Photo credit: John Hannon, Reclamation

Calibration, Validation, and Sensitivity Approach

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Model Calibration

- Model performance is dependent on the input data, algorithms, implementation, and parameters
- Adjusts model physics parameterization of algorithms to better agree with observed record
- Builds confidence that the physical processes are represented adequately
- Begin with the intent in mind
  - Use case is focused on water temperatures, calibration should focus on water temperatures

Mid-Term Peer Review Feedback (Part I)

- Focus on documenting and explaining model performance rather than model validation
- Improve visualization and presentation of the model calibration and performance, how and what scenarios. Highlight model performance during critical periods and model limitations
- Is incidental leakage observed through multilevel discharge structures, and if so, how are they modeled?
- Scenarios expected to cause the inability to meet Performance Measures
- Better evaluate performance of CE-QUAL-W2: how will use of average wind sheltering coefficients for CE-QUAL-W2 affect ability to forecast extreme events.

Mid-Term Peer Review Feedback (II)

- Identify data that are most consequential in terms of evaluating system performance
- More detail on the calibration process: Was calibration manual or automatic? What was the objective function of the calibration?
- Since there were multiple performance metrics, how were they used in the calibration?
- Discuss situations when the model does not perform well in more detail. "This parameterization performs well for the majority of other simulated summer-fall periods" - could potentially be a serious problem.

Quantitative Metrics

- Metrics
  - Mean bias
  - Mean absolute error (MAE)
  - Root mean square error (RMSE)
  - Nash-Sutcliffe efficiency (NSE)
- Performance thresholds

$$\epsilon = \frac{1}{n}\sum_{i=1}^{n}\left(X_{sim,i} - X_{meas,i}\right)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|X_{sim,i} - X_{meas,i}\right|$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{\mathrm{sim,i}} - X_{meas,i}\right)^2}{n}}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(X_{sim,i} - X_{meas,i}\right)^2}{\sum_{i=1}^{n}\left(X_{sim,i} - \overline{X_{meas,i}}\right)^2}$$

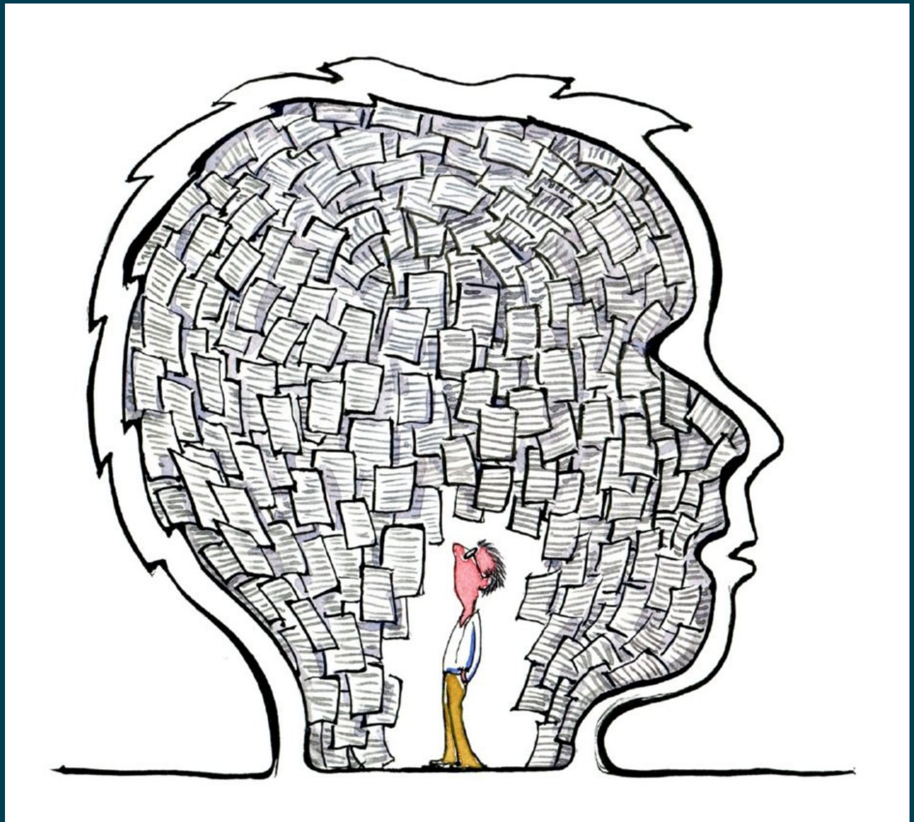
Parameter	Mean Bias	MAE	RMSE	NSE
Stage	±0.5 ft (0.15 m)	≤1.0 ft (0.3 m)	≤1.5 ft (0.45 m)	≥0.65
Flow	±50 cfs (1.4 cms)	≤150 cfs (4.2 cms)	≤500 cfs (14.2 cms)	≥0.65
Water Temperature	±0.75°C	≤1.0°C	≤1.5°C	≥0.65

