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RESEARCH ARTICLE

WILEY

The mechanics of diurnal thermal stratification in river pools: Implications for water management and species conservation

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Abstract

We examined conditions that form or prevent thermal stratification in river pools using field measurements, statistical modelling, and three-dimensional (3D) computational fluid dynamics (CFD) modelling. Our motivation is to identify variables that control stratification for exploitation to enhance or prevent thermal gradients as needed to benefit species in rivers. One study pool (UT) is located above water storage reservoirs and receives natural flows, and the other pool (PT) is regulated and receives unnaturally high, cold water in summer; both pools are on the Trinity River, California. Thermal stratification formed in UT pool in spring at a critical flow of 1.01 m^3/s, peaked at 8.1°C in summer, and exhibited diurnal formation and destruction under sub-critical flows until fall. At PT pool, the 14.2 m^3/s baseflow caused mixing that prevented stratification and formed a spatially homogenous thermal environment. Statistical analyses indicated the daily range in air and inlet water temperature at UT pool best correlated with the occurrence and strength of stratification but were progressively irrelevant as flows increased above the critical value. The validated CFD model was used to reproduce the diurnal stratification and explain the processes involved. The CFD model correctly predicted the observed critical flow and replicated the dynamics of stratification at UT pool and isohyets observed at PT pool. The CFD results also confirmed that low flows are the main variable for stratification to form, and the daily range in inlet water temperature drives the strength of the thermal gradient. The model estimated a critical discharge at PT pool of 2.0 m^3/s, twice that for UT pool owing to its 2.6-times larger area, suggesting critical flows scale with pool size. Results showed that releasing critical and lower flows in summer on regulated streams may conserve water and provide thermal gradients that benefit poikilothermic species; alternately, higher than critical flows can prevent stratification where needed to improve water quality.

KEYWORDS
3D CFD modelling, Chinook salmon, flow regulation, statistical modelling, thermal stratification, water quality

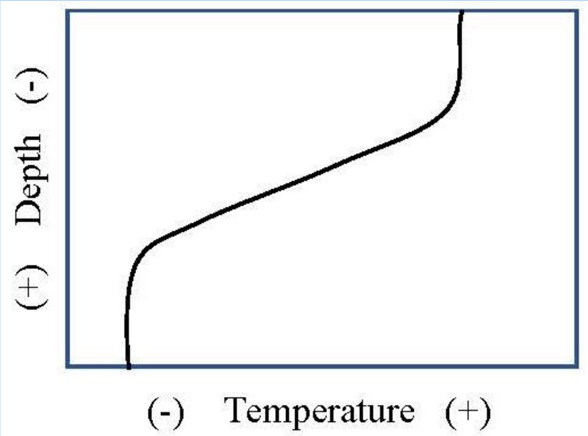
Mechanics of diurnal thermal stratification in river pools: implications for water management and species conservation

Trinity River Restoration Program
Restore • Adapt • Improve

Motivation and Hypothesis

- The Trinity River channel is about 55% narrower than predam, yet the summer baseflow is 2.4 times higher than the median summer flow before the dams.
- The unseasonably high flows provide cold water for holding spring Chinook but suppress the foodbase for juvenile salmonid rearing.
- Smaller juveniles survive at lower rates to adult, so the objective for high baseflows to benefit adult salmon may instead depress future populations.
- Both warm and cold water is necessary for species to thrive, and our hypothesis is summer baseflows that are closer to natural levels will promote temperature diversity by enabling thermal stratification in pools.

Thermal stratification



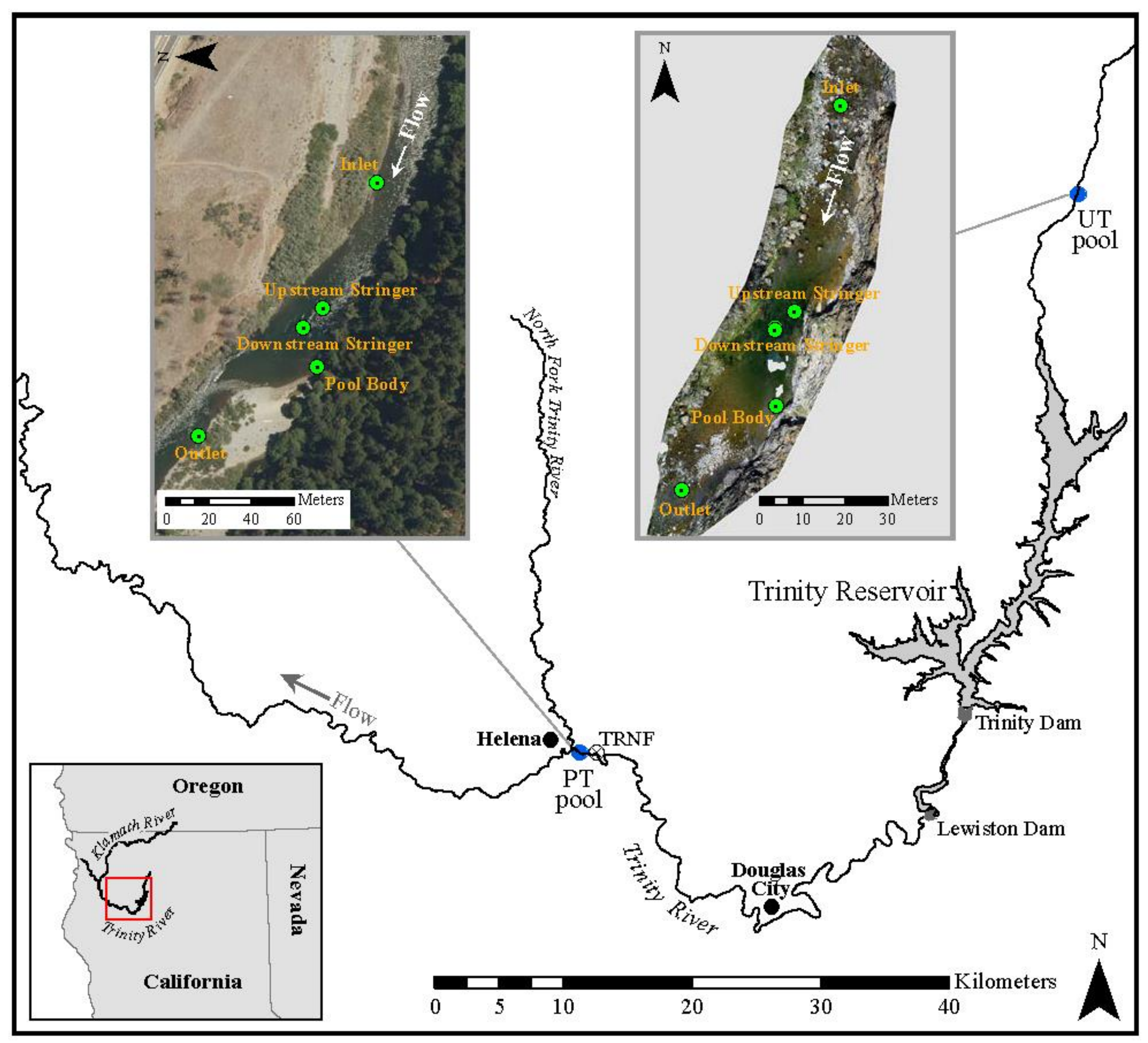
- Thermal stratification occurs when water temperatures arrange in a thermocline in deep (>2m) pools.
- Stratification has been documented in other studies, but the mechanics of the stratification process remain undefined.
- Understanding what controls temperature stratification will enable regulated flow releases to be designed to promote stratification.
- Temperature stratification can help meet the warm and cold-water requirements of species in rivers.

