Model Development

Michael Wright, PhD, PE
Reclamation, Bay Delta Office

Outline

- Recap
  - Selected Models and Domain
  - Shasta/Trinity System – WTMP Representations
- Model Performance Metrics
- CE-QUAL-W2
  - Model Development
  - Model Calibration (preliminary)
- HEC-ResSim
  - Model Development
  - Model Calibration (preliminary)

Model Performance Philosophy

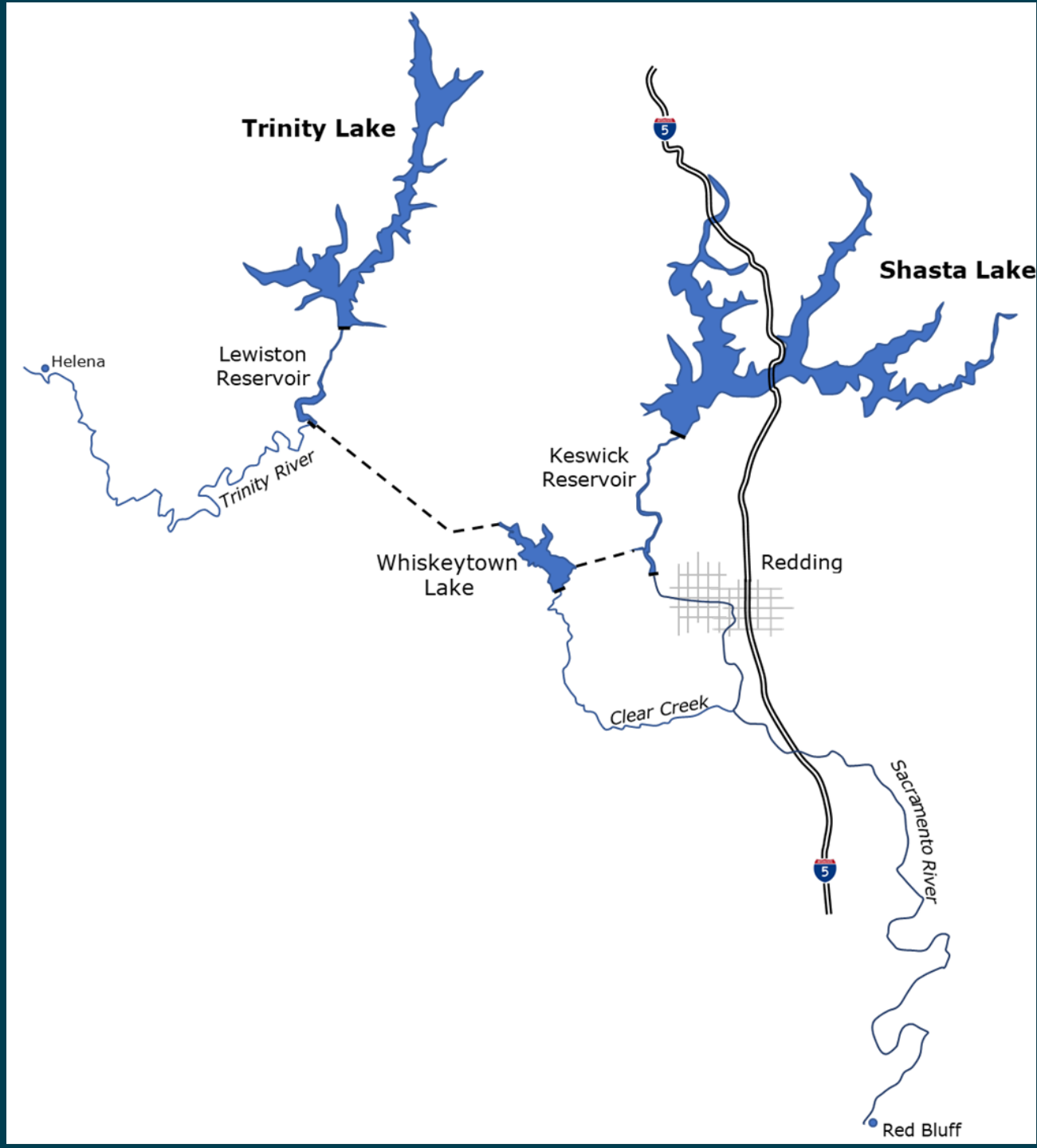
- Assure community using model results that output is valid, useful
- Representation of unique elements
  - Shasta: Temperature Control Device
- Establishment of reasonable statistics and thresholds for calibration
- Special focus on performance in periods when the system is stressed
  - Droughts
  - Low storage
  - High temperature

WTMP Model Representations

- Reservoir Models
  - HEC-ResSim (1-D vertical)
  - CE-QUAL-W2 (2-D vertical and longitudinal)
- River Model
  - HEC-ResSim (1-D longitudinal)
- System Model
  - HEC-ResSim
    - Reservoir (1-D vertical)
    - River (1-D longitudinal)
- Different models for different use cases

WTMP Domain

- Sacramento River and Trinity River basins
- Facilities:
  - Sacramento
    - Shasta Lake, Keswick Reservoir
    - Sacramento River (to Red Bluff)
    - Whiskeytown Lake
    - Clear Creek (to Sacramento River)
  - Trinity
    - Trinity Lake
    - Lewiston Lake
    - Trinity River (to North Fork)



WTMP Model Representations Shasta/Trinity System

- Model development data period: 2000 to 2021
- Models

Reservoir/River	CE-QUAL-W2	HEC-ResSim
Shasta Lake	X	X
Keswick Reservoir	X	X
Sacramento River	-	X
Trinity Lake	X	X
Lewiston Lake	X	X
Trinity River	-	X
Whiskeytown Lake	X	X
Clear Creek	-	X

- HEC-ResSim is also applied as a system model

Unique Aspects of the Trinity/Shasta System

- Facilities
  - Temperature curtains - Whiskeytown
  - Temperature Control Device – Shasta

Model Progress

- Model Performance Metrics
- Shasta W2
  - Description of model
  - Review of TCD representation
  - Calibration
  - Additional validation years (show graphical presentation – no model metrics)
- Keswick W2
  - Brief description of model
  - Calibration
  - Additional validation years (show graphical presentation – no model metrics)
- ResSim Work

Model Performance Metrics

- Graphical (qualitative) and Statistical (quantitative)
- Statistical Metrics
  - Mean bias: systematic model over- or under-prediction
  - Mean absolute error (MAE): estimate of overall model error
  - Root-mean squared error (RMSE): large values indicate that there are periods where differences are appreciable (e.g., outliers)
  - Nash-Sutcliffe Efficiency (NSE): an indication of how well the plot of observed versus simulated data fits the 1:1 line, and is sensitive to differences in the observed and modeled means as well as variances

WTMP Model Performance Metrics for Water Temperature (Time Series and Profiles), Flow, and Reservoir Stage

Parameter	Mean Bias	MAE	RMSE	NSE
Stage	±0.5 feet (0.15 meters)	≤1.0 feet (0.3 meters)	≤1.5 feet (0.45 meters)	≥0.65
Flow	±50 cubic feet per second (cfs) (1.4 cubic meters per second (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

- Determined from experience and literature search
- Indicates areas modelers need to pay attention to

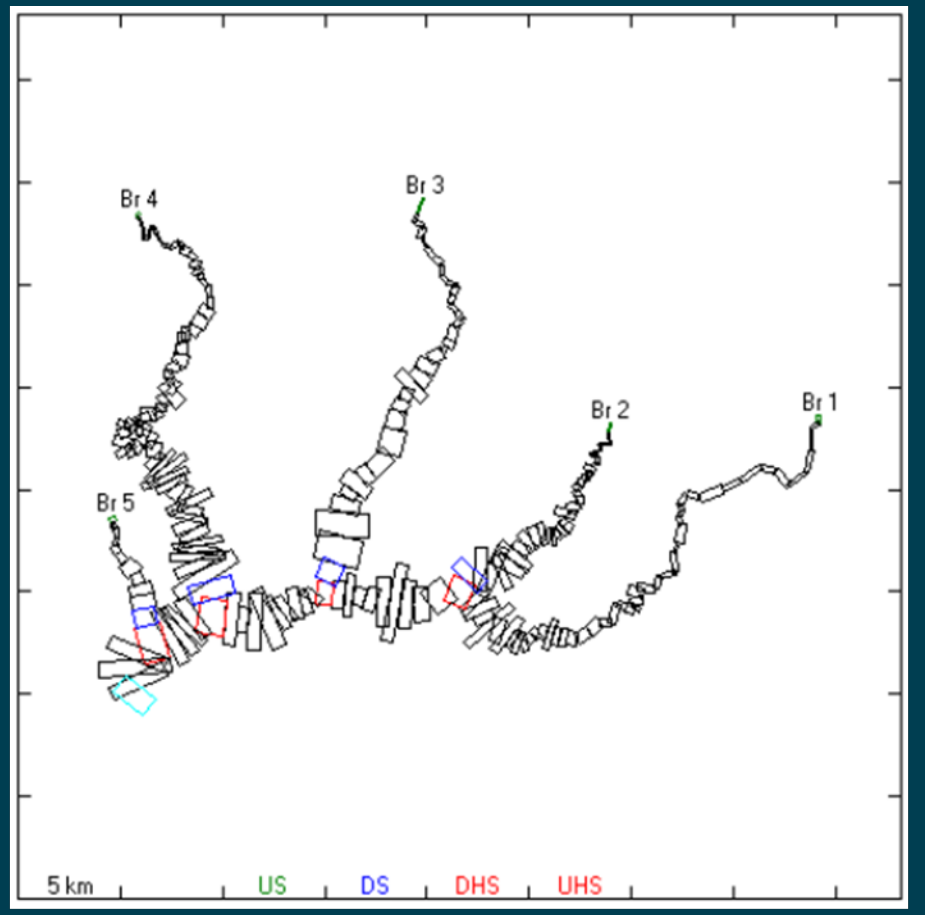
BUREAU OF RECLAMATION

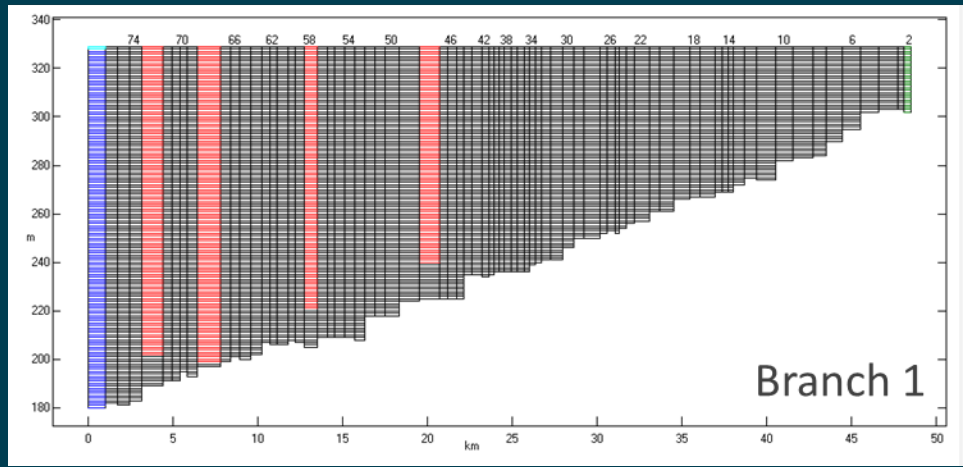
Sacramento/Trinity Water Temperature Models (Part 1)

1. Shasta Lake and Keswick Reservoir W2 Model

Shasta Lake: CE-QUAL-W2 Geometry

- Shasta Lake Model
  - Five branches
  - Layer thickness: 1 meter
  - Maximum number of layers: 149
  - Shasta Lake bathymetry (historic)
  - 2000-2021 calendar year simulations



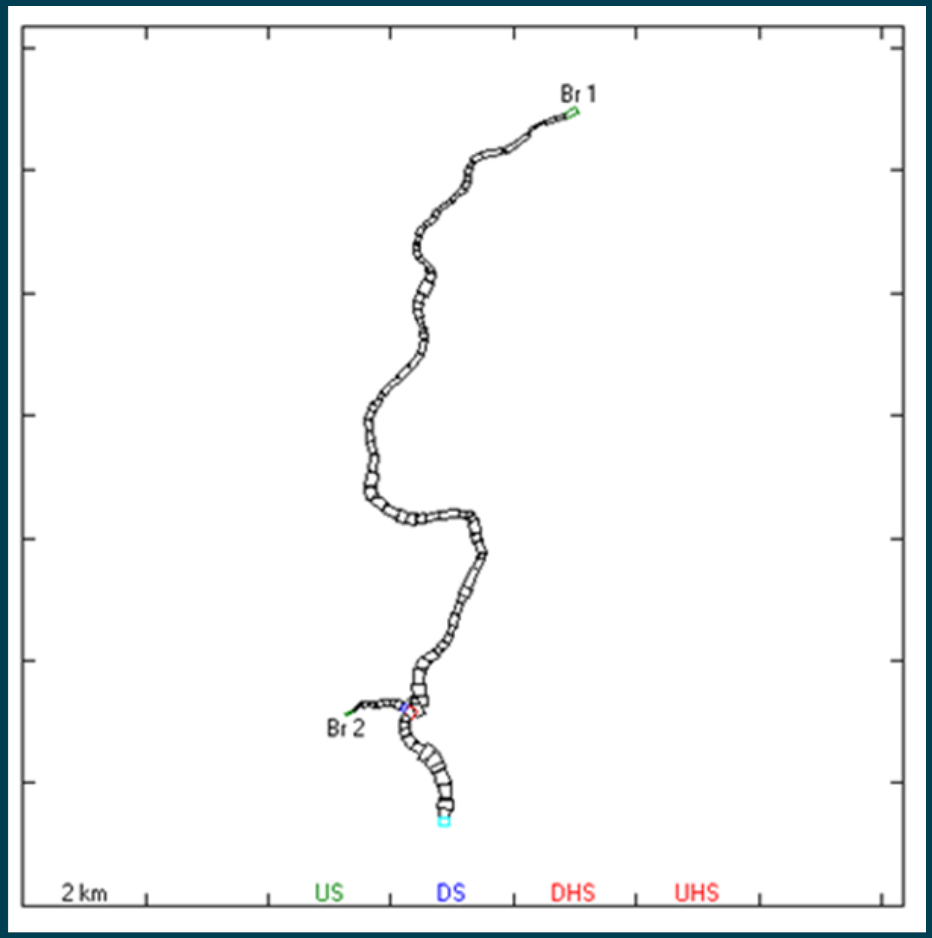


Shasta Lake: CE-QUAL-W2 Geometry

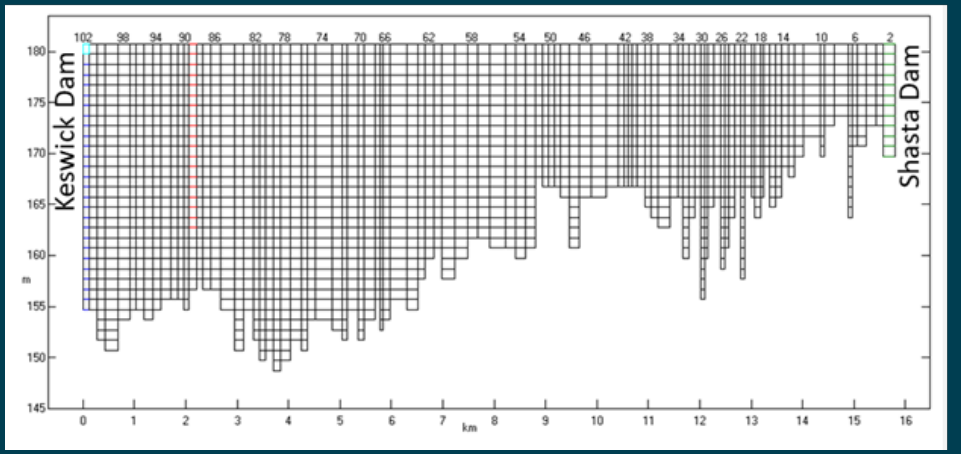
Branch Name	Total Number of Segments in Branch	Total Length of Arm	Average Segment Length	Minimum Segment Length	Maximum Segment Length
[#]	[]	[ft (m)]	[ft (m)]	[ft (m)]	[ft (m)]
Pit River arm (1)	76	156,988 (47,850.0)	2,066 (629.6)	820 (250.0)	4,429 (1,350.0)
Squaw Creek arm (2)	33	46,014 (14,025.2)	1,394 (425.0)	656 (200.0)	2,461 (750.2)
McCloud River arm (3)	34	74,020 (22,561.2)	2,177 (663.6)	1,066 (325.0)	4,429 (1,350.0)
Sacramento River arm (4)	70	96,441 (29,395.1)	1,378 (419.9)	492 (150.0)	2,937 (895.1)
Big Backbone Creek arm (5)	12	19,324 (5,890.1)	1,610 (490.8)	689 (210.0)	2,740 (835.1)

Keswick Reservoir: CE-QUAL-W2 Geometry

- Keswick Reservoir Model
  - Two branches
  - Layer thickness: 1 meter
  - Maximum number of layers: 31
  - Keswick Reservoir bathymetry (historic)
  - 2000-2021 calendar year simulations

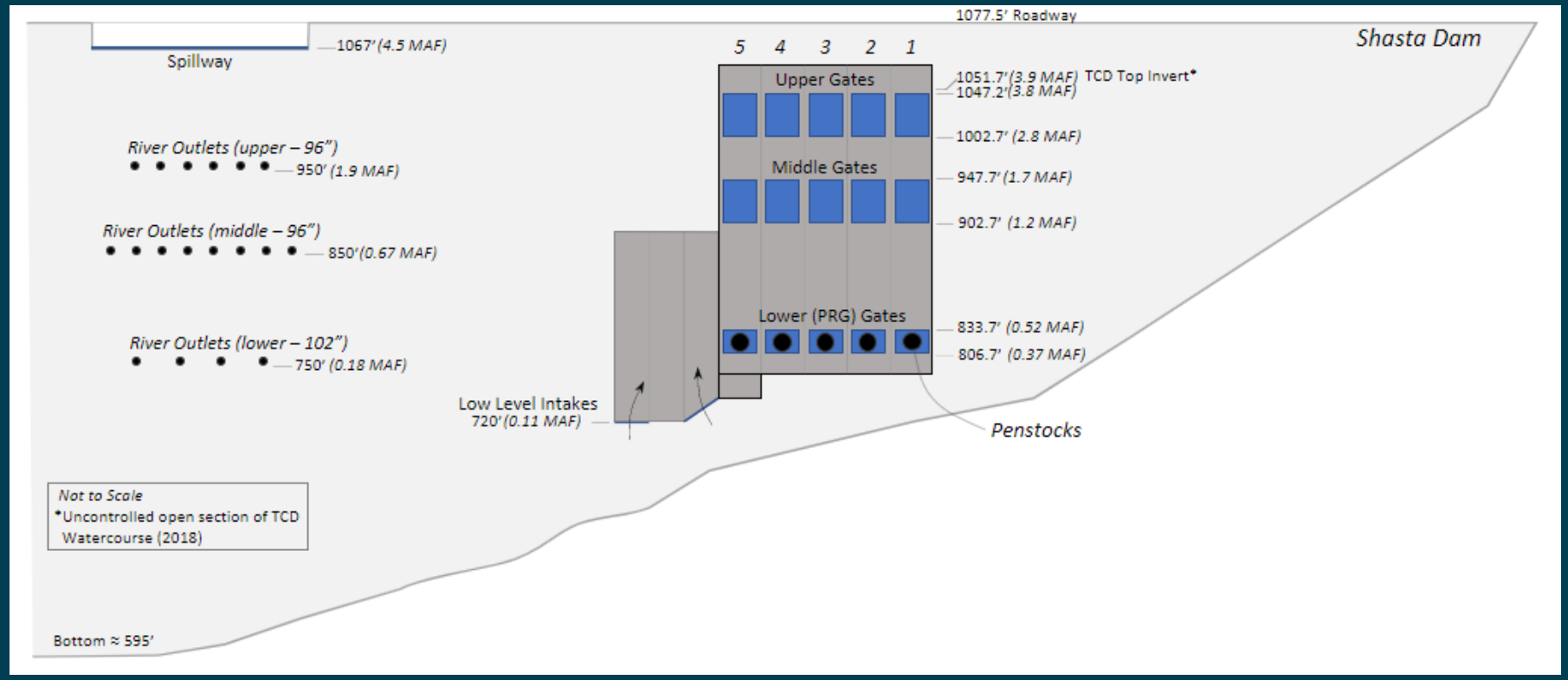


Branch Name	Total Number of Segments in Branch	Total Length of Arm	Average Segment Length	Minimum Segment Length	Maximum Segment Length
[#]	[]	[ft (m)]	[ft (m)]	[ft (m)]	[ft (m)]
Main Reservoir (1)	101	51,823 (15,796)	513 (156)	163 (50)	1,132 (345)
Spring Creek arm (2)	12	3,512 (1,071)	293 (89)	137 (42)	492 (150)



Shasta Lake Model: CE-QUAL-W2 Representations

- Shasta Dam River Outlets and Spill
- Shasta Dam Temperature Control Device (TCD)

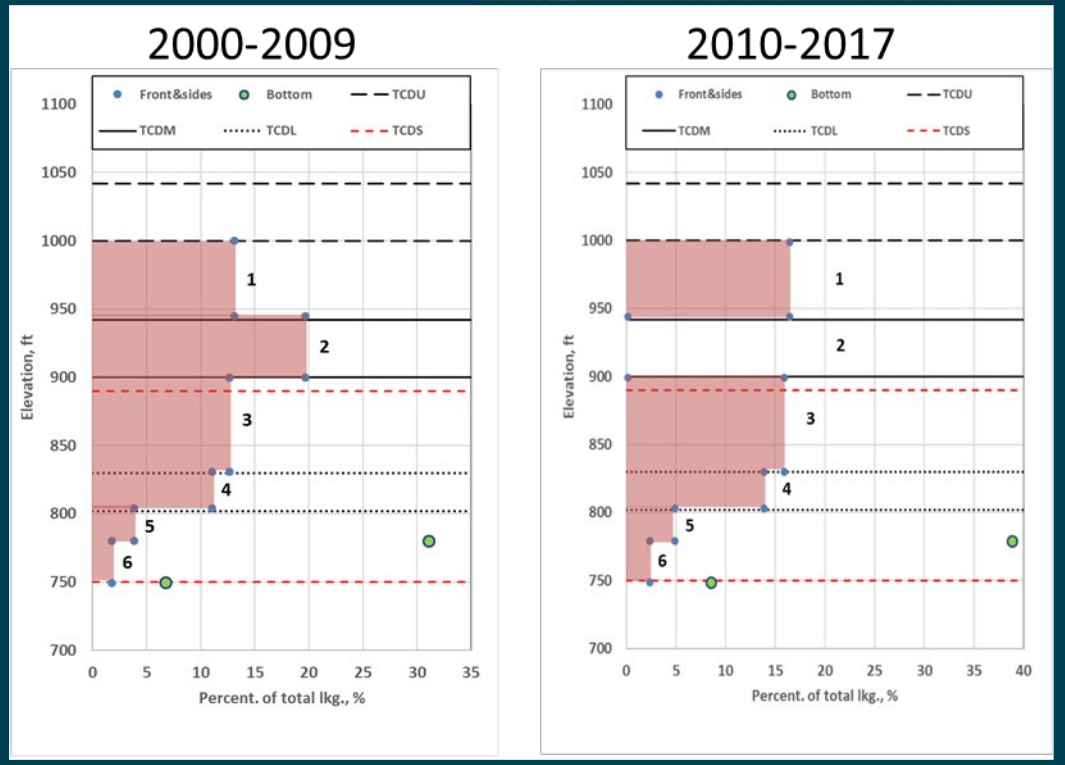


Shasta Lake: CE-QUAL-W2

- TCD Considerations
    - Leakage
    - Temperature Control Device (TCD)
    - Sidegate Operations

TCD Leakage

- Total “theoretical” leakage: 20%
  - Maximum total leakage at full pool and all gates closed except at upper gate level
- Leakage repairs: January 2010
- Repairs reduce leakage area identified by USBR (1999) to about 16.1%
- Test sensitivity of leakage to
  1. Total leakage
  2. Leakage distribution



