In Situ Observational Study of Water Circulation and Physical Properties in Falls Lake, North Carolina

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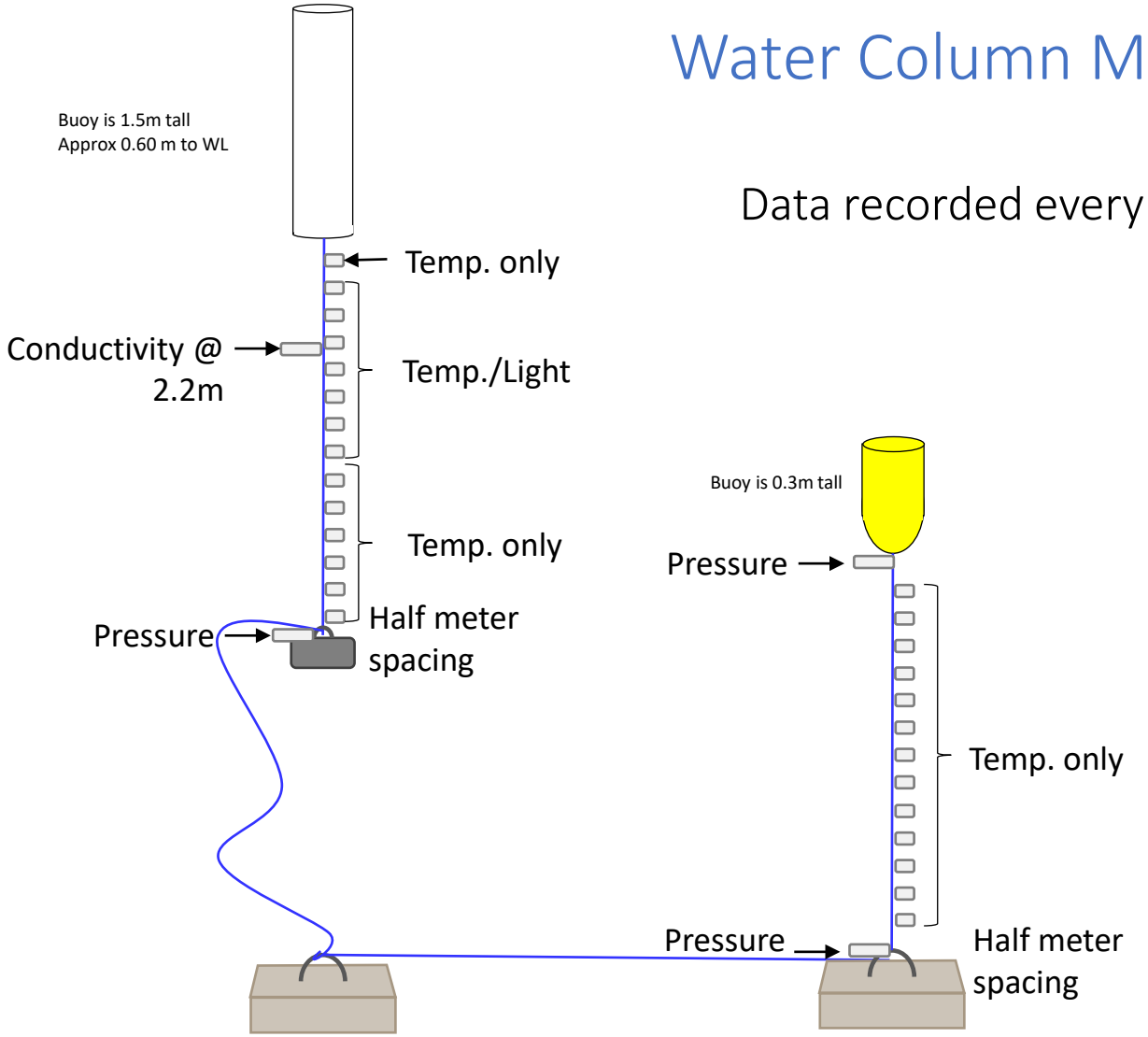
Research Questions

- What are the primary circulation pattern(s) and physical characteristics in Falls lake?
  - Across a range of time scales, e.g., hours to seasonal
- How do these vary based on
  - Inflows / Outflows
  - Physical Properties
  - Seasons
- Implications for Water Quality
  - Requires synthesis with other observations and modeling

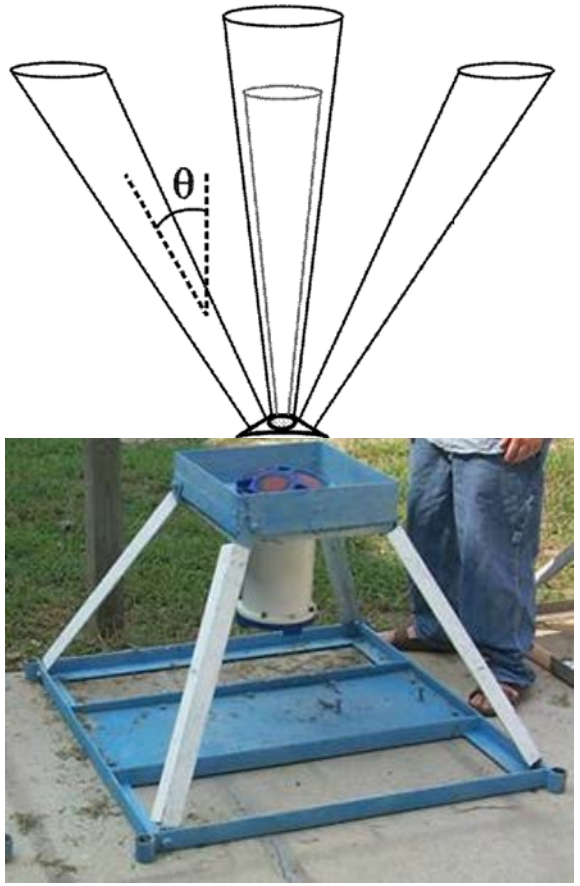
Instrumentation Deployed November 2019 – February 2021

Water Column Moorings

Data recorded every 6 min



Instrumentation Deployed November 2019 – February 2021



Bottom mounted acoustic doppler current profilers

Data recorded every 10 min

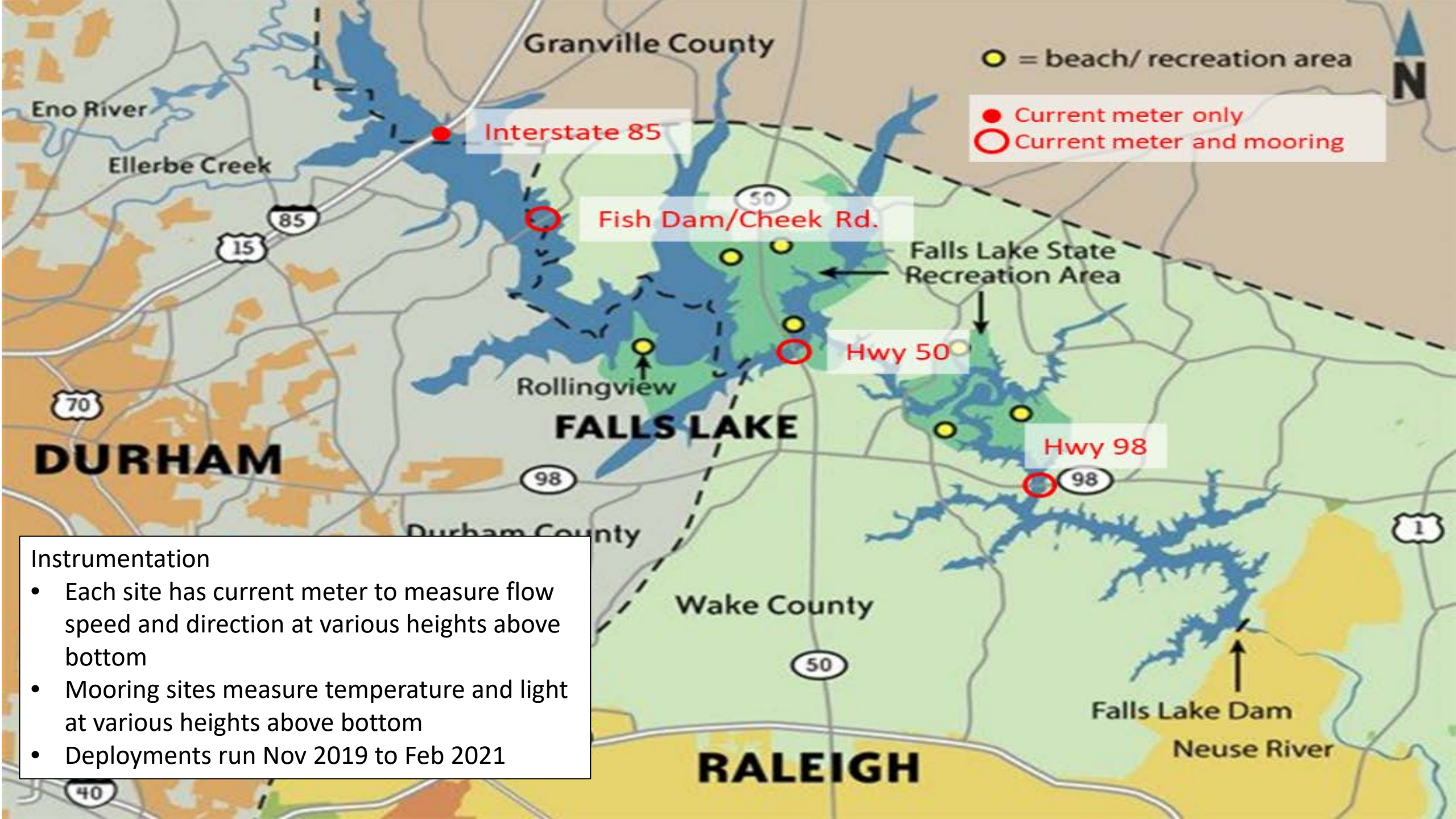
Horizontal water velocity
@ 0.5m vertical resolution
through the water column