System Attributes

- Different systems require different performance assessment
- Range of hydrology, operations, meteorology, and temperature
- All years of available data

System	Focused Attributes	Calibration Approach	Examples
Large Reservoir	Long residence time, persistent seasonal stratification	Match thermal profile and outflow temperature	Shasta, Trinity, Folsom, New Melones
Medium Reservoir	Long residence time, upstream influence, persistent stratification	Match thermal profile and outflow temperature	Whiskeytown, Tulloch
Small Reservoir	Short residence time, upstream influence, intermittent stratification	Match outflow temperature (profile secondary)	Keswick, Lewiston, Natoma
River	Short residence time, upstream influence, meteorology response	Match diurnal range and mean daily temperature (longitudinal heating)	Sacramento, Trinity, American, Stanislaus

Qualitative Metrics



Source: Wikimedia Commons

- Graphical plots to visually compare simulated and observed values
- Captures features difficult to convey in statistical alone
  - Magnitude/phase
  - Short/long term response
- Provides context for statistics
  - Some metrics are overly sensitive some circumstances

Summary of Model Calibration Data

- The right table summarizes the availability/quality of data by model and by system/element.
- Observed effects of data limitations on model calibration results in the Stanislaus River system

System/Element	CE-QUAL-W2	HEC-ResSim
Lake Shasta	Good	Good
Keswick Reservoir	Good	Good
Sacramento River	n/a	Good
Whiskeytown Lake	Good	Good
Clear Creek	n/a	Good
Trinity Lake	Good	Good
Lewiston Lake	Good	Good
Trinity River	n/a	Good
Folsom Lake	Good	Good
Lake Natoma	Good	Good
American River	n/a	Good
New Melones Lake	Fair/Good	Fair/Good
Tulloch Lake	Fair/Good	Fair/Good
Stanislaus River	n/a	Fair/Good

LEGEND Good Fair Poor

Manual versus Automated Calibration

- Manual calibration: Human actively involved making qualitative judgments about model parameterization changes
- Automated calibration: Human creates quantitative objective function representing qualitative tradeoffs that an algorithm uses for model parameterization changes

- Either approach can yield satisfactory model performance
- Prefer manual when objective function is difficult to construct
- Use initial feedback to build toward quantitative calibration