Methods

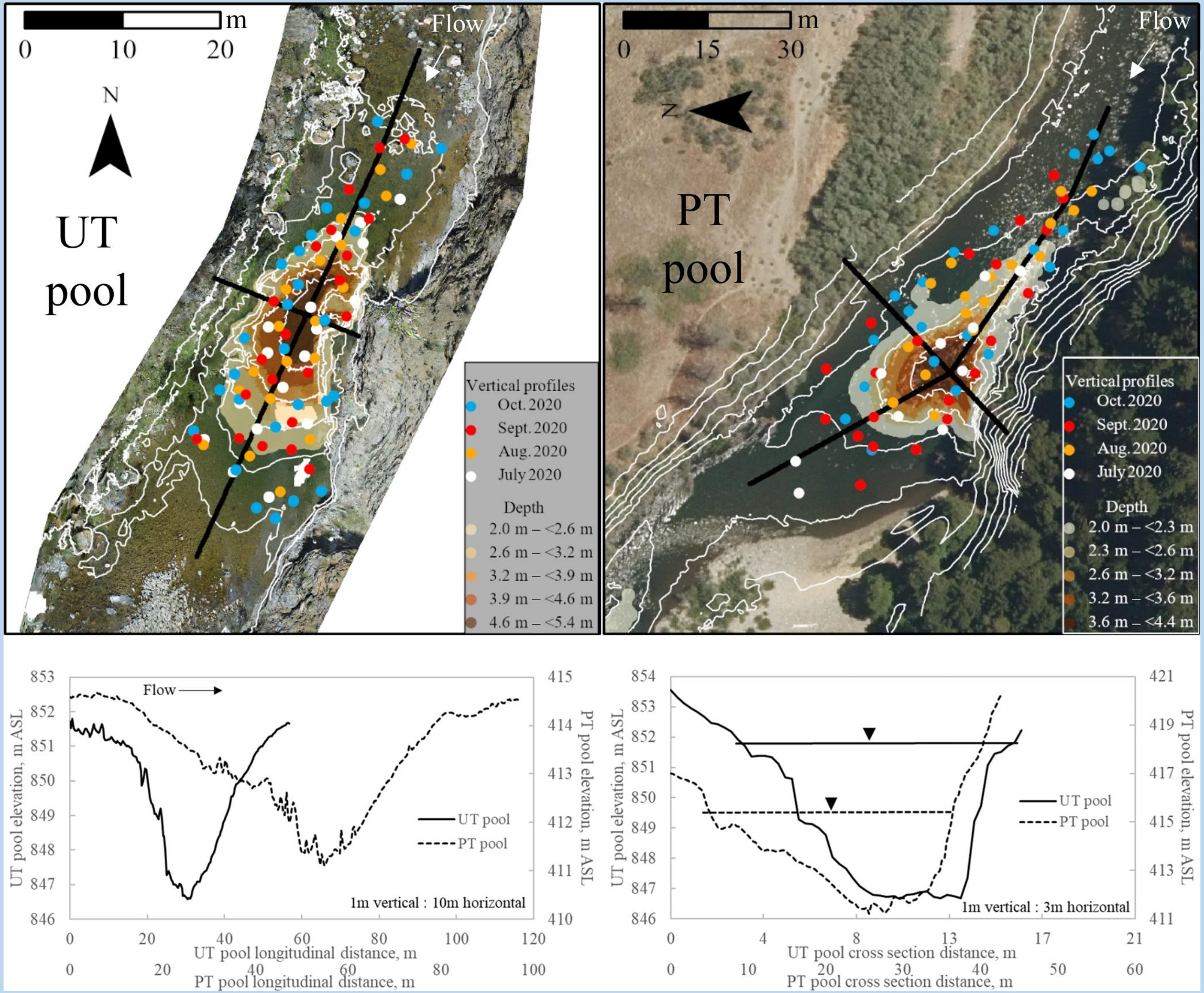
- Survey pool bathymetries;
- Monitor meteorological conditions (air temperature, sun exposure, atmospheric pressure, et al.);
- Measure flows and temperatures in and entering, exiting each pool;
- Measure temperature and velocity profiles in the pools;
- Explain the dynamics of stratification with field data;
- Use statistical modeling to identify variables controlling stratification;
- Use numerical modeling to predict critical discharge for stratification and describe the stratification process.
  - 3-dimensional computational fluid dynamics model U^{2}RANS.

Lai, Y.G., T.H. Buxton, B. Abban (2022). Adaptive planning and Design in an age of risk and uncertainty. In J. Pierson & E. Grubert (Eds.), 3D CFD modeling of river pool stratification characteristics. World Environmental & Water Resources Congress, June 5–8, 2022. https://doi.org/10.1061/9780784484258

Study areas

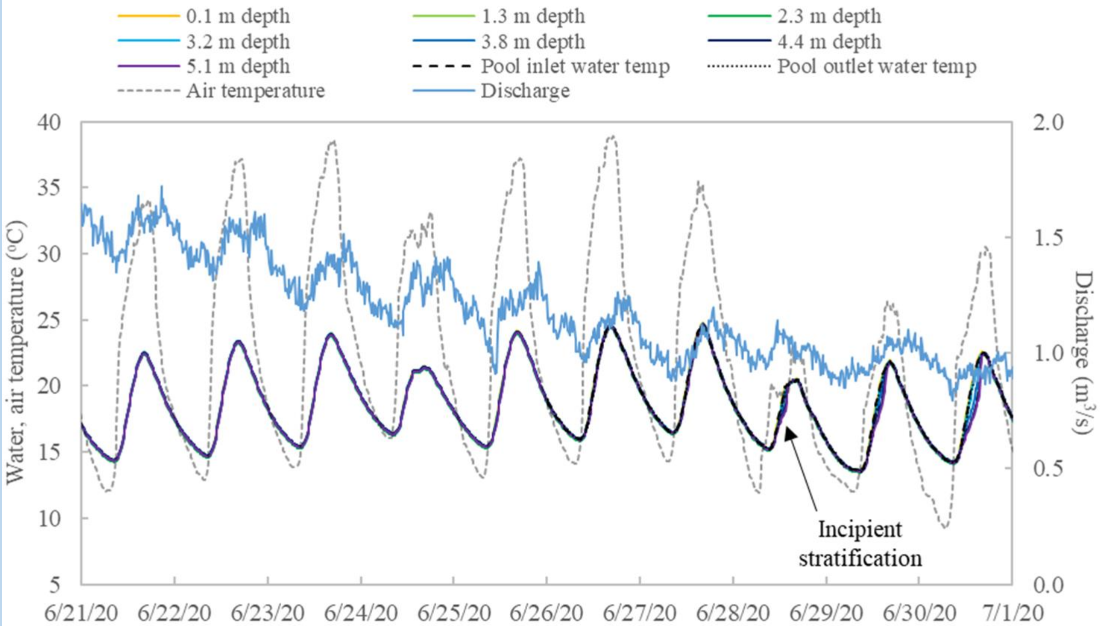

Flow
Inlet
Upstream Stringer
Downstream Stringer
Pool Body
Outlet
Meters
0 20 40 60
N
Inlet
Flow
Upstream Stringer
Downstream Stringer
Pool Body
Outlet
Meters
0 10 20 30
UT pool
North Fork Trinity River
Trinity Reservoir
Flow
Helena
TRNF
PT pool
Trinity Dam
Lewiston Dam
Trinity River
Douglas City
Oregon
Klamath River
Nevada
Trinity River
California
Kilometers
0 5 10 20 30 40
N

