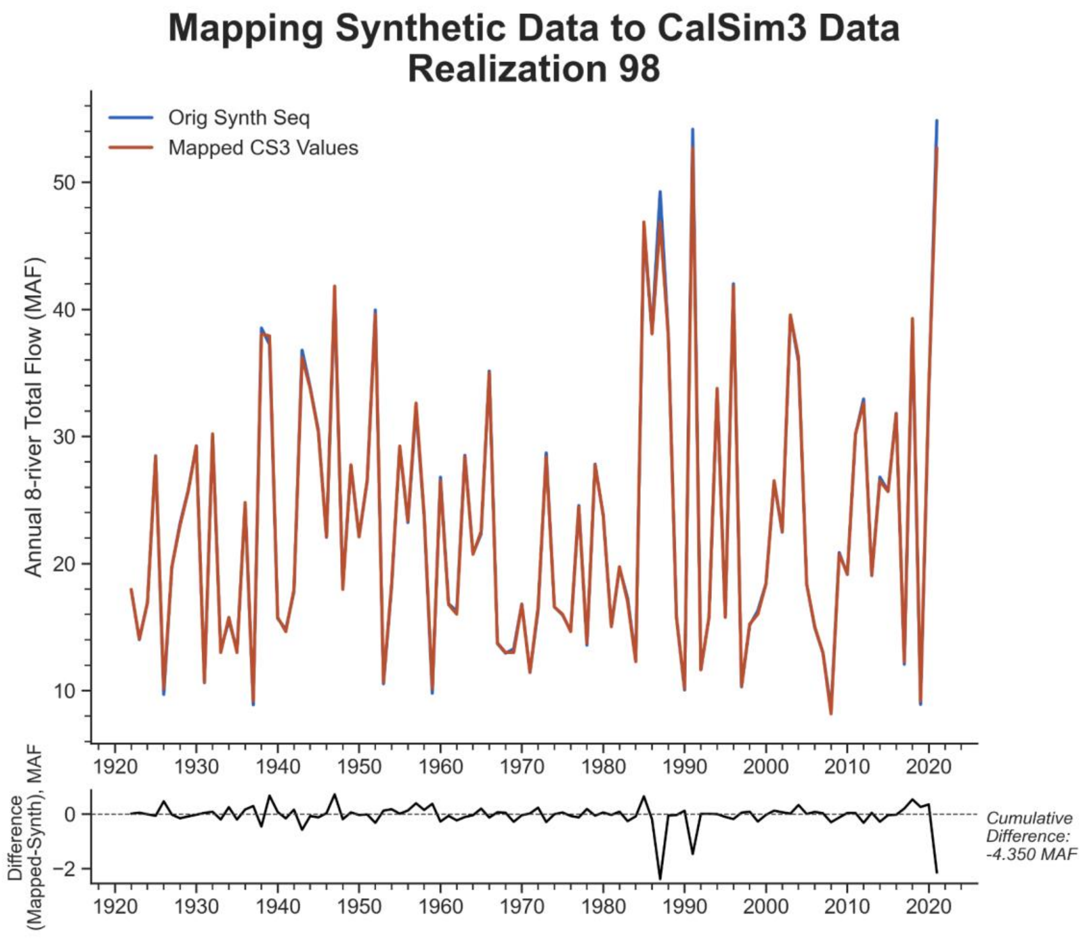
NOAA FISHERIES

Generated flow ensemble & CalSim3

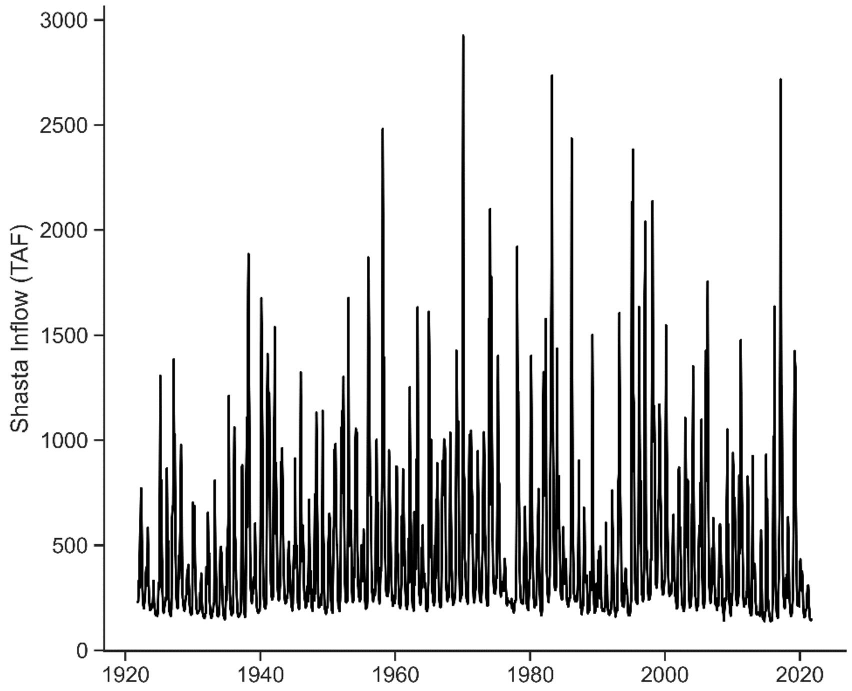
- Generated 8-river annual flow alone is not sufficient for running CalSim3
- Need to translate generated annual flow sequences into CalSim3 input files
- Solution: bootstrap resampling of existing CalSim3 input datasets
  - Select WY from CalSim3 input dataset with 8-river index total that best matches the generated drought value
  - Append selected WY to new CalSim3-compatible input dataset
- Method is simple and ensures completeness, but also prevents any year from being drier/wetter than the driest/wettest in the base record