Instrumentation Deployed November 2019 – February 2021

Shipboard sensors

- YSI multiparameter probe
  - temperature
  - conductivity
  - turbidity
  - Chl-a
  - dissolved oxygen
  - pH
- LiCor PAR sensor

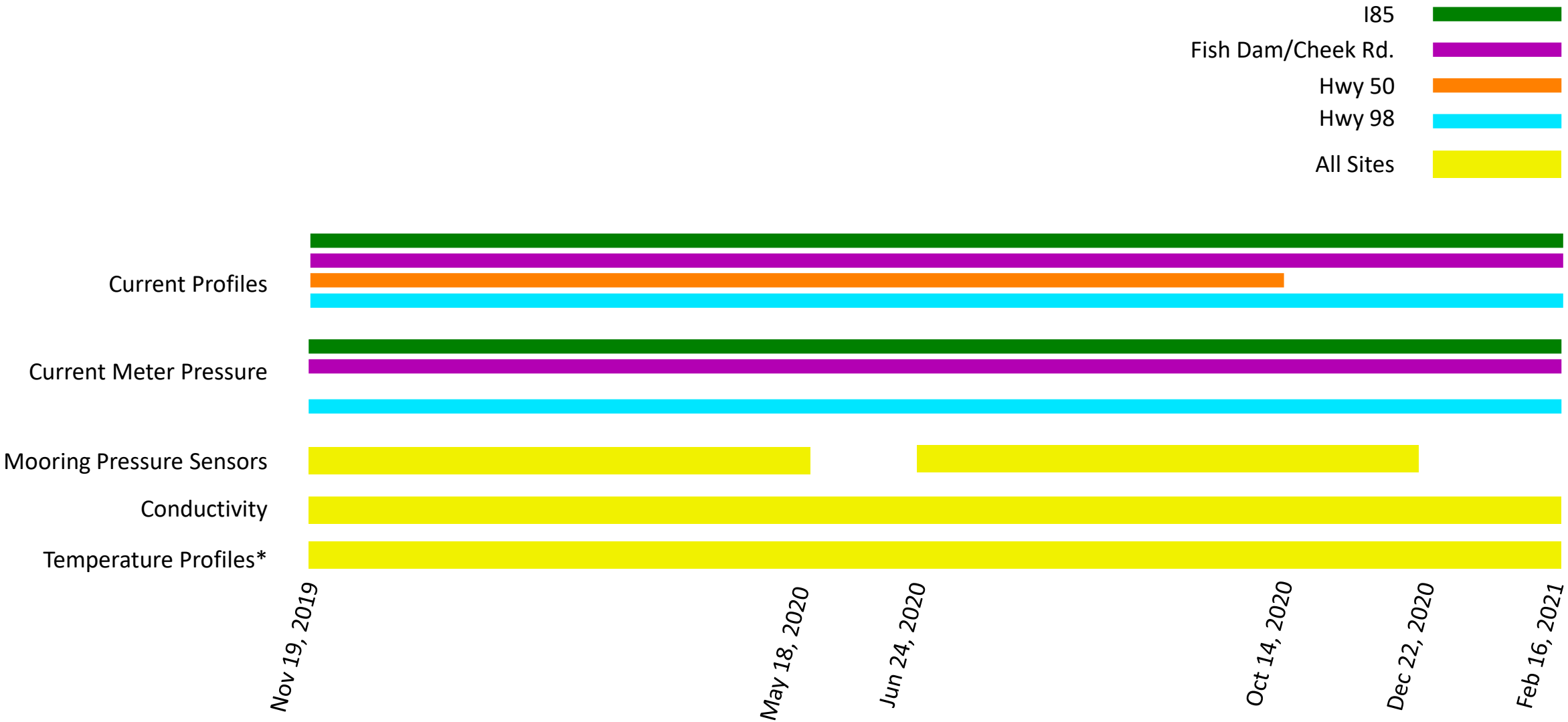
Vertical measurement through the water column
Data recorded every 1-2 months during trips to clean / service the moorings



Instrumentation

- Each site has current meter to measure flow speed and direction at various heights above bottom
- Mooring sites measure temperature and light at various heights above bottom
- Deployments run Nov 2019 to Feb 2021

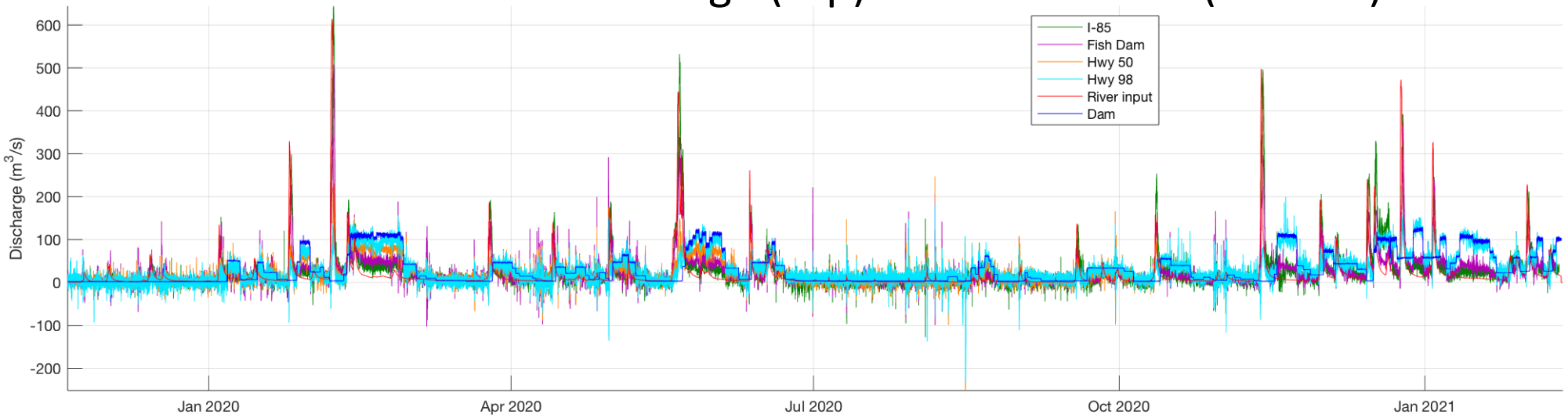
Data Recovery November 2019 – February 2021