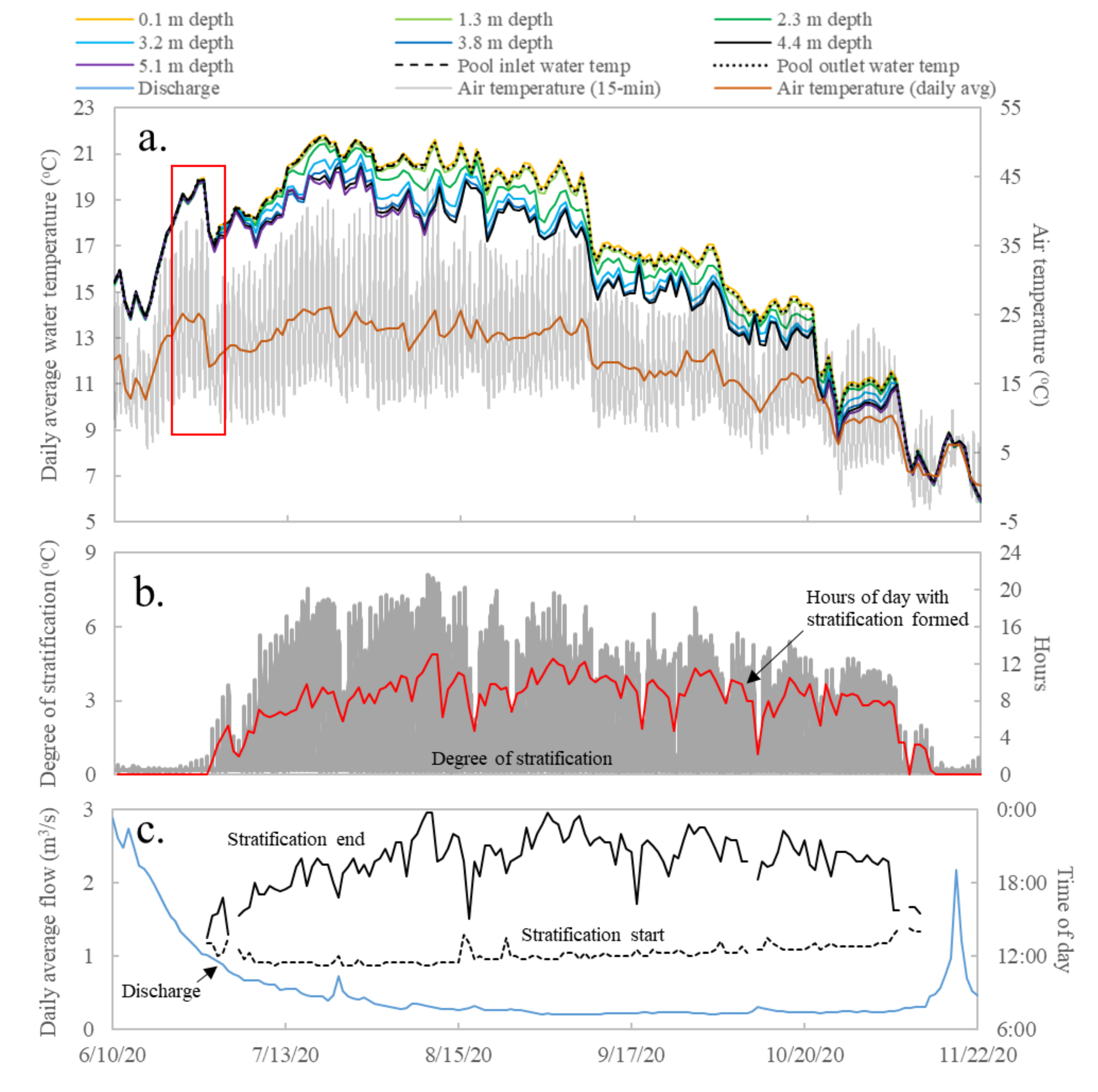
Study areas



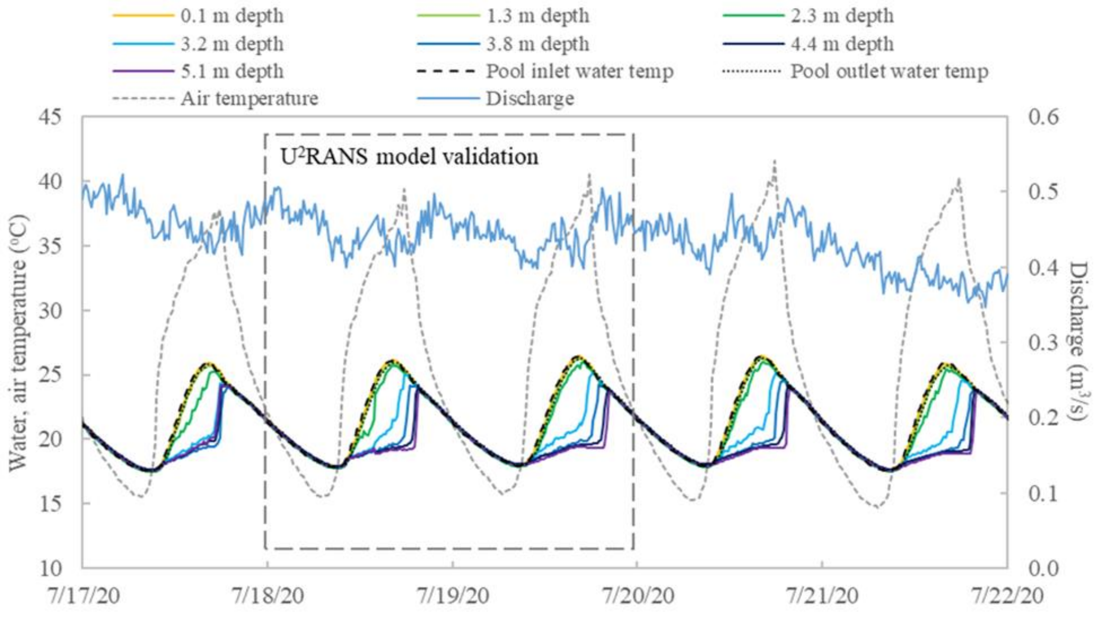
m
0 10 20
Flow
N
UT
pool
Vertical profiles
Oct. 2020
Sept. 2020
Aug. 2020
July 2020
Depth
2.0 m – <2.6 m
2.6 m – <3.2 m
3.2 m – <3.9 m
3.9 m – <4.6 m
4.6 m – <5.4 m
m
0 15 30
Flow
N
PT
pool
Vertical profiles
Oct. 2020
Sept. 2020
Aug. 2020
July 2020
Depth
2.0 m – <2.3 m
2.3 m – <2.6 m
2.6 m – <3.2 m
3.2 m – <3.6 m
3.6 m – <4.4 m
Flow
UT pool elevation, m ASL
PT pool elevation, m ASL
UT pool
PT pool
1m vertical : 10m horizontal
UT pool longitudinal distance, m
PT pool longitudinal distance, m
UT pool elevation, m ASL
PT pool elevation, m ASL
UT pool
PT pool
1m vertical : 3m horizontal
UT pool cross section distance, m
PT pool cross section distance, m