TCD Leakage

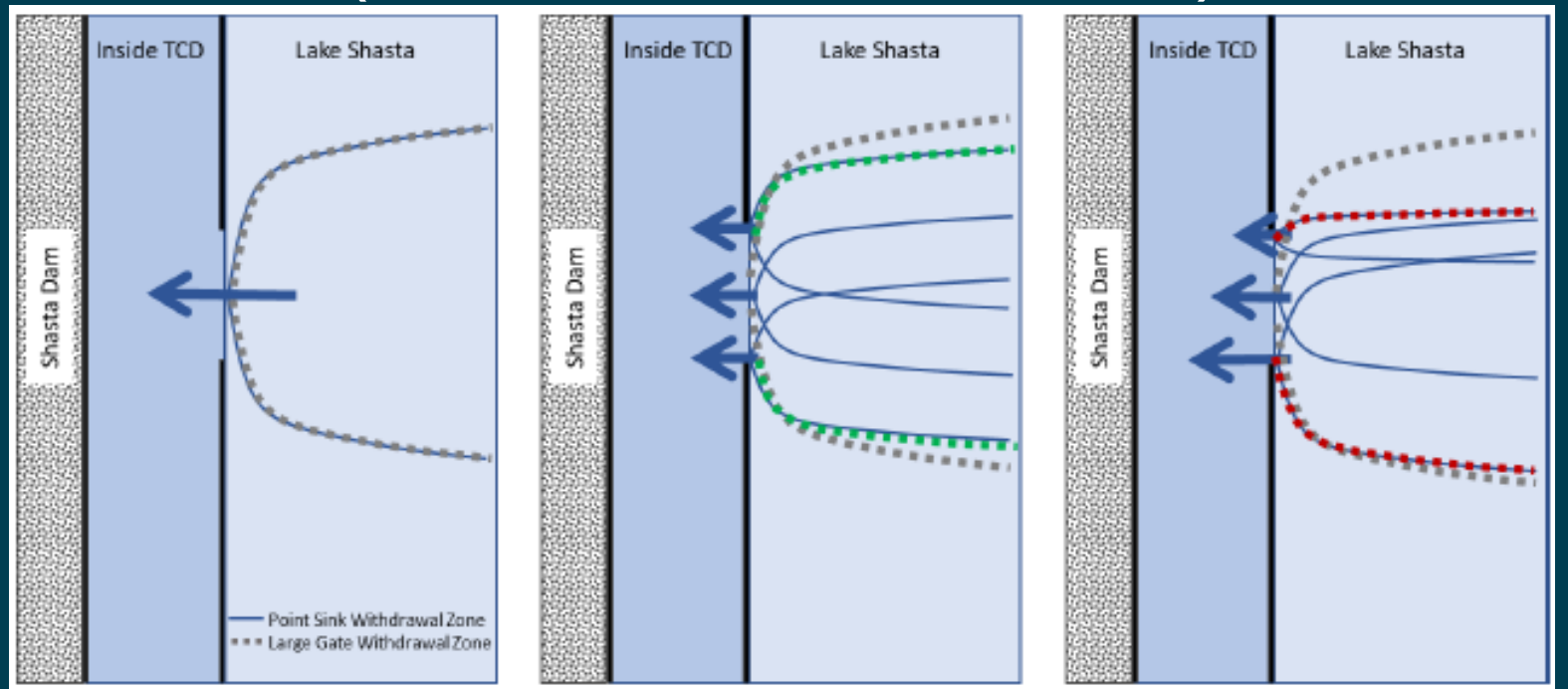
- Results relatively insensitive to:
  - Total leakage
  - Leakage distribution
- Explanation
  - Leakage only makes up a fraction of total TCD outflow
  - When a gate is open, leakage is zero from that vertical “zone”
  - Selective withdrawal targets TCD gate operations to meet outflow temperature target (leakage is always present)

TCD: Large Gate Representation

- Large gate representation
  - Upper and Middle: 45 feet high; Lower: 27 feet high
  - Outflow temperatures are at times cooler than all available water temperatures across a gate level
  - Extended duration releases at a single gate level
  - Potential considerations
    - Point sink representation
    - Minimum flow fractions
    - Density gradient considerations for point/line sinks (superposition)
    - CE-QUAL-W2 representation/limitations
      - lateral averaging
      - TCD
      - Reservoir boundaries

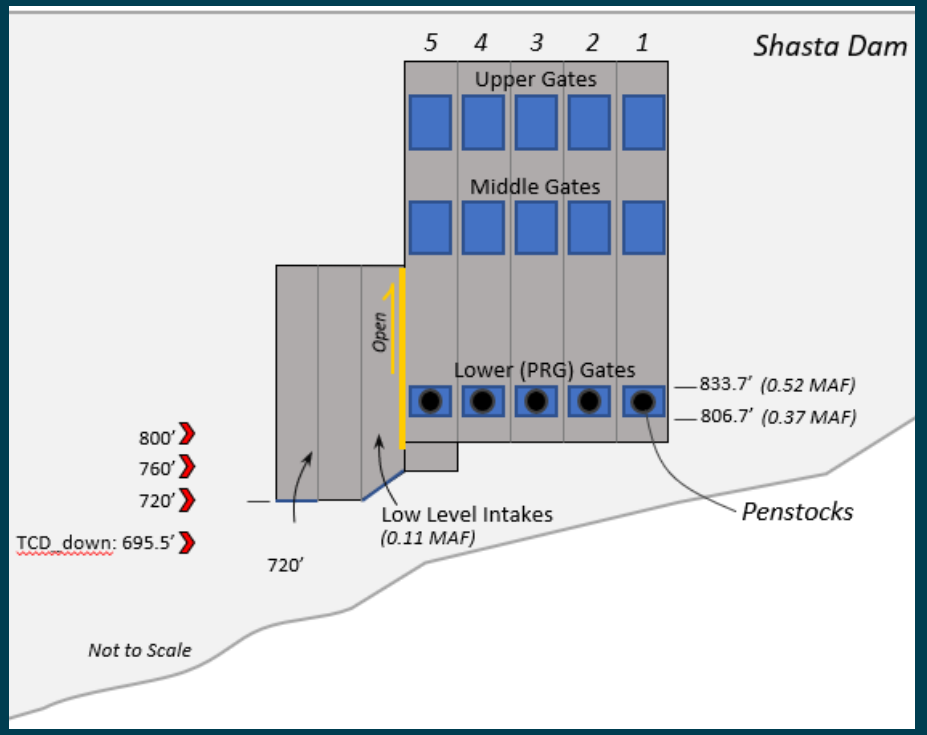
TCD: Large Gate Representation

- One individual versus three individual point sinks
- Three individual point sinks
  - Uniform distribution
  - Varying distribution (with minimum flow fractions)



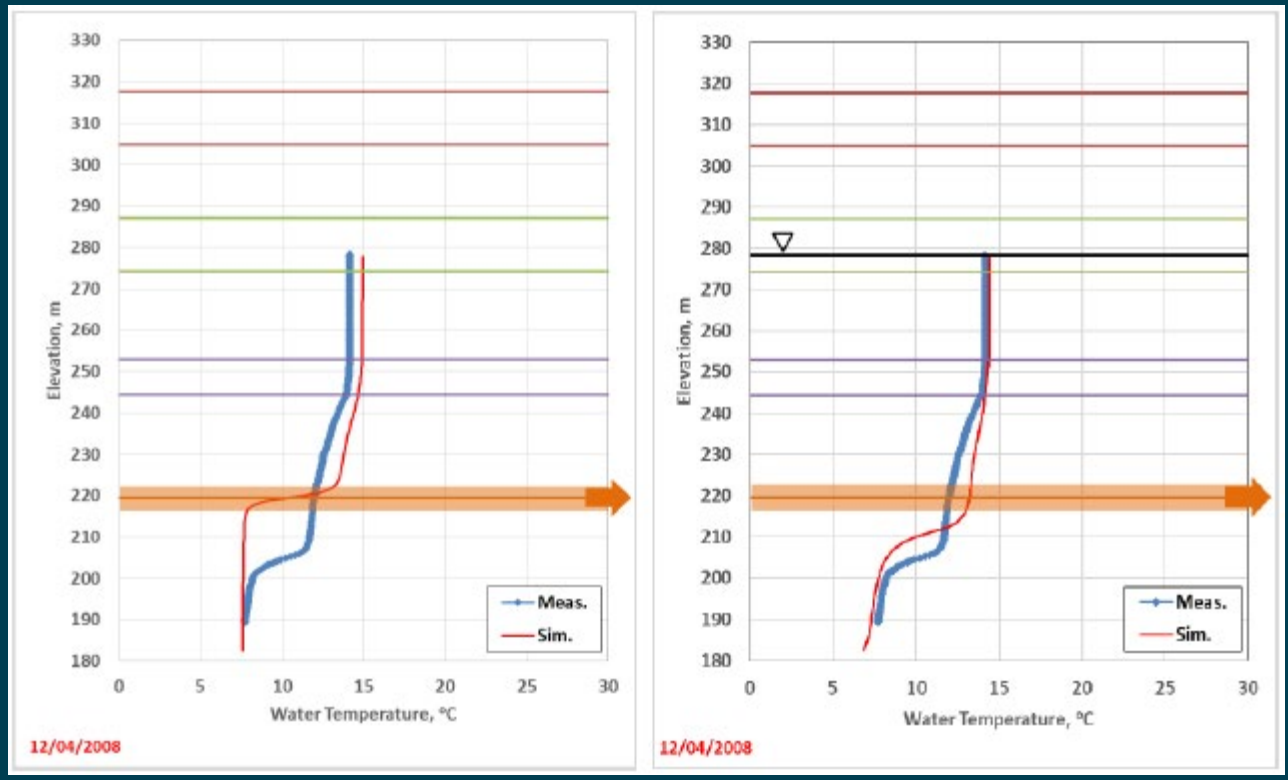
TCD: Side Gate Representation

- Side Gate located on spillway side of dam
  - Vertical flow pattern induced by side gate structure
  - Reservoir boundaries
  - High thermal gradient challenge
  - CE-QUAL-W2 representation (previous slide)
- Representation
  - Three individual point sinks (matching outflow temperatures under side gate only
  - TCD_down to capture low storage conditions and high temperature gradient conditions



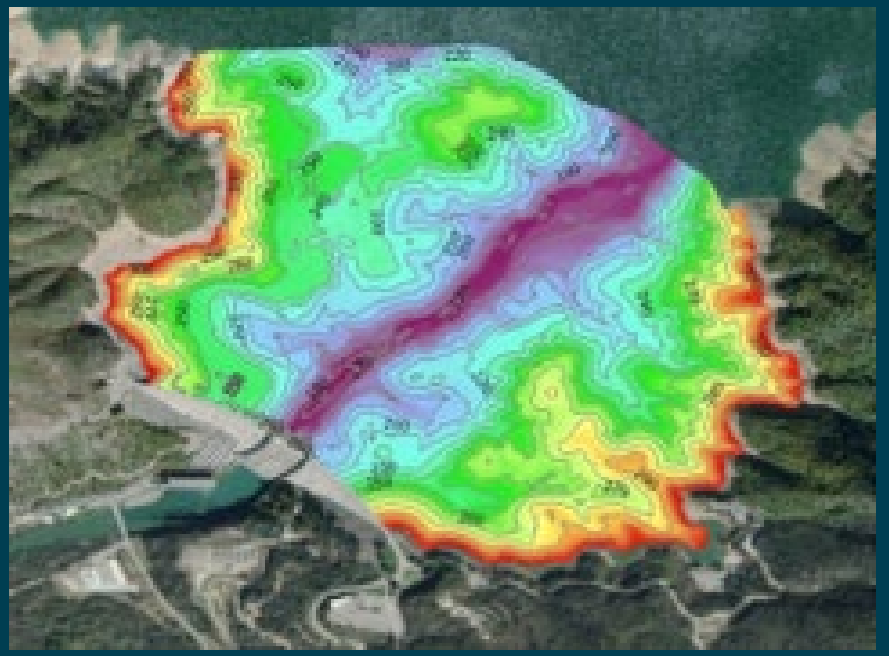
TCD: Side Gate Representation

- Model results with and without TCD_down representation
- Tested over a range of years and representations



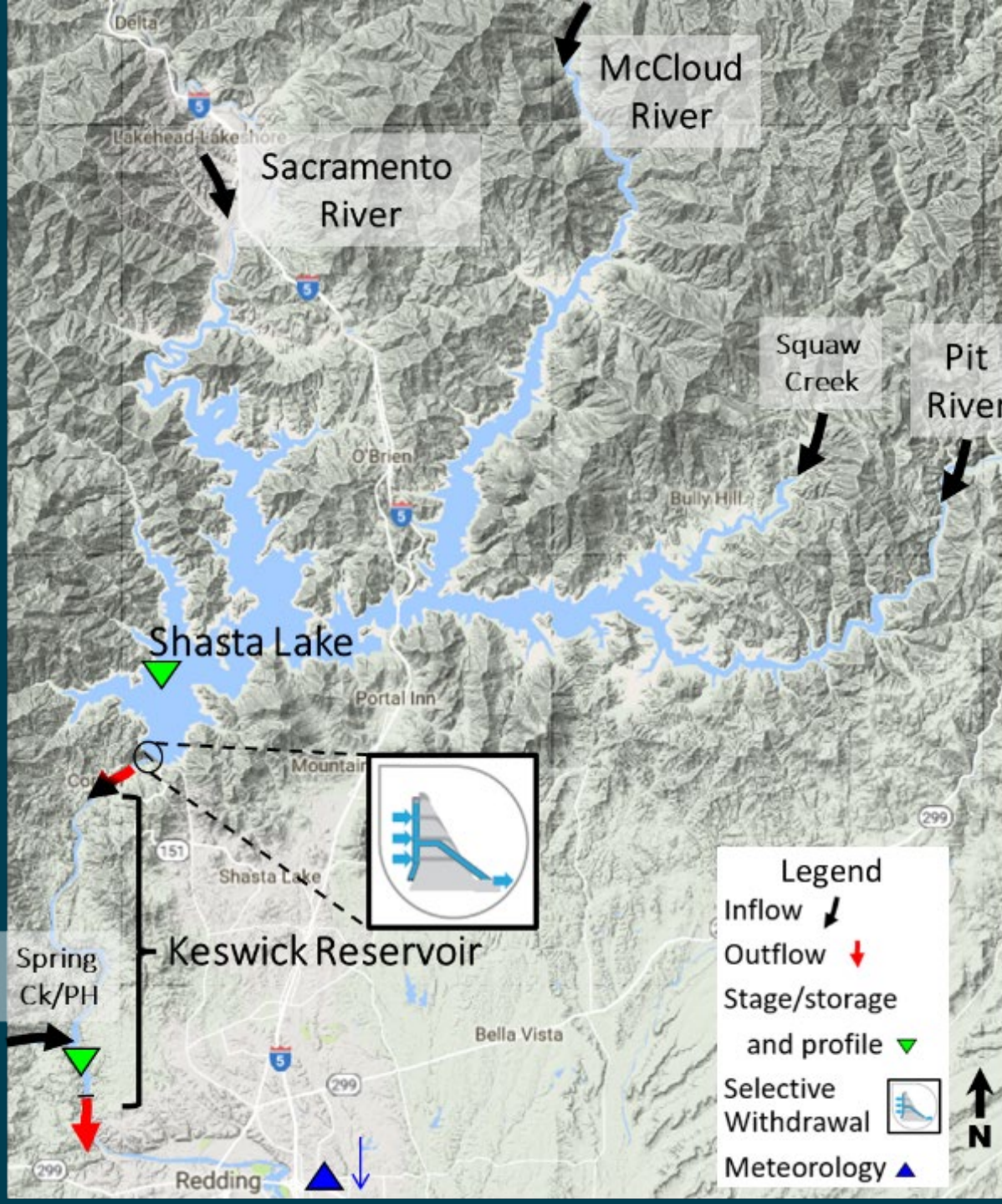
TCD: Side Gate Representation

- Status: “working” solution
  - Degrees of freedom
    - Number of outlets
    - Elevation of outlets
    - TCD_down elevation and flow fraction
- Field Studies: U.C. Davis
  - Bathymetry, sonar, exploratory ADCP (2019)
  - Additional ADCP exploration (2021)
  - Delta Stewardship Council Project (Pending)
- Objective: Identify local flow patterns upstream of TCD and determine flow through individual gates to improve model representations.



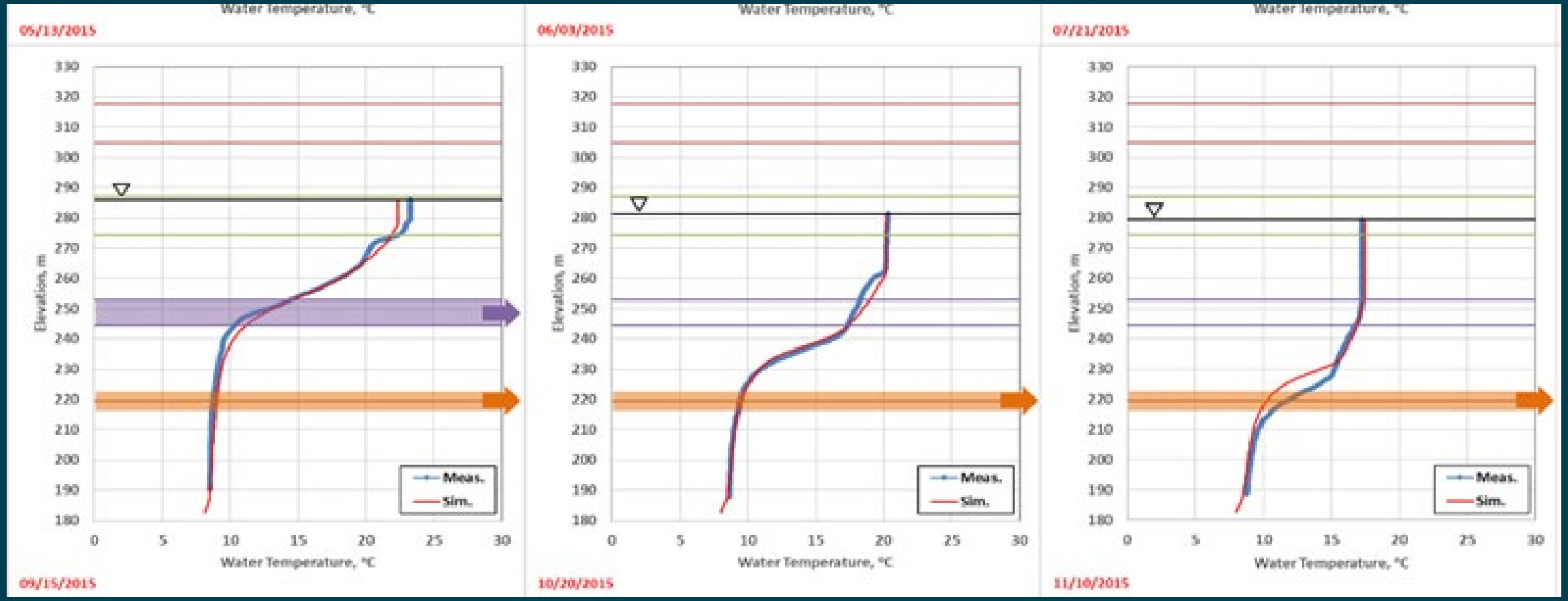
Hydrology, Temperature, Meteorology Data

- Flow
  - Inflow (hourly, daily) USGS
  - Outflow/operations (hourly) USBR
  - Storage (hourly, daily) USBR
  - Selective withdrawal operations (daily, weekly) USBR
- Water Temperature
  - Inflow (hourly, daily) USGS
  - Outflow (hourly, daily) USBR
  - Temperature profiles (weekly, monthly) USBR
- Meteorology
  - Solar, air temperature, dew point, wind speed/direction, cloud cover, barometric pressure (hourly) NWS
- Geometry
  - Dam outlet structures USBR
  - Bathymetry (and tributary/diversion locations) USGS/Other
  - Topographic shading (minor) USGS

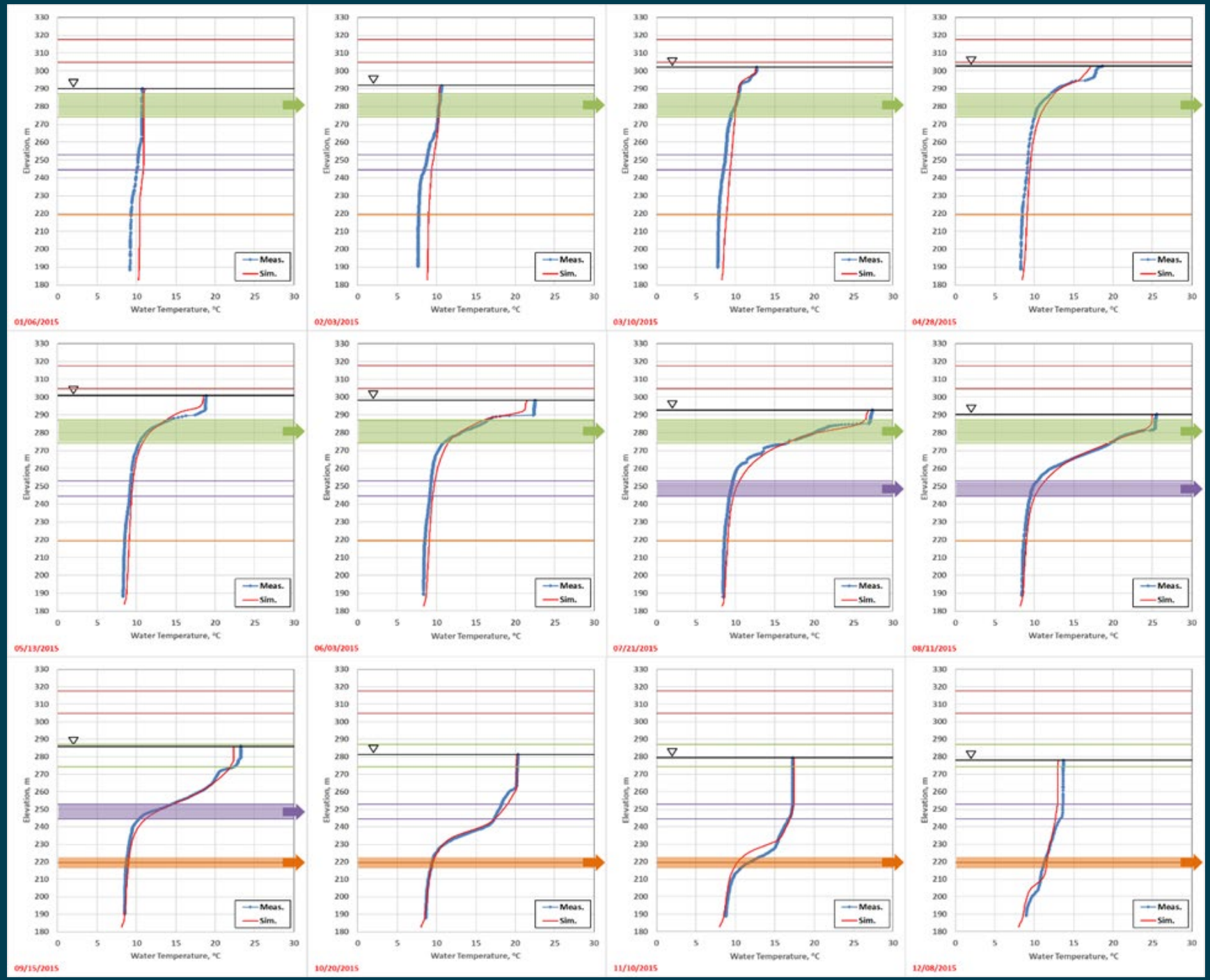


Shasta Calibration Results – CE-QUAL-W2

2015 (selected)

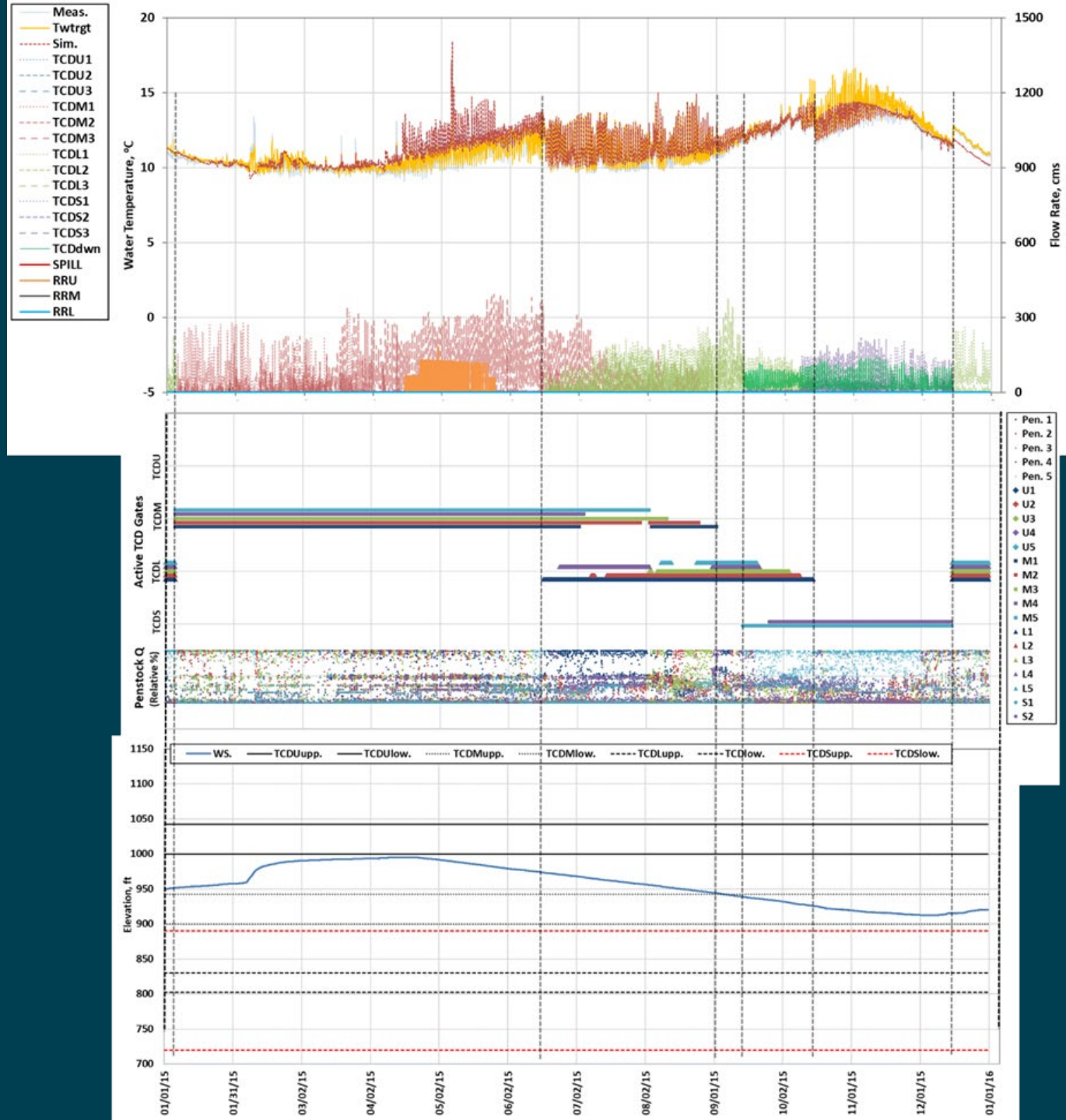


2015 (all)