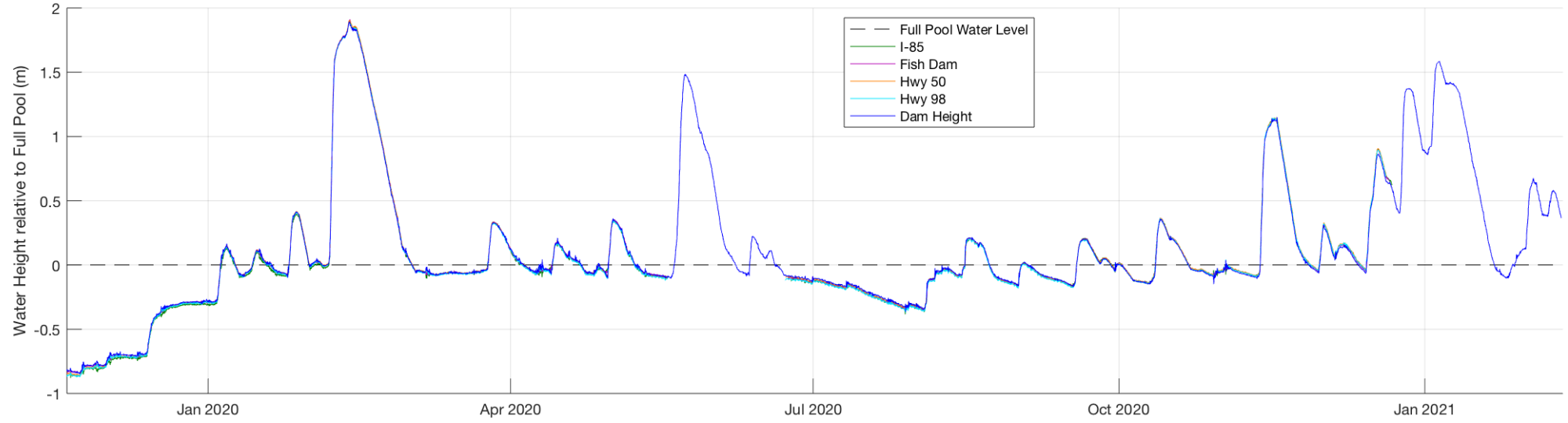


*Temperature Profiles include light, although bio-fouling is a QA/QC issue

Physical Characteristics

Full time series of discharge (top) and water level (bottom)