BUREAU OF RECLAMATION

CE-QUAL-W2 Calibration

Shasta Calibration Parameters

Parameter	Default	Shasta Lake	Keswick Reservoir	Description
DLTMIN	NA	0.40-1.00	1.00	Minimum time step, sec
DLTMAX	NA	360-3,600	Variable	Maximum time step, sec
DLTF	NA	0.4-0.9	Variable	Fraction of calculated maximum time step necessary for numerical stability
SLOPE	NA	0.00	0.00	Branch bed slope
AX	1.00	1.00	1.00	Longitudinal eddy viscosity, m^2sec^{-1}
AZC	TKE	TKE	TKE	Form of vertical turbulence closure algorithm
AZSLC	IMP	IMP	IMP	IMP specifies implicit treatment of the vertical eddy viscosity in the longitudinal momentum equation.
AZMAX	1.00	1.00	1.00	Maximum value for vertical eddy viscosity, m^2sec^{-1}
FRICC	CHEZY	CHEZY	CHEZY	Bed friction type
T2I	NA	-1.00	11.00	Initial Temperature, ^oC
PQC	OFF	ON	ON	Density placed inflows
EVC	ON	ON	ON	Evaporation included in water budget
PRC	OFF	OFF	OFF	Precipitation included
SLHTC	TERM	TERM	TERM	Specify either term-by-term (TERM) or equilibrium temperature computations (ET) for surface heat exchange
SROC	OFF	ON	ON	Read in observed short wave solar radiation
RHEVC	OFF	OFF	OFF	Ryan-Harleman evaporation formula
METIC	ON	ON	ON	Meteorological data interpolation
FETCHC	OFF	OFF	OFF	Fang and Stefan fetch calculation
AFW	9.2	9.45	9.20	"a" coeff. in wind speed formulation, Wm^{-2} mm Hg^{-1}
BFW	0.46	0.46	0.46	"b" coeff. in wind speed formulation, Wm^{-2} mm Hg^{-1} $(m/s)^{-1}$
CFW	2.0	2.05	2.00	"c" coefficient in wind speed formulation, [-]
WINDH	-	2.00	2.00	Wind speed measurement height, m
ICEC	OFF	OFF	OFF	Ice calculations
SLTRC	ULTIMATE	ULTIMATE	ULTIMATE	Transport solution scheme
THETA	0.55	0.55	0.55	Time-weighting for vertical advection scheme
CBHE	0.3	0.60	0.30	Coefficient of bottom heat exchange, $Wm^{-2}\,^oC^{-1}$
TSED	-	6.00	10.00	Sediment temperature, ^oC
FI	0.01	0.01	0.01	Interfacial friction factor
TSEDF	1.0	1.0	1.0	Heat lost to sediments added back to water column
EXH2O	0.45	0.45	0.45	Extinction for pure water, m^{-1}
BETA	0.45	0.40	0.45	Fraction of incident solar radiation absorbed at the water surface
DX	1.00	1.00	1.00	Longitudinal eddy diffusivity, m^2sec^{-1}
Wind Sheltering	1.00	1.00	1.00	Wind sheltering coefficient (1.00 – no sheltering values. <1.00 – sheltering)

CE-QUAL-W2: Shasta

- Calibration period (2000 – 2017)
- Validation period (2018 – 2021)
- Time Series (hourly)
  - Temperature
  - Flow (TCD, River outlets, spill)
  - Active TCD gates (and gate changes)
  - Powerhouse operations
  - Reservoir Elevation and TCD gate elevations
- Profiles
  - Temperature
  - Active Gates
  - Reservoir Elevation and TCD gate elevations

Source: Reclamation

CE-QUAL-W2: Keswick

- Calibration period (2000 – 2017)
- Validation period (2018 – 2021)
- Time Series (hourly)
  - Reservoir Elevation
  - Flow
  - Temperature
- Profiles
  - Temperature

Source: Wikimedia Commons

CE-QUAL-W2: Trinity

Source: Reclamation

- Calibration period
  - Determined by data availability
  - 2005, 2010, 2011-2013, 2019
- Validation period
  - 2006, 2009, 2015, 2017, 2018, 2020
- Time Series (hourly)
  - Reservoir Elevation
  - Flow
  - Temperature
- Profiles
  - Temperature

CE-QUAL-W2: Lewiston

Source: Reclamation

- Calibration period
  - Determined by data availability
  - 2005, 2010, 2011, 2019
- Validation period
  - 2006, 2009, 2012, 2018-2020
- Time Series (hourly)
  - Reservoir Elevation
  - Flow
  - Temperature
- Profiles
  - Temperature