Elevation, m
Water Temperature, °C
Meas.
Sim.
01/06/2015
02/03/2015
03/10/2015
04/28/2015
05/13/2015
06/03/2015
07/21/2015
08/11/2015
09/15/2015
10/20/2015
11/10/2015
12/08/2015

2015

- Release temperature
- Gates
- Powerhouses
- Stage



Shasta profiles: Mean Bias 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.11	0.21	-0.29	-0.23	-0.07	-0.13	-0.07	-0.08	-0.13	0.23	0.02	-0.38
2001	0.03	0.01	-0.01	0.21	0.48	0.40	0.52	0.74	1.19	1.57	1.30	-0.16
2002	-0.15	0.08	0.24	0.38	0.36	0.45	0.39	0.56	0.56	0.84	0.80	--
2003	0.33	-0.04	0.02	0.27	0.43	0.25	0.11	0.16	0.12	0.07	-0.03	0.07
2004	0.32	0.13	0.19	0.09	0.09	0.01	-0.09	-0.16	-0.31	-0.44	-0.59	-0.74
2005	0.04	0.13	0.09	0.39	0.36	0.52	0.33	0.51	0.64	0.69	0.52	0.42
2006	-0.15	-0.17	-0.28	0.03	0.00	0.19	0.10	0.00	0.06	-0.19	-0.06	-0.22
2007	0.37	0.12	0.38	0.19	0.13	0.12	0.08	-0.08	0.00	-0.78	-0.68	-0.50
2008	0.20	-0.02	0.32	0.45	0.29	0.08	0.27	0.14	0.13	-0.70	-0.31	-0.10
2009	0.56	0.90	0.26	0.57	0.71	0.82	0.71	0.75	0.72	0.41	0.47	0.54
2010	0.25	-0.45	-0.45	--	0.08	0.43	0.35	0.20	0.26	0.07	0.04	-0.11
2011	0.13	0.34	0.21	0.12	0.06	0.18	0.19	0.26	0.43	0.48	0.34	0.08
2012	0.18	0.28	0.40	--	0.55	0.43	0.37	0.22	0.27	0.08	0.26	--
2013	0.35	0.35	0.54	0.58	0.87*	--	--	0.30	0.72	0.27	-0.05	-0.38
2014	0.39	0.56	1.09	1.21	1.26	1.10	1.24	1.37	0.94	0.71	0.54	0.53
2015	0.75	0.82	0.62	0.39	0.22	0.23	0.49	0.25	0.17	0.06	-0.29	-0.38
2016	0.36	-0.12	0.56	0.48	0.56	0.68	0.59	0.71	0.69	0.57	0.36	--
2017	0.41	0.25	-	0.20	0.46	0.54	0.63	0.54	0.60	0.57	0.50	0.37

Shasta profiles: Mean Absolute Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.28	0.41	0.30	0.26	0.15	0.37	0.29	0.37	0.43	0.52	0.38	0.41
2001	0.24	0.44	0.41	0.61	0.62	0.54	0.55	0.79	1.19	1.57	1.30	0.60
2002	0.17	0.29	0.44	0.51	0.66	0.73	0.63	0.66	0.67	0.84	1.00	--
2003	0.36	0.23	0.23	0.50	0.62	0.40	0.37	0.31	0.39	0.32	0.30	0.28
2004	0.42	0.44	0.52	0.33	0.25	0.29	0.22	0.33	0.56	0.48	0.63	0.74
2005	0.43	0.46	0.35	0.66	0.59	0.66	0.54	0.64	0.68	0.80	0.67	0.58
2006	0.27	0.80	0.28	0.29	0.36	0.42	0.24	0.22	0.26	0.25	0.37	0.28
2007	0.37	0.40	0.66	0.50	0.41	0.34	0.42	0.31	0.32	0.80	0.74	0.55
2008	0.22	0.50	0.66	0.58	0.68	0.54	0.47	0.45	0.40	0.91	0.59	0.55
2009	0.62	1.02	0.49	0.72	0.74	0.85	0.82	0.76	0.76	0.47	0.47	0.54
2010	0.26	0.45	0.45	--	0.37	0.54	0.42	0.40	0.43	0.34	0.48	0.47
2011	0.14	0.39	0.39	0.20	0.16	0.36	0.32	0.44	0.57	0.64	0.50	0.26
2012	0.19	0.30	0.59	--	0.93	0.68	0.58	0.54	0.47	0.52	0.37	--
2013	0.35	0.44	0.67	0.64	1.08	--	--	0.50	0.75	0.59	0.43	0.76
2014	0.39	0.61	1.31	1.32	1.32	1.24	1.34	1.37	0.95	0.88	0.73	0.60
2015	0.75	0.86	0.68	0.56	0.51	0.58	0.59	0.42	0.38	0.23	0.47	0.49
2016	0.75	0.27	0.81	0.58	0.71	0.83	0.78	0.88	0.88	0.87	0.77	--
2017	0.61	0.54	-	0.42	0.48	0.71	0.70	0.61	0.66	0.75	0.74	0.44

Shasta profiles: Root Mean Square Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.31	0.43	0.39	0.52	0.20	0.61	0.37	0.44	0.48	0.64	0.46	0.50
2001	0.26	0.47	0.56	0.75	0.69	0.59	0.62	0.95	1.48	1.86	1.70	0.67
2002	0.20	0.32	0.49	0.60	0.81	0.84	0.74	0.84	0.85	1.20	1.36	--
2003	0.48	0.30	0.28	0.53	0.66	0.59	0.50	0.40	0.48	0.40	0.35	0.33
2004	0.52	0.46	0.56	0.47	0.41	0.57	0.35	0.39	0.73	0.58	0.76	0.95
2005	0.48	0.52	0.39	0.68	0.66	0.81	0.70	0.73	0.78	0.91	0.81	0.83
2006	0.29	0.41	0.40	0.33	0.61	0.69	0.38	0.32	0.36	0.30	0.45	0.36
2007	0.46	0.42	0.76	0.68	0.69	0.54	0.50	0.43	0.45	1.29	1.14	0.68
2008	0.26	0.52	0.69	0.63	1.01	0.64	0.50	0.62	0.60	1.54	1.03	0.73
2009	0.82	1.16	0.52	0.76	0.96	0.98	0.91	0.82	0.84	0.68	0.66	0.80
2010	0.34	0.51	0.47	--	0.60	0.76	0.54	0.62	0.52	0.41	0.61	0.54
2011	0.21	0.45	0.41	0.22	0.20	0.68	0.52	0.66	0.80	0.84	0.71	0.42
2012	0.21	0.34	0.65	--	1.12	0.76	0.70	0.60	0.53	0.59	0.43	--
2013	0.42	0.50	0.73	0.71	1.16	--	--	0.56	0.94	0.65	0.48	0.86
2014	0.49	0.73	1.41	1.43	1.37	1.35	1.39	1.43	1.08	0.94	0.85	0.74
2015	0.83	0.99	0.75	0.60	0.64	0.70	0.73	0.50	0.47	0.35	0.79	0.56
2016	0.82	0.35	0.89	0.67	0.93	1.00	1.00	1.10	1.15	1.11	0.93	--
2017	0.69	0.58	-	0.47	0.58	0.96	0.90	0.75	0.83	0.99	0.94	0.71

Shasta profiles: Nash Sutcliffe Efficiency 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.93	0.74	0.48	0.91	0.99	0.98	0.99	0.99	0.99	0.97	0.97	0.90
2001	0.90	0.26	0.83	0.88	0.96	0.98	0.99	0.98	0.94	0.85	0.71	0.74
2002	0.88	0.87	0.71	0.94	0.92	0.96	0.98	0.98	0.98	0.93	0.83	--
2003	0.79	0.82	0.91	0.83	0.90	0.98	0.99	0.99	0.99	0.99	0.99	0.97
2004	0.56	0.68	0.41	0.95	0.98	0.99	1.00	1.00	0.98	0.98	0.92	0.50
2005	0.74	0.70	0.91	0.75	0.91	0.95	0.98	0.98	0.97	0.94	0.90	0.75
2006	0.91	0.80	0.60	0.84	0.93	0.97	0.99	1.00	1.00	1.00	0.98	0.98
2007	0.81	0.82	0.35	0.87	0.96	0.99	0.99	0.99	0.99	0.88	0.81	0.90
2008	0.92	0.21	0.55	0.78	0.90	0.98	0.99	0.99	0.99	0.88	0.86	0.88
2009	0.60*	-0.44	0.01	0.77	0.90	0.95	0.97	0.98	0.98	0.97	0.95	0.85
2010	0.88	0.36	0.50	--	0.91	0.94	0.99	0.99	0.99	0.99	0.97	0.90
2011	0.94	0.81	0.43	0.93	0.99	0.96	0.99	0.98	0.98	0.96	0.95	0.97
2012	0.97	0.81	0.48	--	0.79	0.95	0.98	0.99	0.99	0.99	0.99	--
2013	0.84	0.77	0.64	0.82	0.84	-	-	0.99	0.97	0.98	0.97	0.63
2014	0.84	0.37	-0.14	0.37	0.83	0.91	0.95	0.95	0.96	0.95	0.93	0.76
2015	-0.93	0.17	0.64	0.94	0.96	0.97	0.98	0.99	0.99	0.99	0.95	0.87
2016	0.03	0.84	-0.18	0.90	0.85	0.93	0.96	0.96	0.95	0.95	0.88	--
2017	0.43	0.53	--	0.90	0.96	0.96	0.97	0.98	0.98	0.95	0.89	0.91

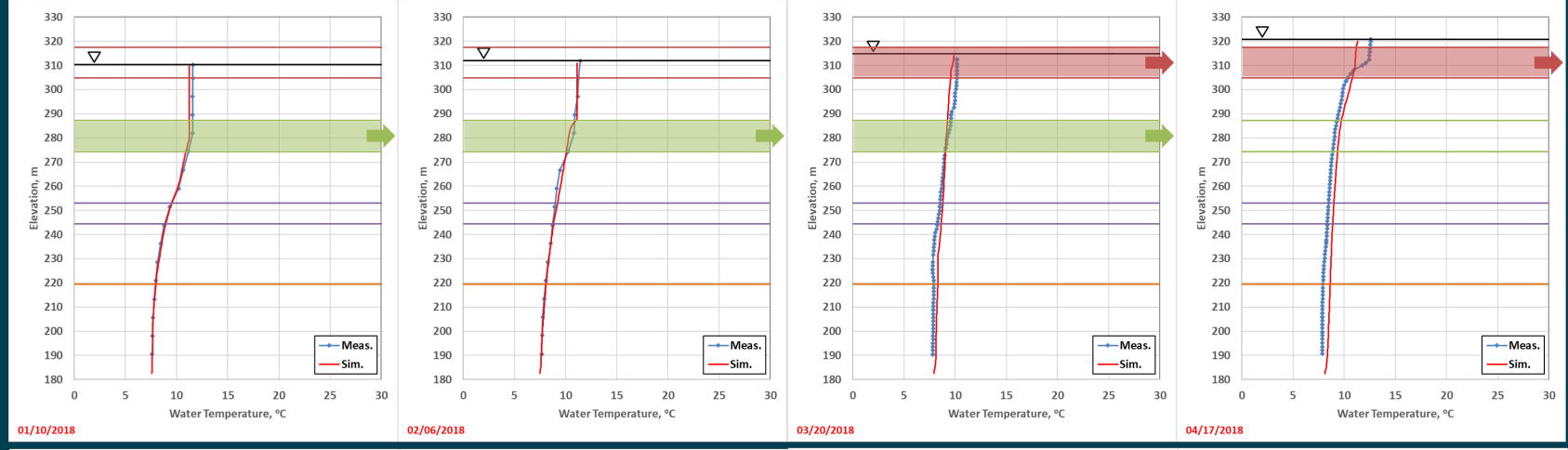
Shasta outflow temperature: Summary 2000-2017 (DRAFT)

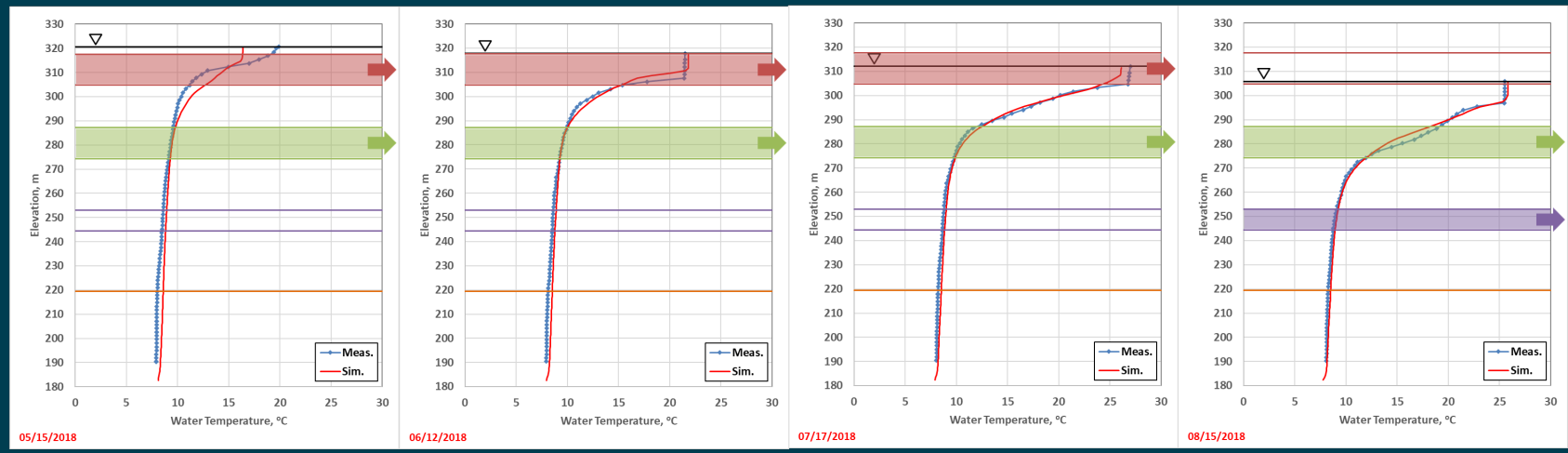
Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008
Mean Bias (°C)	-0.08	0.09	-0.01	-0.11	-0.42	-0.06	-0.31	-0.29	-0.24
MAE (°C)	0.60	0.36	0.31	0.20	0.47	0.15	0.33	0.38	0.38
RMSE (°C)	0.74	0.59	0.45	0.31	0.73	0.25	0.47	0.64	0.69
Nash-Sutcliffe (NSE)	0.54	0.85	0.88	0.88	0.85	0.97	0.78	0.82	0.92
COUNT	8,472	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784

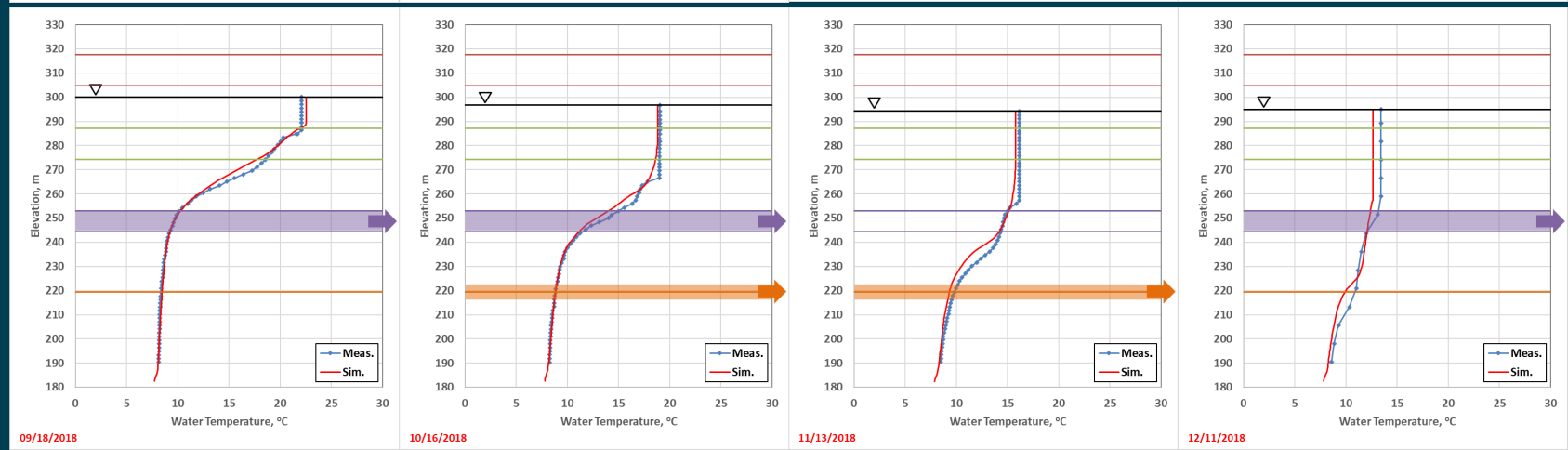
Statistic	2009	2010	2011	2012	2013	2014	2015	2016	2017
Mean Bias (°C)	0.23	-0.19	-0.12	-0.04	-0.06	-0.03	0.07	0.20	0.07
MAE (°C)	0.41	0.30	0.19	0.24	0.45	0.43	0.39	0.38	0.30
RMSE (°C)	0.60	0.49	0.32	0.36	0.66	0.66	0.58	0.59	0.39
Nash-Sutcliffe (NSE)	0.90	0.64	0.82	0.88	0.80	0.93	0.83	0.52	0.84
COUNT	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Validation: Shasta Lake Temperature Profiles 2018