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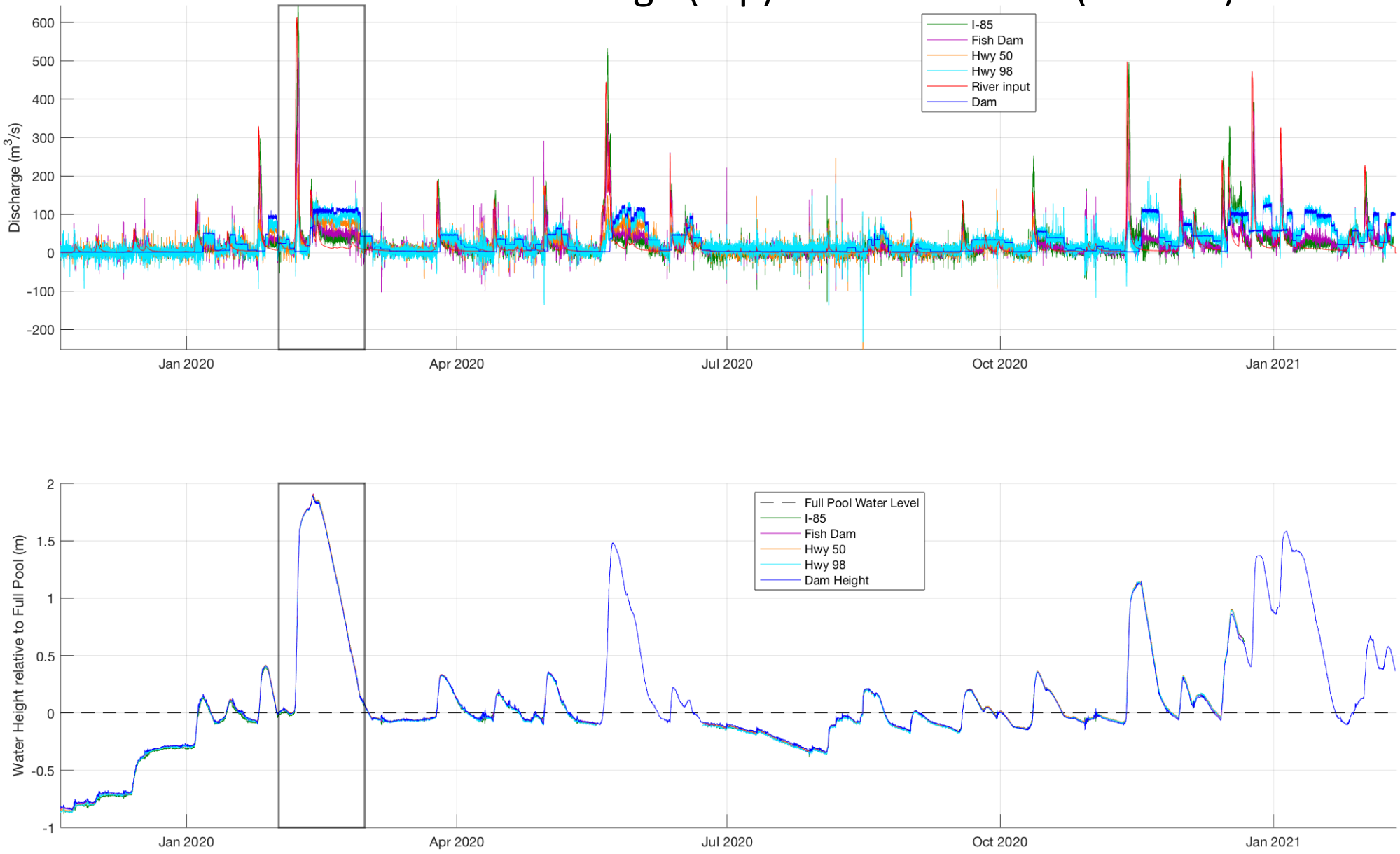
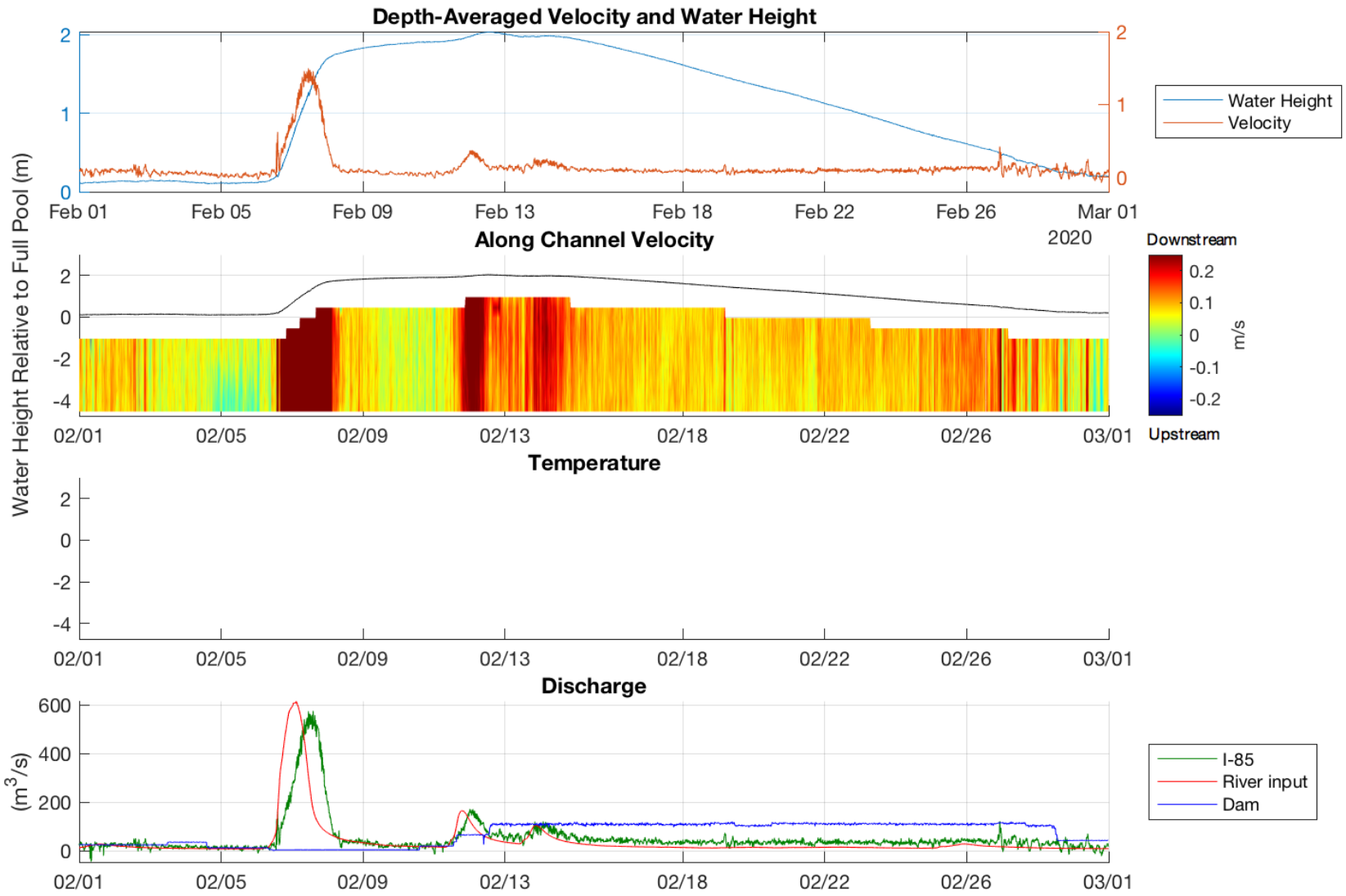
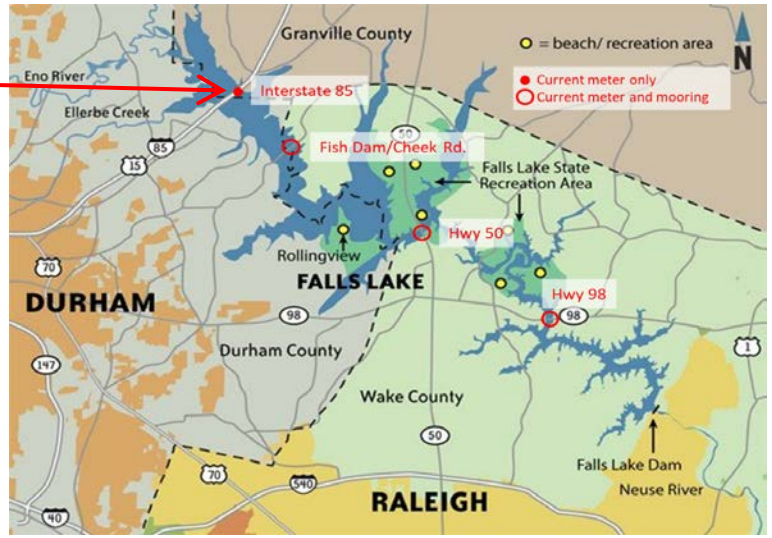
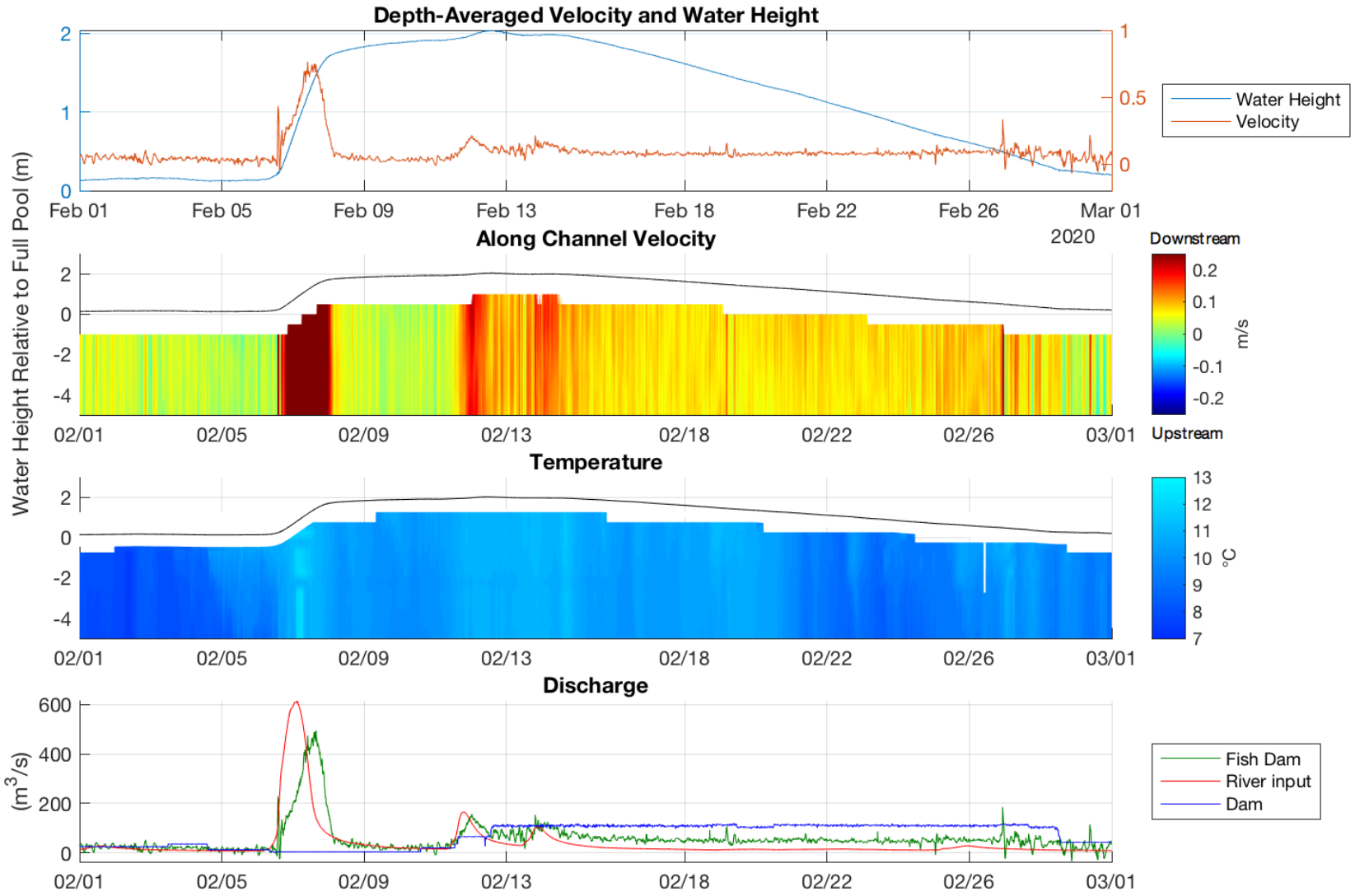