CE-QUAL-W2: Whiskeytown

- Calibration period (2016-2019)
- Validation period
  - Limited data was used for calibration
- Time Series (hourly)
  - Reservoir Elevation
  - Flow
  - Temperature
- Profiles
  - Temperature

Source: Reclamation

CE-QUAL-W2: Folsom

Source: Reclamation

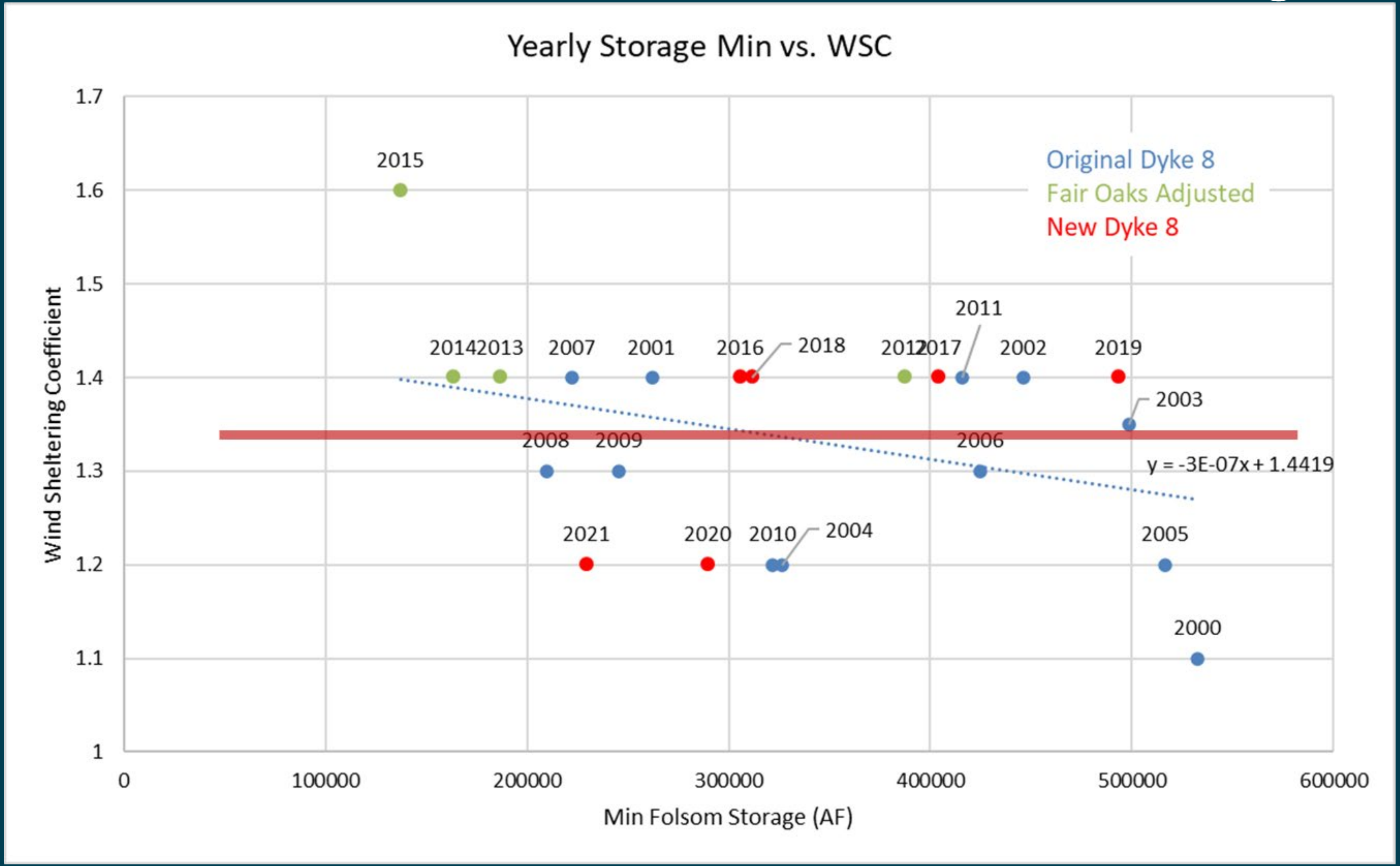
- Calibration period (2001-2017)
- Validation period (2018-2021)
- Time Series (hourly)
  - Reservoir Elevation
  - Flow
  - Temperature
- Profiles
  - Temperature