- Monthly vertical temperature profiles 2018

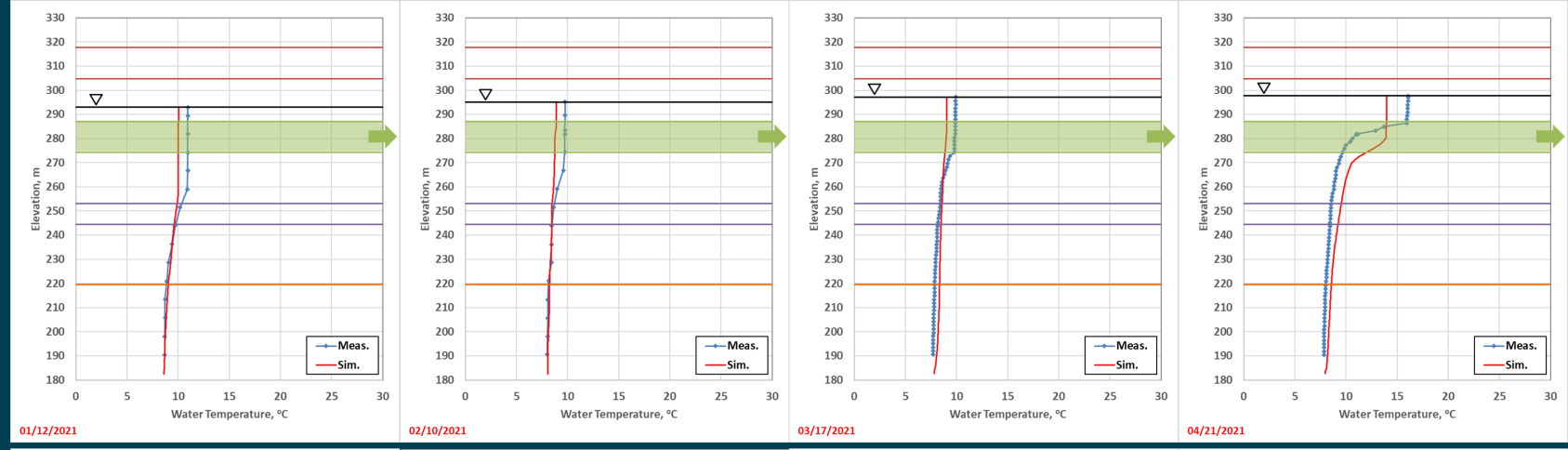


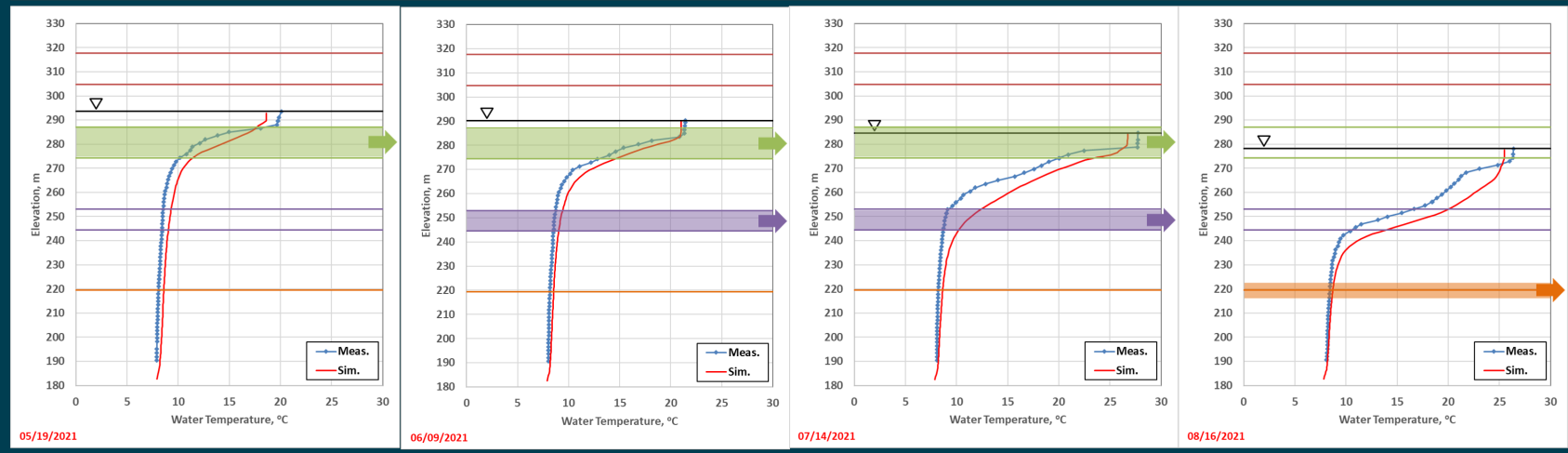


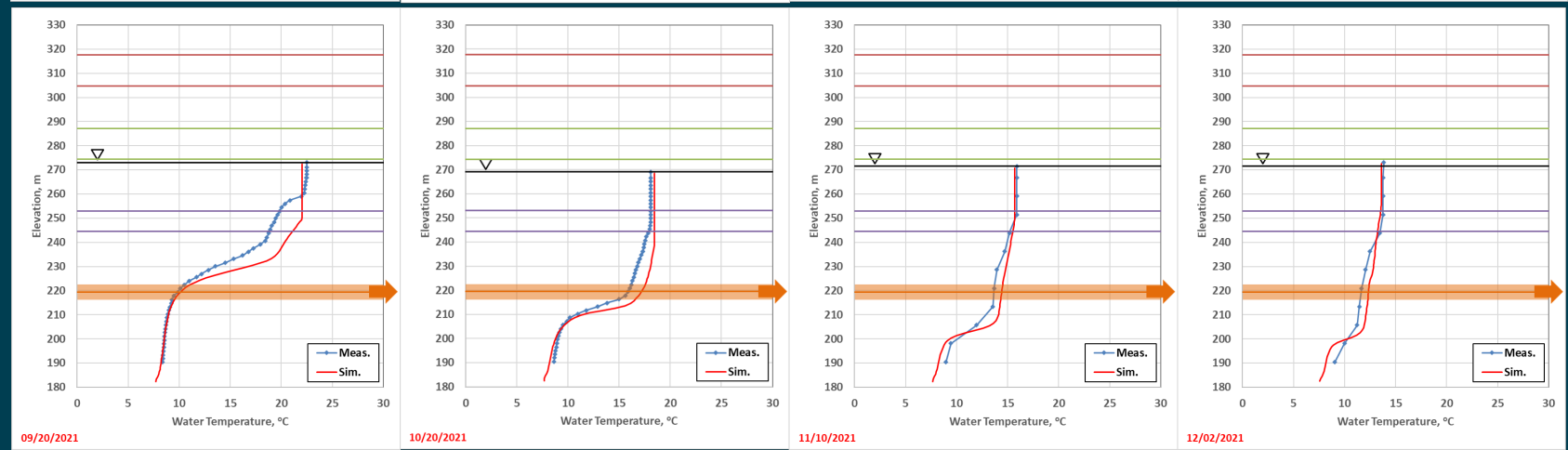


Validation: Shasta Lake Temperature Profiles 2021

- Monthly vertical temperature profiles 2021

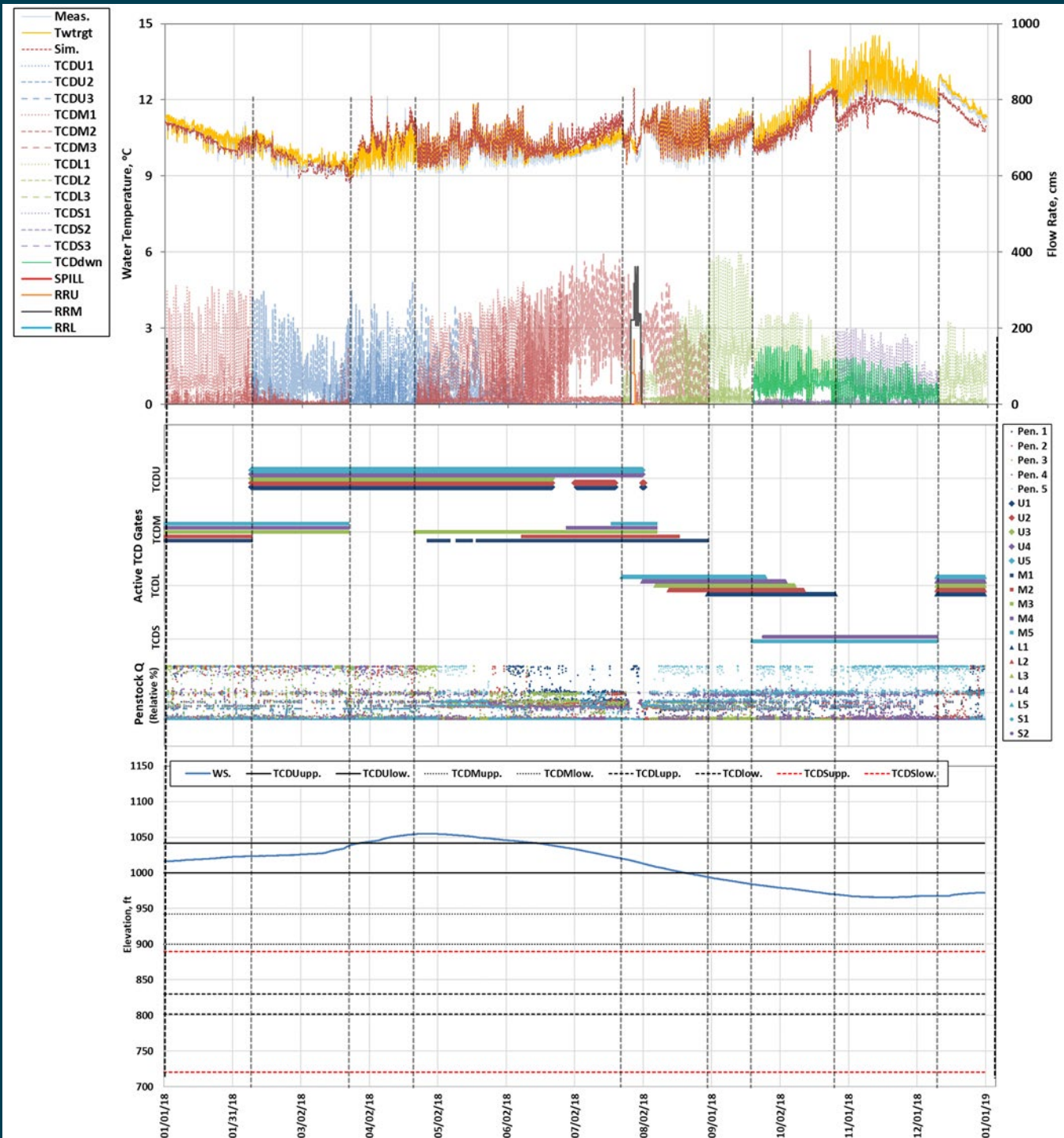






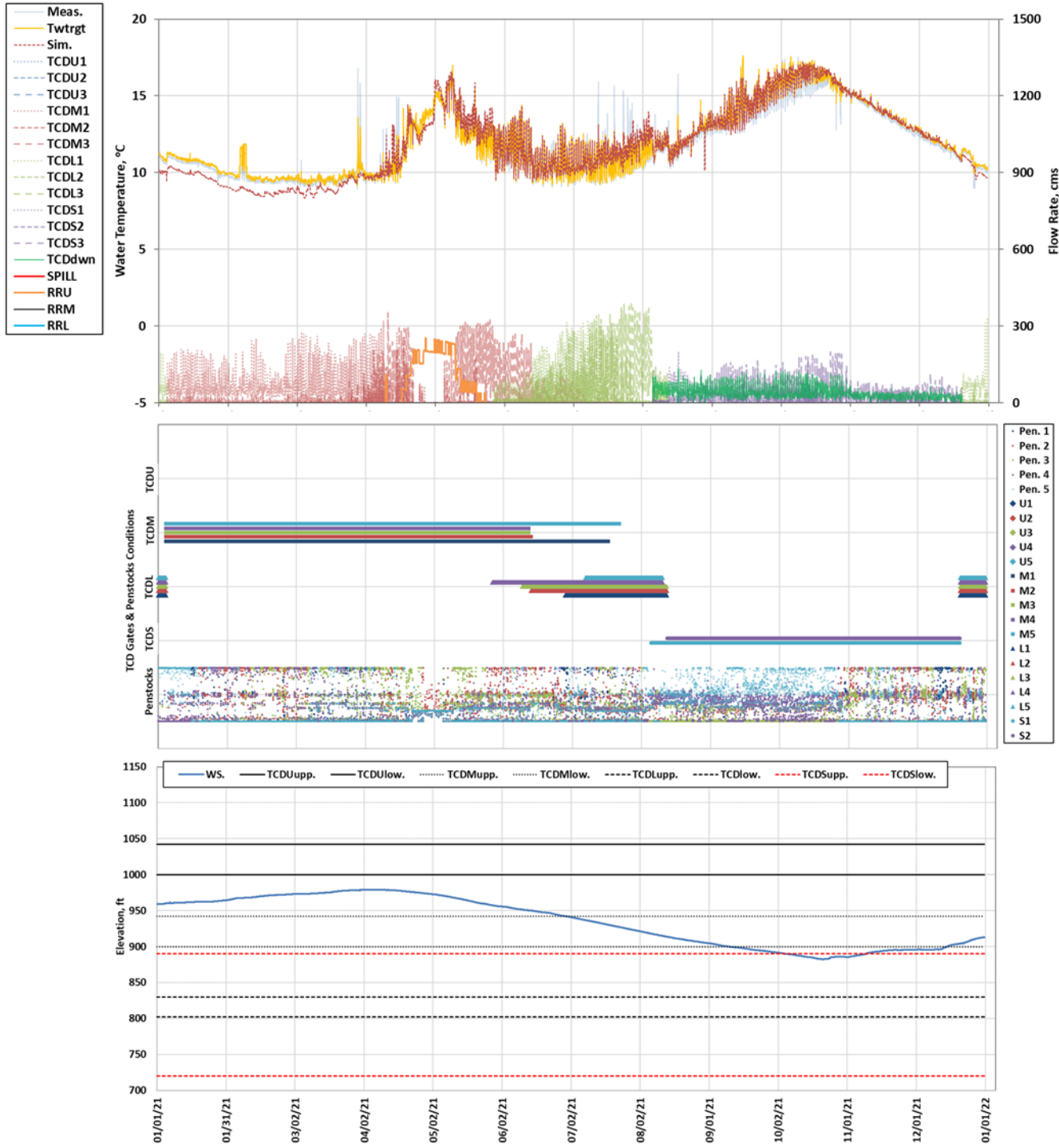
Validation: Shasta Lake Outflow Temperature 2018

- Outflow temperature
  - TCD gate operations
  - Powerhouse
  - Stage
- 2018



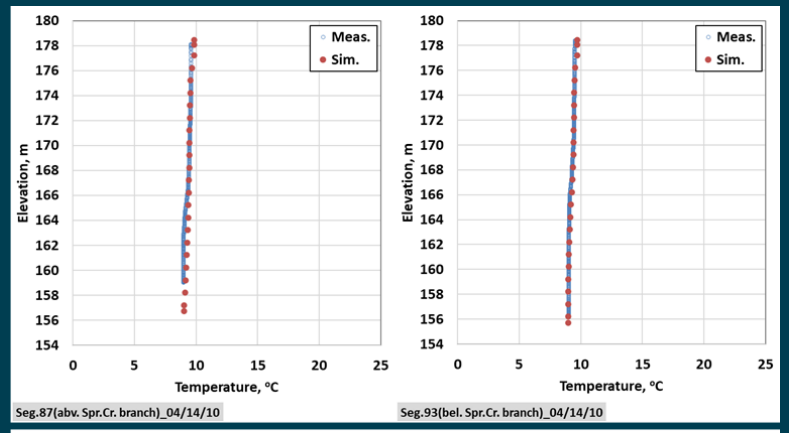
Validation: Shasta Lake Outflow Temperature 2021

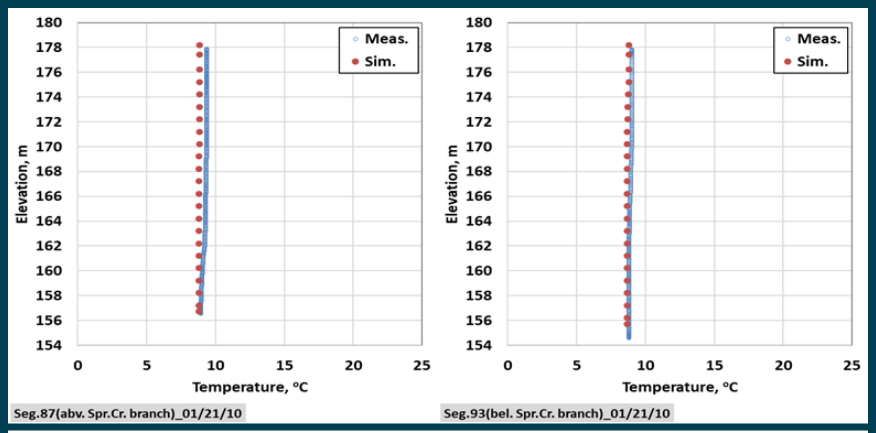
- Outflow temperature
  - TCD gate operations
  - Powerhouse
  - Stage
- 2021

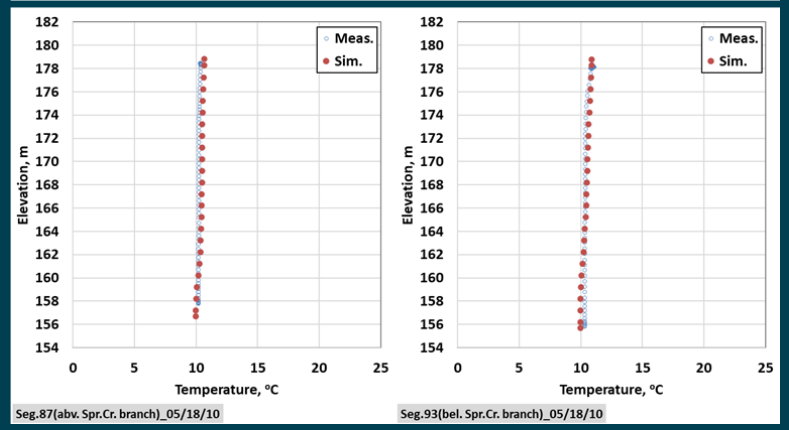


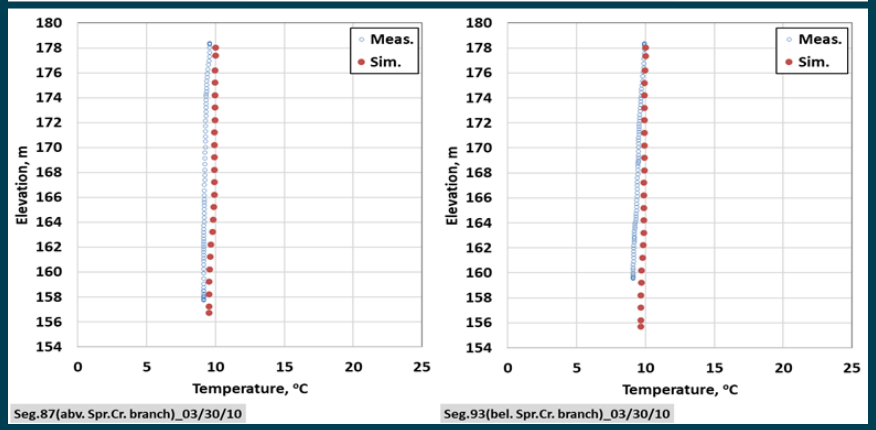
Keswick Calibration Results - CE-QUAL-W2

Results (2010)









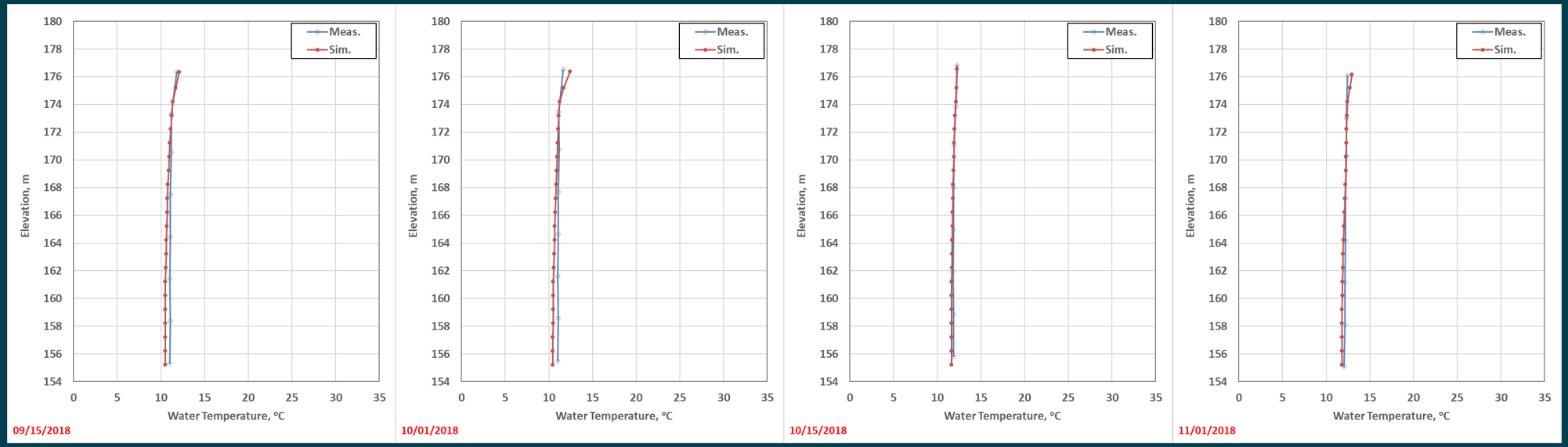
Statistic	Above Spring Ck	Below Spring Ck	Above Spring Ck	Below Spring Ck	Above Spring Ck	Below Spring Ck	Above Spring Ck	Below Spring Ck
Date	1/21/10	1/21/10	3/30/10	3/30/10	4/14/10	4/14/10	5/18/10	5/18/10
Mean Bias (°C)	-0.47	-0.24	0.57	0.37	0.09	0.02	0.16	-0.01
MAE (°C)	0.47	0.24	0.57	0.37	0.13	0.06	0.20	0.18
RMSE (°C)	0.48	0.25	0.58	0.42	0.16	0.07	0.21	0.21
Nash-Sutcliffe (NSE)	-14.02	-6.64	-14.88	-1.73	0.53	0.88	-23.14	-1.35
COUNT	20	23	21	20	19	22	21	23

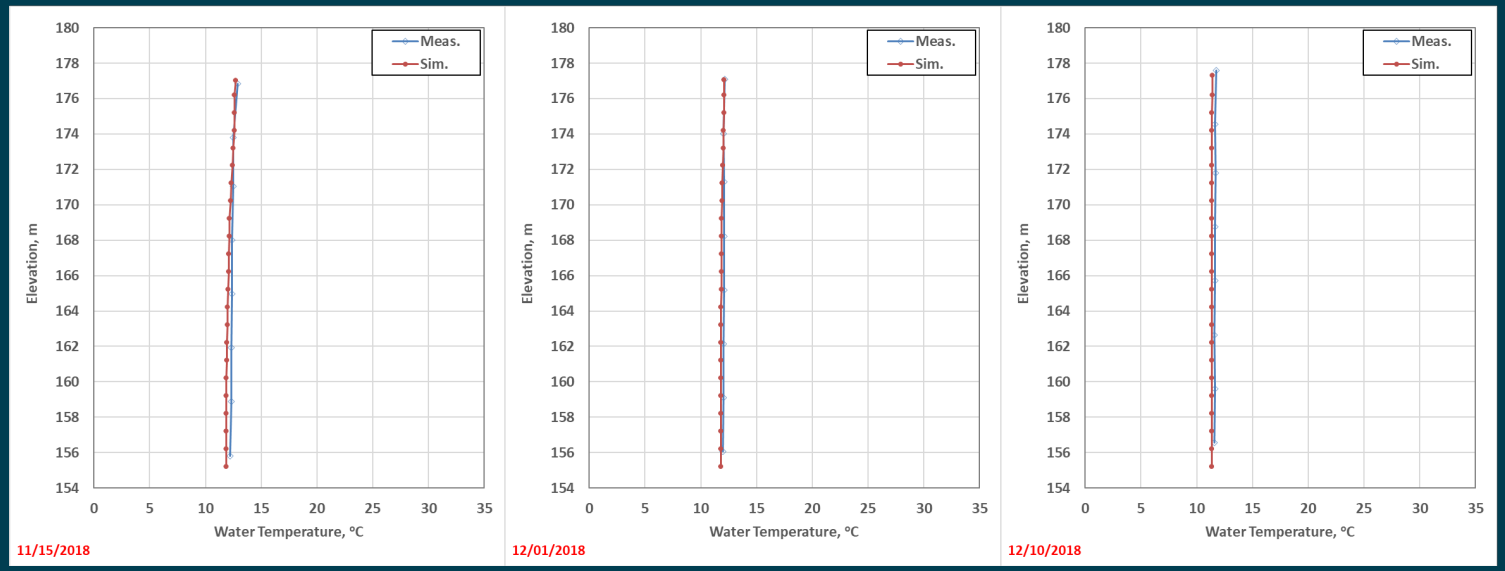
Keswick Outflow Temperature: Summary 2000-2017 (DRAFT)

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008
Mean Bias (°C)	0.01	0.01	0.07	0.00	-0.01	-0.03	0.01	0.00	0.00
MAE (°C)	0.15	0.18	0.21	0.15	0.16	0.19	0.14	0.19	0.21
RMSE (°C)	0.19	0.24	0.28	0.19	0.21	0.24	0.20	0.26	0.29
Nash-Sutcliffe (NSE)	0.96	0.97	0.94	0.94	0.98	0.96	0.96	0.96	0.98
COUNT	8,268	8,568	8,239	8,365	8,018	8,665	8,717	8,619	8,465

Statistic	2009	2010	2011	2012	2013	2014	2015	2016	2017
Mean Bias (°C)	0.01	-0.01	0.08	-0.01	0.04	0.03	0.03	-0.03	0.00
MAE (°C)	0.21	0.24	0.24	0.17	0.22	0.22	0.26	0.18	0.15
RMSE (°C)	0.29	0.32	0.32	0.23	0.33	0.29	0.34	0.23	0.21
Nash-Sutcliffe (NSE)	0.97	0.82	0.82	0.94	0.93	0.98	0.92	0.93	0.96
COUNT	8,739	8,668	8,735	8,739	8,639	8,731	8,642	8,762	8,745

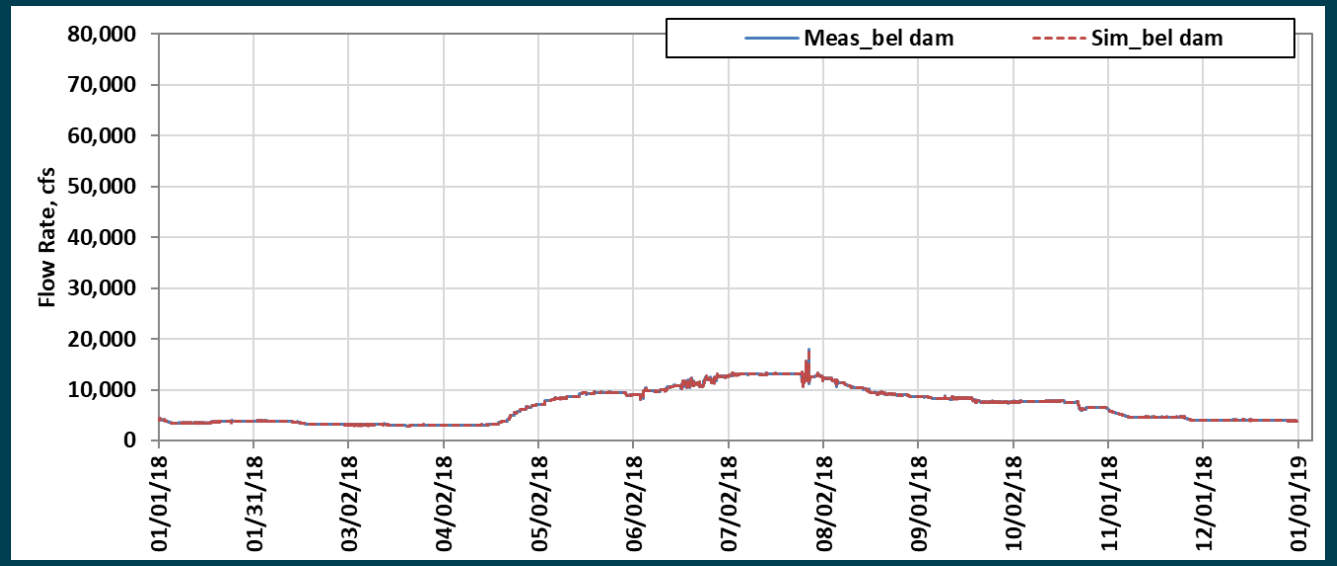
Validation: Keswick Reservoir Profiles: 2018

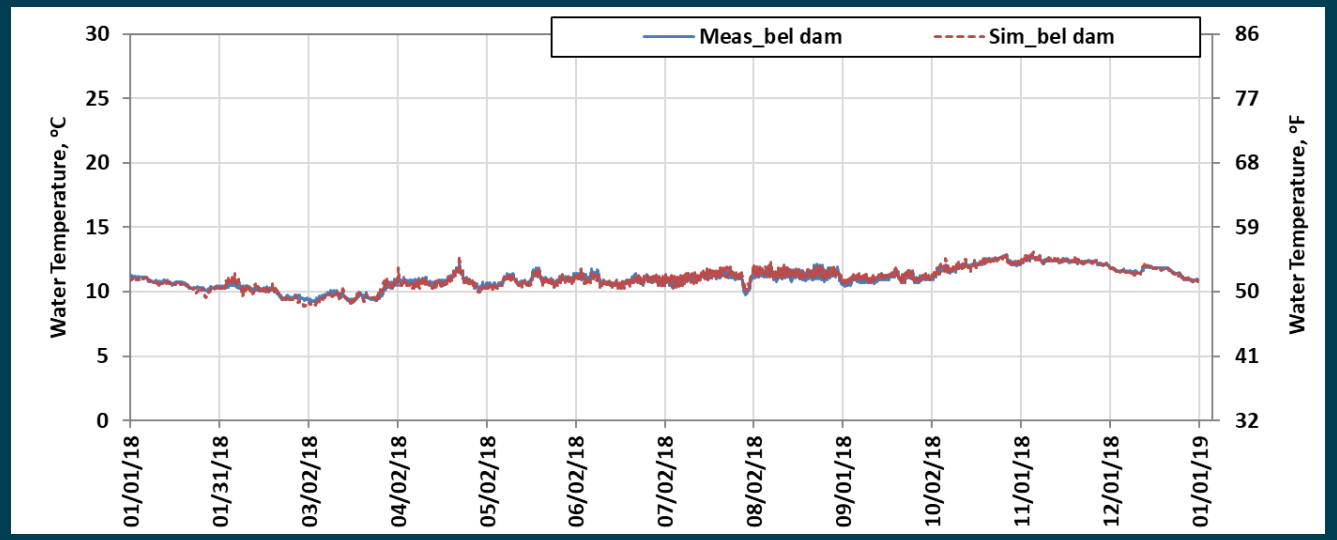




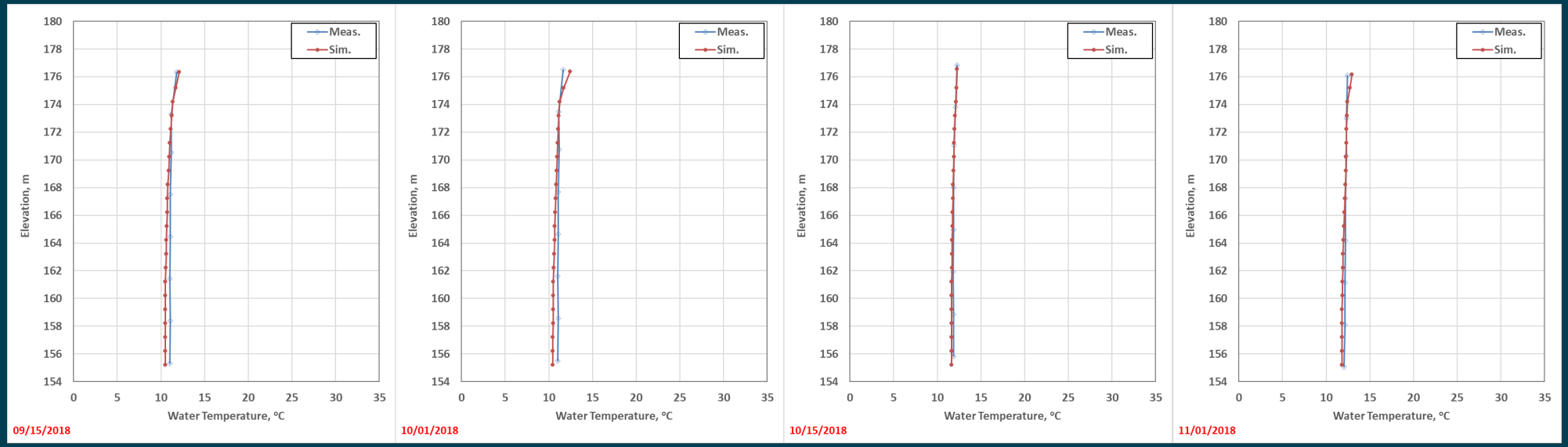
Validation: Keswick Reservoir Outflow Temperature: 2018