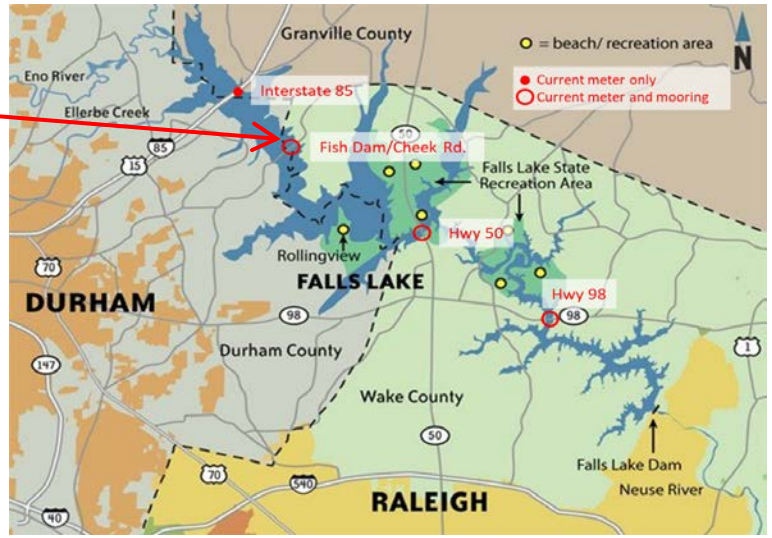
I 85 - February 2020



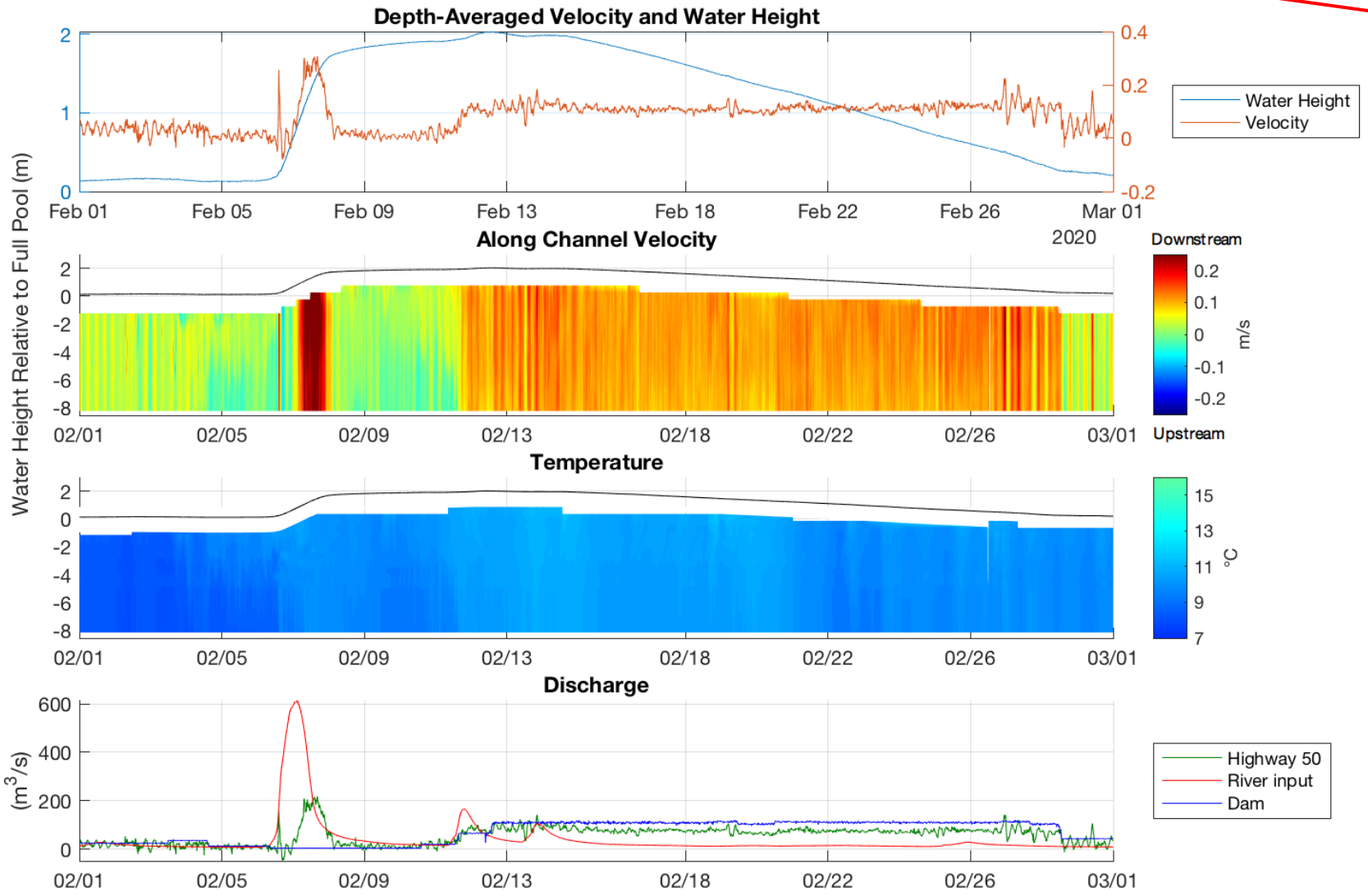


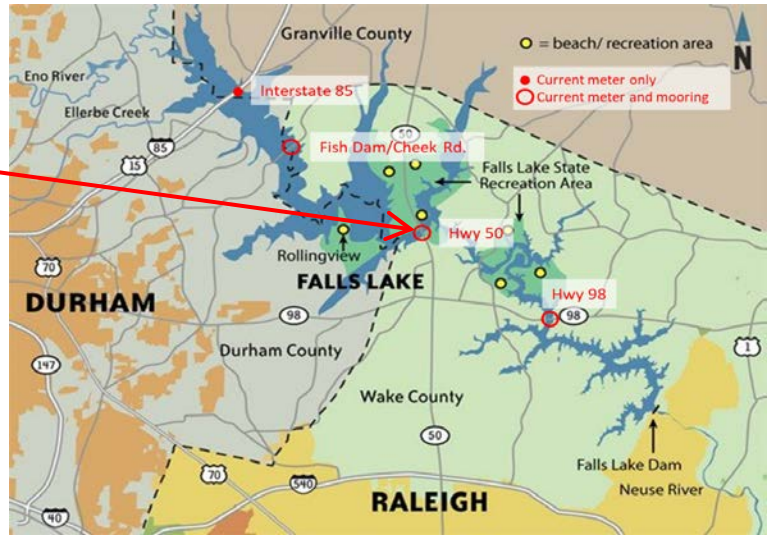
Fish Dam Rd- February 2020



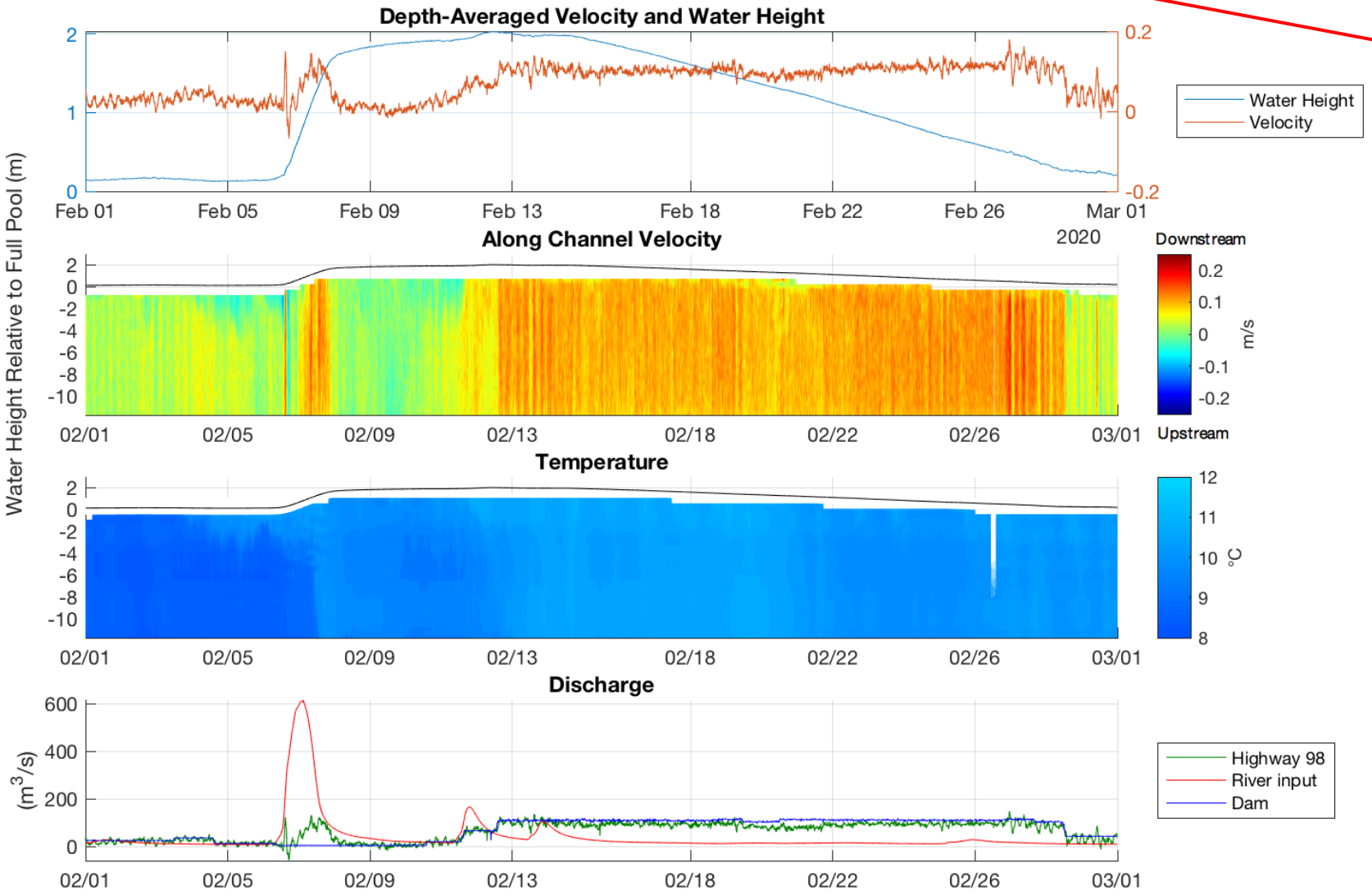


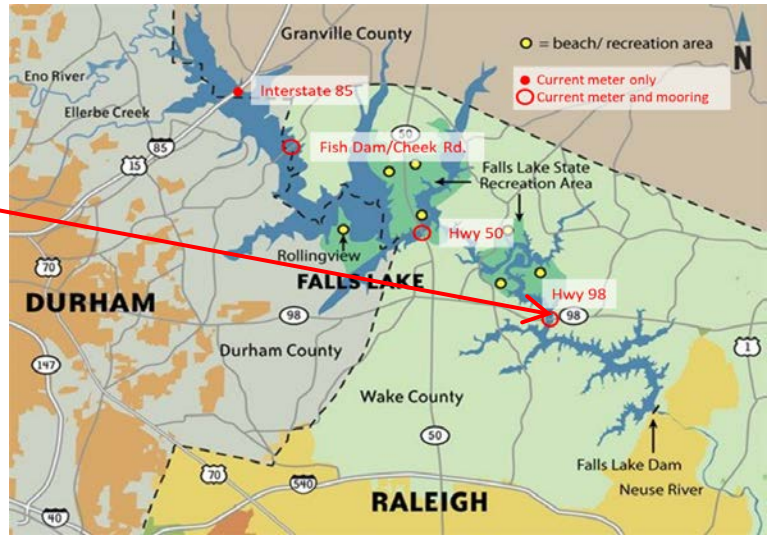