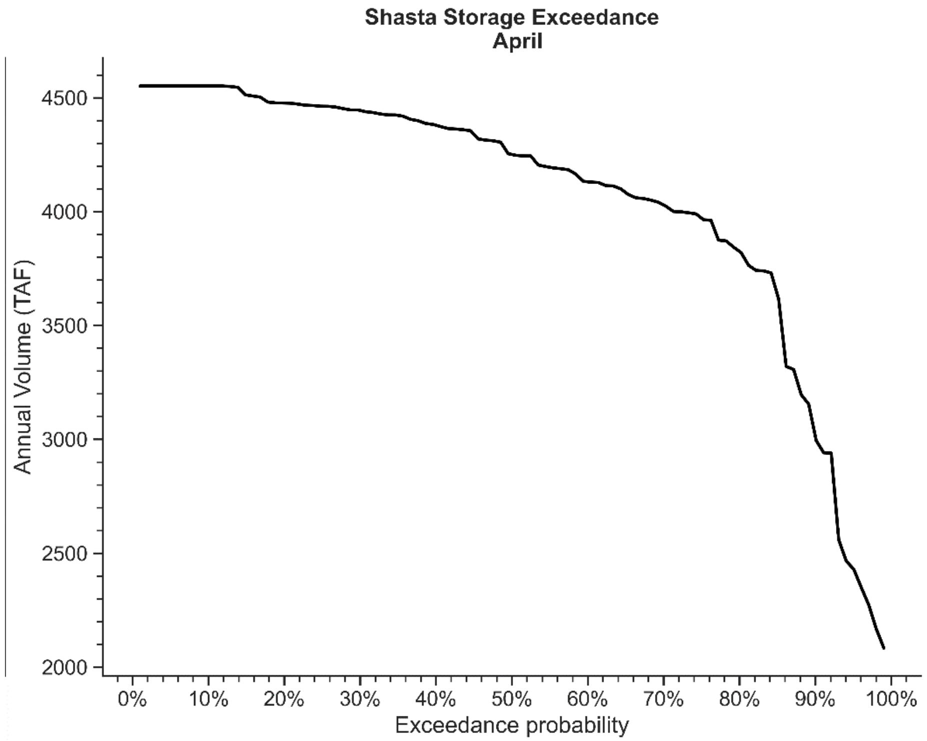
Example drought sequence – bootstrap resampled timeseries





CalSim3 – Ensemble Output



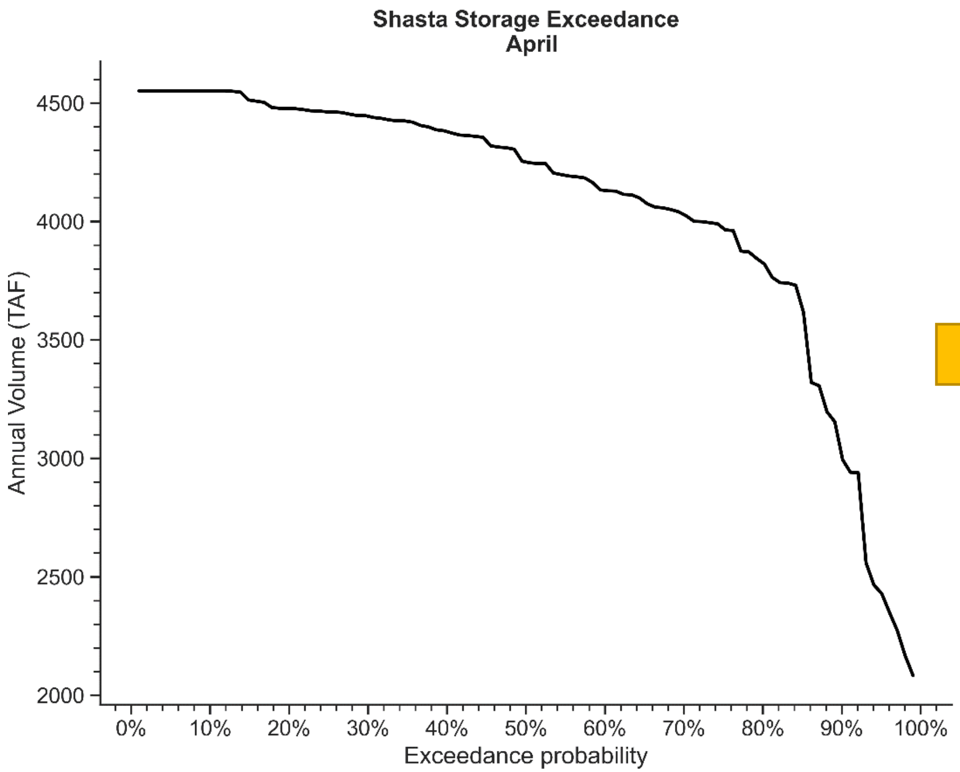


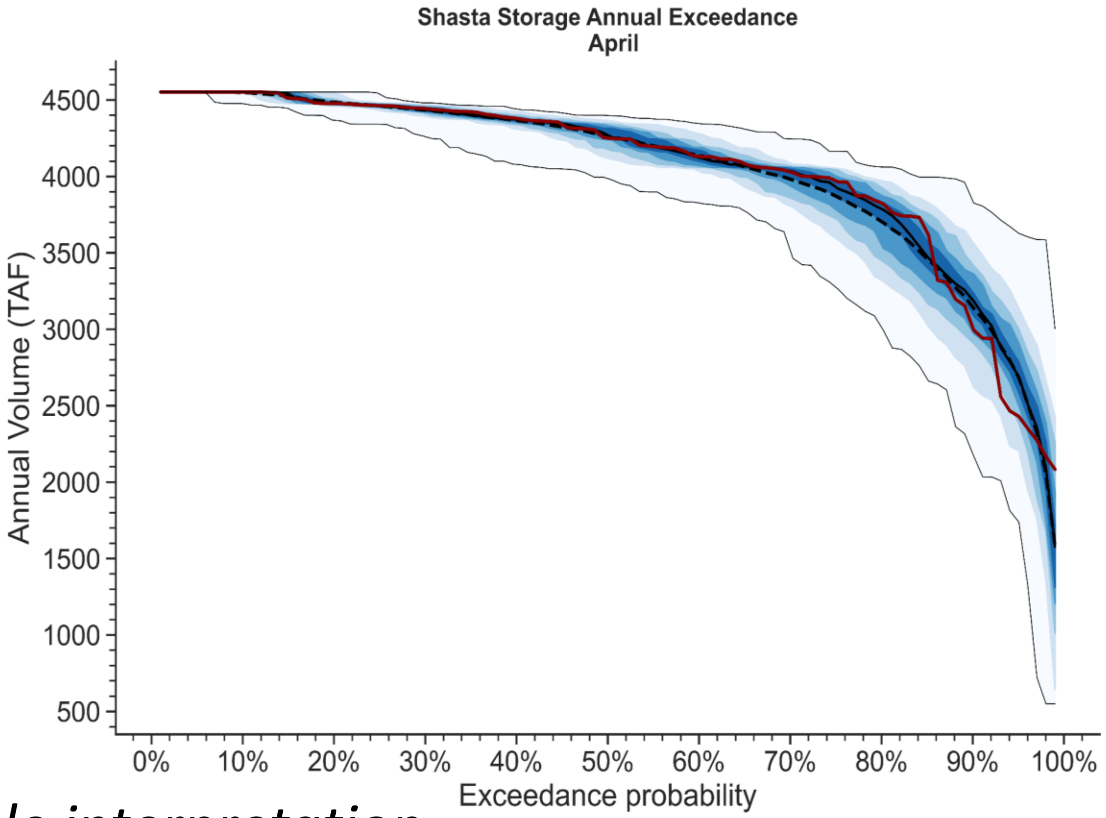
Conventional single-scenario interpretation….