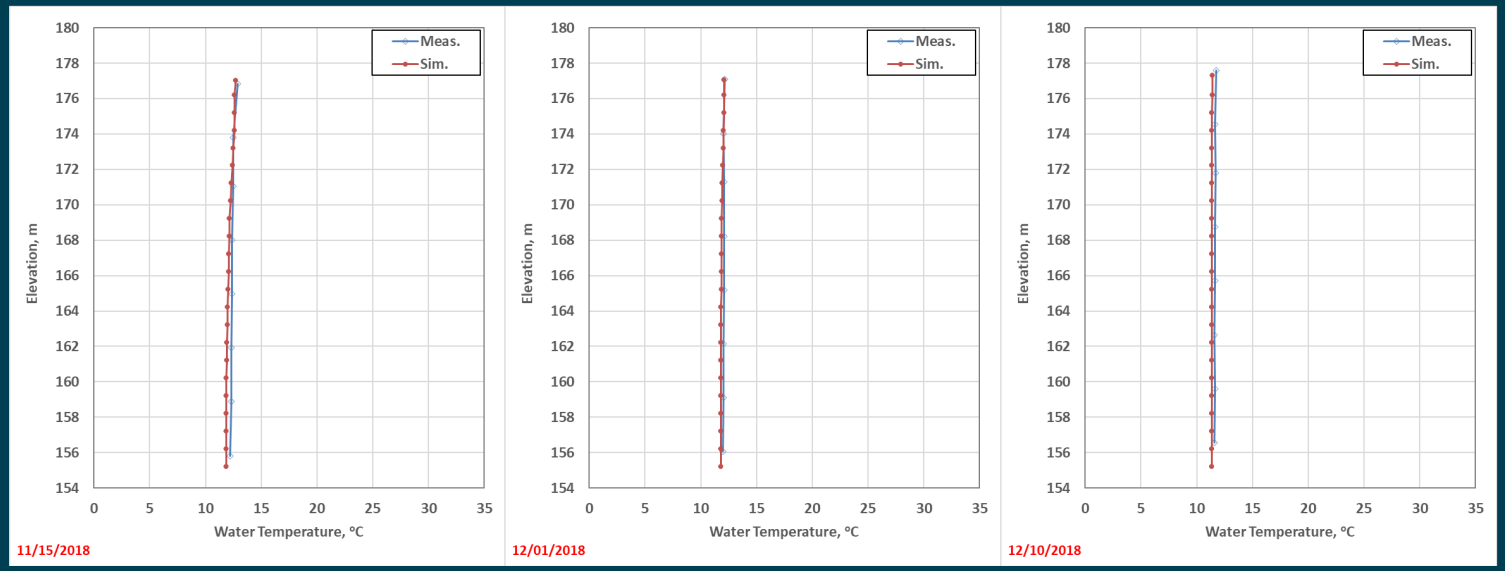
- Flow
- Temperature





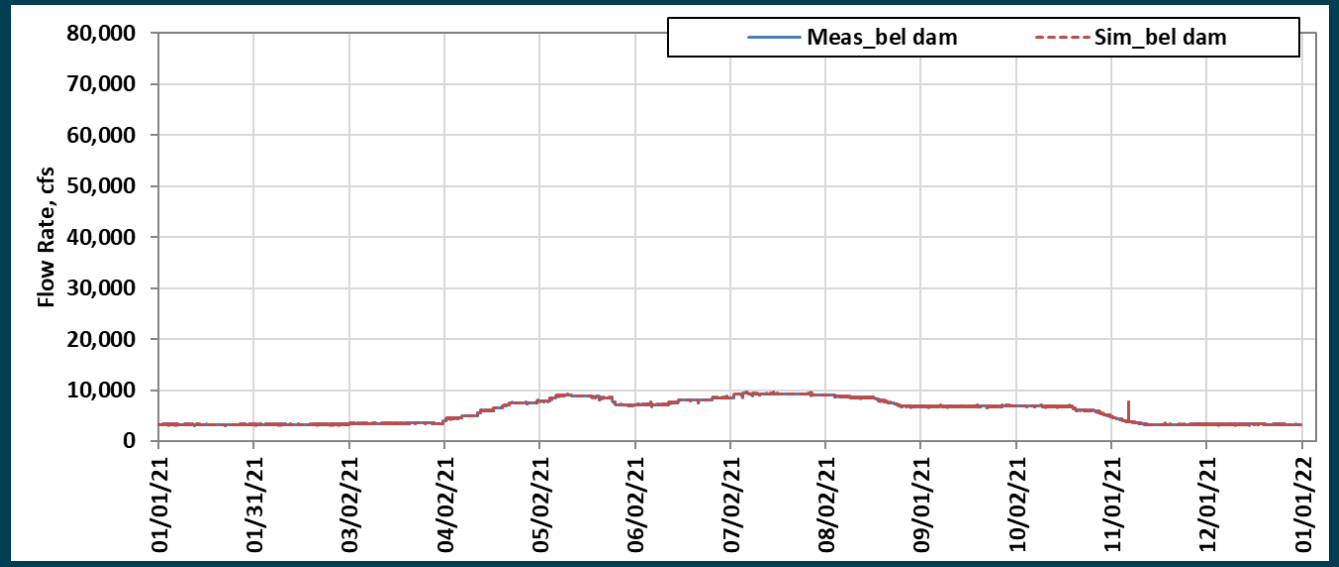
Validation: Keswick Reservoir Profiles: 2021

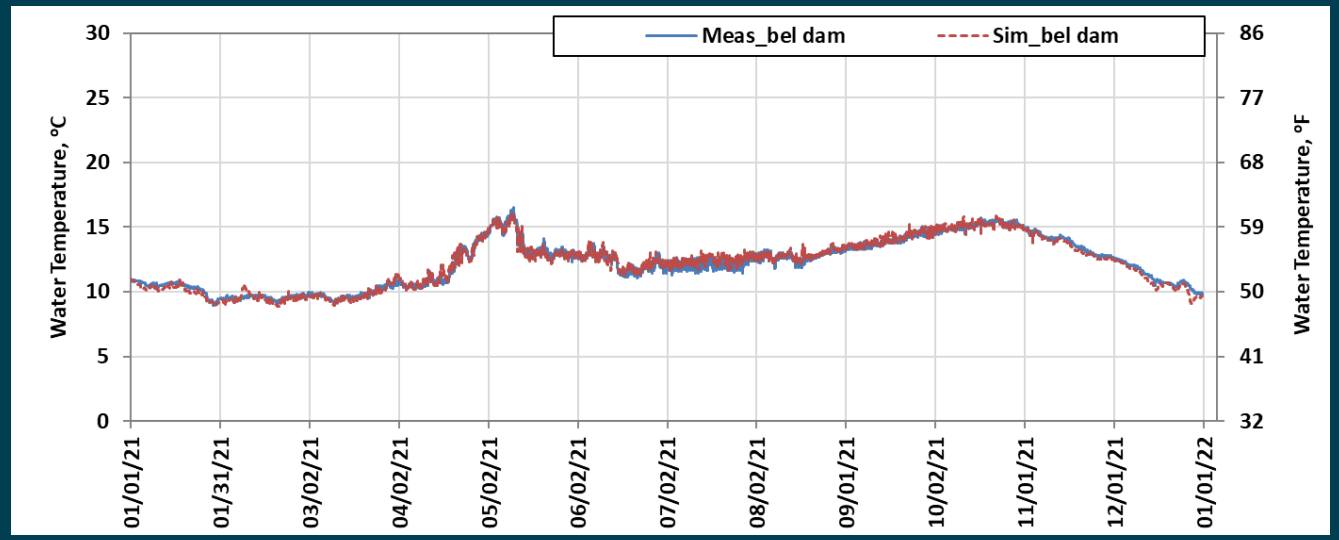




Validation: Keswick Reservoir Outflow Temperature: 2021

- Flow
- Temperature
- No Profiles for 2021





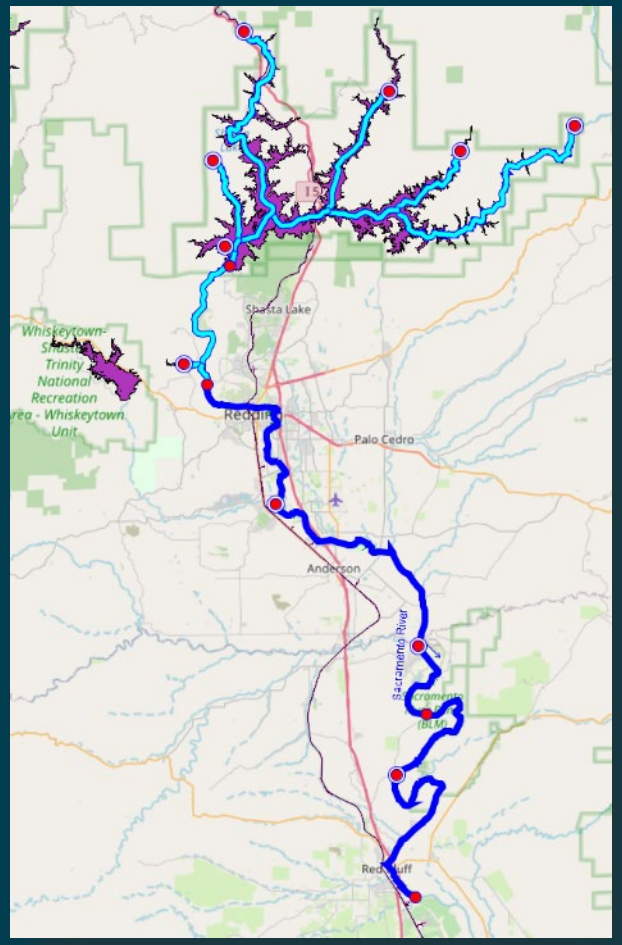
BUREAU OF RECLAMATION

Sacramento/Trinity Water Temperature Models (Part 2)

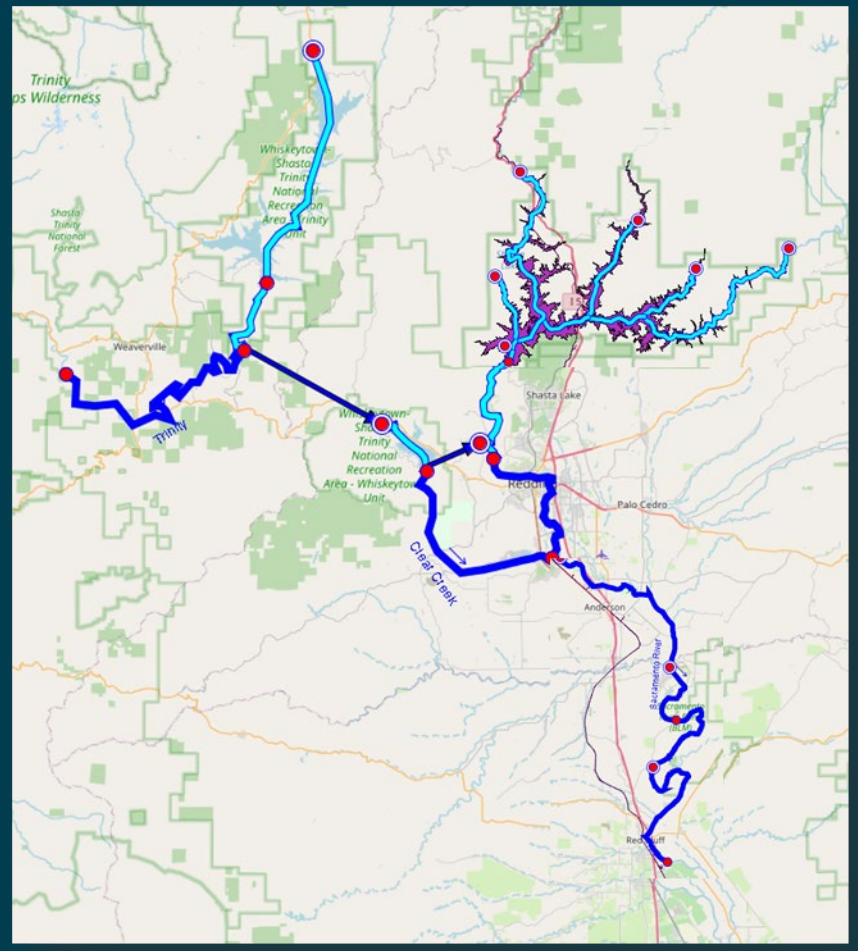
2. Upper Sacramento ResSim Model

Upper Sacramento ResSim Model

Shasta to Red Bluff



ResSim Upper Sacramento System



HEC Water Quality Transport Engine
Density Stratified Reservoirs

Vertical Diffusion and Mixing Layers

- Vertical diffusion and layer stability related to surface wind and density gradient, which is in turn a function of temperature, salinity, or suspended solids

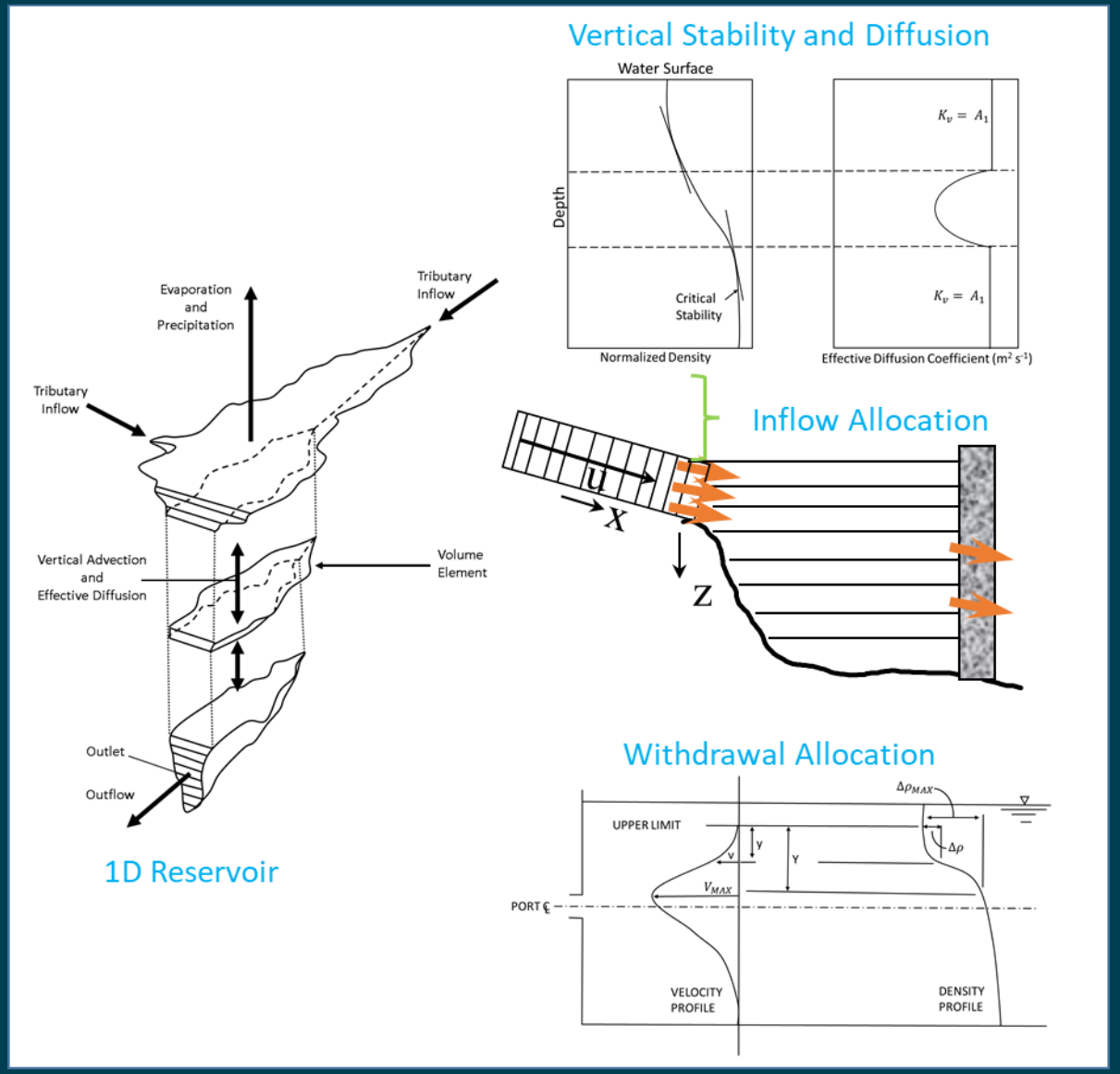
Inflow Allocation

- Determine reservoir layer with density equal to inflow density
- If in upper or lower mixed zones (epilimnion or hypolimnion), distribute over zone
- If in stratified zone, determine thickness of inflow zone

Withdrawal Allocation

- Layers from which water is withdrawn is a function of the outlet elevation and size, density distribution, and flow rate

Methodologies adapted from HEC-RAS WQ beta, ERDC CE-QUAL-R1, CE-QUAL-W2, and HEC5Q



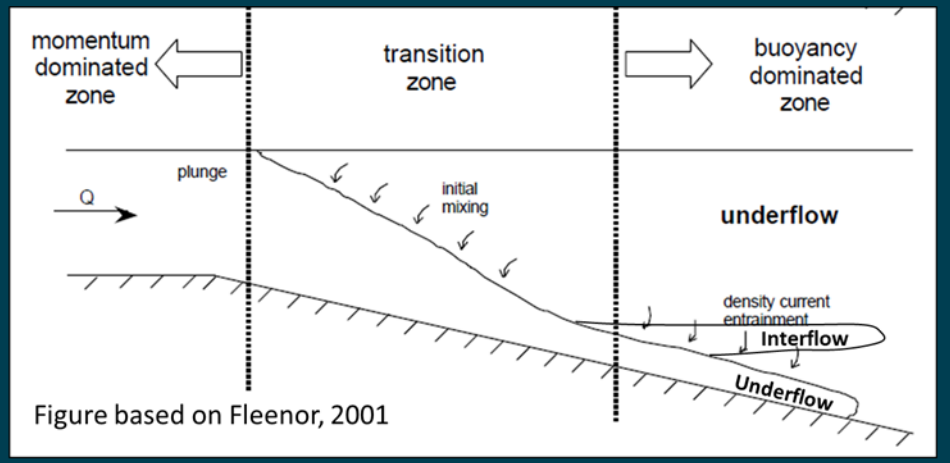
Entrainment of Inflow

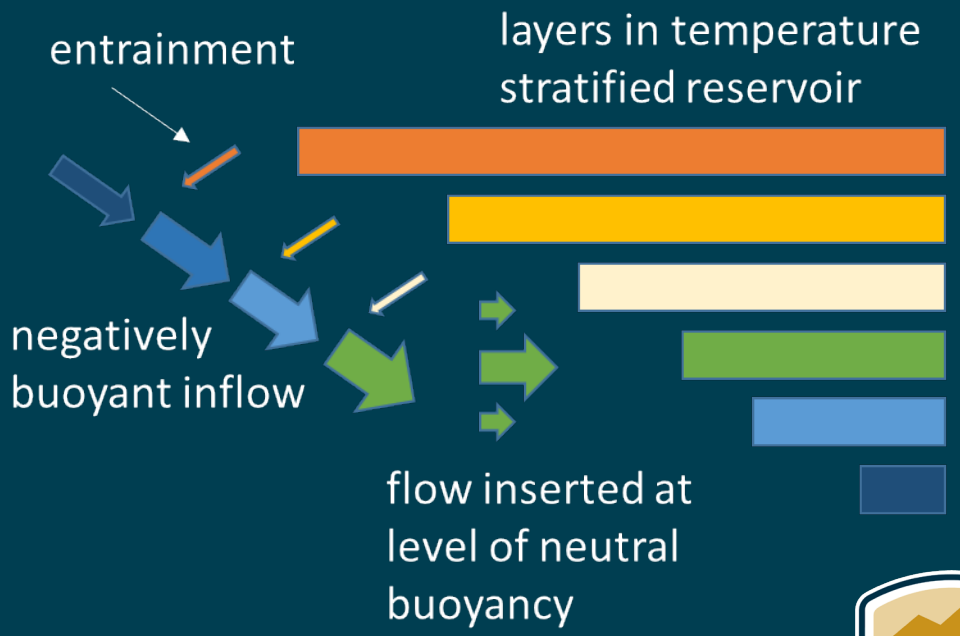
- Theoretically, when negatively buoyant inflows enter a reservoir, they flow along the submerged river valley until they reach the reservoir level with matching density
- However, as these flows pass through the upper layers of the reservoir, they entrain some fraction of the warmer water, increasing the magnitude of the inflow intrusion and decreasing the density
- This acts to transport some heat from shallower layers of the reservoir to deeper layers
- Inflow density and in-reservoir entrainment determine the density of the inflow intrusion to determine the elevation of matching density within the reservoir
- The physical process is modeled explicitly in 2D models (W2) but needs to be parameterized in 1D models (ResSim)

Entrainment of Inflow

From the top layer until either the point of neutral buoyancy or the reservoir bottom is reached:

- Update the inflow depth
- Update the inflow flow
- Update the inflow density
- At neutral density, flow is inserted using half-flow thickness calculations