Folsom Calibration Parameters

Parameter	Default	Folsom Lake	Lake Natoma	Description
DLTMIN	NA	0.5	1.00	Minimum time step, sec
DLTMAX	NA	10--75 - Variable	Variable	Maximum time step, sec
DLTF	NA	0.6	Variable	Fraction of calculated maximum time step necessary for numerical stability
SLOPE	NA	0.00	0.00	Branch bed slope
AX	1.00	1.00	1.00	Longitudinal eddy viscosity, m^2sec^{-1}
AZC	TKE	TKE	TKE	Form of vertical turbulence closure algorithm
AZSLC	IMP	IMP	IMP	IMP specifies implicit treatment of the vertical eddy viscosity in the longitudinal momentum equation.
AZMAX	1.00	1.00	1.00	Maximum value for vertical eddy viscosity, m^2sec^{-1}
FRICC	CHEZY	MANN	MANN	Bed friction type
T2I	NA	Profile Data	11.00	Initial Temperature, ^oC
PQC	OFF	OFF	ON	Density placed inflows
EVC	ON	ON	ON	Evaporation included in water budget
PRC	OFF	OFF	OFF	Precipitation included
SLHTC	TERM	TERM	TERM	Specify either term-by-term (TERM) or equilibrium temperature computations (ET) for surface heat exchange
SROC	OFF	ON	ON	Read in observed short wave solar radiation
RHEVC	OFF	OFF	OFF	Ryan-Harleman evaporation formula
METIC	ON	ON	ON	Meteorological data interpolation
FETCHC	OFF	OFF	OFF	Fang and Stefan fetch calculation
AFW	9.2	9.20	9.20	"a" coeff. in wind speed formulation, Wm^{-2} mm Hg^{-1}
BFW	0.46	0.46	0.46	"b" coeff. in wind speed formulation, Wm^{-2} mm Hg^{-1} $(m/s)^{-1}$
CFW	2.0	2.00	2.00	"c" coefficient in wind speed formulation, [-]
WINDH	-	2.00	2.00	Wind speed measurement height, m
ICEC	OFF	OFF	OFF	Ice calculations
SLTRC	ULTIMATE	ULTIMATE	ULTIMATE	Transport solution scheme
THETA	0.55	0.55	0.55	Time-weighting for vertical advection scheme
CBHE	0.3	0.30	0.30	Coefficient of bottom heat exchange, Wm^{-2} $^oC^{-1}$
TSED	-	12.00	10.00	Sediment temperature, ^oC
FI	0.01	0.01	0.01	Interfacial friction factor
TSEDF	1.0	1.0	1.0	Heat lost to sediments added back to water column
EXH2O	0.45	0.45	0.45	Extinction for pure water, m^{-1}
BETA	0.45	0.45	0.45	Fraction of incident solar radiation absorbed at the water surface
DX	1.00	1.00	1.00	Longitudinal eddy diffusivity, m^2sec^{-1}
Wind Sheltering	1.00	Variable (1.1-1.6) / 1.33	1.00	Wind sheltering coefficient (1.00 – no sheltering values. <1.00 – sheltering)