UC SANTA CRUZ

NOAA FISHERIES

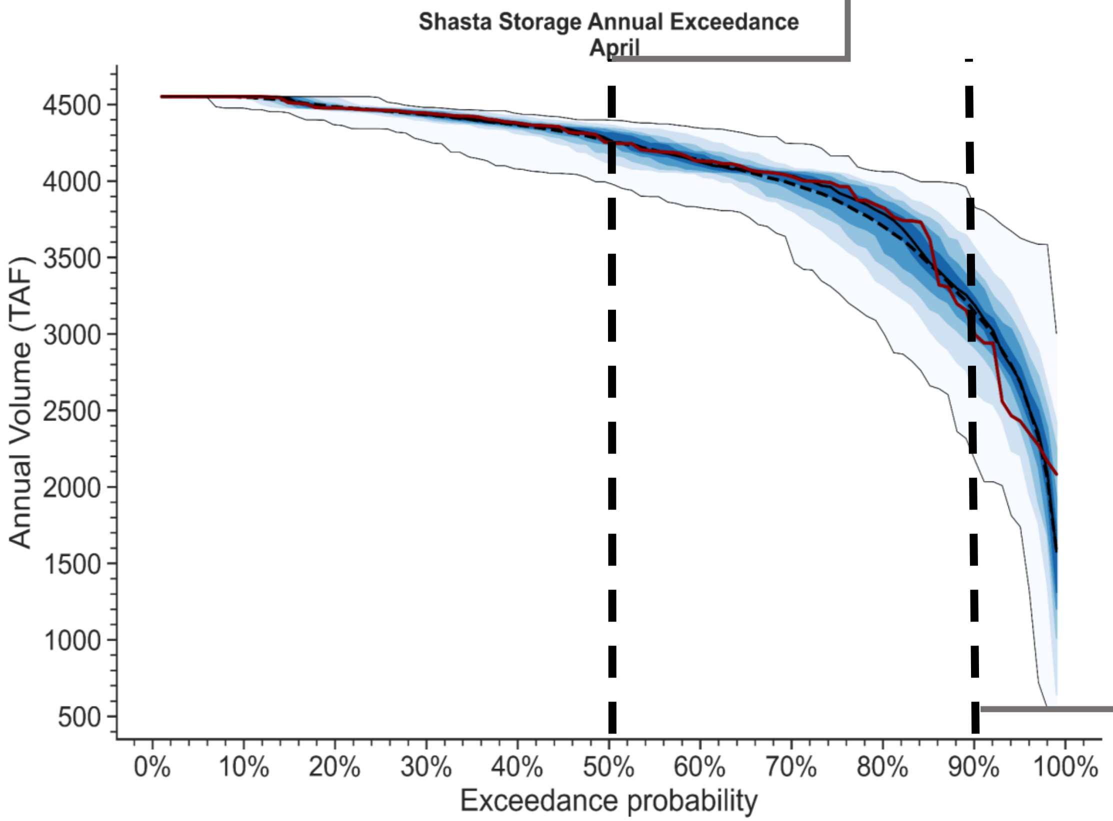
CalSim3 – Ensemble Output

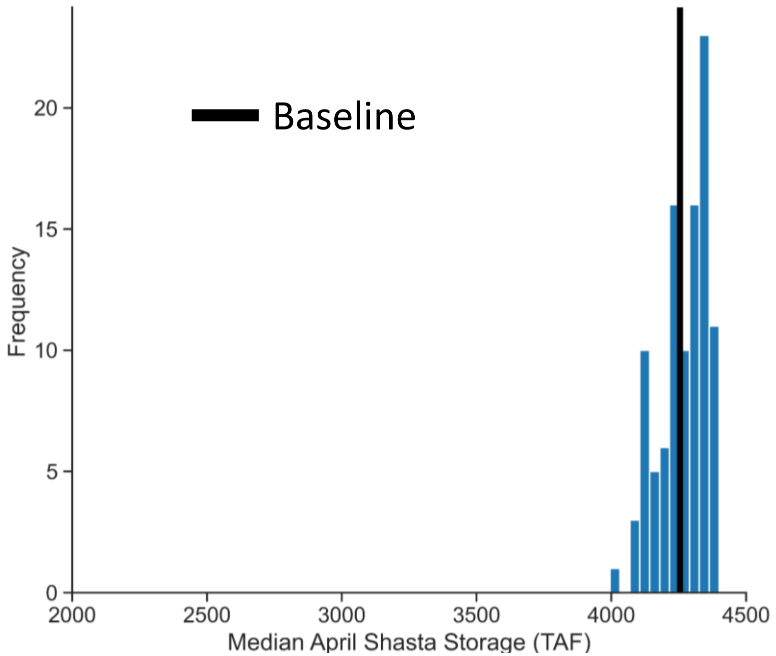


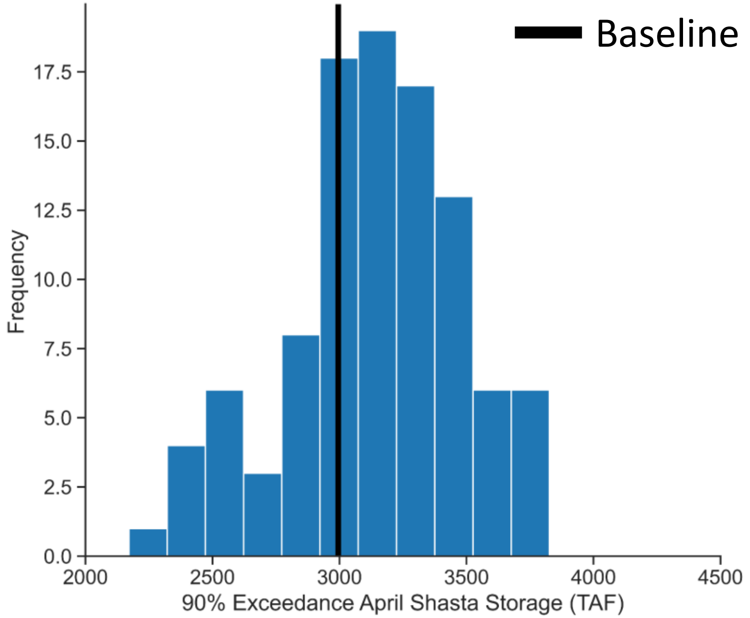


…and an expanded ensemble interpretation

CalSim3 – Interpreting Ensemble Output



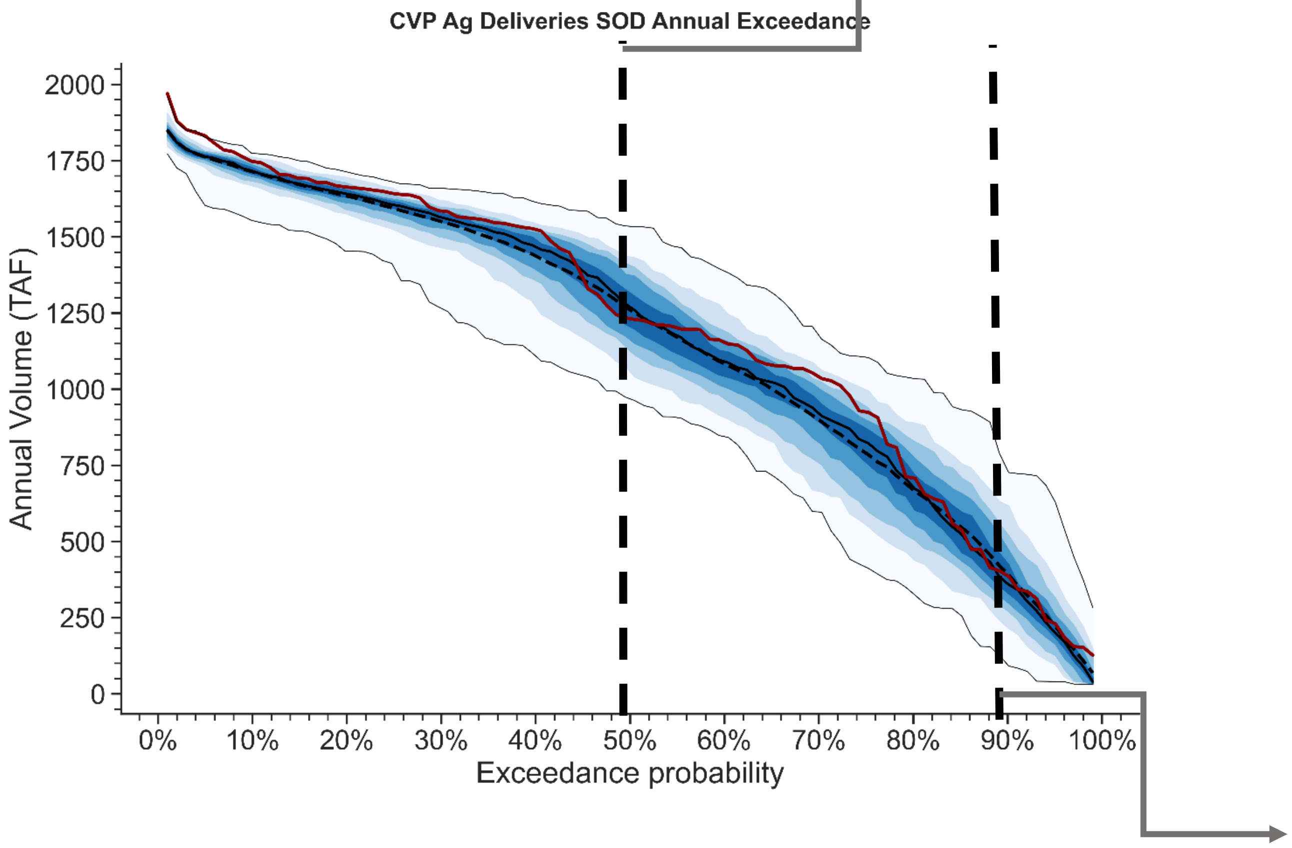