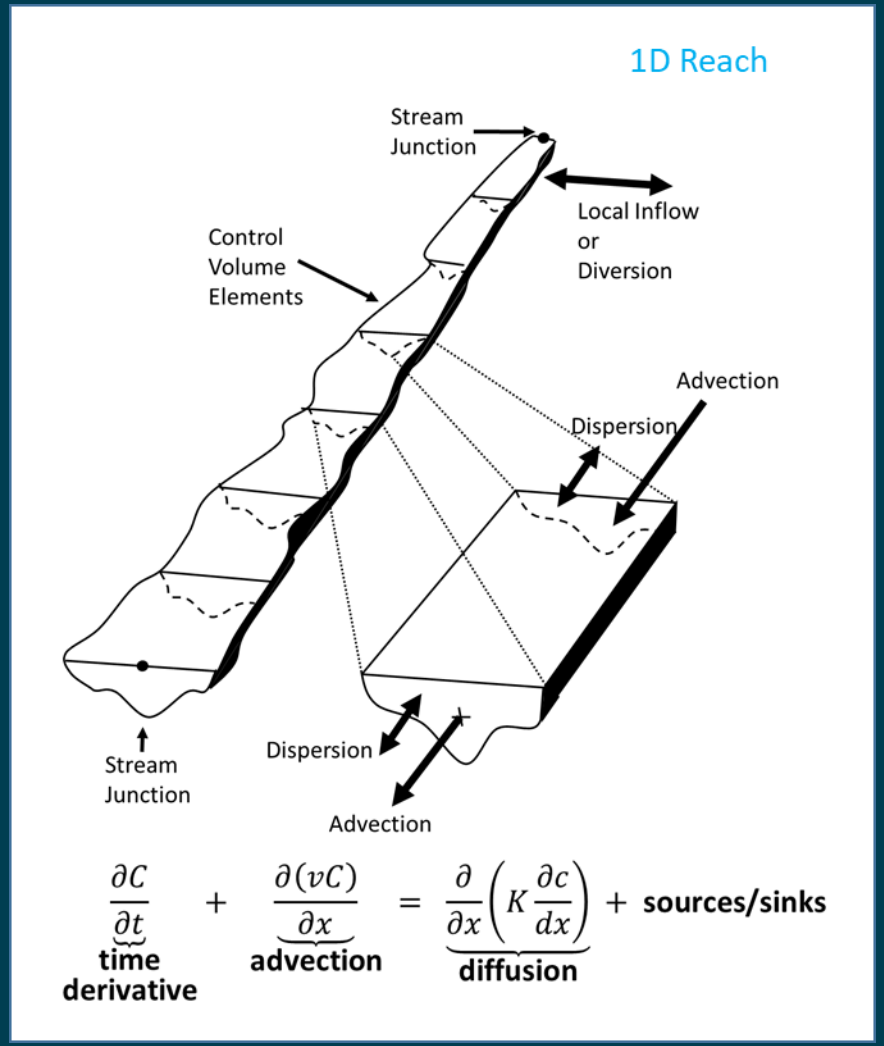




HEC Water Quality Transport Engine
River Segments

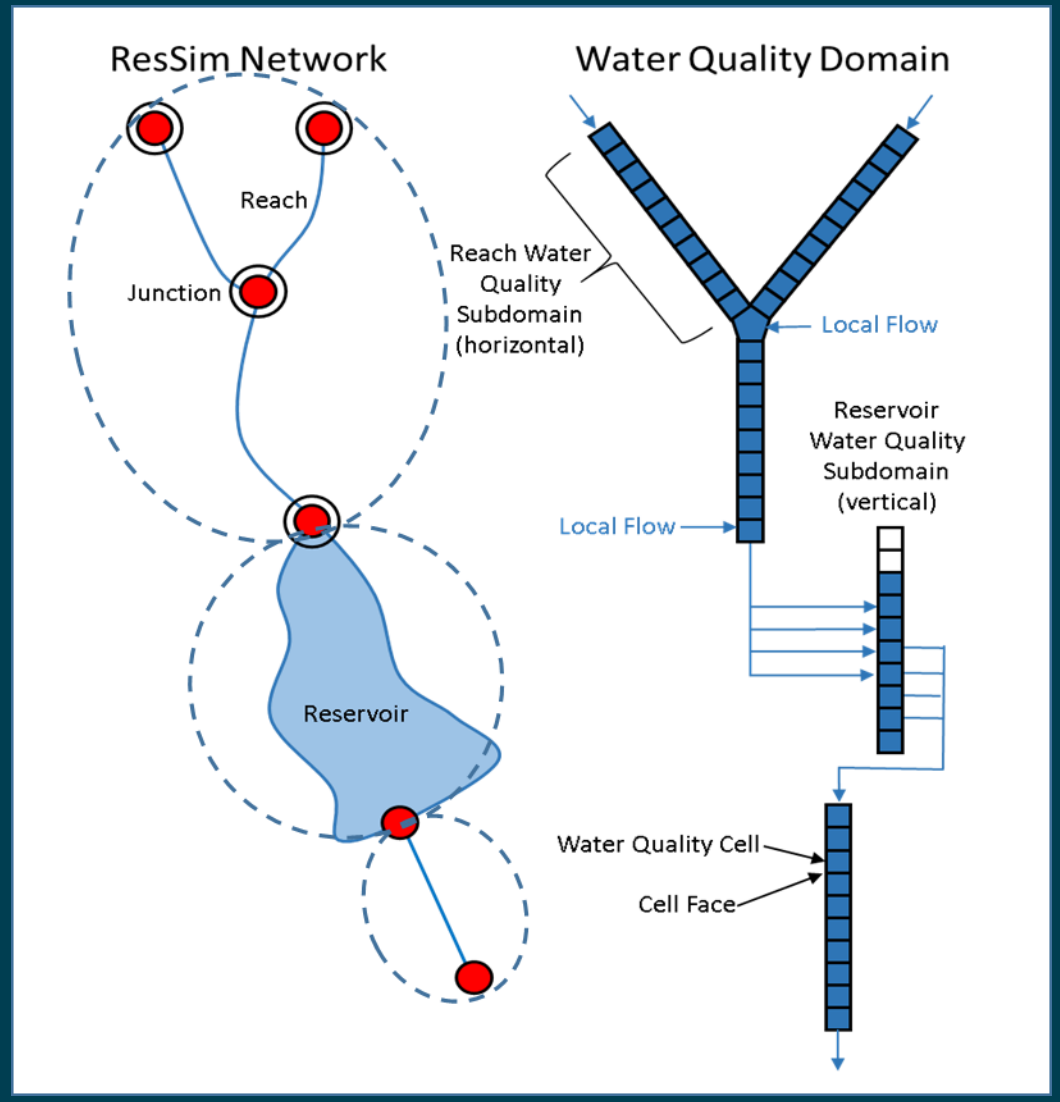
- Unsteady 1D Finite Volume Numerical Scheme
- Explicit solution scheme with sub-stepping
- Cell face concentrations determined with 1st order upwind method; 2nd order flux-limiting method in testing.
- Accept flows computed by hydraulic or hydrologic routing
- Cell geometry imported from HEC-RAS cross-sections
- Hydraulic parameter lookup tables derived from HEC-RAS flow simulations

Technical Documentation -"Generalized One-Dimensional Reservoir and River Water Quality Engine Prototype", USACE Hydrologic Engineering Center, November 2017



Model Subdomains

- An example ResSim network composed of stream reaches and a reservoir, and its corresponding discretized water quality domain



ResSim Reservoir Outlet Geometry

- Outlet Types
  - Uncontrolled Outlet
  - Controlled Outlet
  - Power Plant
  - Pump
- Hierarchical release structure
  - Total Reservoir Release
  - Dam Release
  - Diverted Outlets
  - Outlet Groups
- Multi-port Water Control Device (WCD) can be placed over any outlet or outlet group
- Intake or WCD Port specifications
  - Shape and size – circular or rectangular
  - Invert Elevation
  - Opens from – top, bottom, center

Example

Shasta Reservoir Outlet Structure

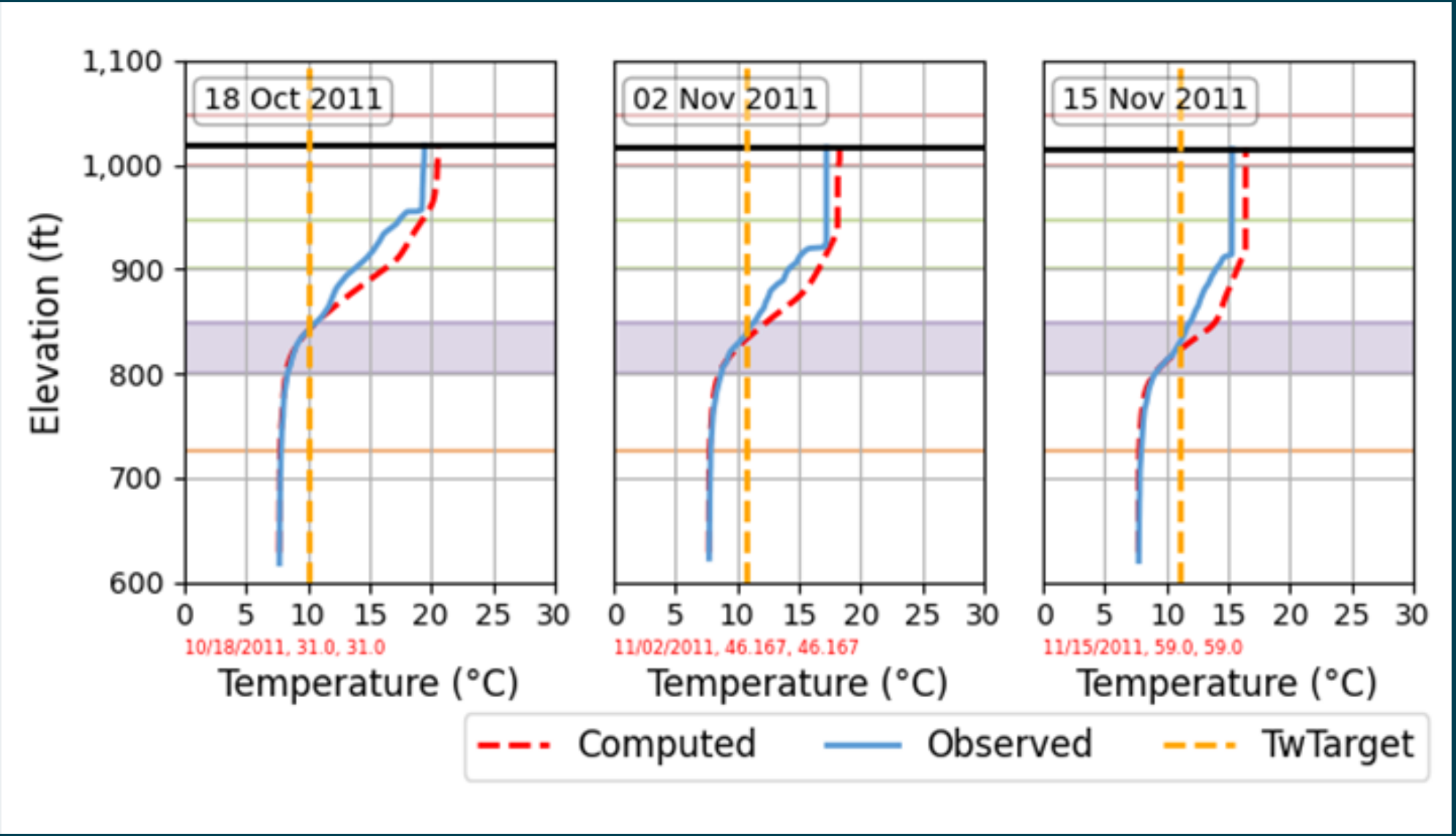
- Dam at Sacramento River
  - Spillway
  - River Outlets-Upper
  - River Outlets-Middle
  - River Outlets-Lower
  - Power Penstocks
    - TCD
      - Upper Gates
      - Middle Gates
      - Lower Gates
      - Low Level Intakes

ResSim TCD Representation

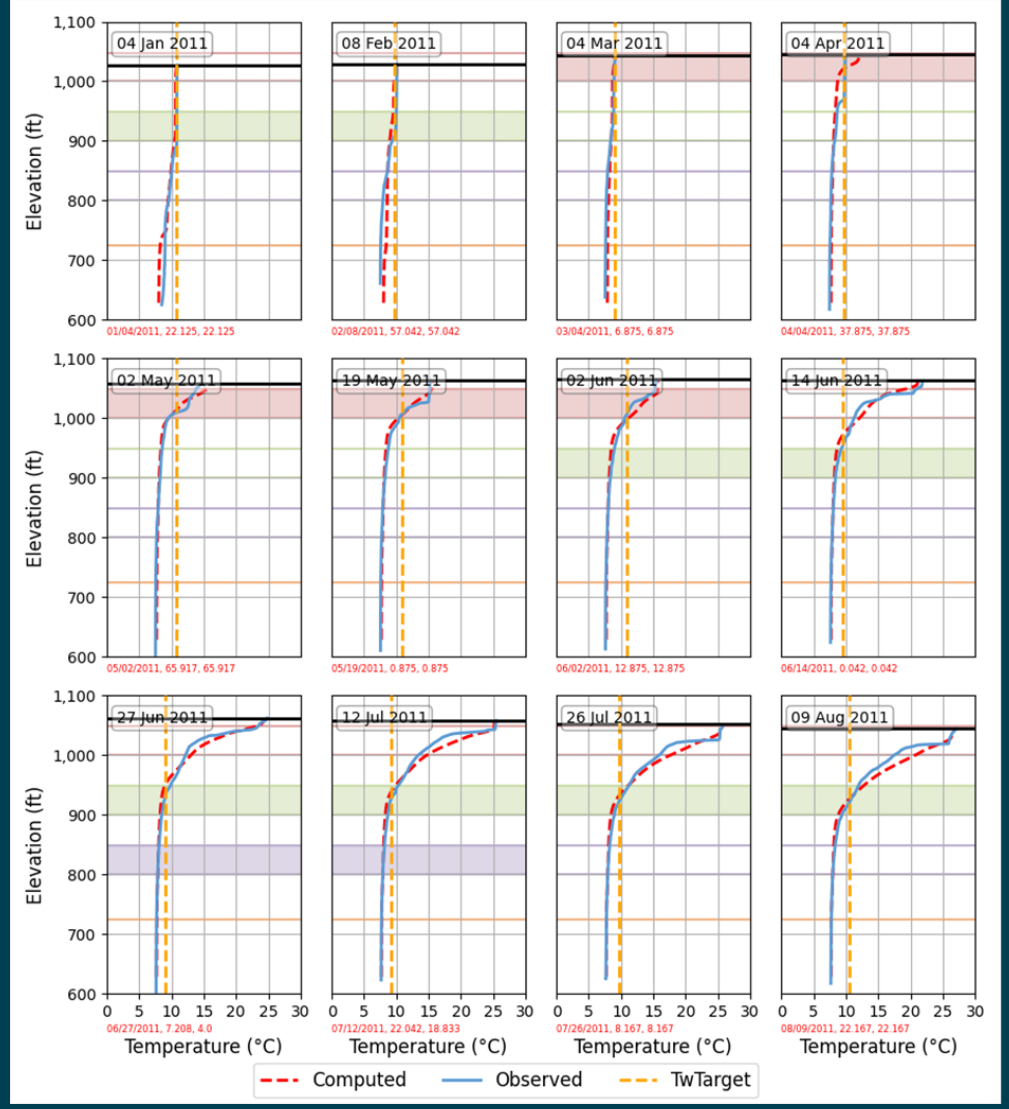
- Water Quality Control Device element of ResSim defined, customized
- Multiple withdrawal elevations defined for each level of TCD, leakage zones
- Scripted Rule (Python/Jython script) used to govern operations
  - Optimizes for flow distribution across active levels given known outflow temperature

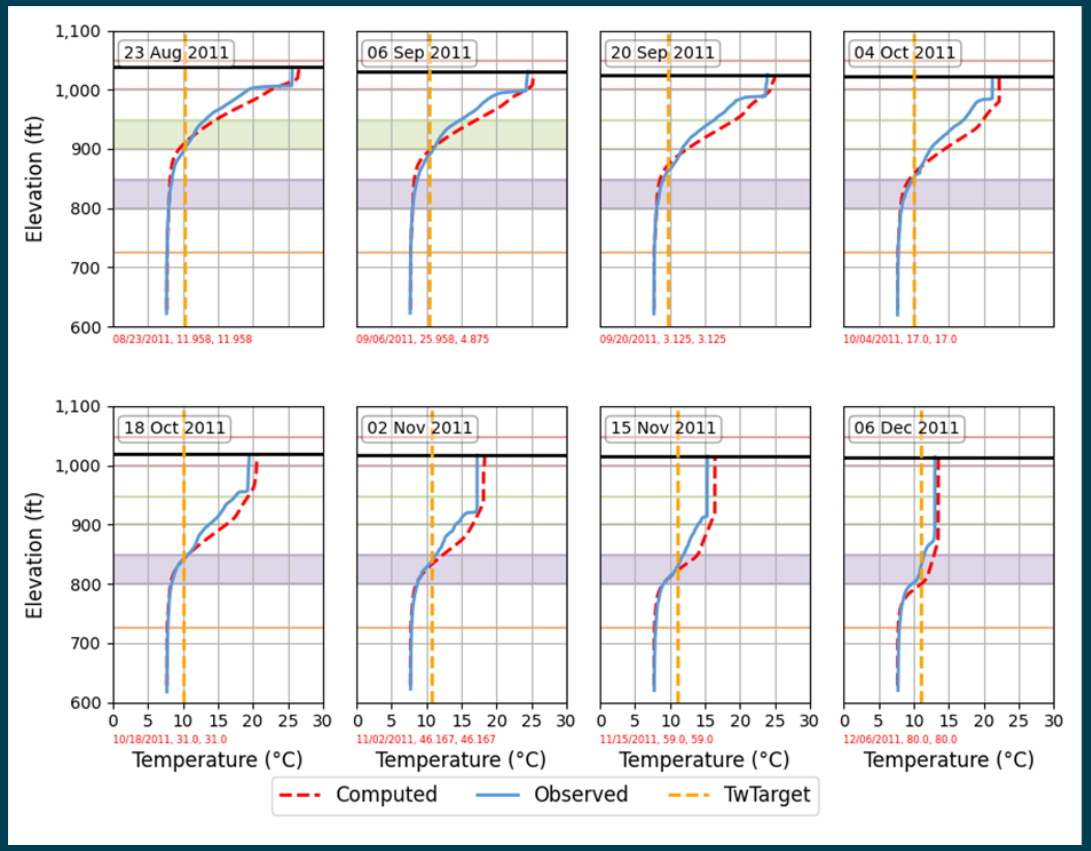
Shasta Calibration Results - ResSim

2011 (selected)



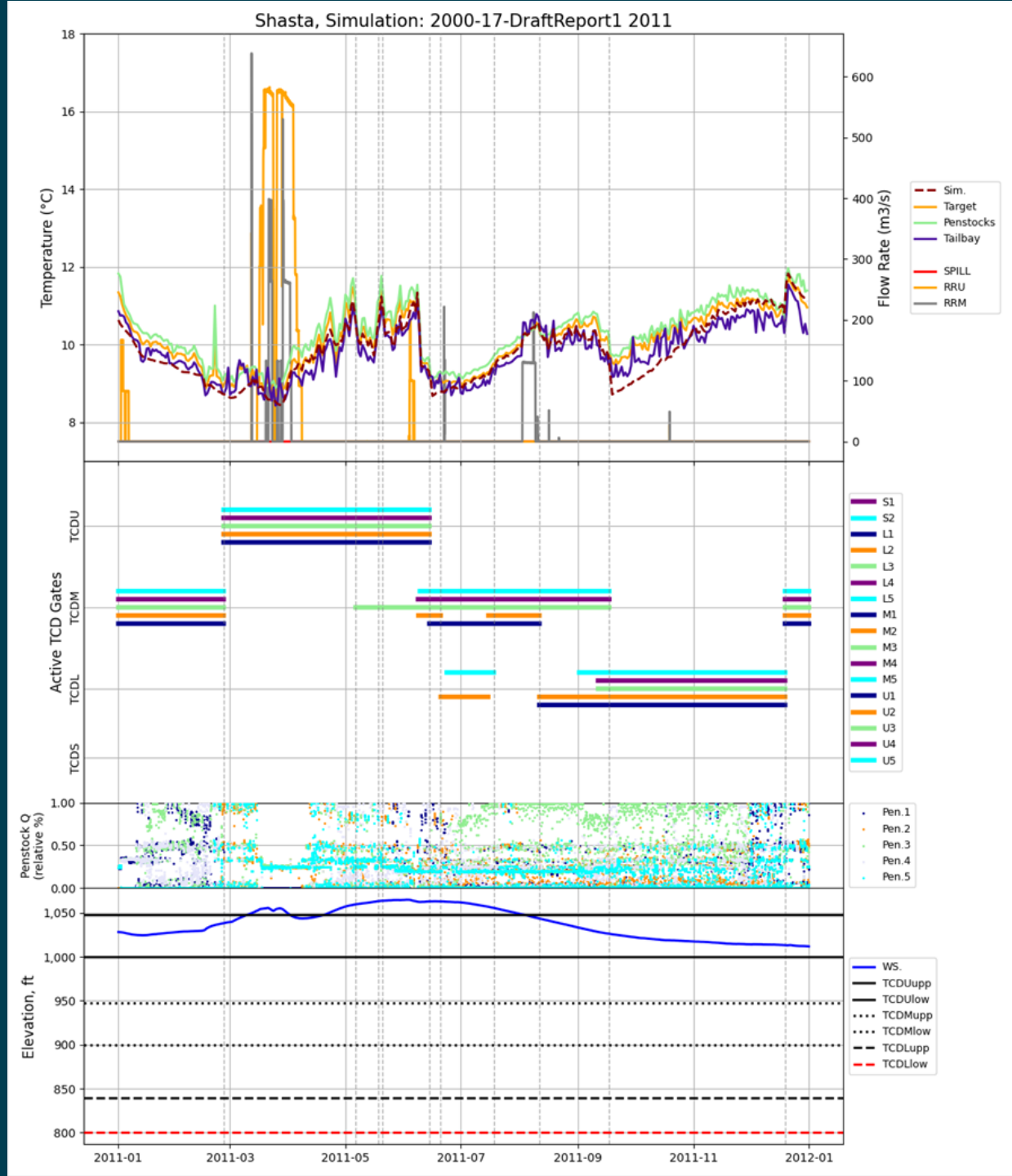
2011 (all)


04 Jan 2011
08 Feb 2011
04 Mar 2011
04 Apr 2011
02 May 2011
19 May 2011
02 Jun 2011
14 Jun 2011
27 Jun 2011
12 Jul 2011
26 Jul 2011
09 Aug 2011
Elevation (ft)
Temperature (°C)
Computed
Observed
TwTarget

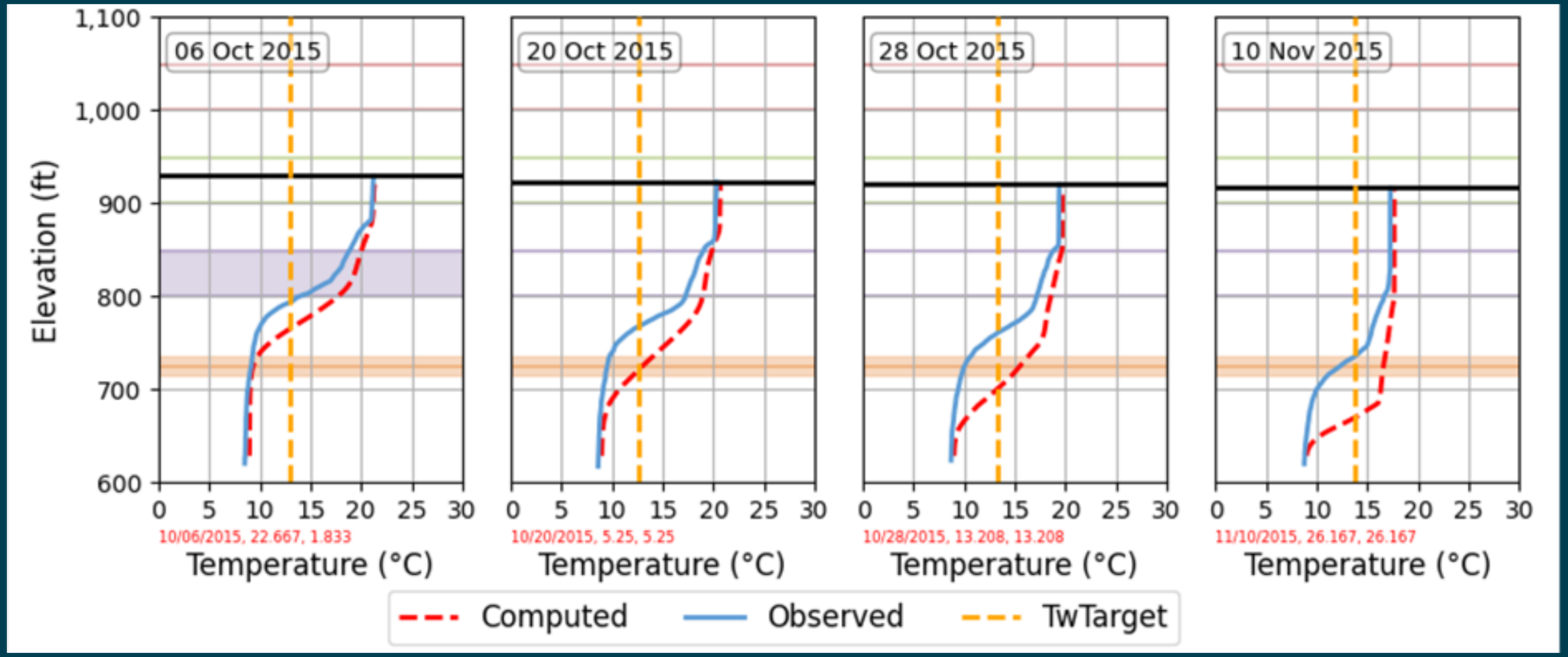

23 Aug 2011
06 Sep 2011
20 Sep 2011
04 Oct 2011
18 Oct 2011
02 Nov 2011
15 Nov 2011
06 Dec 2011
Elevation (ft)
Temperature (°C)
Computed
Observed
TwTarget

