Large Spatial Scale Water Temperature Modeling – Range-wide Application to the Sierra Nevada

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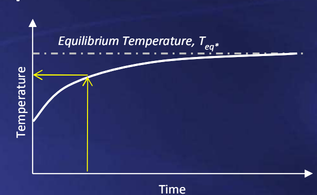
Objective

- Develop a Sierra Nevada-scale water temperature model with the following capabilities:
  - Assess implications of climate change under unimpaired and an impaired hydrologic settings
  - Encompass a large spatial area (western slope of the Sierra Nevada)
  - Provide sufficient temporal resolution to describe sub-monthly water temperature response

Approach: Dynamic Equilibrium Water Temperature Modeling

- Theoretical Equilibrium Water Temperature (T_{eq})



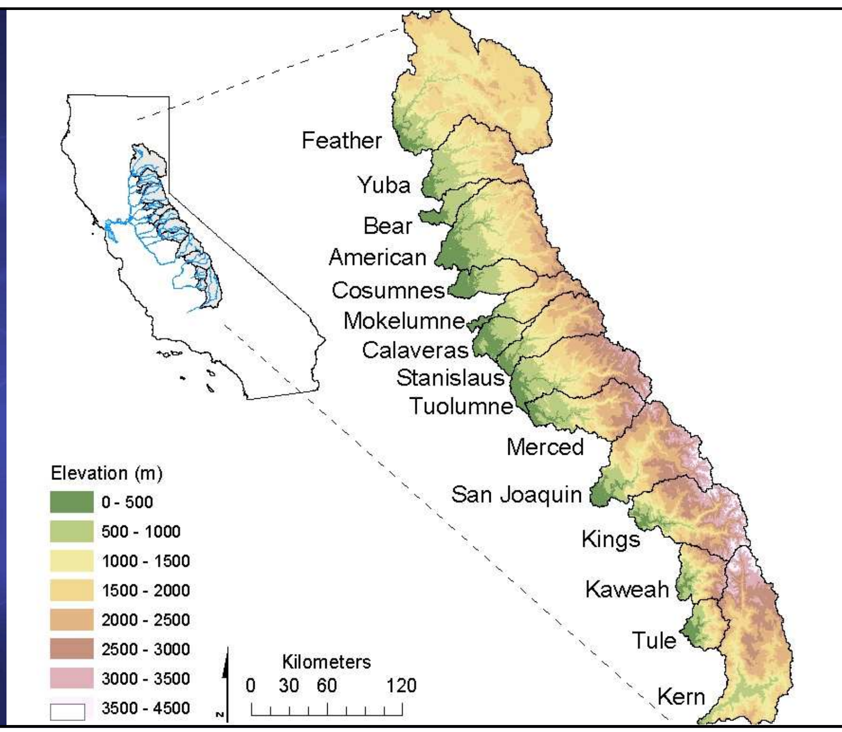
$$Q_n = Q_s + Q_{la} - Q_{lt} - Q_e + Q_{bed}$$

- Dynamic Equilibrium Water Temperature (T_{eq*})

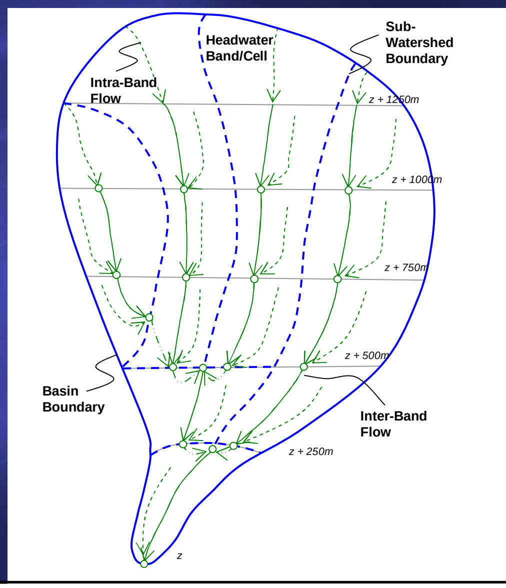
$$\frac{dT}{dt} = \frac{Q_n A}{C_p \rho V}$$