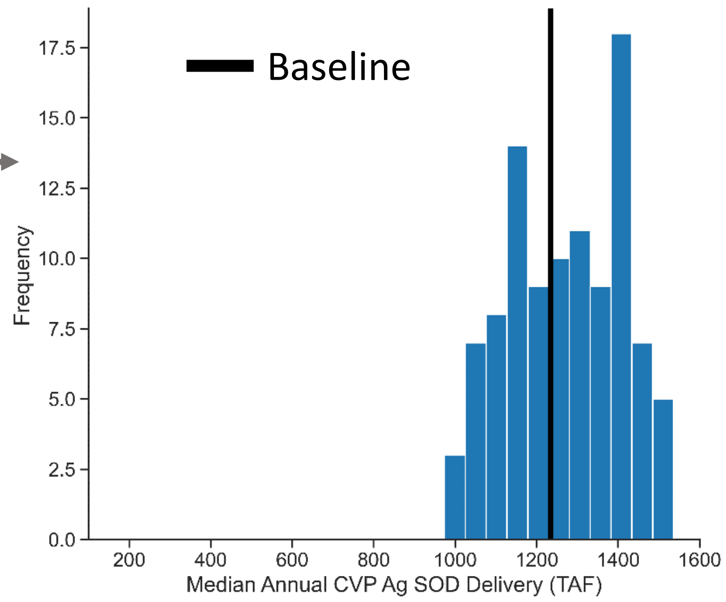


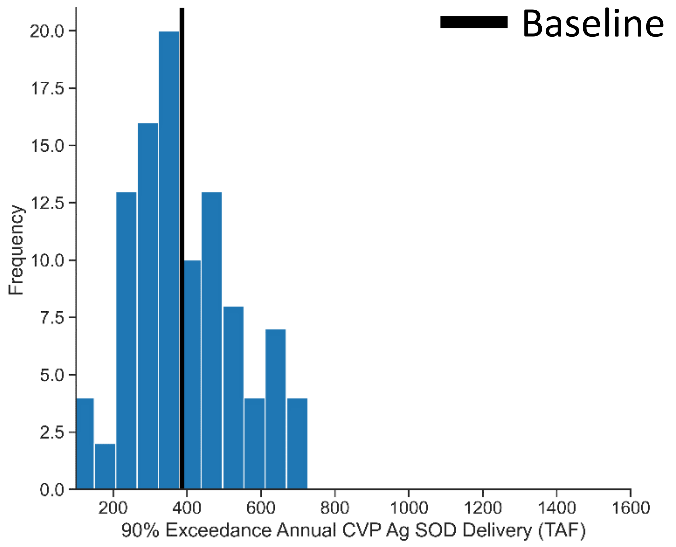
Distribution around values at select exceedance levels indicates how much the sequence variation affects the outcome

Examples shown – 50% exceedance (median) values are less variable across hydrologic ensemble than 90% exceedance