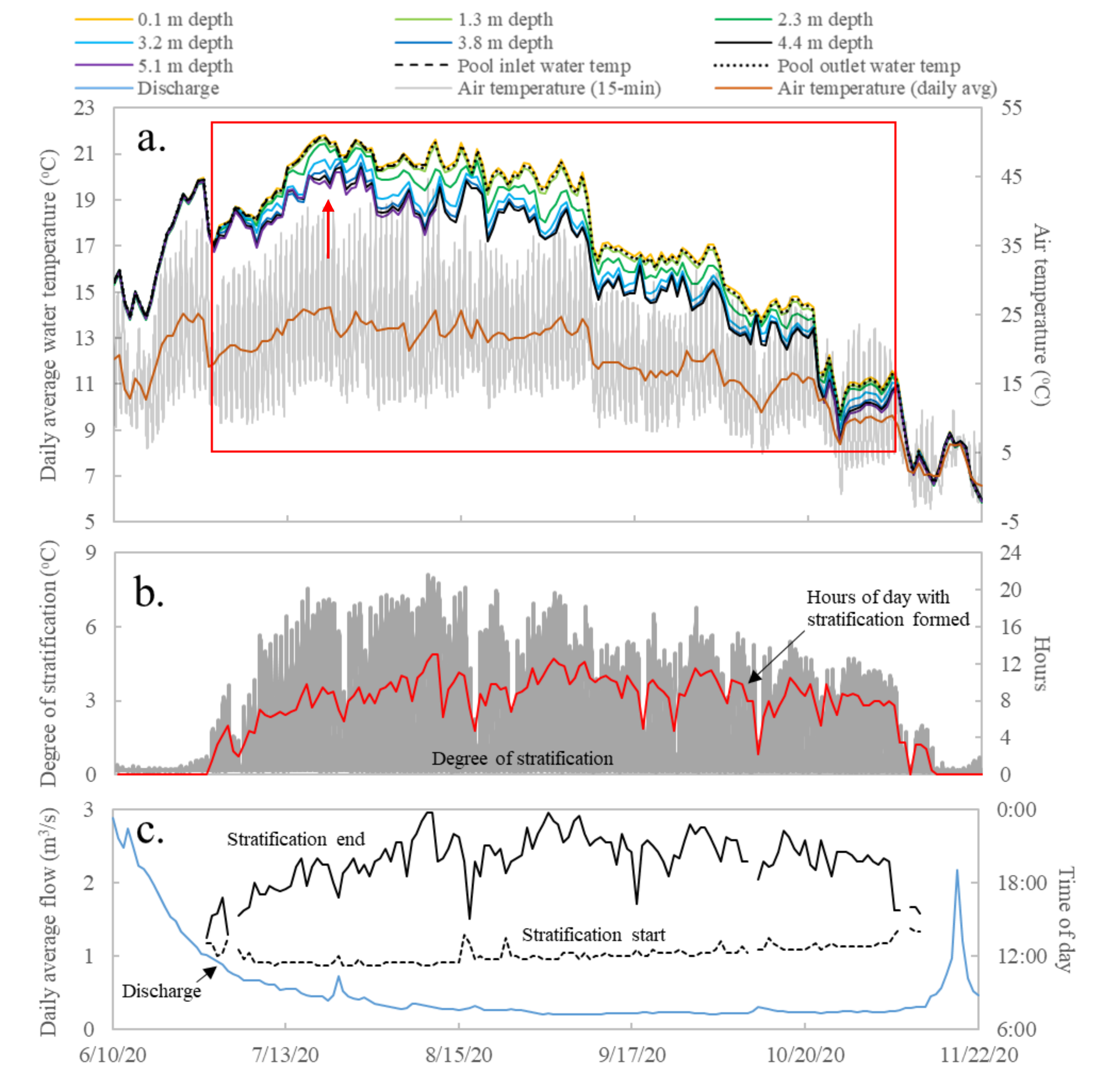
Results-UT pool



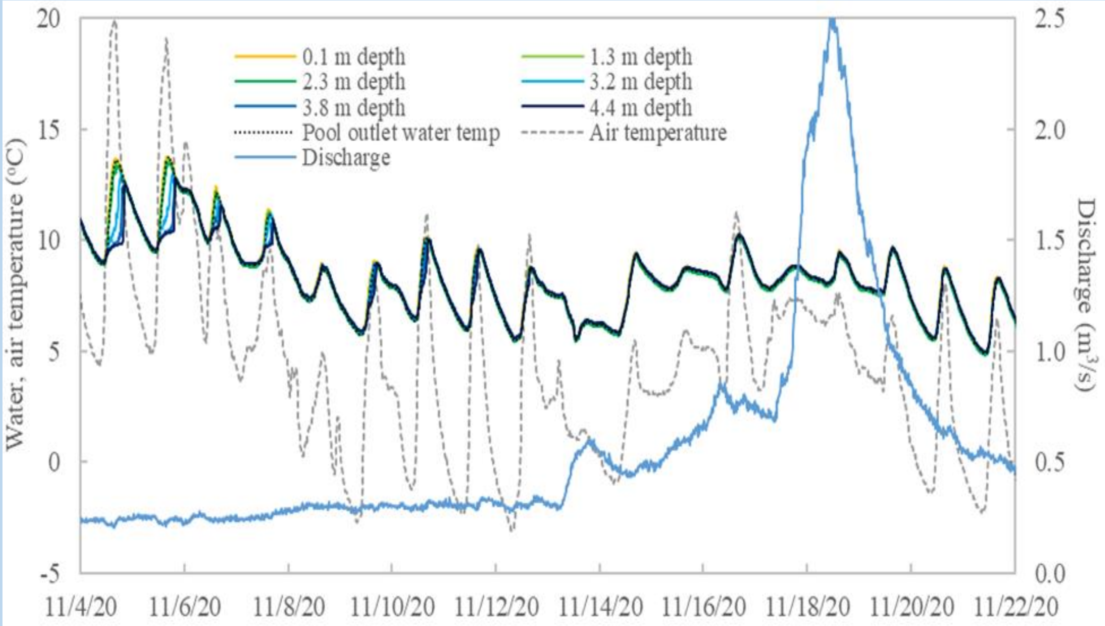


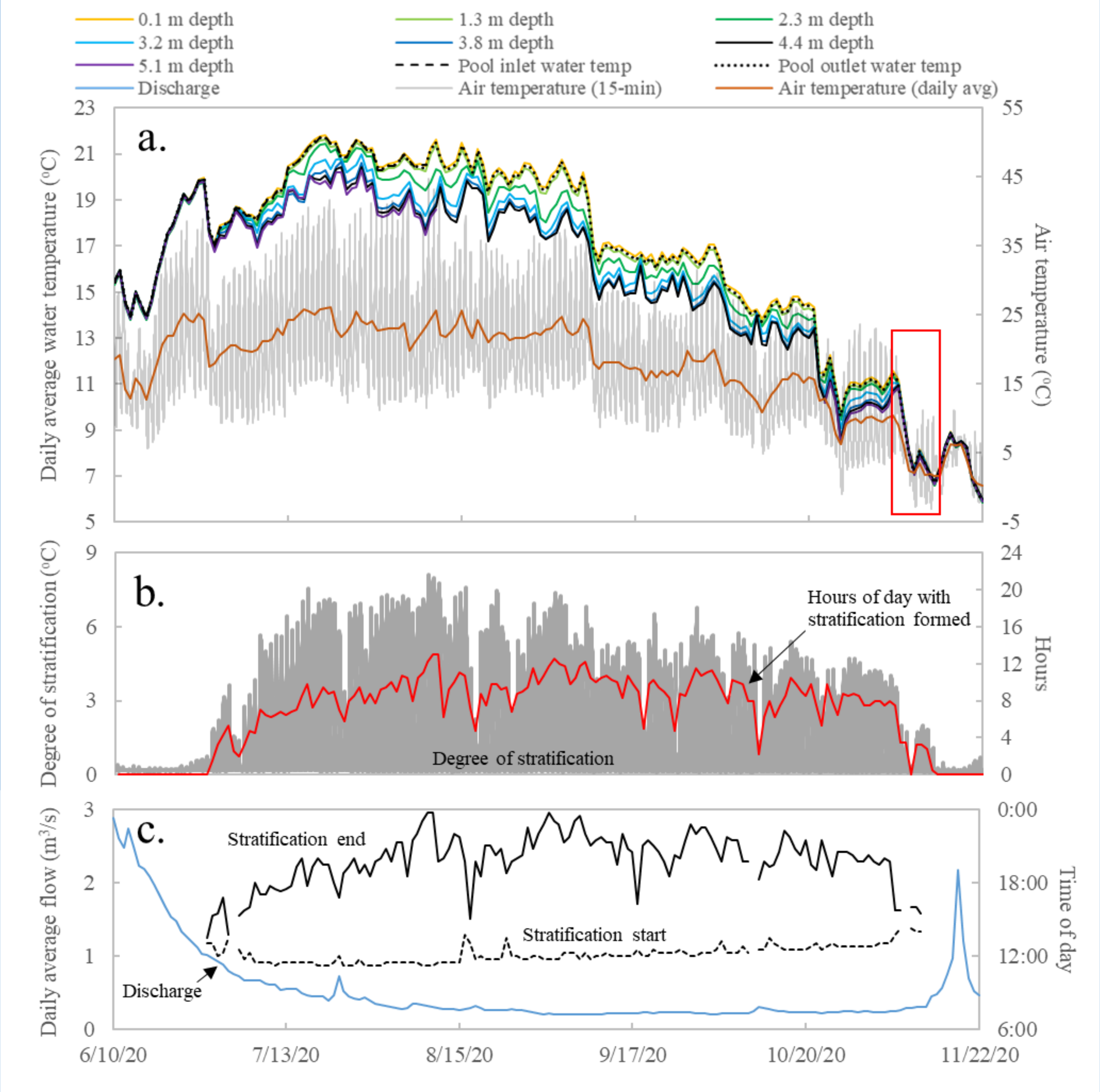
Results-UT pool



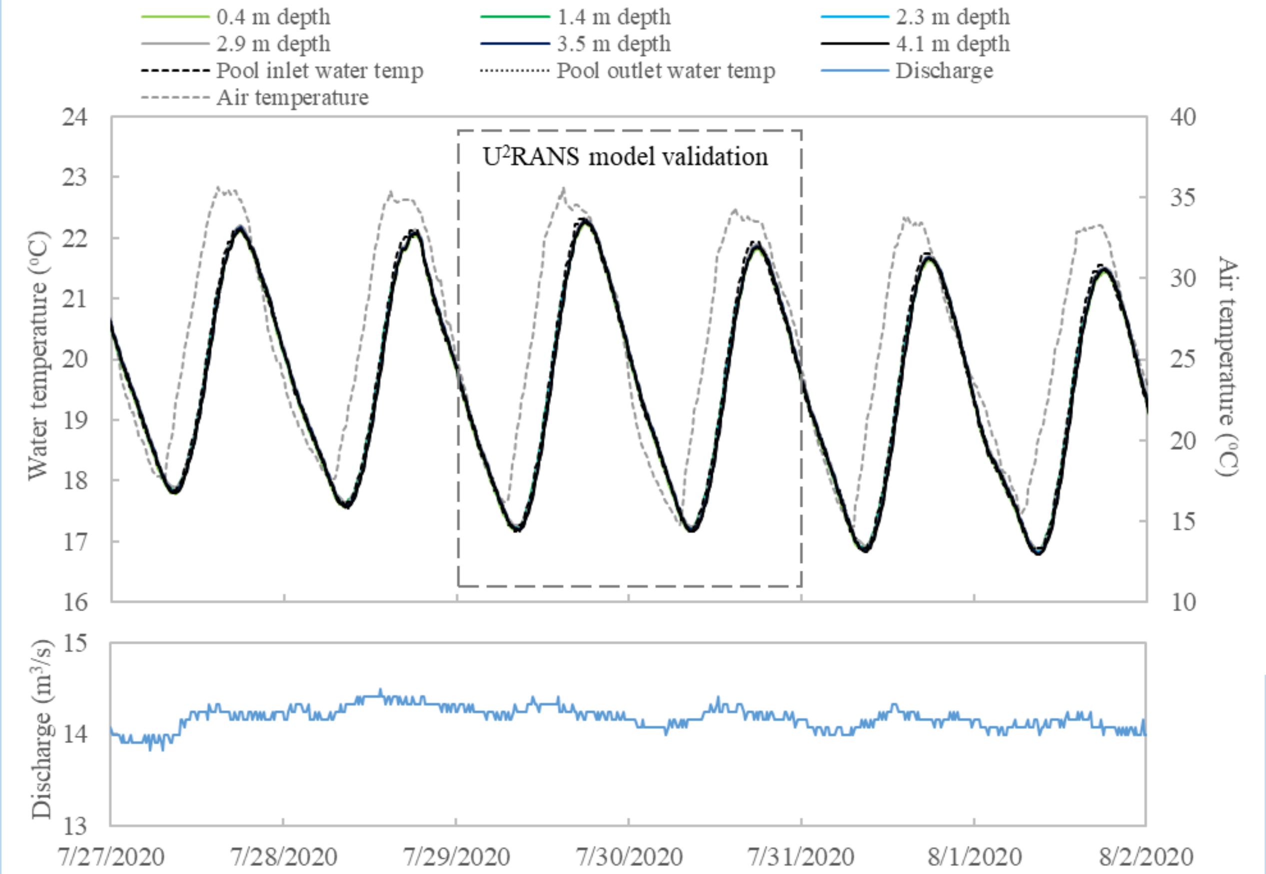


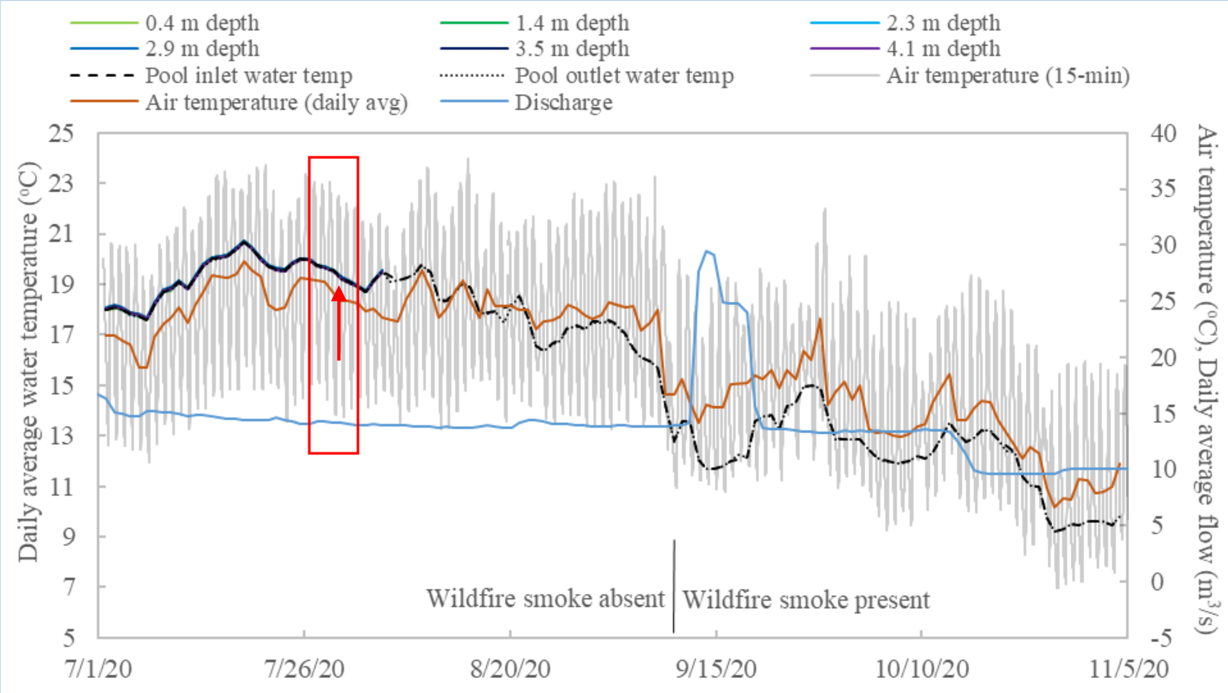
Results-UT pool



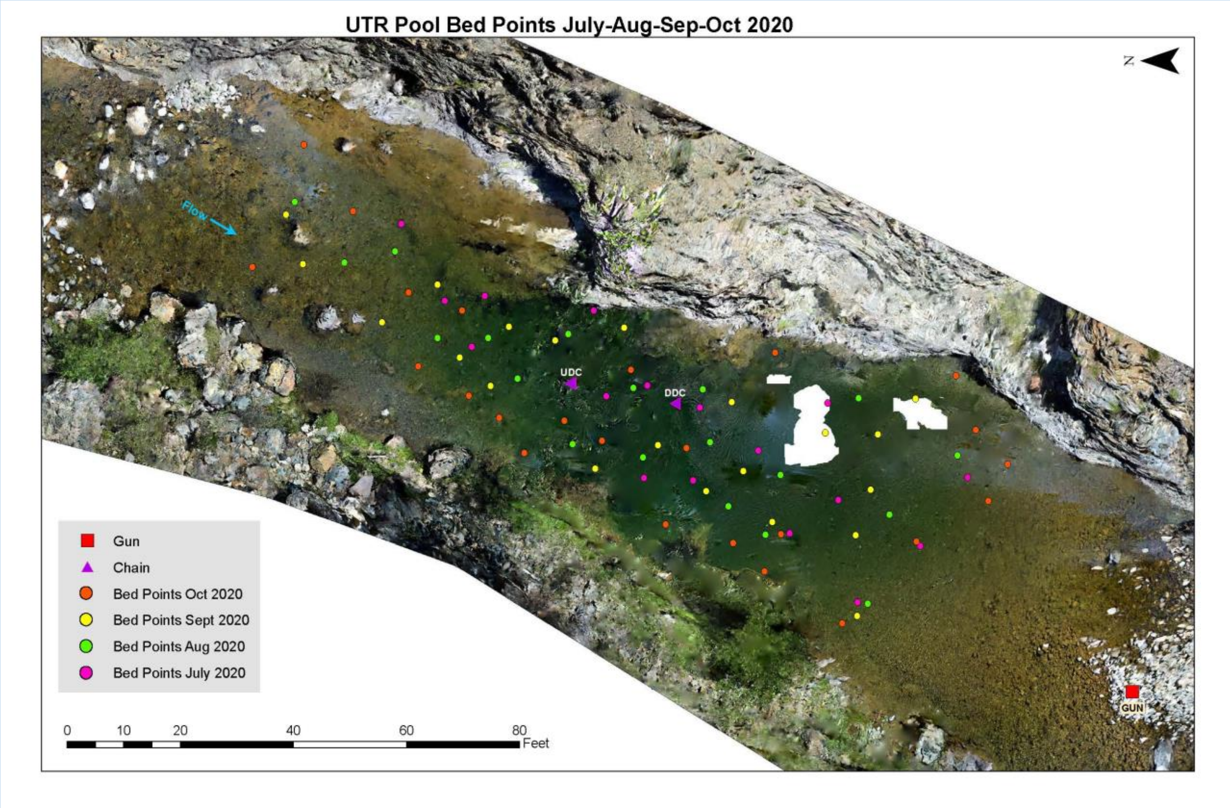


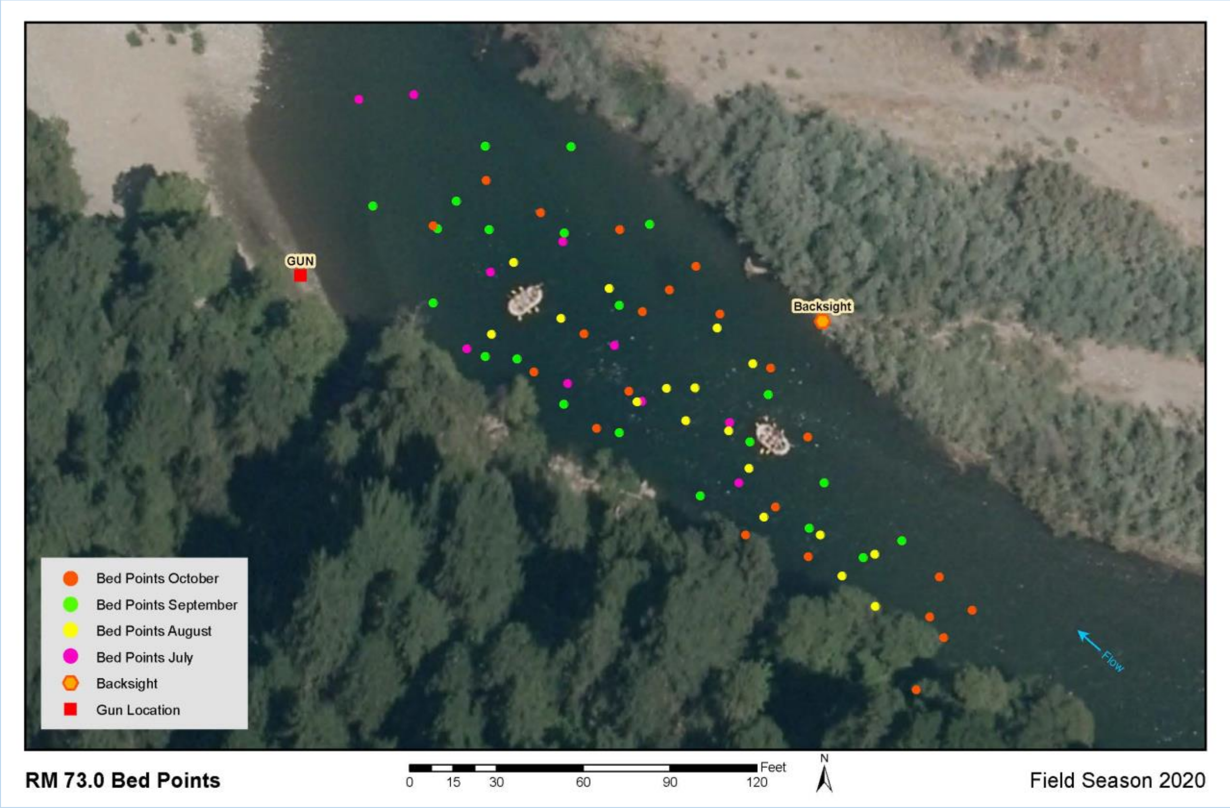
Results-PT pool





Results-velocity, temperature profiles

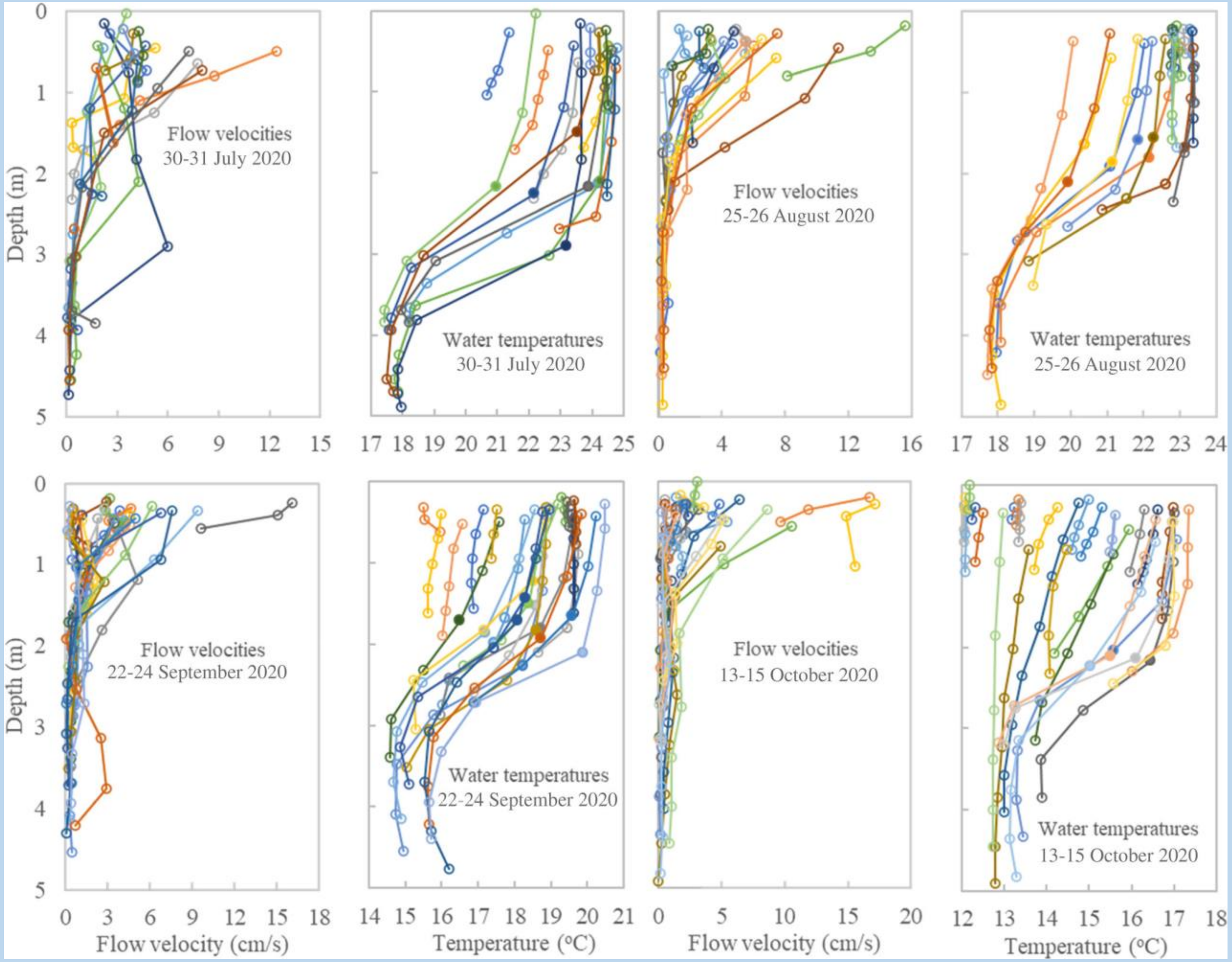




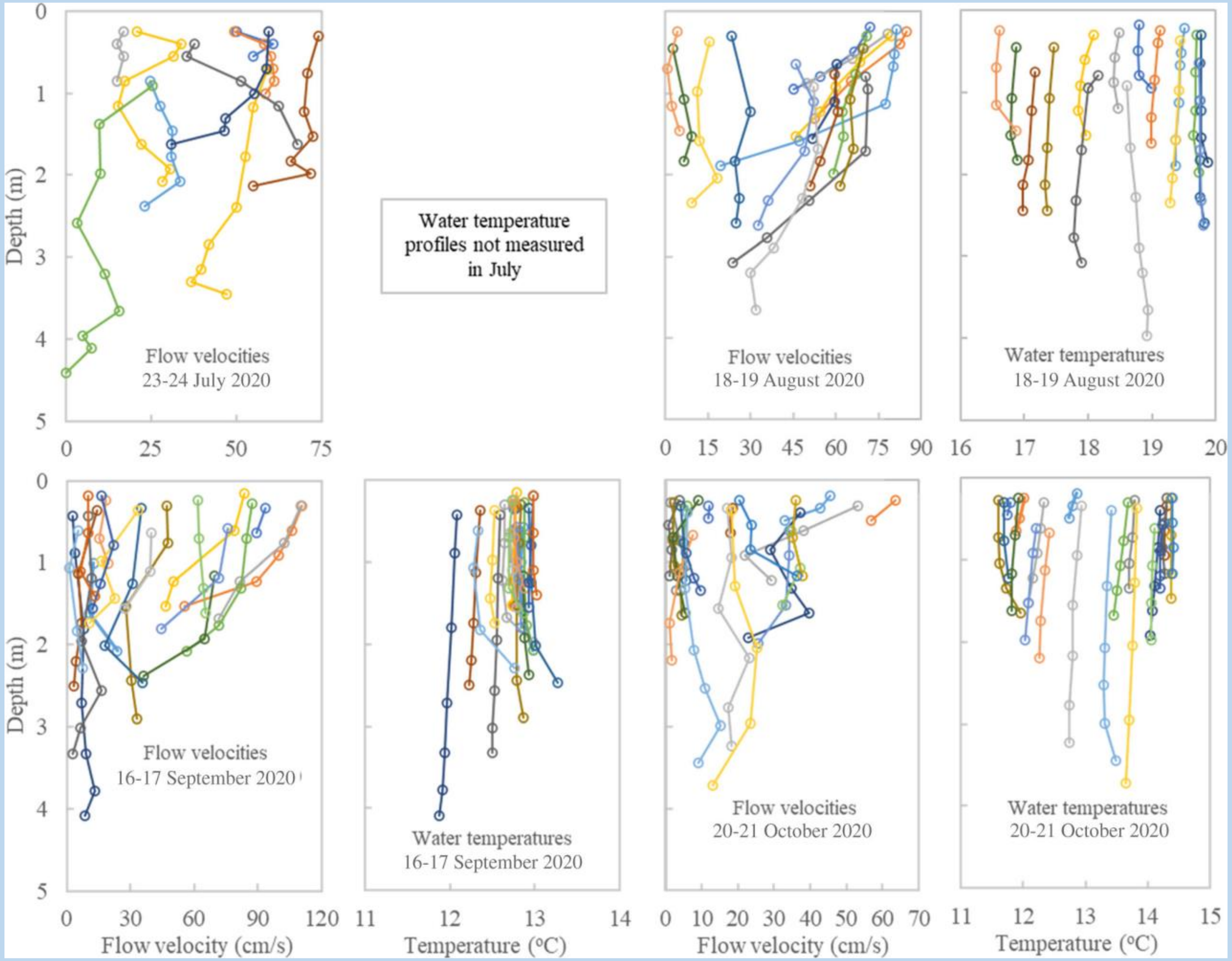
UT pool

PT pool

Results-velocity, temperature profiles



UT pool



PT pool

Statistical modeling

DATD has a strong effect on S_d at low Q_{avg}, but the effect decreases to zero as flow rises.