Hwy 50 - February 2020



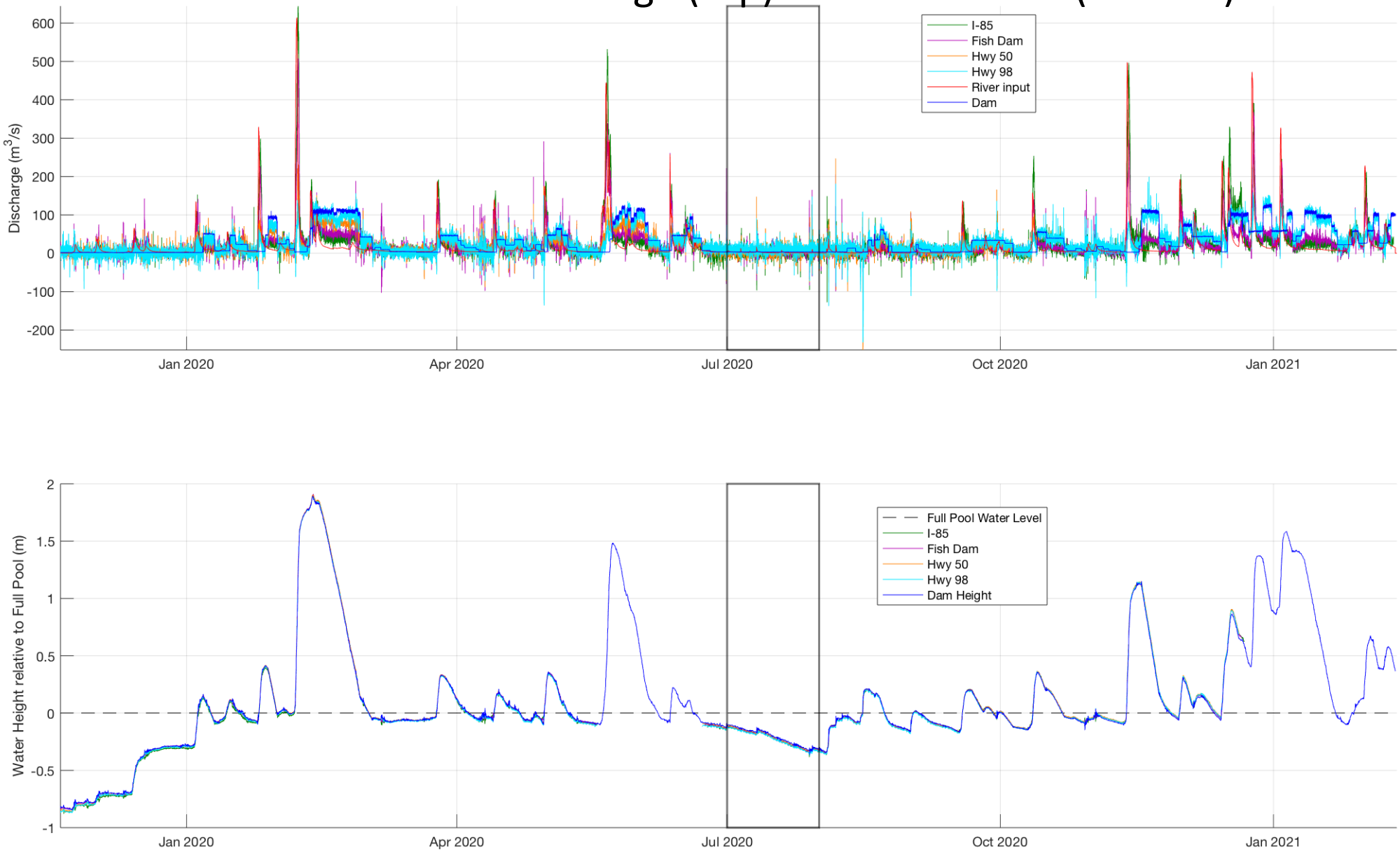


Hwy 98 - February 2020

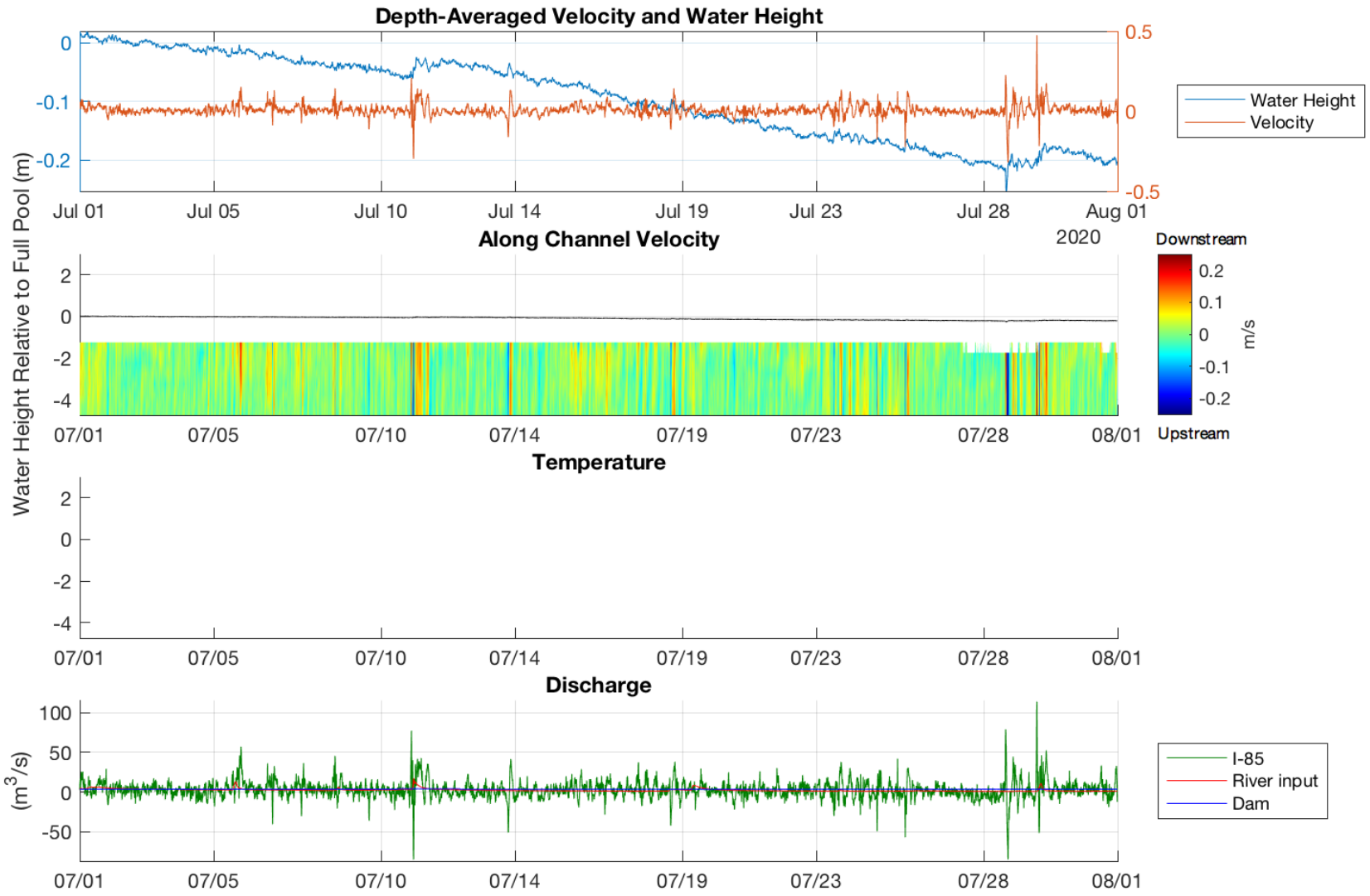


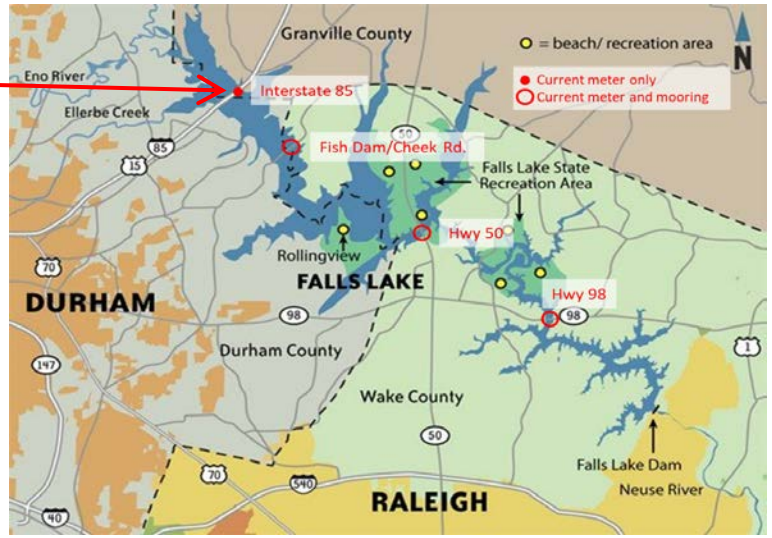


Full time series of discharge (top) and water level (bottom)