CalSim3 – Interpreting Ensemble Output







Distribution around values at select exceedance levels indicates how much the sequence variation affects the outcome

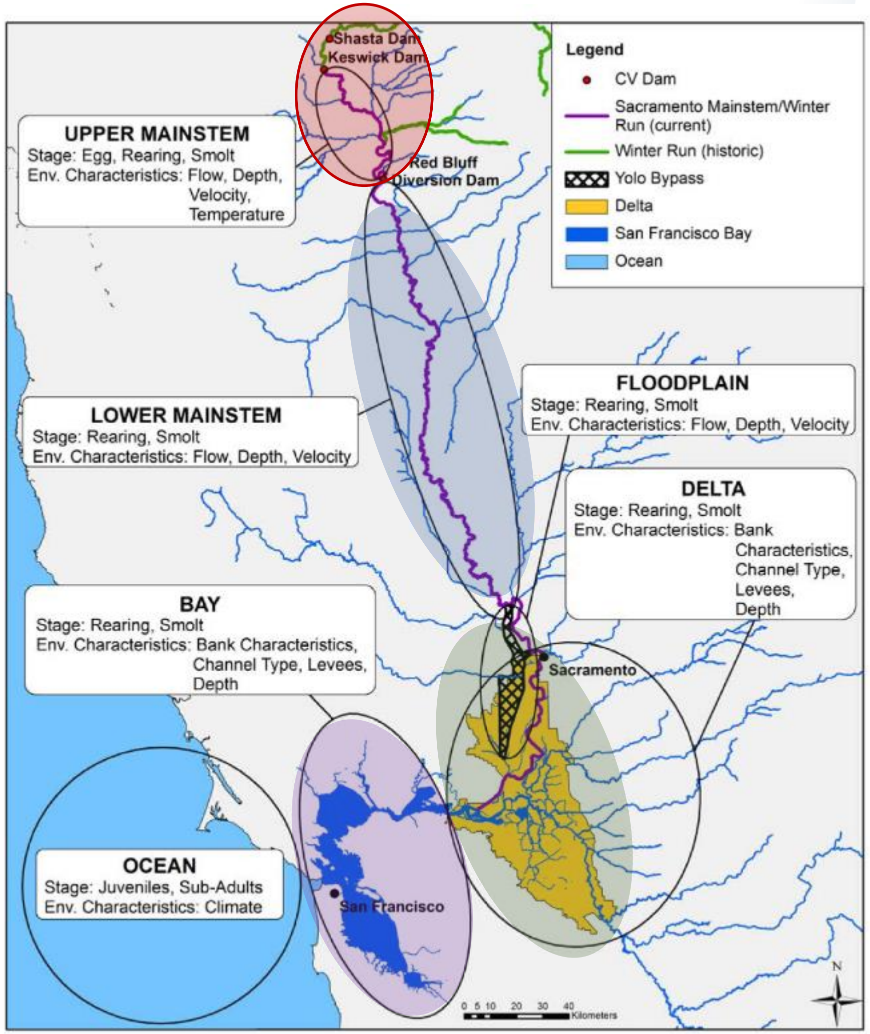
Examples shown – 50% exceedance (median) and 90% exceedance values have roughly the same variability