S_d allows low at high flows regardless of DATD; High S_d can only be achieved when DATD is high and Q_{avg} is low.

Same findings for DIWT.

Explanatory Variables Tested
Discharge (Qavg)
Avg Air Temperature
Minimum Air Temperature
Maximum Air Temperature
Range in Air Temperature (DATD)
Depth Integrated H2O Temperature
Maximum H2O Temperature Differential in Vertical
Minimum H2O Temperature Differential in Vertical
Maximum H2O Temperature in Vertical
Avg Daily Inlet H20 temperature (MDIWT)
Range Inlet H2O temperature (DIWT)
Minimum Inlet H2O temperature
Maximum Inlet H2O temperature
Sunrise 2 Sunset Hrs (SE)
Day length (DL)
Response Variable: Sd (degree of stratification)

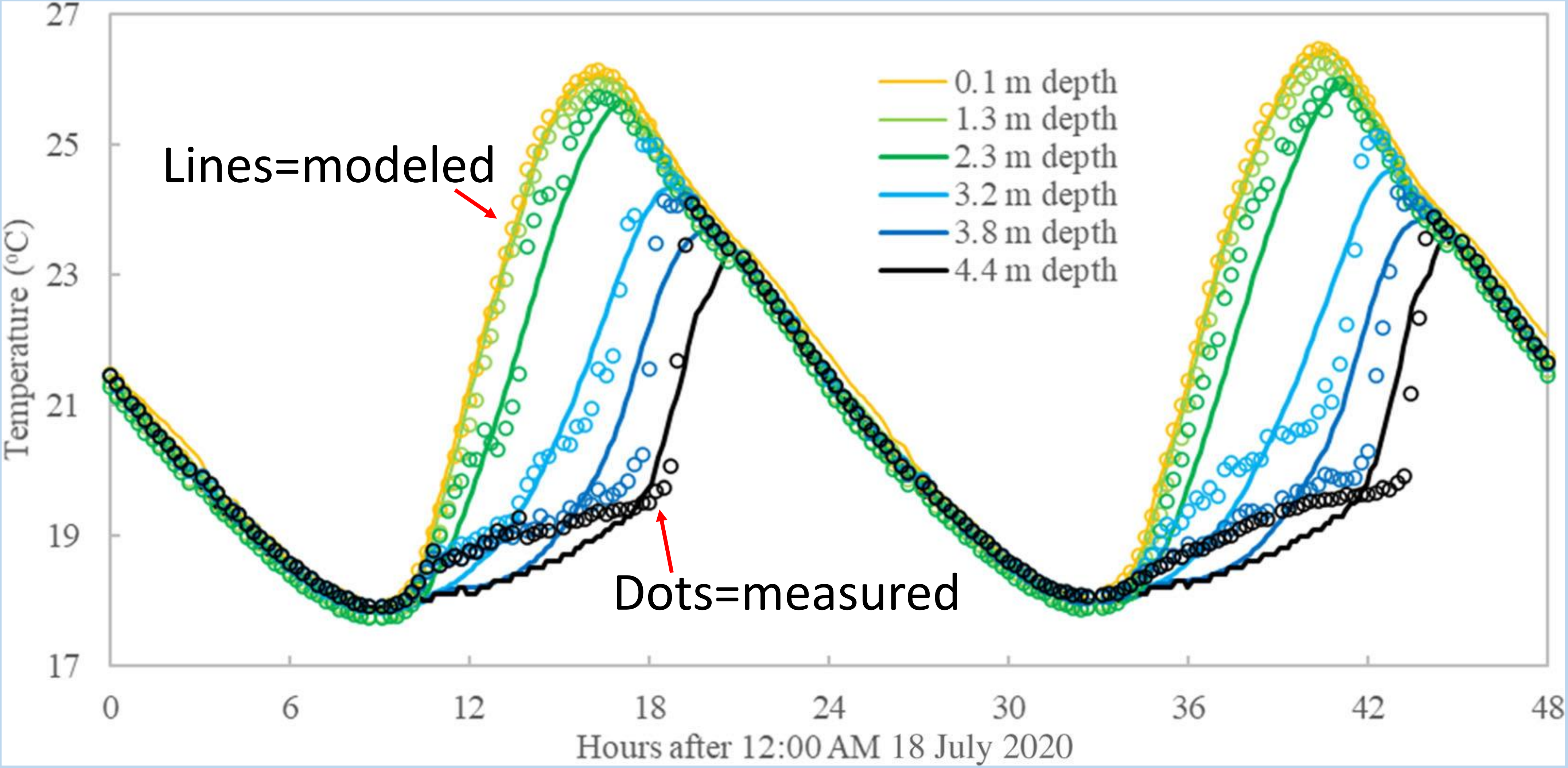
TABLE 3 Model selection results and AIC values for evaluating evidence of variables associated with pool stratification

Explanatory variables	*k*	AIC	ΔAIC^1	ΔAIC^2
Step 1: AR(1) variance component				
DIWT	4	161.09	3.27	25.81
DATD	4	157.82	0	22.54
MDIWT	4	161.26	3.44	25.98
Step 2: AR(1) variance component				
DATD, Q_{avg}	5	138.56	0	3.28
DATD, SE	5	159.75	21.19	24.47
DATD, DL	5	154.69	16.13	19.41
DATD, SE, Q_{avg}	6	139.65	1.09	4.37
DATD, DL, Q_{avg}	6	139.71	1.15	4.43
Step 3: AR(1) variance component				
DATD, Q_{avg}, DATD:Q_{avg}	6	135.28		0