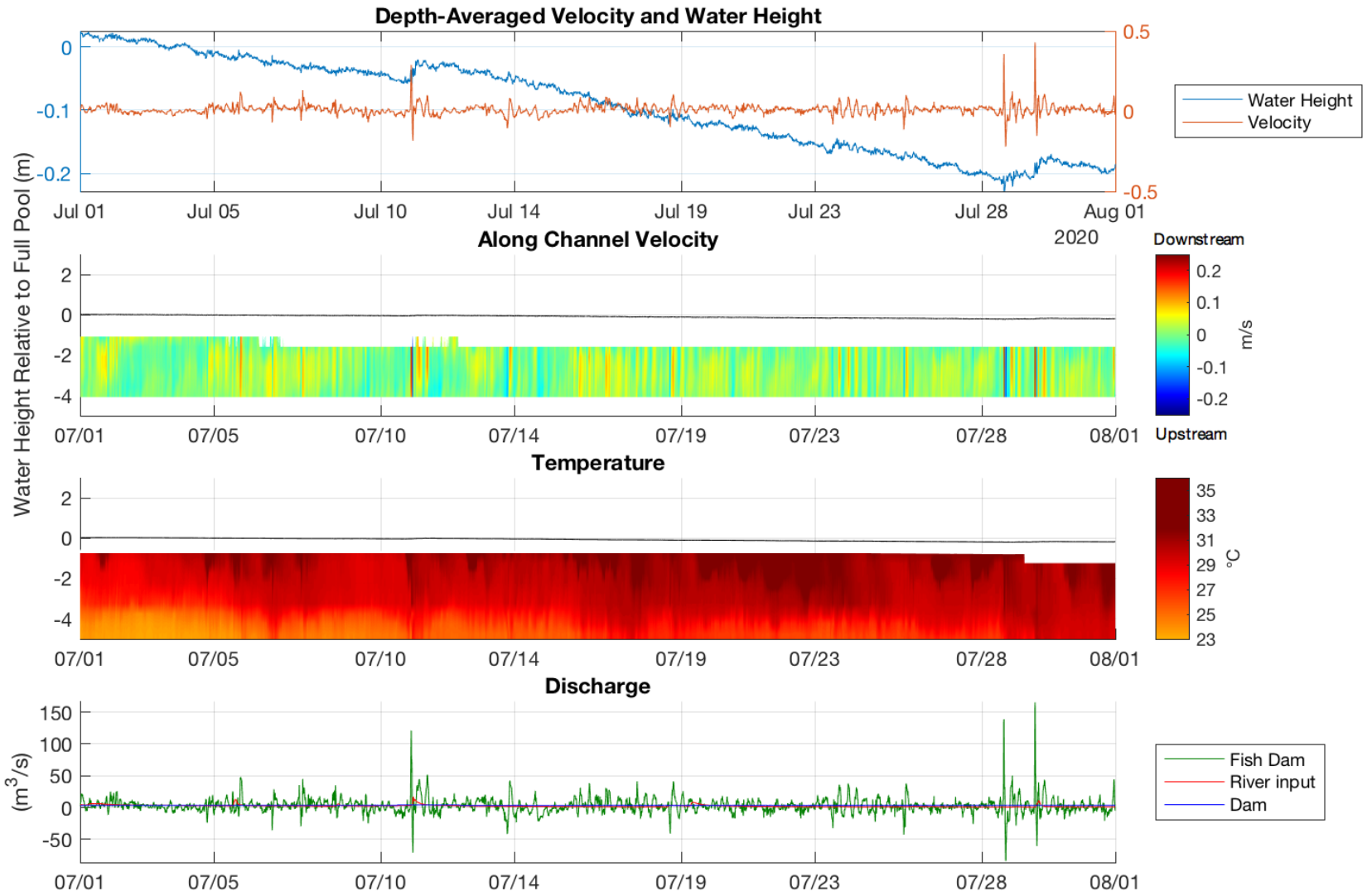


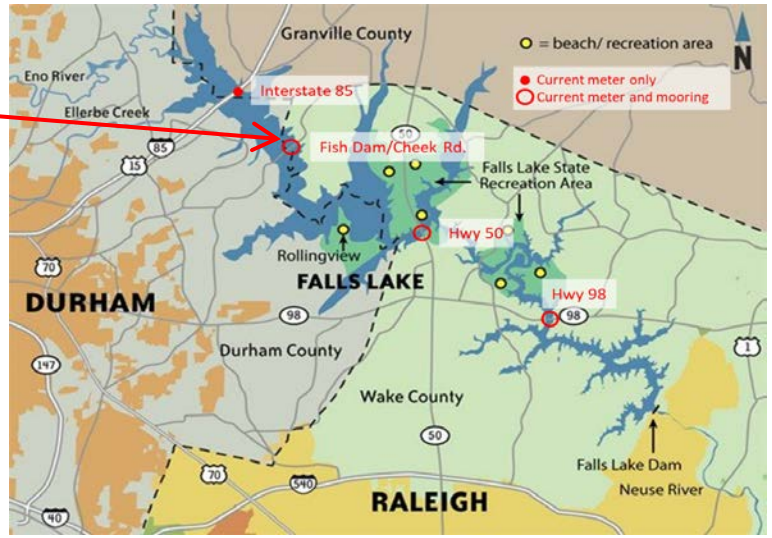
I 85 - July 2020



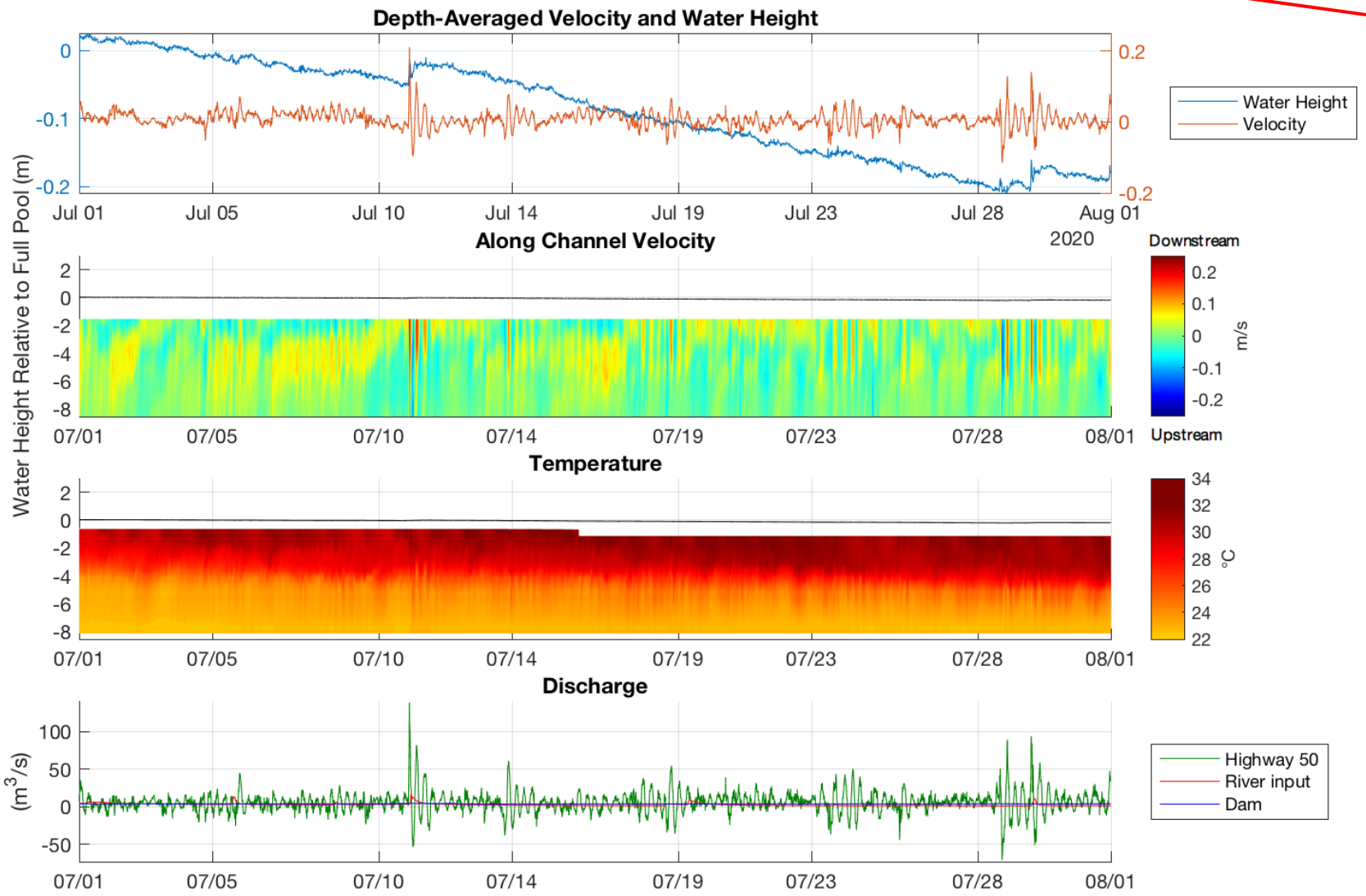