UC SANTA CRUZ

NOAA FISHERIES

Connecting CalSim3 Results to Salmon Outcomes

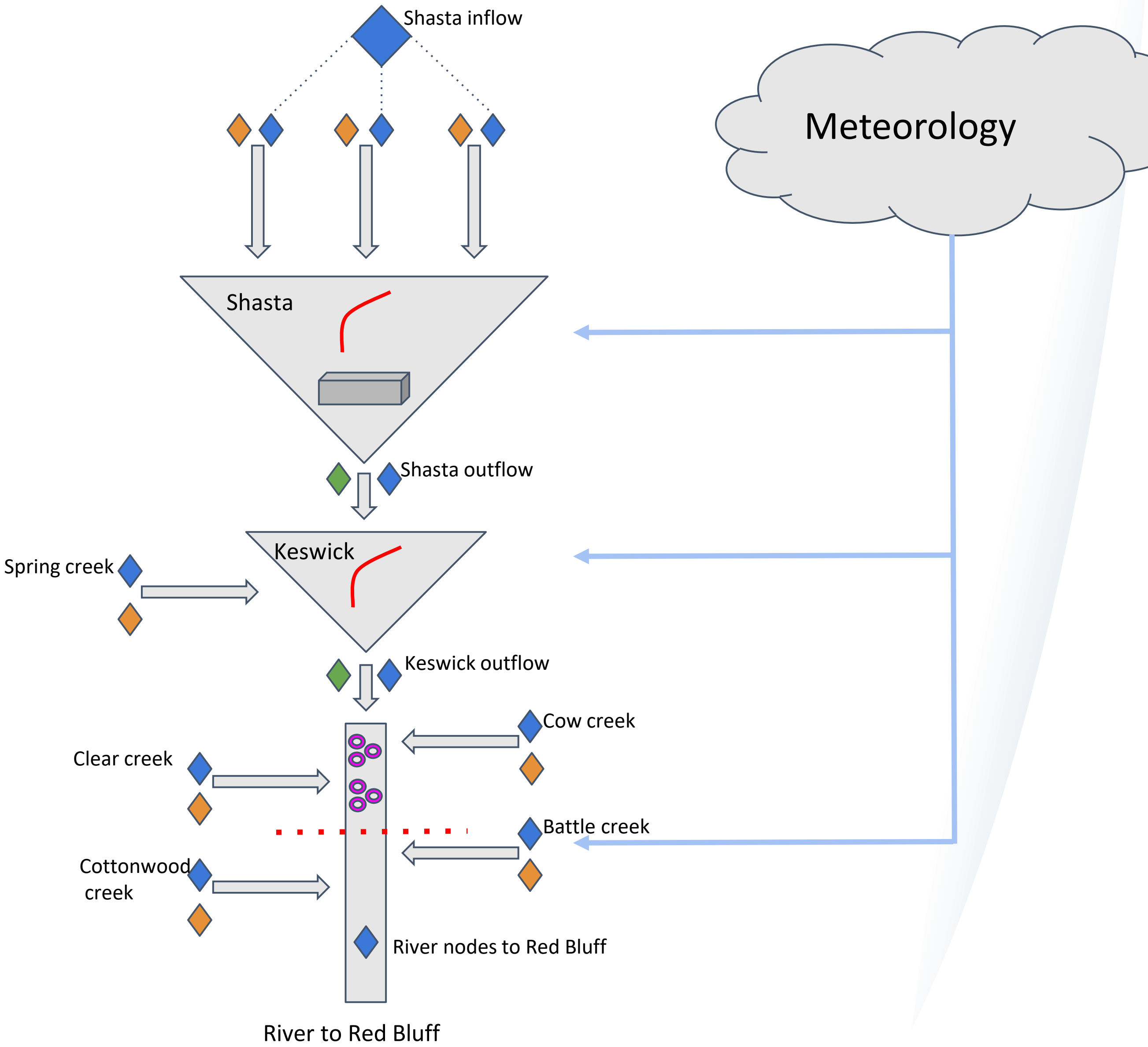
- Different parts of the CalSim3 domain inform different aspects of the Winter Run lifecycle
  - Shasta-Keswick-Upper Sacramento River → Early life stage
  - Mainstem Sacramento River & Yolo Bypass → Rearing
  - Delta & Bay → Rearing & Outmigration
- Each component requires translation of CalSim3 output to



Translating CalSim3 Outputs & Creating Reservoir Temperature Model Inputs

LEGEND

- Flow from CalSim
- Water Temperature - Inputs
- Temperature
  - Simulate w/ model
- Redd (space and time distribution)
- Temperature distribution (initial condition)
- Dam (TCD) Operations
- Meteorology
- Temperature target



Creating Temperature Model Inputs

- Challenge 1: Monthly CalSim3 → Temperature model daily/subdaily resolution
- Challenge 2: Temperature models require multiple variable inputs that are not part of CalSim3 datasets
- Solution:
  - Resample by month from recent daily/hourly observational record used to create temperature model datasets
  - Condition resampling on monthly Shasta inflow inputs from CalSim3
  - Adjust daily inflow volumes to match CalSim3 monthly totals

Water Temperature Modeling Considerations

- Shasta & Keswick releases set by CalSim3 results, but Shasta TCD operations are *not*
- How best to represent temperature management given storage and release time series?
  - Target temperature & location in upper Sacramento River below Keswick
  - **Targets dependent on spring conditions (Shasta tier frameworks from recent LTO consultations)?**
  - An optimization approach to minimize temperature dependent mortality or temperatures above a threshold?

Next Steps

- Reservoir temperature modeling is ongoing
- Data from CalSim3 has been translated to inputs to other WRLCM sub-models as well
  - River and Delta habitats
  - DSM2 -> ePTM -> Delta survival
- Combine sub-model outputs into complete WRLCM inputs & run for each
- Evaluate Winter Run population changes under the full ensemble

Final points

- Wet and dry periods of the last 100 years will not occur in the same sequence or intensity in the next 100 years
  - This might matter for how we evaluate effects to salmon
- We can generate ensembles of re-sequenced hydrology with plausible droughts that vary in duration, frequency, and intensity from the historical record
- Results give us a measure of uncertainty that arises from different sequences & intensity of drought that could occur
  - For water resources outcomes, this might be a distribution rather than a single number for a performance metric
- Ongoing work will bring together all of the model components to evaluate Winter Run population outcomes – stay tuned!