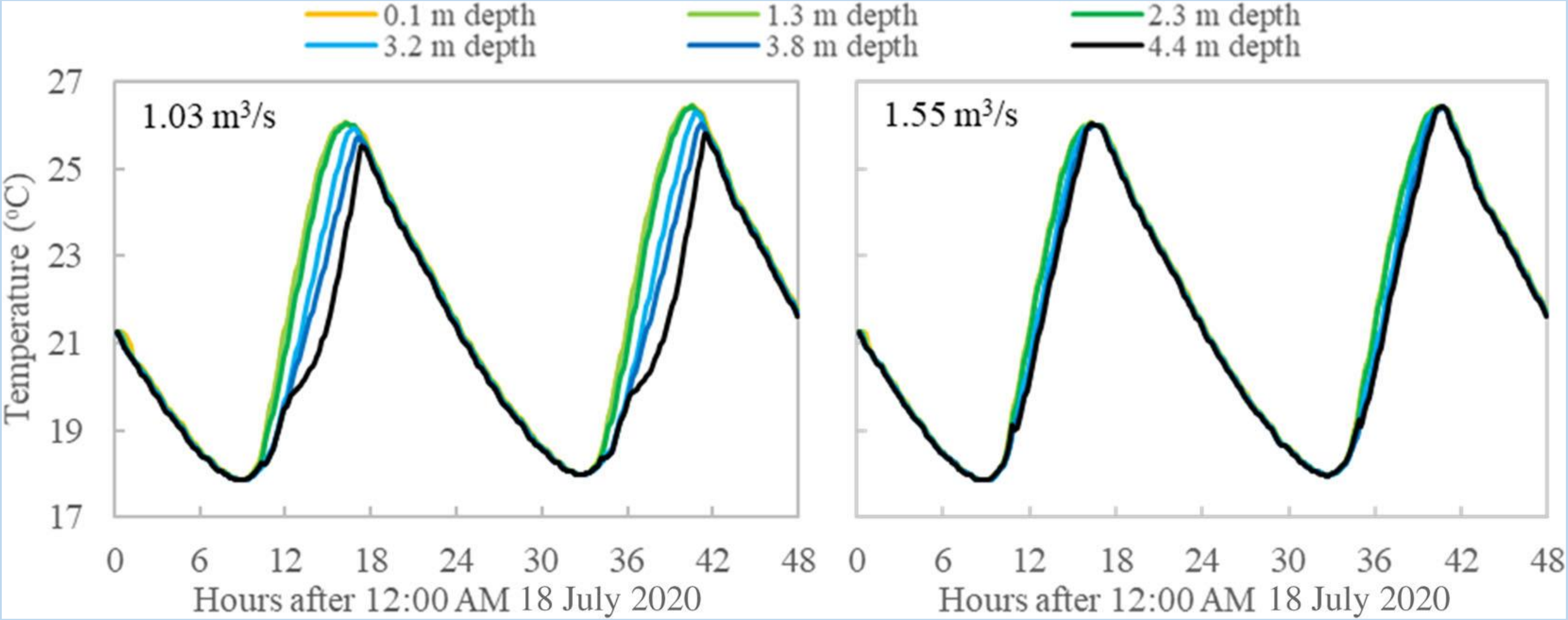
Smaller AIC values indicate preferred models

Model with DATD				Model with DIWT			
Variable	Estimate	Standard error	*p*-Value	Variable	Estimate	Standard error	*p*-Value
Intercept	2.53	0.61	<0.001	Intercept	1.71	0.78	0.03
Q_{avg}	−2.27	0.73	0	Q_{avg}	−1.63	1.05	0.13
DATD	0.02	0.02	0.54	DIWT	0.15	0.09	0.09
Q_{avg}:DATD	−0.07	0.03	0.03	Q_{avg}:DIWT	−0.27	0.12	0.03