Wind Sheltering Coefficients

- WSC vs Minimum Folsom Reservoir Storage



CE-QUAL-W2: Natoma

- Calibration period (2001-2017)
- Validation period (2018-2021)
- Time Series (hourly)
  - Reservoir Elevation
  - Flow
  - Temperature

Source: Wikipedia

CE-QUAL-W2: New Melones

Source: Wikipedia

- Calibration period (2006, 2010-2013)
- Validation period (2005, 2007-2009)
- Time Series (hourly)
  - Reservoir Elevation
  - Flow
  - Temperature
- Profiles
  - Temperature

CE-QUAL-W2: Tulloch

- Calibration period (2009-2013)
- Validation period (2004-2008)
- Time Series (hourly)
  - Reservoir Elevation
  - Flow
  - Temperature
- Profiles
  - Temperature

Source: Wikipedia

BUREAU OF RECLAMATION

ResSim Calibration

Reservoirs

- Same metrics to allow for comparison between models
- Continuous simulation rather than individual years
  - Typically consistent with CE-QUAL-W2 calibration/validation periods
  - Driven by data availability across both models
- Generally kept default ResSim parameters
  - Primarily variations in wind, mixing, and vertical dispersion coefficients
- Comparison to depth profiles during calibration/validation periods

Riverine

Source: Water Education Foundation

Domains

- Sacramento River
- Trinity River
- Clear Creek
- American River
- Stanislaus River

Process

- Compare performance at stream temperature locations
- Does not have depth profiles

Sacramento/Trinity Parameters (Part I)

Parameter	Default	Shasta Lake	Keswick Reservoir	Sacramento River & Clear Creek	Trinity Lake	Lewiston Lake	Trinity River	Whiskeytown Lake	Description
Coefficient a in Wind Function	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	Minimum wind function parameter [10^{-9} mb^{-1}]
Coefficient b in Wind Function	2.5	4.0	2.5	2.5	1.5	1.0	1.5	2.0	Scalar wind function parameter [10^{-9} mb^{-1}]
Coefficient c in Wind Function	1.0	0.5	1.0	1.0	0.5	1.0	1.0	1.0	Exponential wind function parameter [10^{-9} mb^{-1}]
Sediment Layer Thickness	0.25	0.25	0.25	0.25	0.25	0.25	0.2	0.25	Thickness of the sediment temperature layer [m]
Shortwave Radiation Bed Reflectivity	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	Fraction of radiation reflected by sediment/bed [0-1]
Background Light Attenuation	0.45	0.45	0.45	0.45	0.33	0.05	0.2	0.15	Base shortwave absorption by water [m^{-1}]
Mixed Layer Tolerance	0.08	0.04	0.08	n/a	0.04	0.08	N.A.	0.005	Density gradient at which entrainment is effectively blocked [kg m^{-3}]

Sacramento/Trinity Parameters (II)

Vertical Dispersion Coefficient	Keswick Reservoir	Lewiston Lake	Description
D_{Zmin}	1.08e-5	2.5e-4	Minimum vertical dispersion [ft^2 s^{-1}]
A_1	3.28e-5	0.0	Linear dispersion scalar [ft]
A_z	2.0	1.5	Exponential dispersion scalar [dimensionless]