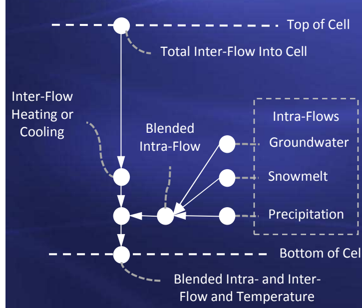
Conceptual Model

- Using T_{eq} concept, track water in individual reaches from the Sierra Nevada crest to the Central Valley
- "Map" the history of this as:
  - Parcels seek T_{eq} in respond to local meteorological conditions (elevation bands or cells)
  - Adjust water temperature in response to deviations from T_{eq} (e.g., snowmelt, colder or warmer tributaries, groundwater contributions)



Representative Watershed





Model Details

- Model Δt: weekly average
- Model Δz: 250 m (820 ft) elevation bands
- Model Δx and Δy: reach lengths from GIS
- Input Data:
  - Flow data derived from WEAP (weekly)
  - Meteorological data from DAYMET (weekly)
  - Temperature boundary conditions
    - 1°C at snowline
    - Groundwater (user specified, 7°C)
    - Otherwise local equilibrium temperature (air temperature)
  - Spatial data developed from GIS maps & WEAP schematics

Model Outputs

- User can select which outputs to print
  - Intra- (within cell) and inter- (between cell) flow and temperature
  - Equilibrium water temperature (T_{eq^*}) for each cell
  - Groundwater, snowmelt, and precipitation flow and temperatures for each cell (if applicable)
  - Wet bulb temperature
  - Echoed input values

Limitations

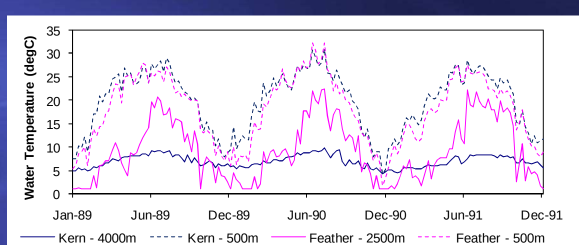
- Simplified representation of channel/stream
  - Uniform velocity (single value)
  - Uniform area/volume/depth relationship coefficients for all basins ($d = aQ^b$)
  - Lumped stream lengths
- Snow coverage
  - Complete or none, but no partial coverage

Preliminary Application

- Based on output from a WEAP model of the Sierra Nevada
  - Unimpaired hydrology (no infrastructure)
  - 20 water years (WY1981 - WY2001), weekly
  - 15 river basins (Feather, Yuba, Bear, American, Cosumnes, Mokelumne, Calaveras, Stanislaus, Tuolumne, Merced, San Joaquin, Kings, Kaweah, Tule, and Kern)

Multi-Basin

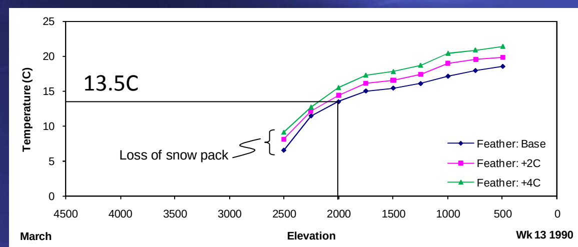
- Feather and Kern Rivers are the northern and southern-most basins (respectively) included
- Higher elevations tend to have more constant temperatures whereas lower elevations vary more during the year