Numerical modeling-verification at UT pool

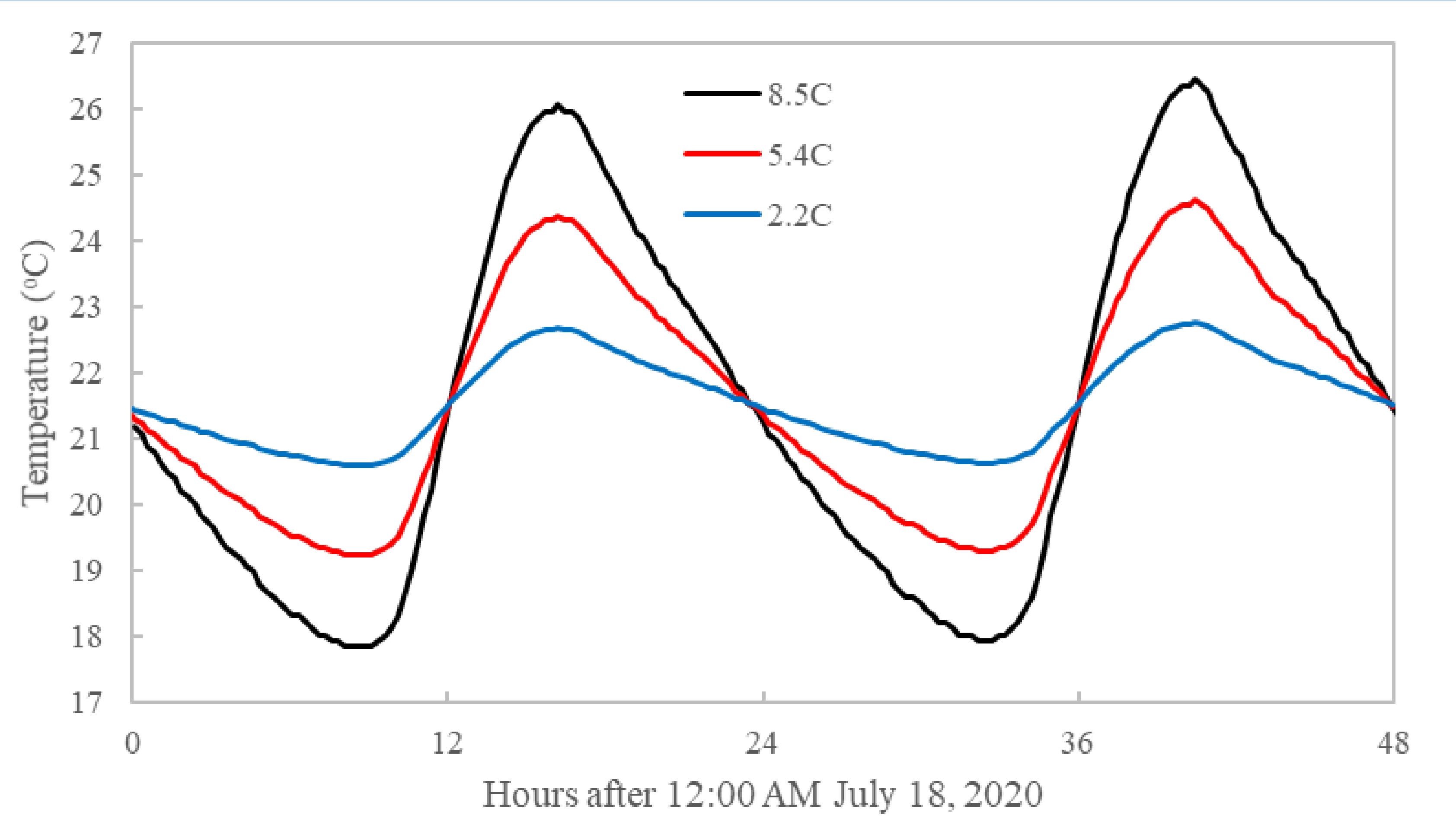


Numerical modeling-verification at UT pool

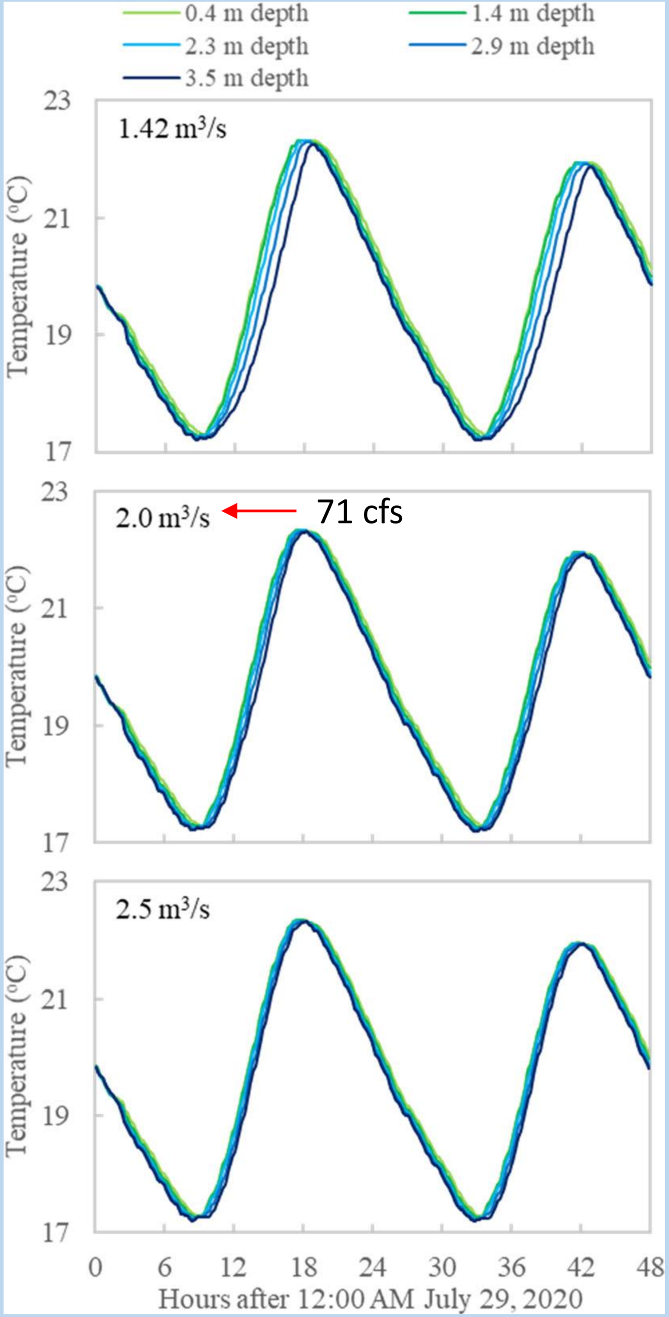


Numerical modeling-application

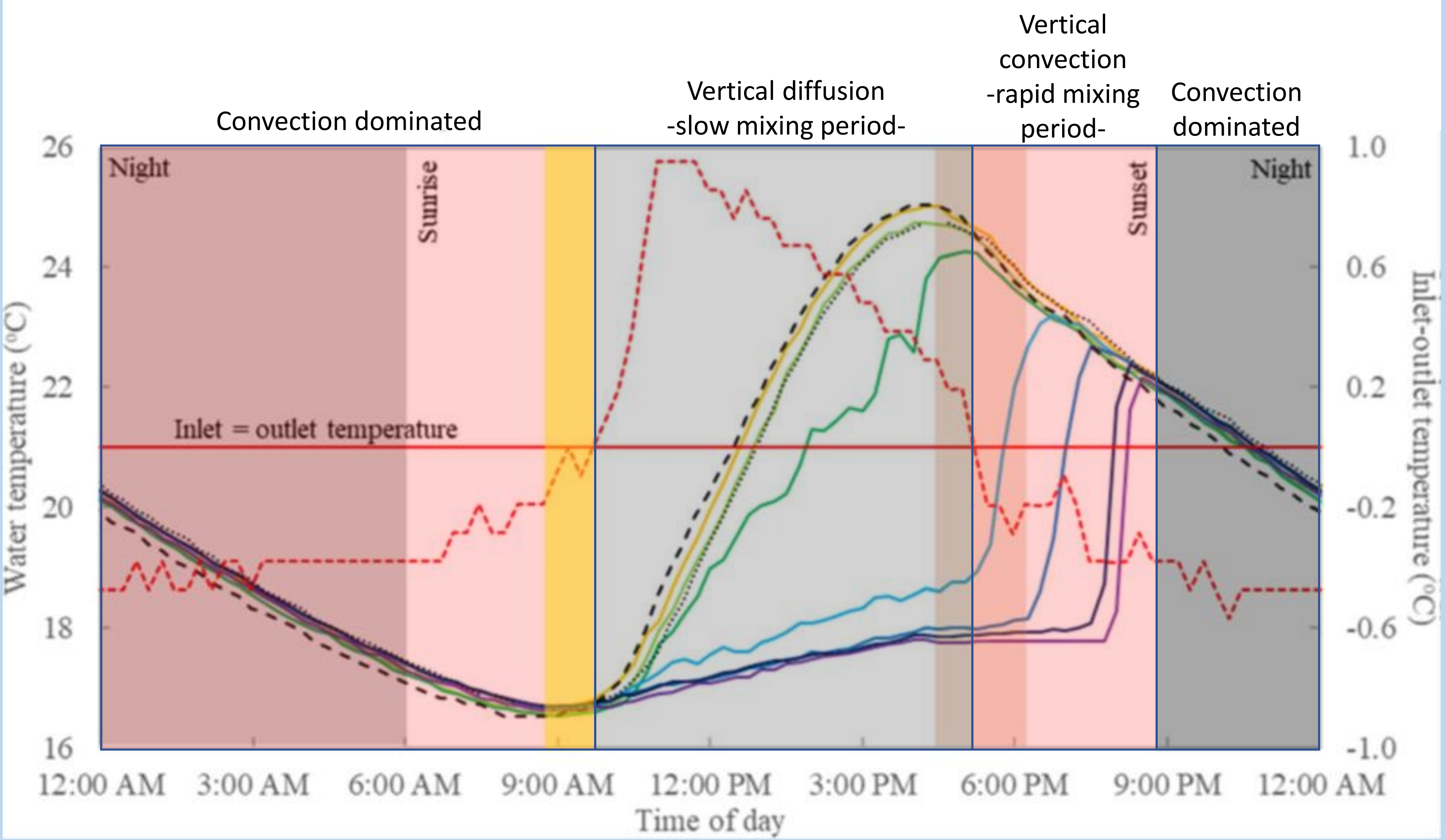
Sensitivity analysis on inlet temperature at sub-critical flows at UT pool



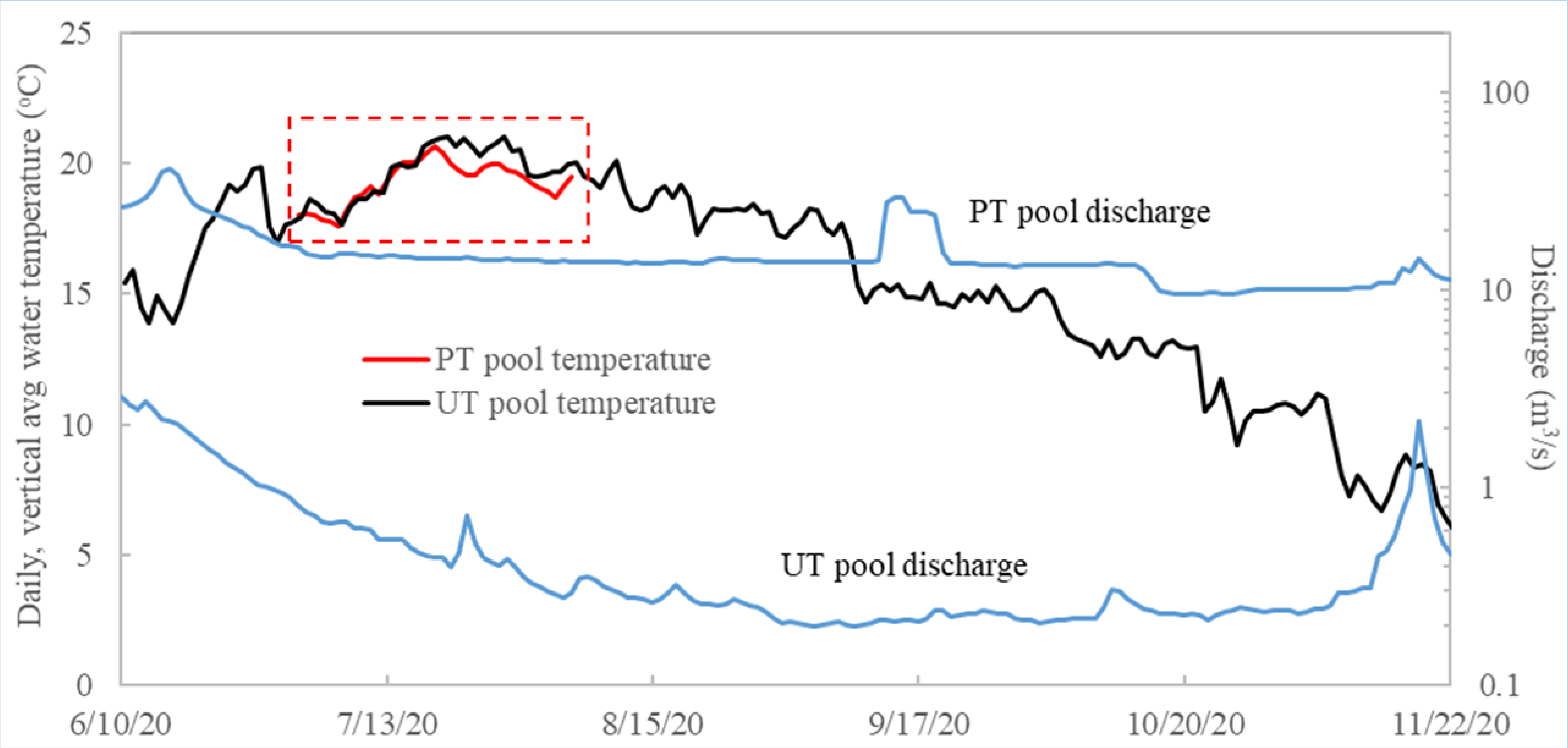
Critical discharge at PT pool



Numerical modeling-stratification process



Implications of stratification-flow management



Implications of stratification-Species conservation

- Stratified pools provide poikilothermic species (organisms that rely on environmental temperatures for thermoregulation) variable water temperatures they need to thrive:
  1. The availability of warm water in rivers can shorten the reproductive timeframe for macroinvertebrates, resulting in more food for rearing juvenile salmon.
  2. When fed to satiation, juvenile salmon able to rest and digest in warm pool margins and near the surface maximize growth.
  3. When food is less plentiful, juveniles can shelter in cold pool water to slow metabolism and better survive lean times.
  4. Adults rest in slow, cold water at pool bottom in summer to conserve energy and sexually mature before spawn.
  5. Warm areas in pool margins benefits growth in Western Pond Turtles (WPT) and Foothill Yellow-legged frogs (FYLF)
     a) WPT and FYLF growth rates in the restoration reach of the Trinity River are a fraction of those in the much warmer and unregulated SF Trinity River.

Next steps

- Model 14 additional pools on the Trinity River to estimate critical flows for pool stratification (Conor Shea, Todd Buxton);
- Derive a discharge to holding area curve to estimate the flow that provides the escapement target for spring Chinook (6,000) cold, stratified temperatures they require for holding;
- Estimate temperatures at the above flow throughout the river and evaluate their effects on macroinvertebrates, juvenile salmon, and FYLF in the restoration reach;
- Iteratively adjust summer flows to best meet warm and cold-water requirements of species to define what a functional summer hydrograph looks like on the Trinity River.