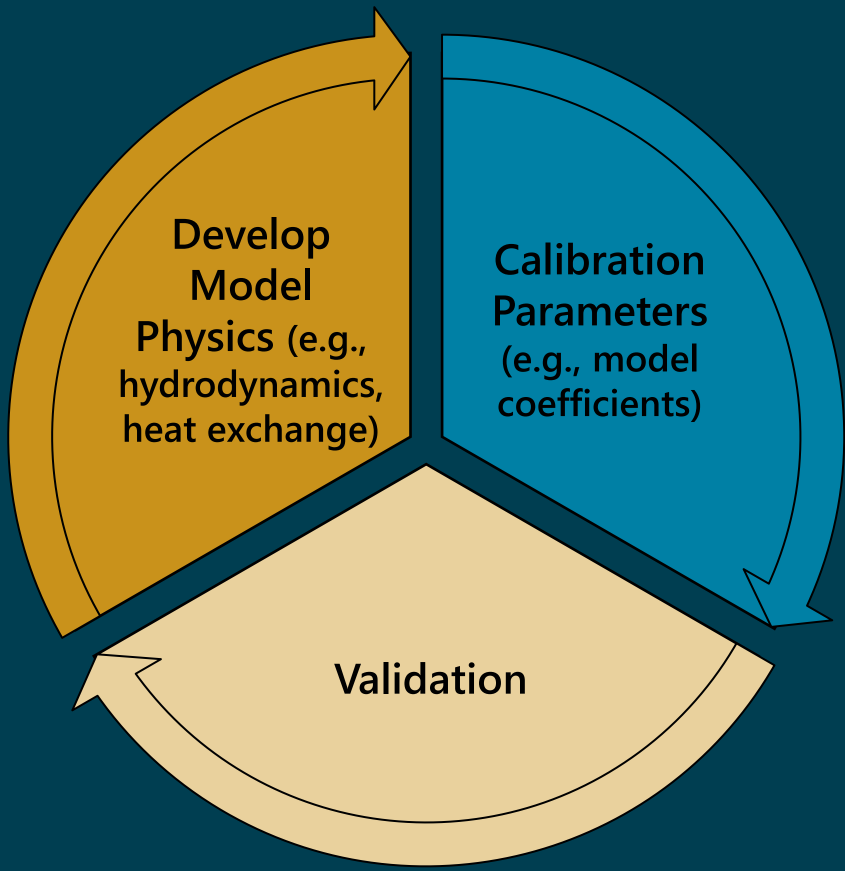
Vertical Dispersion Coefficient	Shasta Lake	Trinity Lake	Whiskeytown Lake	Description
a	0.1	0.1	0.2	Empirical coefficient – linear density scaling [dimensionless]
b	0.65	0.75	0.75	Empirical coefficient – exponential density scaling [dimensionless]
c	0.05	0.05	0.05	Empirical coefficient – overall + wind scaling [ft]
Dz_{min}	7.5e-5	1.5e-5	1.5e-5	Minimum vertical dispersion [ft^2 s^{-1}]

BUREAU OF RECLAMATION

Validation & Sensitivity

Model Validation

- Calibration/validation data sets available on most element models
  - Real-time operations and flow/hydrology
  - Biological monitoring
  - Meteorology
- Once calibrated, model uncertainties are accepted as appropriate for application (e.g., forecasts)
- Forecast uncertainty



Validation Approach

- Model simulations were completed without modifying any calibration parameters to test if the models performed similar in years that were not used in calibration
- Same metrics as for the calibration
  - Practice like you play
- Build confidence when used in other study types