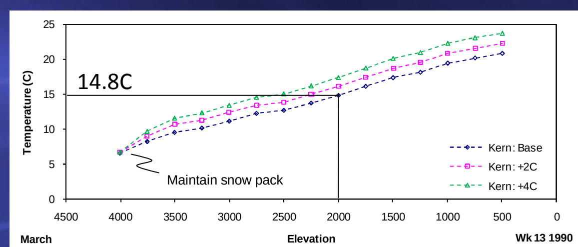
Unimpaired

Feather & Kern Comparison

- Feather
  Unimpaired



- Kern
  Unimpaired



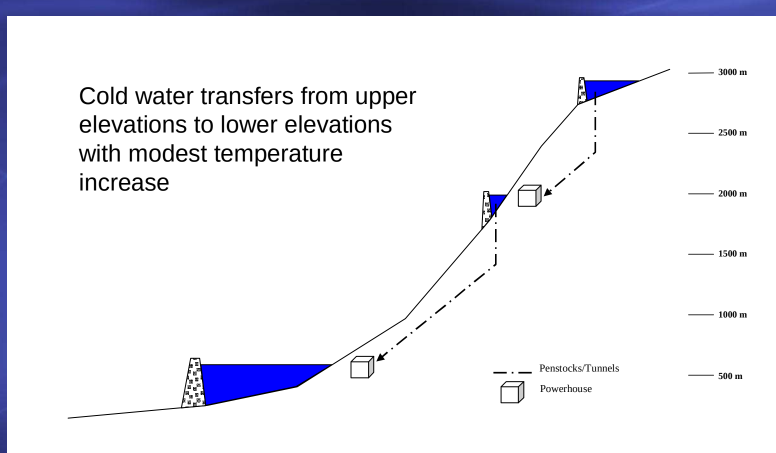
General Observations

- Higher elevations experience less seasonal variability in temperature
- Generally cooler in the Northern Sierra than in the Southern Sierra (for same elevation band)
- Loss of snow pack evident at lower elevations
- Increased air temperature results in increased water temperature
- Equilibrium temperature is a function of elevation, latitude, and flow and will be impacted by climate change

Current Work

- Implementation of infrastructure and operations
  - Reservoirs (large and small)
  - Conveyance facilities (canals and tunnels)
  - Operations
- Calibration
- Testing under impaired hydrology
- Application

Impact of Facility Elevations on Water Temperature



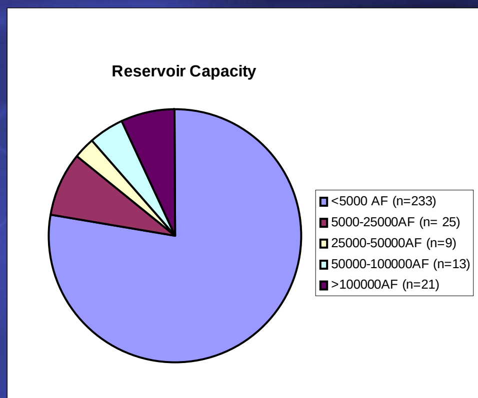
Facilities Representation

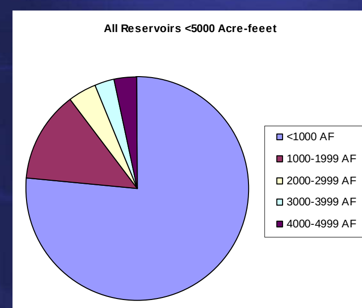
- Reservoir Depth Considerations
  - Seasonal stratification vs. weak intermittent
- Reservoir Volume Considerations
  - Impact on heat loading within reach
  - Moderation of diurnal range (daily maximum)
- Infrastructure
  - Influence of tunnels
  - Outlet works

Reservoir Information

- Data for 379 dams (above 250m)
- Basic Statistics (name, number, ID, owner, type, stream)
- Physical information (Capacity, area, depth, drainage area, dam length/height)
- Stage-Area-Volume data (79 Reservoirs)
- Outlet works (elevation, capacity, stage-discharge information)

Reservoir Volumes in Project Area





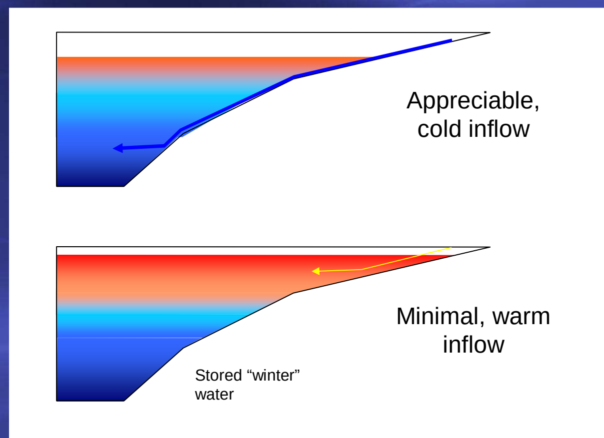
Reservoir Representation

- Small reservoirs
  - <5000 acre-feet
  - <10 meters in depths
  - “Inductors” represented as a function of residence time (volume/inflow rate)
- Large reservoirs
  - >5000 acre-feet
  - >10 meters in depth
  - Stratified conditions with evolving cold water volumes
    - Evacuation
    - Replenishment