2011

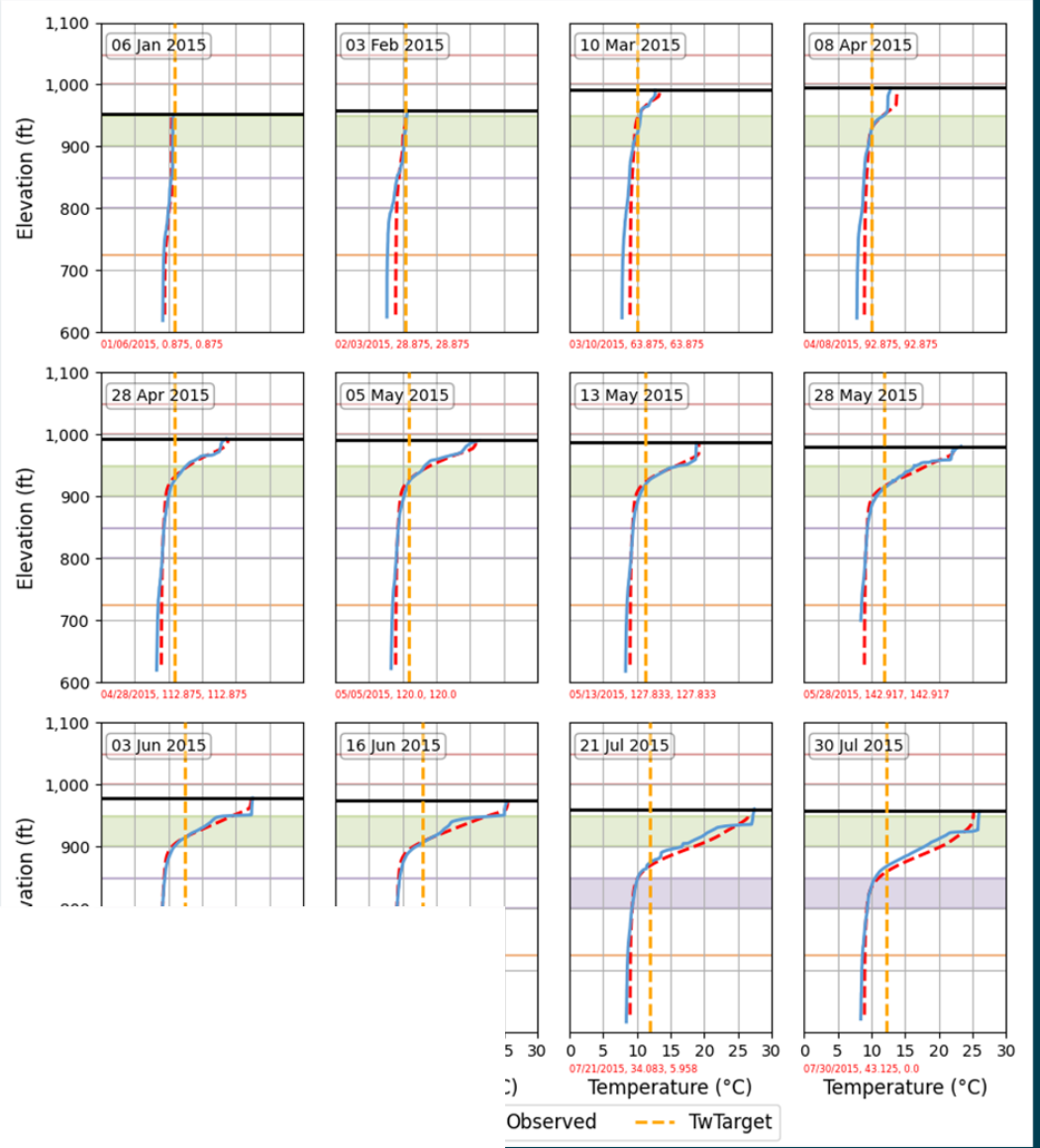
- Release temperature
- Gates
- Powerhouses
- Stage

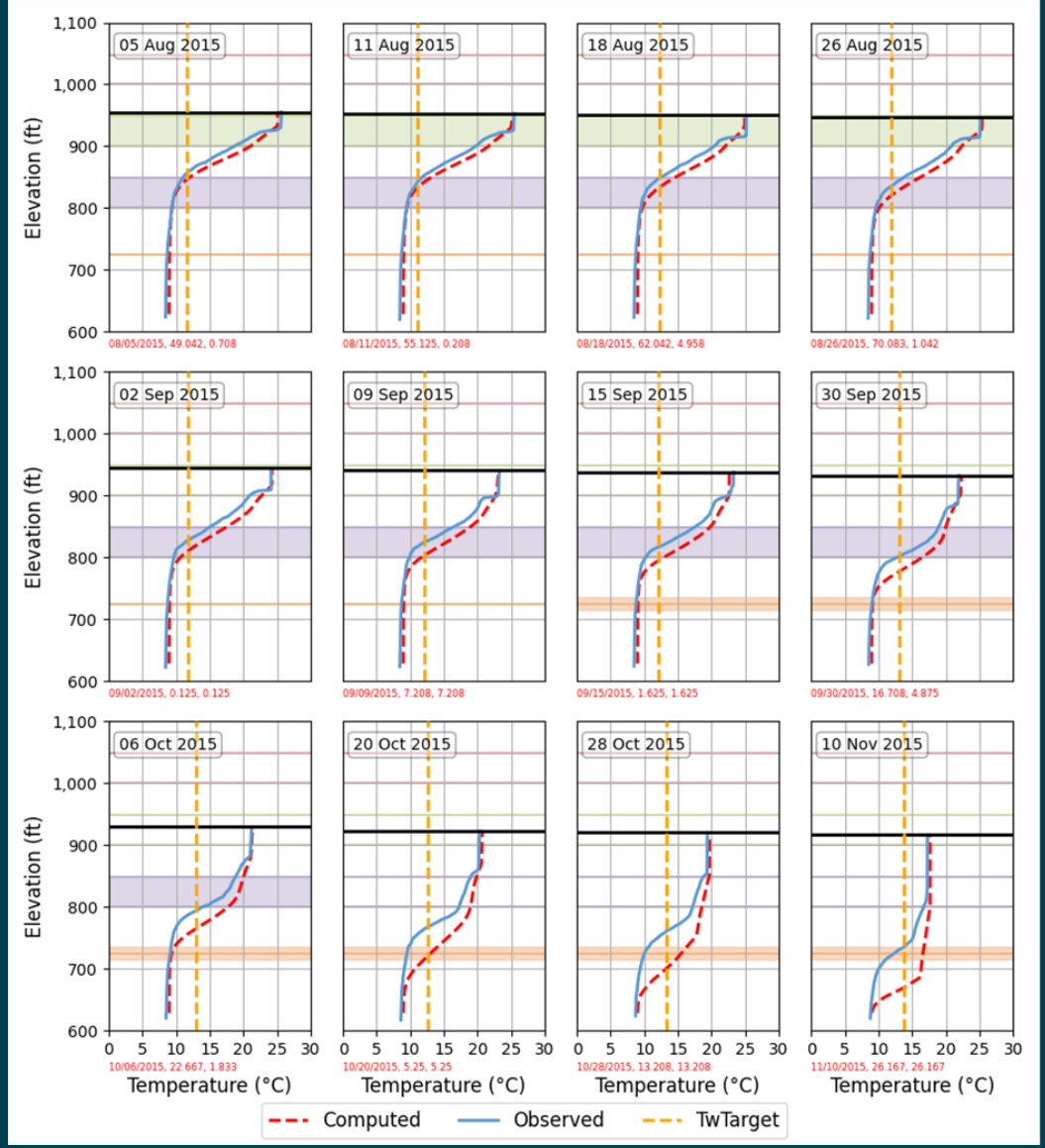


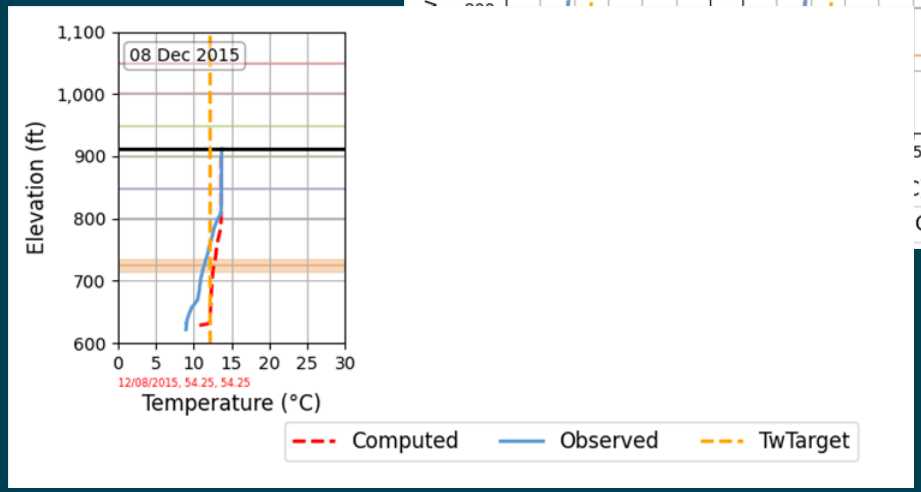
2015 (selected)



2015 (all)

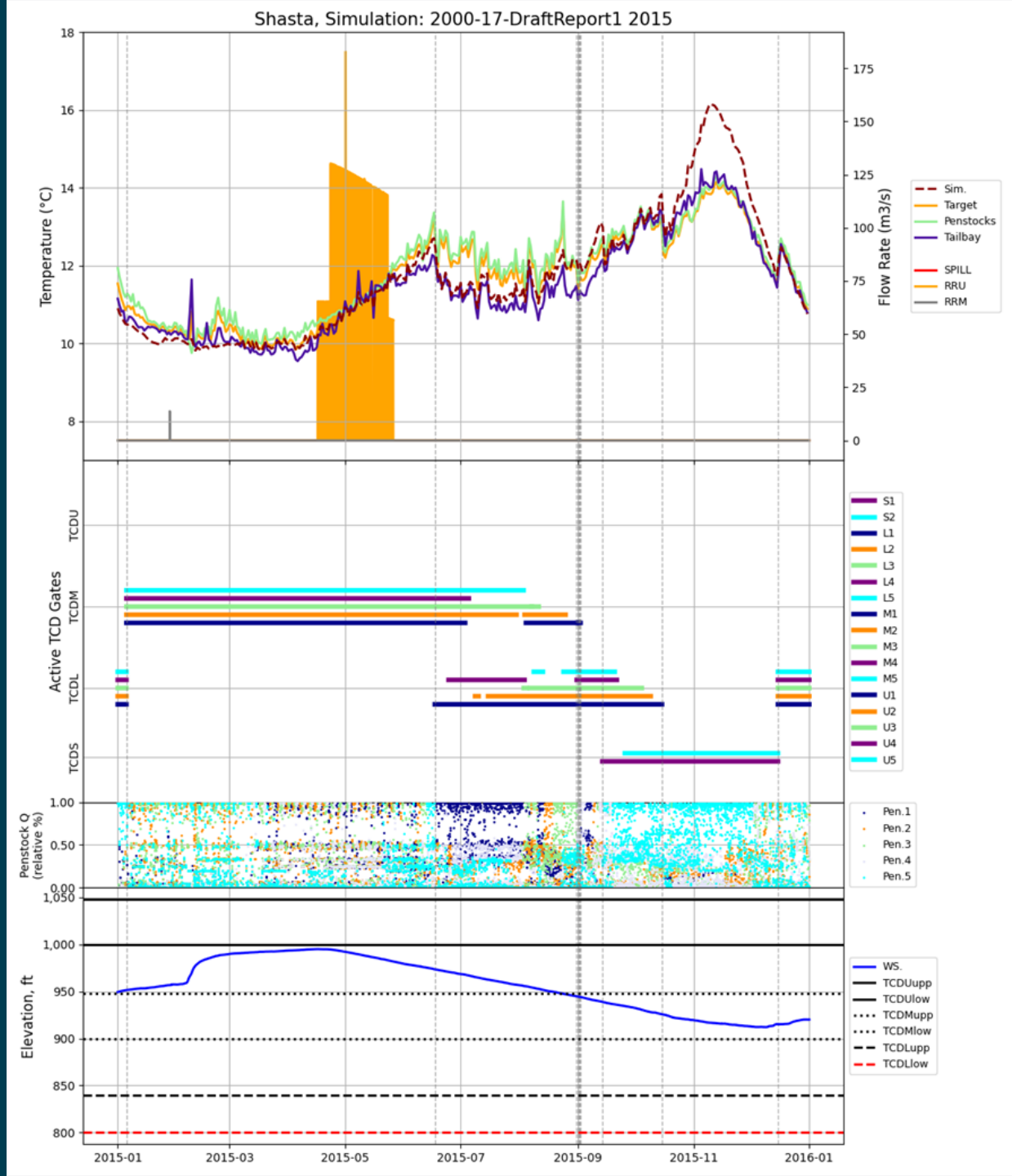

06 Jan 2015
03 Feb 2015
10 Mar 2015
08 Apr 2015
28 Apr 2015
05 May 2015
13 May 2015
28 May 2015
03 Jun 2015
16 Jun 2015
21 Jul 2015
30 Jul 2015
Elevation (ft)
Temperature (°C)
Observed
TwTarget


05 Aug 2015
11 Aug 2015
18 Aug 2015
26 Aug 2015
02 Sep 2015
09 Sep 2015
15 Sep 2015
30 Sep 2015
06 Oct 2015
20 Oct 2015
28 Oct 2015
10 Nov 2015
Elevation (ft)
Temperature (°C)
Computed
Observed
TwTarget


08 Dec 2015
Elevation (ft)
Temperature (°C)
Computed
Observed
TwTarget

2015

- Release temperature
- Gates
- Powerhouses
- Stage



Shasta profiles: Mean Bias 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.69	0.35	0.32	0.03	-0.14	0.01	0.24	0.42	0.89	1.25	0.87
2001	-	-	-	-	-0.33	-0.19	-0.15	0.02	0.16	0.29	0.26	-0.20
2002	-0.29	0.07	0.05	-0.21	-0.18	-0.27	-0.20	-0.08	-0.09	-0.05	-0.15	-
2003	-0.31	-0.04	0.07	-0.02	-0.09	-0.16	0.05	0.14	0.28	0.24	0.23	0.26
2004	-0.05	0.17	0.05	-0.01	-0.00	-0.06	-0.10	0.04	-0.03	-0.05	-0.21	-0.23
2005	-0.13	0.01	0.07	-0.06	-0.13	-0.25	-0.39	-0.18	-0.21	-0.47	-0.73	-0.63
2006	-0.31	0.01	-0.20	-0.15	-0.40	-0.39	-0.14	-0.07	-0.06	-0.32	-0.17	-0.44
2007	-0.37	-0.08	-0.05	-0.10	-0.22	-0.16	-0.16	-0.17	-0.15	-0.42	-0.44	-0.38
2008	-0.17	-0.22	-0.02	-0.05	-0.26	-0.26	-0.23	-0.18	-0.31	-0.66	-0.63	-0.16
2009	0.12	0.52	-0.08	-0.39	-0.42	-0.27	-0.19	0.01	0.20	0.07	0.31	0.51
2010	0.56	0.07	0.23	-	-0.02	-0.11	-0.06	-0.05	0.06	0.06	-0.00	-0.33
2011	-0.30	0.17	0.14	-0.03	-0.02	0.01	0.17	0.31	0.48	0.65	0.59	0.42
2012	0.39	0.52	0.45	-	-0.04	-0.05	-0.03	0.02	0.13	0.18	0.18	-
2013	0.20	0.59	0.64	0.57	0.41	-	-	0.47	0.70	0.60	0.72	0.50
2014	0.74	0.72	0.42	0.41	0.38	0.38	0.52	0.75	0.91	1.22	1.27	0.84
2015	0.09	0.69	0.59	0.42	0.17	0.19	0.48	0.67	0.96	1.61	2.04	0.93
2016	0.10	-0.15	0.02	-0.20	-0.18	-0.08	-0.01	0.11	0.25	0.34	0.25	-
2017	0.11	0.30	-	0.02	-0.09	-0.12	0.07	0.11	0.22	0.15	0.26	0.35
All	0.02	0.26	0.17	0.03	-0.07	-0.10	-0.03	0.14	0.28	0.31	0.27	0.15

Shasta profiles: Mean Absolute Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.73	0.48	0.49	0.33	0.39	0.39	0.56	0.56	0.96	1.26	1.06
2001	-	-	-	-	0.49	0.38	0.38	0.50	0.53	0.67	0.80	0.56
2002	0.29	0.45	0.41	0.54	0.38	0.44	0.46	0.38	0.40	0.31	0.37	-
2003	0.44	0.31	0.36	0.35	0.33	0.40	0.51	0.75	0.80	0.88	0.70	0.56
2004	0.21	0.52	0.44	0.30	0.36	0.43	0.52	0.64	0.85	0.79	0.57	0.65
2005	0.53	0.62	0.53	0.46	0.41	0.54	0.70	0.78	0.88	1.03	0.88	0.65
2006	0.37	0.55	0.25	0.31	0.44	0.52	0.63	0.83	0.89	0.82	0.72	0.60
2007	0.48	0.51	0.59	0.53	0.44	0.44	0.40	0.47	0.55	0.69	0.74	0.45
2008	0.39	0.25	0.48	0.42	0.42	0.36	0.46	0.61	0.71	1.33	1.03	0.68
2009	0.67	0.67	0.20	0.61	0.56	0.52	0.61	0.71	0.93	1.12	0.93	0.76
2010	0.60	0.31	0.33	-	0.28	0.32	0.40	0.52	0.66	0.80	0.77	0.54
2011	0.34	0.49	0.24	0.34	0.22	0.30	0.38	0.54	0.68	0.77	0.70	0.51
2012	0.44	0.52	0.54	-	0.40	0.33	0.30	0.32	0.31	0.27	0.28	-
2013	0.29	0.61	0.82	0.64	0.63	-	-	0.53	0.72	0.60	0.73	0.53
2014	0.77	0.73	0.79	0.59	0.58	0.59	0.62	0.81	0.92	1.24	1.32	0.85
2015	0.20	0.78	0.70	0.52	0.37	0.43	0.66	0.76	1.01	1.61	2.04	0.96
2016	0.29	0.40	0.35	0.36	0.33	0.44	0.49	0.55	0.60	0.62	0.53	-
2017	0.17	0.46	-	0.29	0.34	0.42	0.50	0.62	0.71	0.49	0.54	0.58
All	0.41	0.54	0.46	0.45	0.40	0.42	0.49	0.61	0.72	0.82	0.78	0.66

Shasta profiles: Root Mean Square Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.88	0.58	0.57	0.40	0.55	0.54	0.77	0.75	1.11	1.69	1.31
2001	-	-	-	-	0.89	0.58	0.51	0.69	0.75	0.82	0.92	0.64
2002	0.41	0.51	0.47	0.94	0.52	0.68	0.66	0.51	0.52	0.39	0.48	-
2003	0.51	0.37	0.43	0.42	0.44	0.58	0.80	1.06	1.14	1.10	0.82	0.66
2004	0.29	0.54	0.48	0.35	0.52	0.69	0.79	0.91	1.05	0.94	0.75	0.70
2005	0.59	0.66	0.60	0.57	0.48	0.74	0.96	1.09	1.17	1.36	1.35	1.07
2006	0.43	0.58	0.34	0.44	0.78	0.77	0.94	1.17	1.16	0.99	0.86	0.77
2007	0.54	0.57	0.64	0.69	0.57	0.59	0.54	0.63	0.74	1.01	1.20	0.67
2008	0.43	0.33	0.58	0.66	0.77	0.54	0.68	0.86	0.86	1.67	1.55	0.98
2009	0.77	0.75	0.28	0.81	0.78	0.72	0.84	0.97	1.12	1.21	0.97	0.84
2010	0.74	0.33	0.40	-	0.43	0.48	0.64	0.82	0.92	1.00	0.91	0.74
2011	0.43	0.56	0.26	0.51	0.34	0.53	0.80	1.03	1.20	1.27	1.02	0.68
2012	0.62	0.57	0.62	-	0.57	0.46	0.41	0.46	0.47	0.44	0.37	-
2013	0.40	0.79	0.90	0.75	0.70	-	-	0.62	0.83	0.81	1.02	0.71
2014	0.98	0.88	0.87	0.67	0.69	0.74	0.72	0.99	1.13	1.47	1.75	1.14
2015	0.20	0.93	0.80	0.64	0.48	0.64	0.98	1.05	1.42	2.29	2.90	1.30
2016	0.36	0.49	0.43	0.49	0.41	0.69	0.82	0.81	0.88	0.85	0.73	-
2017	0.19	0.49	-	0.47	0.53	0.75	0.92	1.02	1.10	0.70	0.68	0.69
All	0.53	0.65	0.57	0.62	0.58	0.64	0.77	0.90	1.02	1.17	1.15	0.89

Shasta profiles: Nash Sutcliffe Efficiency 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	-0.30	0.65	0.90	0.96	0.98	0.99	0.98	0.98	0.93	0.52	0.22
2001	-	-	-	-	0.92	0.98	0.99	0.99	0.98	0.97	0.93	0.70
2002	0.50	0.66	0.71	0.83	0.97	0.97	0.99	0.99	0.99	0.99	0.98	-
2003	0.76	0.72	0.75	0.88	0.93	0.97	0.97	0.95	0.95	0.93	0.91	0.88
2004	0.86	0.56	0.55	0.97	0.97	0.97	0.98	0.97	0.96	0.95	0.94	0.72
2005	0.61	0.50	0.74	0.81	0.95	0.95	0.95	0.95	0.94	0.87	0.72	0.59
2006	0.81	0.60	0.66	0.70	0.87	0.95	0.95	0.95	0.94	0.94	0.94	0.90
2007	0.74	0.66	0.53	0.84	0.96	0.98	0.99	0.99	0.99	0.95	0.83	0.87
2008	0.77	0.68	0.67	0.75	0.92	0.98	0.98	0.98	0.98	0.88	0.74	0.78
2009	0.65	0.38	0.71	0.77	0.89	0.97	0.97	0.97	0.96	0.92	0.90	0.83
2010	0.44	0.72	0.60	-	0.94	0.97	0.98	0.97	0.96	0.95	0.91	0.81
2011	0.74	0.71	0.78	0.62	0.97	0.96	0.96	0.96	0.94	0.92	0.92	0.91
2012	0.74	0.47	0.51	-	0.94	0.98	0.99	0.99	0.99	0.99	0.99	-
2013	0.85	0.42	0.40	0.76	0.95	-	-	0.99	0.98	0.97	0.90	0.72
2014	0.33	0.07	0.55	0.84	0.95	0.97	0.98	0.97	0.96	0.89	0.66	0.43
2015	0.88	0.24	0.56	0.89	0.98	0.98	0.97	0.97	0.93	0.77	0.27	0.29
2016	0.81	0.67	0.77	0.93	0.96	0.96	0.97	0.98	0.97	0.97	0.95	-
2017	0.96	0.66	-	0.88	0.96	0.96	0.96	0.96	0.96	0.97	0.96	0.91
All	0.75	0.53	0.67	0.87	0.95	0.97	0.97	0.97	0.96	0.94	0.88	0.79

Shasta outflow temperature: Mean Bias 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.62	0.07	0.09	0.02	-0.15	-0.01	-0.01	0.01	0.00	0.17	0.30
2001	-0.03	-0.47	-0.34	-0.20	-0.08	0.02	-0.02	-0.14	0.02	-0.24	-0.14	-0.16
2002	-0.68	-0.50	-0.19	0.01	-0.04	-0.02	0.01	-0.01	-0.02	0.01	-0.00	-0.24
2003	-0.42	-0.37	0.08	0.08	-0.14	-0.61	-0.82	-0.19	-0.01	-0.00	0.00	-0.01
2004	-0.37	-0.51	-0.12	0.00	-0.05	0.00	-0.02	-0.16	0.00	0.00	-0.05	-0.46
2005	-0.82	-0.61	0.00	-0.01	0.01	0.07	-0.46	-1.11	-0.40	-0.12	-0.15	-0.41
2006	-0.67	-0.52	-0.46	-0.26	0.00	-0.09	-0.03	-0.62	-0.60	-0.09	-0.00	-0.33
2007	-0.81	-0.64	-0.34	-0.00	0.02	0.02	0.01	-0.08	-0.02	-0.05	-0.12	-0.02
2008	-0.25	-0.47	-0.52	-0.01	-0.05	-0.06	0.01	-0.01	-0.15	-0.18	-0.14	-0.00
2009	-0.23	-0.15	-0.20	-0.31	0.00	-0.00	0.01	-0.13	0.01	-0.00	-0.00	0.07
2010	-0.28	-0.34	-0.02	-0.00	0.04	-0.12	-0.05	-0.46	-0.78	-0.43	-0.06	-0.27
2011	-0.37	-0.32	-0.31	0.02	0.04	-0.14	-0.00	0.01	-0.28	-0.40	-0.01	0.15
2012	0.07	0.00	0.03	-0.06	0.10	0.01	0.03	-0.13	-0.10	0.02	-0.00	-0.14
2013	-0.29	-0.17	0.06	0.30	0.02	0.03	0.02	0.11	0.04	0.00	0.00	-0.16
2014	-0.19	-0.04	-0.01	-0.01	0.00	0.02	0.07	0.01	0.00	0.04	0.28	-0.25
2015	-0.38	-0.37	-0.10	-0.01	-0.01	0.12	0.05	0.31	0.26	0.11	1.22	0.10
2016	-0.44	-0.38	-0.04	0.18	0.08	0.01	0.07	0.13	-0.16	-0.00	0.00	0.21
2017	-0.03	-0.28	-0.21	0.05	0.01	-0.00	0.00	0.01	-0.11	-0.07	-0.03	0.19
All	-0.36	-0.31	-0.15	-0.01	-0.00	-0.05	-0.06	-0.14	-0.13	-0.08	0.05	-0.08