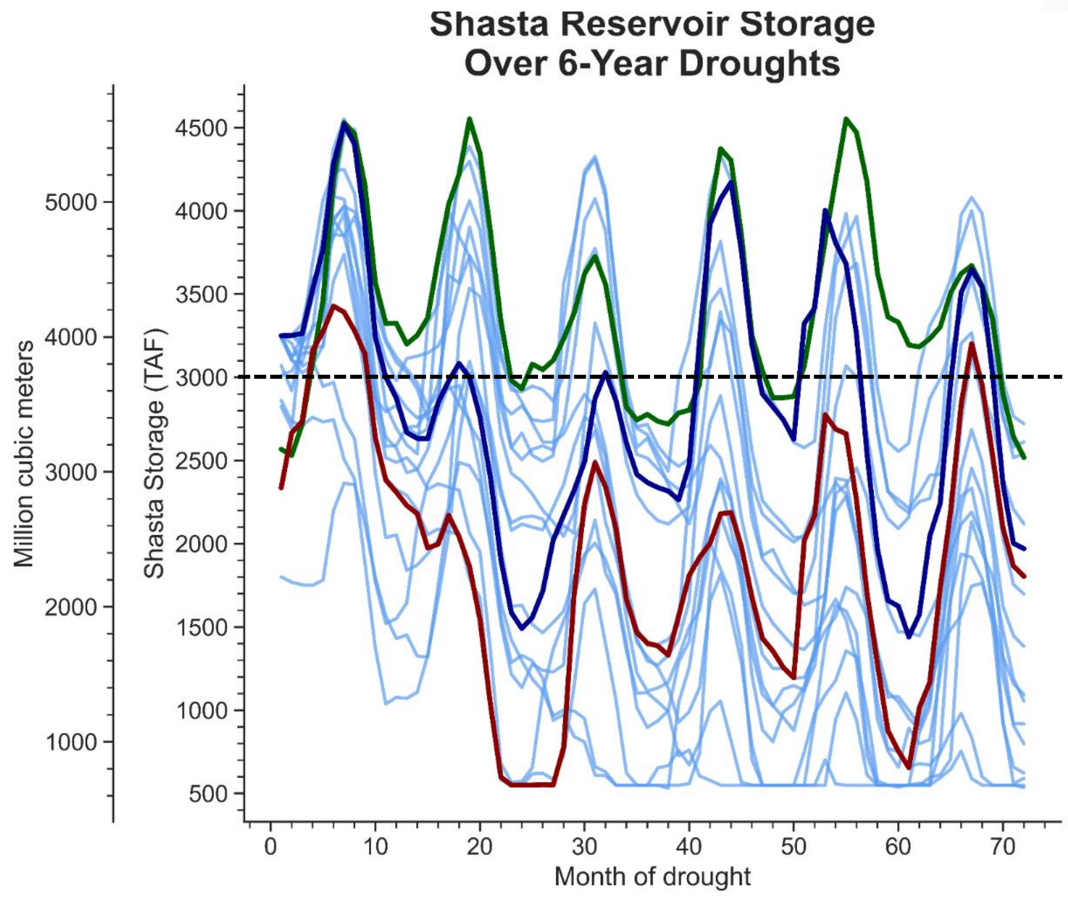
Questions?

james.gilbert@ucsc.edu

Photo credit: NOAA Fisheries

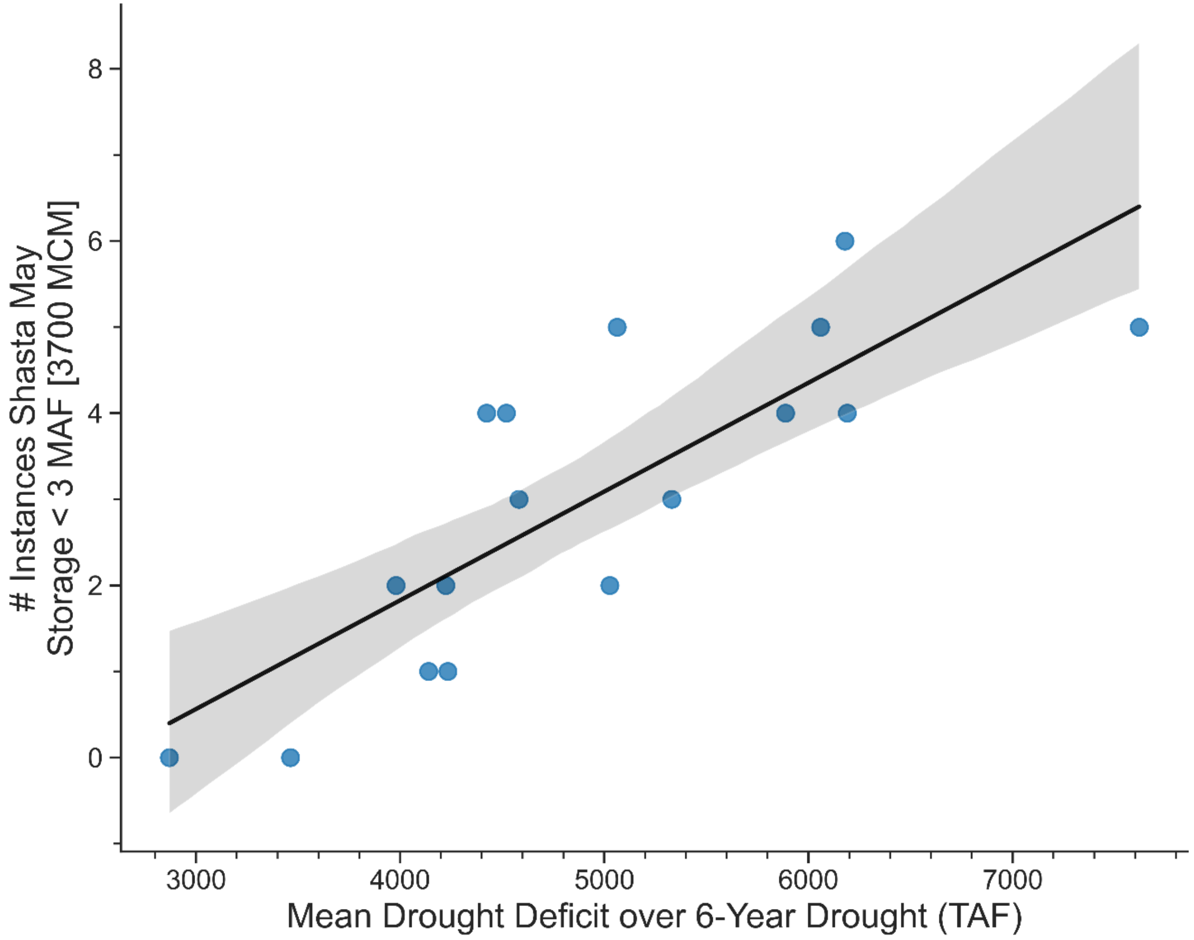
Shasta Reservoir storage affects salmon early life stage survival