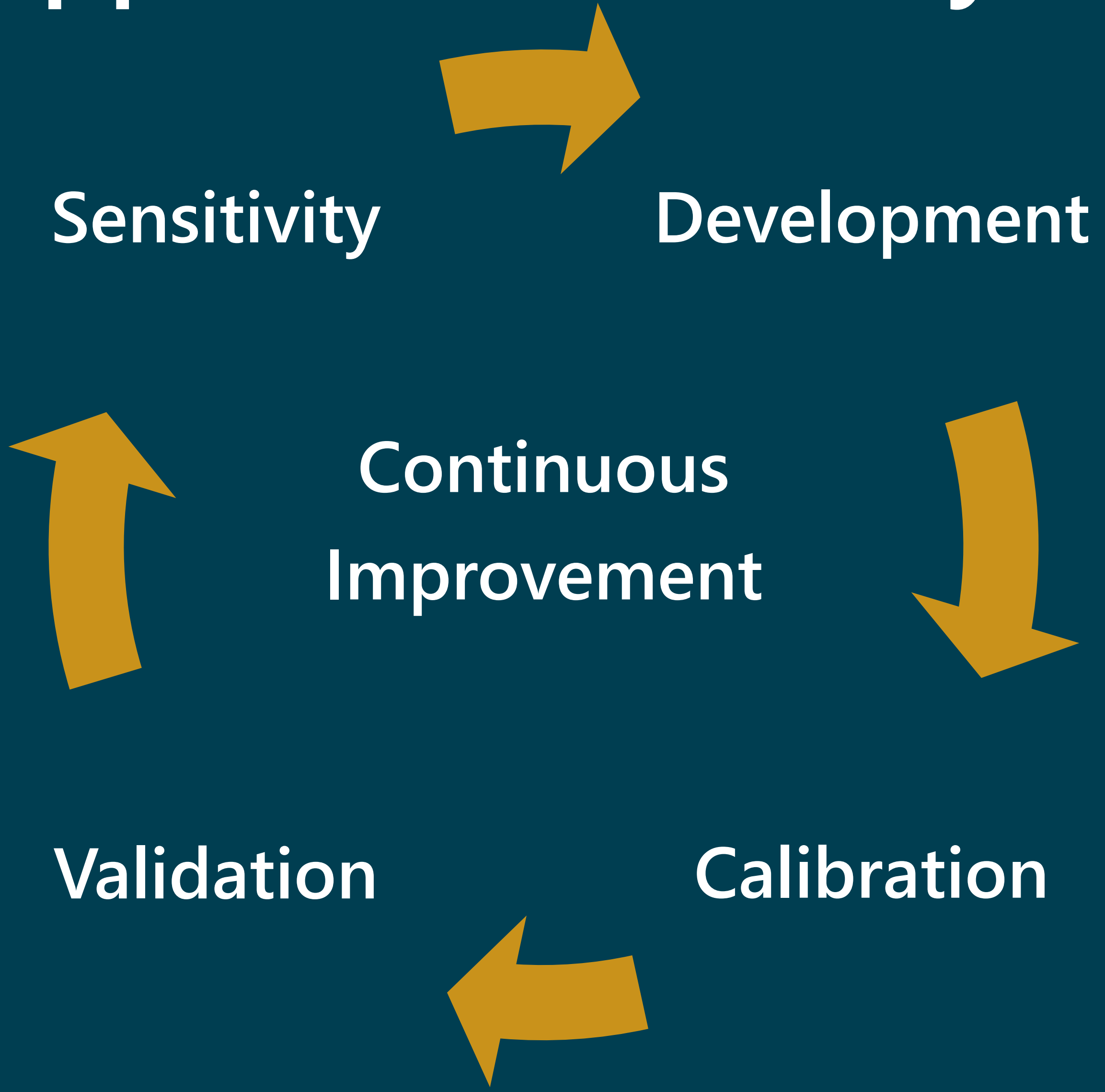
Sensitivity Approach (Part I)

- Sensitivity analysis explores the magnitude of model responses (element models) to individual changes in inputs and parameters
- Sensitivity testing relied on graphical analysis of the effects of perturbations to parameters during calibration, as well as dedicated sensitivity simulations using the calibrated model
- Assessment Metrics:
  - High (H) – Direct implication of calibration
  - Medium (M) – Less impact to calibration
  - Low (L) – Low impact to calibration, modest “fine tuning”
  - Insensitive (I) – No impact to model performance or calibration

Sensitivity Approach (Part II)

- Evaluations were performed concurrent with model development and calibration. Select sets of model parameters were explored to determine relative sensitivity to model results
- A ‘manual’ rather than an ‘algorithm’ assisted approach was used to perform sensitivity testing due to the multifaceted and complex nature of the system
  - Allowed for efficient evaluation compared to quantitative approaches
  - Recognized limitations in computing resources

Approach: Summary



- Calibration driven by intended use and available data
- Data partitioned into calibration/validation periods
- Additional sensitivity conducted to better understand model performance