Shasta outflow T: Mean Absolute Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.62	0.14	0.12	0.02	0.16	0.05	0.04	0.02	0.00	0.17	0.30
2001	0.06	0.47	0.35	0.25	0.12	0.02	0.05	0.15	0.02	0.24	0.14	0.21
2002	0.70	0.50	0.20	0.05	0.05	0.05	0.01	0.03	0.04	0.01	0.00	0.28
2003	0.42	0.37	0.10	0.08	0.18	0.61	0.82	0.19	0.01	0.00	0.00	0.07
2004	0.37	0.51	0.14	0.01	0.05	0.00	0.05	0.18	0.00	0.00	0.05	0.46
2005	0.82	0.61	0.00	0.01	0.02	0.07	0.50	1.11	0.40	0.12	0.15	0.41
2006	0.67	0.52	0.47	0.27	0.01	0.11	0.04	0.62	0.60	0.09	0.00	0.33
2007	0.81	0.64	0.35	0.08	0.02	0.02	0.01	0.11	0.05	0.05	0.12	0.02
2008	0.25	0.47	0.52	0.01	0.05	0.06	0.01	0.02	0.15	0.18	0.14	0.00
2009	0.26	0.18	0.21	0.32	0.00	0.00	0.01	0.16	0.02	0.00	0.00	0.07
2010	0.31	0.34	0.02	0.03	0.05	0.14	0.06	0.47	0.78	0.44	0.06	0.28
2011	0.39	0.32	0.31	0.08	0.09	0.15	0.01	0.02	0.29	0.40	0.01	0.18
2012	0.17	0.09	0.08	0.09	0.14	0.02	0.03	0.16	0.12	0.02	0.00	0.27
2013	0.30	0.17	0.11	0.31	0.02	0.03	0.02	0.11	0.04	0.00	0.01	0.18
2014	0.19	0.04	0.03	0.02	0.01	0.06	0.07	0.01	0.00	0.05	0.29	0.31
2015	0.38	0.37	0.10	0.02	0.02	0.12	0.05	0.31	0.26	0.11	1.22	0.25
2016	0.44	0.38	0.08	0.18	0.11	0.01	0.07	0.13	0.16	0.01	0.00	0.22
2017	0.28	0.30	0.21	0.06	0.08	0.00	0.00	0.01	0.11	0.07	0.03	0.19
All	0.40	0.38	0.19	0.11	0.06	0.09	0.10	0.21	0.17	0.10	0.13	0.22

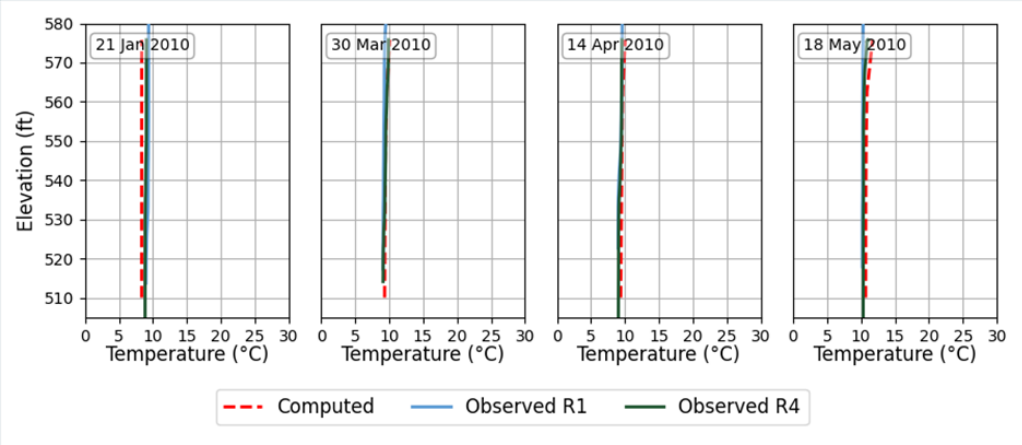
Shasta outflow T: Root Mean Square Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.66	0.27	0.32	0.04	0.22	0.11	0.13	0.05	0.00	0.34	0.39
2001	0.12	0.49	0.46	0.35	0.21	0.03	0.16	0.26	0.03	0.48	0.27	0.32
2002	0.74	0.55	0.29	0.10	0.08	0.09	0.03	0.08	0.10	0.02	0.02	0.45
2003	0.45	0.42	0.20	0.17	0.26	0.66	0.85	0.32	0.05	0.02	0.00	0.12
2004	0.42	0.55	0.28	0.02	0.09	0.02	0.17	0.32	0.01	0.01	0.16	0.64
2005	0.84	0.64	0.01	0.04	0.03	0.08	0.82	1.16	0.42	0.19	0.20	0.47
2006	0.70	0.57	0.49	0.35	0.04	0.18	0.10	0.89	0.68	0.14	0.00	0.39
2007	0.86	0.69	0.51	0.17	0.03	0.02	0.03	0.20	0.13	0.15	0.21	0.05
2008	0.31	0.61	0.88	0.06	0.14	0.13	0.02	0.08	0.36	0.34	0.24	0.03
2009	0.39	0.26	0.37	0.58	0.00	0.00	0.02	0.29	0.03	0.03	0.02	0.13
2010	0.44	0.53	0.05	0.06	0.12	0.22	0.13	0.68	0.84	0.54	0.21	0.36
2011	0.41	0.42	0.41	0.17	0.17	0.34	0.06	0.05	0.47	0.50	0.03	0.30
2012	0.29	0.21	0.17	0.18	0.24	0.04	0.06	0.29	0.21	0.03	0.02	0.36
2013	0.37	0.24	0.25	0.58	0.02	0.06	0.06	0.22	0.13	0.02	0.05	0.23
2014	0.27	0.10	0.08	0.06	0.04	0.18	0.15	0.02	0.02	0.18	0.35	0.40
2015	0.40	0.52	0.20	0.09	0.08	0.32	0.09	0.51	0.45	0.31	1.35	0.32
2016	0.50	0.44	0.17	0.31	0.28	0.02	0.13	0.24	0.29	0.02	0.00	0.34
2017	0.37	0.37	0.28	0.17	0.15	0.03	0.00	0.02	0.32	0.18	0.10	0.29
All	0.50	0.49	0.36	0.27	0.14	0.22	0.29	0.44	0.35	0.25	0.36	0.35

Keswick Calibration Results - ResSim

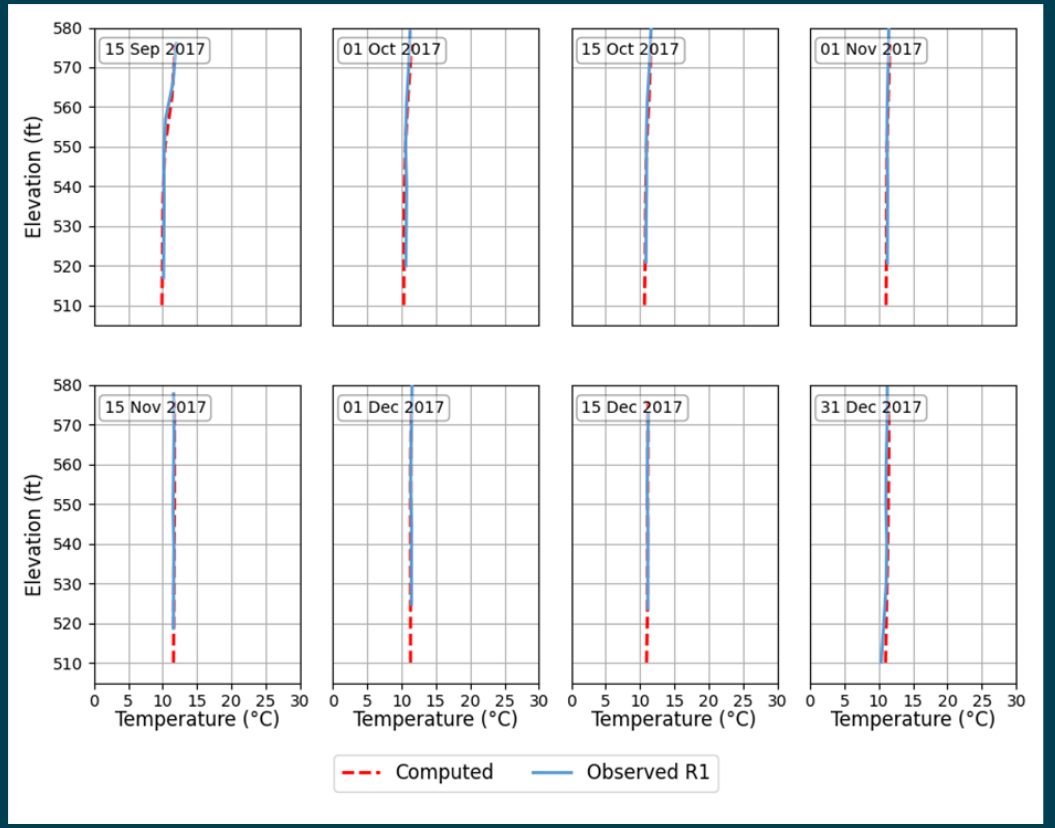
- TBD

Results (2010)



Statistics	21Jan2010	30Mar2010	14Apr2010	18May2010
Mean Bias (°C)	-0.91	0.32	0.29	0.62
MAE (°C)	0.91	0.32	0.29	0.62
RMSE (°C)	0.92	0.35	0.32	0.66
Nash-Sutcliffe (NSE)	-41.49	-21.14	-0.84	-661.14

Results (2017)



Statistics	15Sep2017	01Oct2017	15Oct2017	01Nov2017	15Nov2017	01Dec2017	15Dec2017	31Dec2017
Mean Bias (°C)	0.00	-0.07	0.03	-0.00	0.09	-0.09	-0.00	0.29
MAE (°C)	0.17	0.21	0.12	0.12	0.09	0.09	0.04	0.29
RMSE (°C)	0.20	0.23	0.13	0.13	0.10	0.10	0.05	0.32
Nash-Sutcliffe (NSE)	0.89	-1.50	0.48	-4.66	-8.24	-3.71	-0.42	-0.96

Keswick outflow temperature: Mean Bias 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.15	-0.03	-0.04	0.14	-0.23	-0.00	-0.12	0.04	0.05	0.03	0.00
2001	-0.19	-0.52	-0.38	-0.09	0.15	0.02	-0.17	-0.17	0.02	-0.08	-0.10	-0.45
2002	-0.61	-0.50	-0.07	0.35	0.06	-0.18	-0.12	-0.18	0.21	0.20	-0.02	-0.20
2003	-0.42	-0.26	-0.14	-0.10	-0.15	-0.66	-0.84	-0.37	-0.01	0.14	-0.09	-0.18
2004	-0.47	-0.56	-0.15	0.04	0.23	0.15	-0.12	-0.14	0.06	-0.54	-0.27	-0.36
2005	-0.89	-0.56	-0.09	0.09	-0.01	0.08	-0.34	-1.26	-0.41	0.04	-0.17	-0.54
2006	-0.59	-0.26	-0.43	-0.24	0.11	-0.02	-0.04	-0.62	-0.60	0.08	0.29	-0.29
2007	-0.75	-0.48	-0.24	0.04	0.32	0.22	0.04	-0.12	0.11	-0.03	-0.17	-0.13
2008	-0.33	-0.31	-0.12	0.31	0.47	0.32	0.09	-0.10	-0.04	-0.35	-0.32	-0.07
2009	-0.06	-0.35	-0.36	0.12	0.14	0.30	0.10	-0.13	-0.19	-0.25	0.02	-0.06
2010	-0.40	-0.30	-0.09	0.04	0.33	0.04	-0.08	-0.59	-0.85	-0.18	0.06	-0.03
2011	-0.22	-0.12	-0.21	0.12	0.19	0.05	0.16	0.15	-0.19	-0.20	-0.03	-0.08
2012	0.05	-0.09	-0.13	-0.28	0.29	0.36	0.03	-0.27	-0.29	0.07	0.12	0.13
2013	-0.03	0.04	0.26	0.30	0.21	0.11	0.25	0.21	0.17	0.19	0.09	-0.20
2014	-0.08	0.11	-0.15	-0.01	0.30	0.21	-0.11	-0.10	0.15	-0.22	0.27	-0.13
2015	-0.39	-0.31	0.16	0.24	0.26	0.27	0.16	-0.04	0.23	0.17	1.10	0.00
2016	-0.54	-0.13	-0.16	0.29	0.31	0.37	0.03	0.06	-0.13	0.07	0.08	0.22
2017	-0.04	-0.26	-0.11	-0.08	0.10	0.25	0.09	-0.11	-0.19	-0.01	-0.00	0.10
All	-0.35	-0.26	-0.14	0.06	0.19	0.09	-0.04	-0.22	-0.11	-0.05	0.05	-0.13

Keswick outflow T: Mean Absolute Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.21	0.09	0.32	0.22	0.32	0.16	0.20	0.18	0.12	0.11	0.18
2001	0.21	0.52	0.40	0.28	0.28	0.28	0.23	0.37	0.17	0.14	0.18	0.45
2002	0.61	0.50	0.17	0.43	0.26	0.25	0.16	0.26	0.30	0.25	0.12	0.28
2003	0.42	0.26	0.19	0.21	0.23	0.66	0.84	0.38	0.24	0.15	0.12	0.19
2004	0.47	0.56	0.26	0.19	0.24	0.22	0.20	0.34	0.14	0.54	0.29	0.36
2005	0.89	0.56	0.21	0.19	0.27	0.16	0.56	1.26	0.41	0.10	0.20	0.54
2006	0.59	0.26	0.43	0.39	0.18	0.14	0.11	0.65	0.60	0.10	0.37	0.32
2007	0.75	0.49	0.27	0.28	0.33	0.27	0.15	0.25	0.23	0.18	0.21	0.15
2008	0.34	0.31	0.19	0.39	0.47	0.37	0.38	0.25	0.16	0.36	0.33	0.13
2009	0.31	0.35	0.36	0.20	0.22	0.31	0.21	0.29	0.24	0.26	0.13	0.11
2010	0.40	0.30	0.21	0.21	0.35	0.31	0.14	0.62	0.85	0.32	0.17	0.13
2011	0.22	0.15	0.21	0.24	0.29	0.16	0.21	0.29	0.35	0.23	0.11	0.18
2012	0.15	0.14	0.17	0.31	0.41	0.41	0.12	0.33	0.30	0.15	0.14	0.26
2013	0.21	0.10	0.28	0.43	0.38	0.23	0.29	0.31	0.25	0.22	0.27	0.26
2014	0.15	0.14	0.18	0.25	0.31	0.35	0.31	0.23	0.21	0.25	0.33	0.22
2015	0.39	0.32	0.23	0.28	0.37	0.29	0.31	0.21	0.28	0.23	1.14	0.23
2016	0.54	0.21	0.23	0.31	0.34	0.40	0.19	0.17	0.25	0.16	0.12	0.26
2017	0.27	0.27	0.17	0.20	0.21	0.28	0.26	0.13	0.25	0.15	0.09	0.18
All	0.41	0.31	0.24	0.28	0.30	0.30	0.27	0.36	0.30	0.22	0.25	0.25

Keswick outflow T: Root Mean Square Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.25	0.13	0.39	0.27	0.36	0.21	0.25	0.24	0.15	0.14	0.23
2001	0.26	0.56	0.44	0.35	0.34	0.37	0.33	0.48	0.21	0.19	0.22	0.51
2002	0.62	0.52	0.22	0.48	0.33	0.29	0.20	0.31	0.37	0.29	0.17	0.35
2003	0.45	0.30	0.24	0.25	0.28	0.71	0.88	0.44	0.28	0.18	0.16	0.21
2004	0.49	0.58	0.34	0.25	0.28	0.27	0.28	0.42	0.17	0.58	0.35	0.41
2005	0.90	0.57	0.26	0.24	0.32	0.20	0.75	1.28	0.44	0.12	0.23	0.58
2006	0.63	0.29	0.46	0.42	0.24	0.19	0.15	0.84	0.70	0.12	0.52	0.36
2007	0.81	0.56	0.32	0.35	0.37	0.33	0.19	0.31	0.34	0.32	0.25	0.19
2008	0.37	0.35	0.24	0.42	0.51	0.42	0.46	0.33	0.21	0.42	0.39	0.16
2009	0.35	0.38	0.42	0.24	0.27	0.35	0.27	0.37	0.30	0.31	0.16	0.13
2010	0.49	0.34	0.26	0.25	0.40	0.36	0.17	0.80	0.90	0.41	0.19	0.18
2011	0.25	0.18	0.24	0.31	0.35	0.21	0.26	0.32	0.43	0.28	0.14	0.24
2012	0.17	0.18	0.20	0.37	0.49	0.48	0.16	0.40	0.33	0.19	0.17	0.30
2013	0.27	0.13	0.32	0.70	0.50	0.32	0.38	0.39	0.29	0.25	0.32	0.29
2014	0.18	0.22	0.23	0.30	0.34	0.43	0.38	0.28	0.26	0.29	0.37	0.29
2015	0.44	0.37	0.27	0.34	0.46	0.33	0.37	0.26	0.37	0.29	1.23	0.26
2016	0.57	0.26	0.31	0.36	0.39	0.45	0.25	0.21	0.31	0.20	0.15	0.36
2017	0.33	0.31	0.23	0.25	0.26	0.34	0.31	0.17	0.40	0.18	0.12	0.23
All	0.49	0.38	0.30	0.37	0.36	0.38	0.38	0.51	0.40	0.29	0.39	0.32

Clear Creek Calibration Results - ResSim

- TBD

Clear Creek temperature: Mean Bias 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.10	-0.09	-0.18	0.08	-0.15	0.04	-0.14	-0.06	-0.11	-0.05	-0.13
2001	-0.36	-0.81	-0.60	-0.36	0.11	0.11	-0.07	-0.13	-0.03	-0.21	-0.20	-0.61
2002	-0.72	-0.65	-0.46	0.00	-0.04	-0.11	0.01	-0.19	-0.09	0.02	-0.01	-0.21
2003	-0.50	-0.40	-0.36	-0.44	-0.18	-0.57	-0.74	-0.45	-0.12	-0.06	-0.21	-0.24
2004	-0.61	-0.71	-0.30	-0.16	0.08	0.09	-0.04	-0.18	-0.09	-0.68	-0.49	-0.94
2005	-1.69	-1.19	-0.45	-0.36	-0.19	0.02	-0.32	-1.26	-0.53	0.00	-0.25	-0.95
2006	-0.83	-0.78	-0.58	-0.46	0.03	0.05	0.08	-0.57	-0.60	-0.03	0.06	-0.68
2007	-1.16	-1.30	-0.79	-0.21	0.17	0.20	0.05	-0.24	0.02	-0.02	-0.05	-0.16
2008	-0.54	-0.56	-0.45	-0.17	0.32	0.24	0.21	-0.09	-0.18	-0.46	-0.45	-0.23
2009	-0.23	-0.54	-0.57	-0.09	0.15	0.18	-0.07	-0.29	-0.33	-0.34	-0.13	-0.14
2010	-0.65	-0.50	-0.35	-0.27	0.04	-0.05	0.06	-0.40	-0.80	-0.48	-0.09	-0.21
2011	-0.40	-0.57	-0.32	-0.07	0.06	0.15	0.00	-0.11	-0.42	-0.30	-0.06	-0.23
2012	-0.05	-0.34	-0.51	-0.68	-0.05	0.15	-0.04	-0.33	-0.40	-0.12	-0.02	-0.09
2013	-0.21	-0.27	-0.02	-0.01	0.01	0.20	0.37	0.06	-0.06	-0.14	-0.12	-0.17
2014	-0.21	-0.07	-0.43	-0.24	0.17	0.11	-0.10	-0.10	0.10	-0.39	0.14	-0.54
2015	-0.55	-0.47	-0.03	-0.07	0.06	0.24	0.15	-0.12	-0.03	-0.04	0.98	-0.08
2016	-0.80	-0.32	-0.29	0.13	0.16	0.34	0.12	0.10	-0.17	-0.06	-0.15	-0.03
2017	-0.26	-0.38	-0.19	-0.09	0.11	0.33	0.20	0.12	-0.11	-0.06	-0.13	-0.04
All	-0.57	-0.54	-0.38	-0.21	0.06	0.08	-0.00	-0.24	-0.22	-0.19	-0.07	-0.32

Clear Creek T: Mean Absolute Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.20	0.15	0.39	0.28	0.27	0.19	0.28	0.34	0.27	0.22	0.31
2001	0.39	0.81	0.62	0.49	0.42	0.35	0.24	0.39	0.27	0.36	0.40	0.62
2002	0.72	0.66	0.48	0.43	0.38	0.28	0.16	0.31	0.38	0.34	0.32	0.42
2003	0.50	0.40	0.43	0.51	0.25	0.60	0.74	0.48	0.34	0.28	0.30	0.27
2004	0.61	0.71	0.35	0.35	0.35	0.23	0.22	0.42	0.32	0.69	0.51	0.94
2005	1.69	1.19	0.50	0.42	0.29	0.16	0.54	1.26	0.53	0.17	0.30	0.95
2006	0.83	0.78	0.58	0.55	0.21	0.15	0.16	0.64	0.60	0.18	0.31	0.68
2007	1.16	1.30	0.83	0.33	0.27	0.27	0.16	0.36	0.31	0.34	0.35	0.35
2008	0.60	0.56	0.48	0.27	0.41	0.42	0.41	0.28	0.33	0.49	0.46	0.29
2009	0.41	0.55	0.58	0.35	0.35	0.33	0.27	0.37	0.37	0.37	0.32	0.29
2010	0.65	0.50	0.42	0.39	0.27	0.33	0.21	0.55	0.80	0.49	0.24	0.25
2011	0.40	0.57	0.32	0.26	0.30	0.26	0.18	0.27	0.49	0.35	0.24	0.33
2012	0.26	0.38	0.53	0.69	0.42	0.33	0.13	0.39	0.42	0.25	0.21	0.36
2013	0.37	0.36	0.30	0.36	0.38	0.30	0.41	0.28	0.27	0.28	0.43	0.40
2014	0.26	0.22	0.47	0.38	0.31	0.35	0.26	0.27	0.34	0.41	0.35	0.55
2015	0.55	0.47	0.25	0.35	0.39	0.33	0.32	0.25	0.31	0.25	1.16	0.31
2016	0.80	0.36	0.39	0.38	0.39	0.39	0.24	0.21	0.29	0.22	0.26	0.28
2017	0.31	0.38	0.24	0.21	0.27	0.39	0.30	0.19	0.26	0.21	0.19	0.25
All	0.62	0.58	0.44	0.39	0.33	0.32	0.29	0.40	0.39	0.33	0.36	0.44

Clear Creek T: Root Mean Squared Error 2000-2017 (DRAFT)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.26	0.23	0.52	0.36	0.34	0.24	0.37	0.45	0.35	0.30	0.38
2001	0.48	0.89	0.73	0.62	0.52	0.44	0.34	0.53	0.33	0.45	0.50	0.70
2002	0.76	0.71	0.58	0.53	0.46	0.36	0.22	0.42	0.47	0.42	0.39	0.50
2003	0.53	0.47	0.55	0.65	0.31	0.66	0.79	0.57	0.42	0.36	0.38	0.33
2004	0.67	0.75	0.44	0.47	0.41	0.29	0.29	0.50	0.42	0.78	0.64	1.03
2005	1.71	1.21	0.61	0.54	0.37	0.20	0.75	1.30	0.61	0.21	0.36	1.00
2006	0.87	0.86	0.59	0.60	0.28	0.19	0.20	0.82	0.69	0.23	0.42	0.77
2007	1.21	1.34	0.94	0.43	0.32	0.34	0.21	0.45	0.43	0.47	0.46	0.43
2008	0.66	0.63	0.58	0.37	0.51	0.48	0.50	0.36	0.44	0.62	0.53	0.38
2009	0.50	0.60	0.69	0.44	0.42	0.38	0.34	0.46	0.48	0.47	0.42	0.41
2010	0.74	0.55	0.53	0.50	0.34	0.41	0.27	0.69	0.87	0.59	0.32	0.32
2011	0.45	0.65	0.38	0.35	0.37	0.31	0.23	0.35	0.62	0.40	0.30	0.44
2012	0.33	0.47	0.63	0.80	0.51	0.40	0.16	0.49	0.49	0.33	0.28	0.45
2013	0.48	0.47	0.37	0.45	0.46	0.38	0.49	0.35	0.34	0.37	0.61	0.53
2014	0.34	0.28	0.56	0.48	0.35	0.42	0.31	0.33	0.41	0.50	0.43	0.72
2015	0.61	0.58	0.33	0.42	0.46	0.39	0.39	0.32	0.39	0.32	1.26	0.42
2016	0.85	0.42	0.51	0.45	0.46	0.46	0.32	0.26	0.37	0.30	0.35	0.35
2017	0.36	0.43	0.30	0.25	0.34	0.49	0.36	0.23	0.37	0.25	0.23	0.34
All	0.76	0.70	0.55	0.51	0.41	0.40	0.39	0.55	0.50	0.44	0.51	0.57

Findings

- Calibration shows the models are an adequate representation of reality
- Room for improvement exists in some challenging years
  - Models will undergo further improvement
- Models' performance over 2000-2017 gives room for optimism with regard to their likely performance under future conditions