Thermal Stratification – Seasonal Evolution

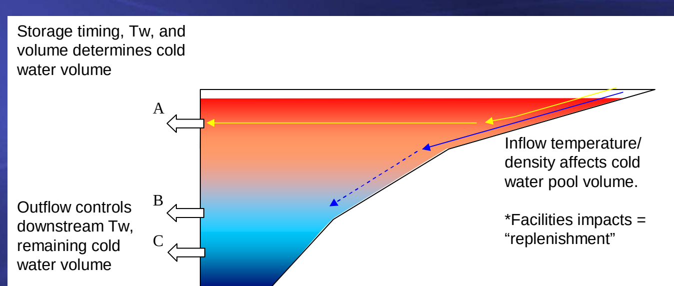
May 1

August 1

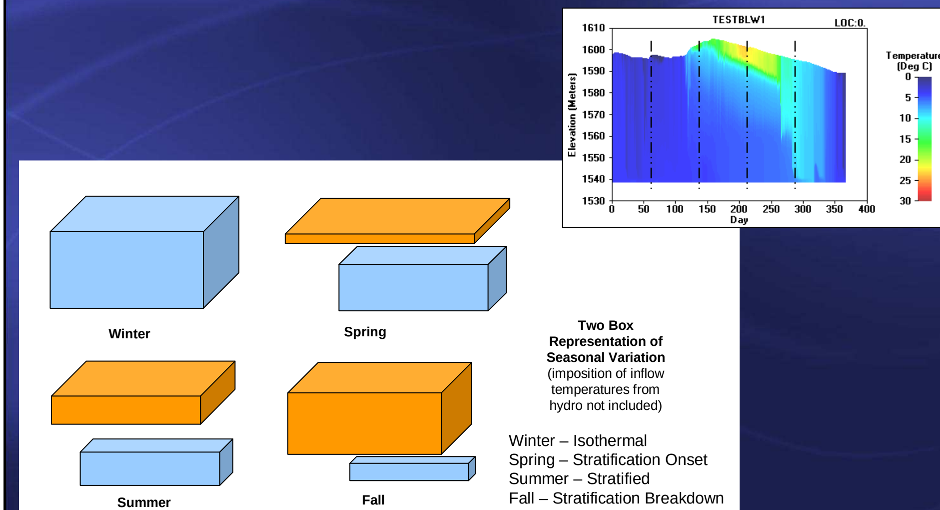


Inflow/Outflow Dynamics

- Winter, cold water management and stored volume
- Inflow temperature (from upstream band or facilities)
- Outflow temperature (low level – year round, upper level – only during spill)
- Selective withdrawal (will not be formally assessed, but the model will inform decision makers where such operations may be helpful by defining in-reservoir and downstream temperatures)



Two-Box Model for Stratified Water Bodies



Tunnel Heat Conduction

$$T_w^{n+1} = e^{-\frac{4h\Delta t}{\rho CpD}}(T_w^n - T_s^n) + T_s^n$$

Where,

- Δt = time step (sec)
- T_s = Outside/rock temperature (°C)
- D= Diameter (m)
- Cp = Specific heat of water (J kg^{-1} °C^{-1})
- ρ = density of water (kgm^{-3})
- h = Heat exchange coefficient (Wm^{-2} °C^{-1})
- n = time

$$h = \frac{0.023k}{R}\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

Where,

- k = thermal conductivity of water (Wm^{-1} °C^{-1})
- R = hydraulic radius (m)
- Re = Reynolds number
- Pr = Prandtl number

Outlet Works

- Lower Level
  - Hydropower intakes
  - River release facilities
- Upper Level
  - Regulated spill
  - Unregulated spill
- Outlet elevations and capacity modifications (gaming for capacity modification)

Future Work

- Develop and test reservoir model
- Develop and test infrastructure elements (e.g., tunnels)
- Implement reservoir and infrastructure logic in RTEMP
- Test and calibrate RTEMP model
- Refine model as appropriate

Conclusions

- Equilibrium temperature concepts provide an appropriate and useful basis for large scale, long-period simulations.
- Weekly, basin-scale temperature modeling provides a useful approach to assess thermal conditions throughout Sierra Nevada
- Additions of infrastructure and storage will allow the model to assess current conditions (vs. unimpaired)

Questions?

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Single Basin

- A preliminary application was developed for single test basin (Mokelumne River)
- Sub-watershed 12 (headwaters of mainstem)