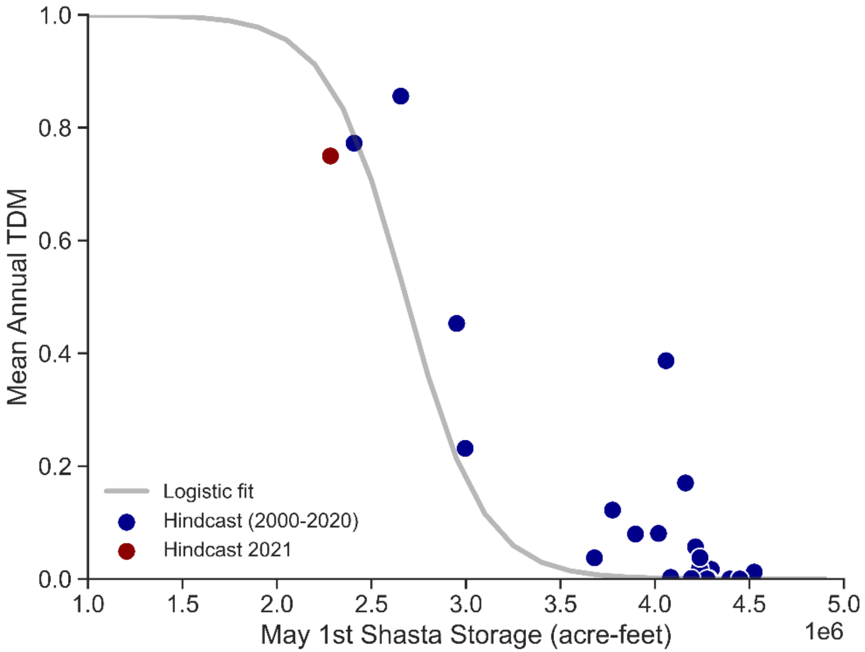
- Shasta reservoir conditions and summer releases determine water temperatures in Sacramento River, where Winter Run spawn
- Shasta storage < 3 MAF in May is associated with an increase in temperature related mortality of eggs
- Multiple years of low storage increase risk to Winter Run population



Reservoir storage affects salmon early life stage survival

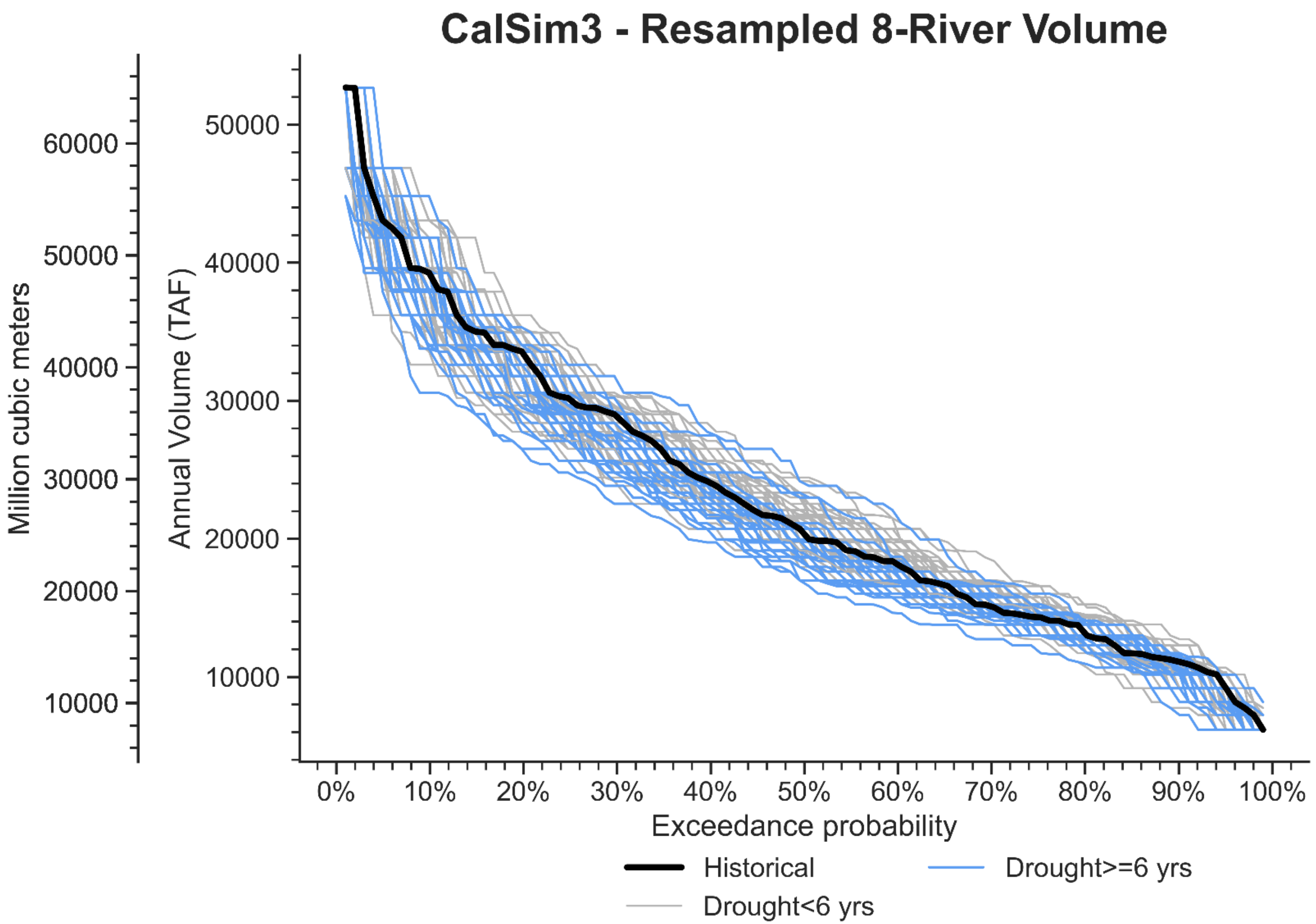
- Frequency of May storage below 3 MAF during a 6-year drought is directly correlated with average drought intensity (average deficit/year)
- Provides a heuristic by which to judge risk in future projections
  - More detailed early life stage modeling still needed for a more accurate picture!





1.0
0.8
0.6
0.4
0.2
0.0
Mean Annual TDM
Logistic fit
Hindcast (2000-2020)
Hindcast 2021
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
1e6
May 1st Shasta Storage (acre-feet)

Droughts of at least 6 years occur in many realizations



Out of *n=100* 100-year realizations,

28 have at least one drought lasting 6 years or longer

Most are drier than the historical record, but several are wetter

Drought Characterization & Synthesis: Data

- Comparing **paleohydrology** and **gage records**
- Gage data has higher skew & variance (tends drier, but has wetter extremes)
- Paleo record does have a few drier years