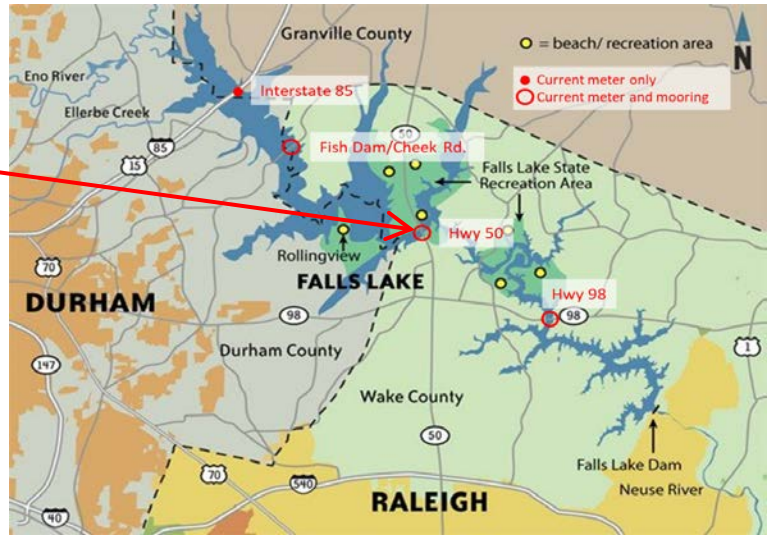
Fish Dam Rd- July 2020



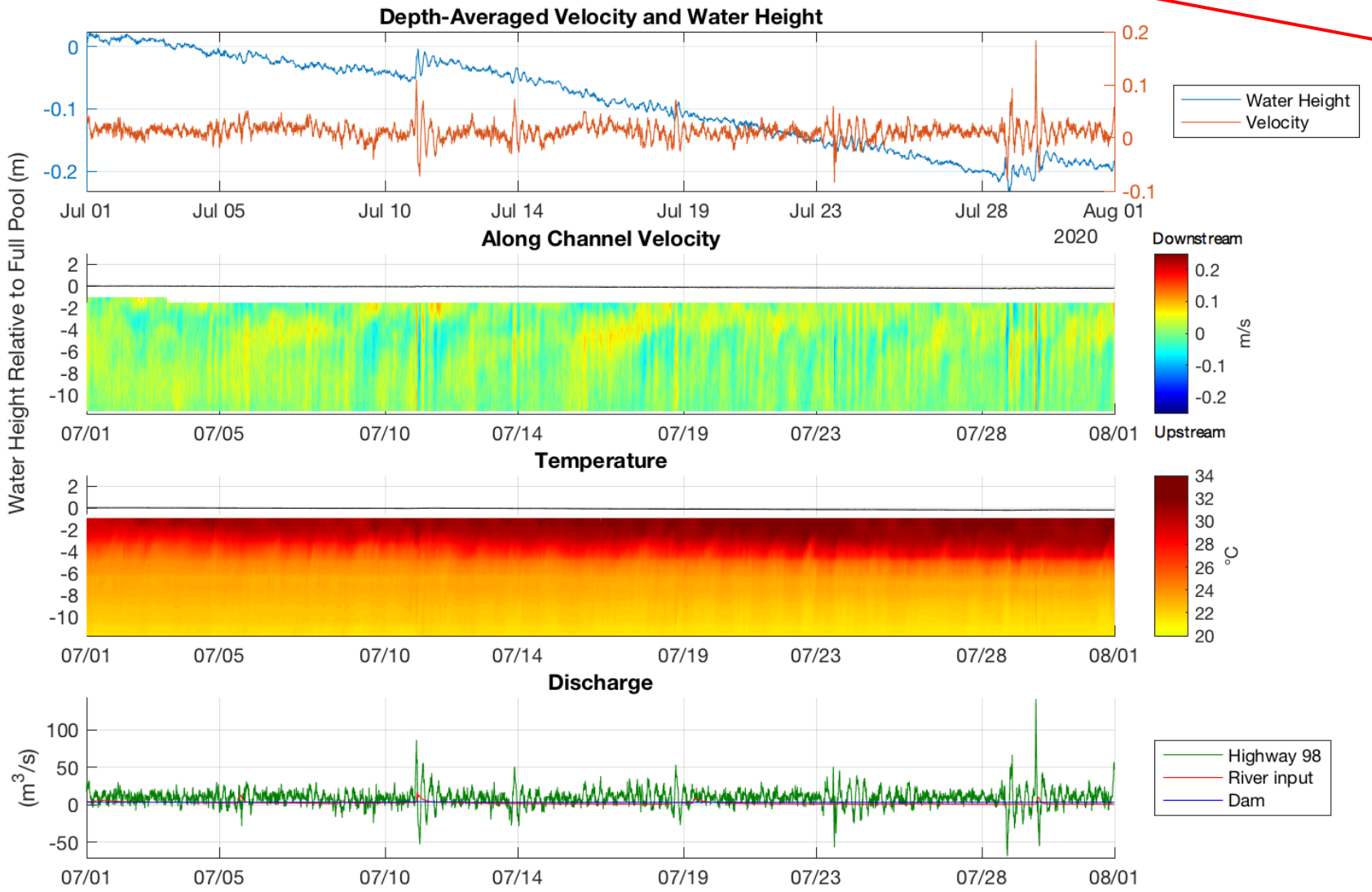


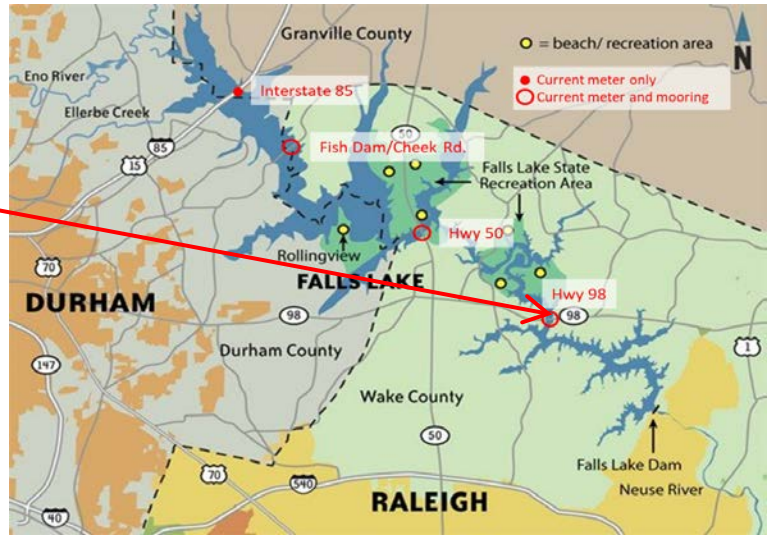
Hwy 50 - July 2020





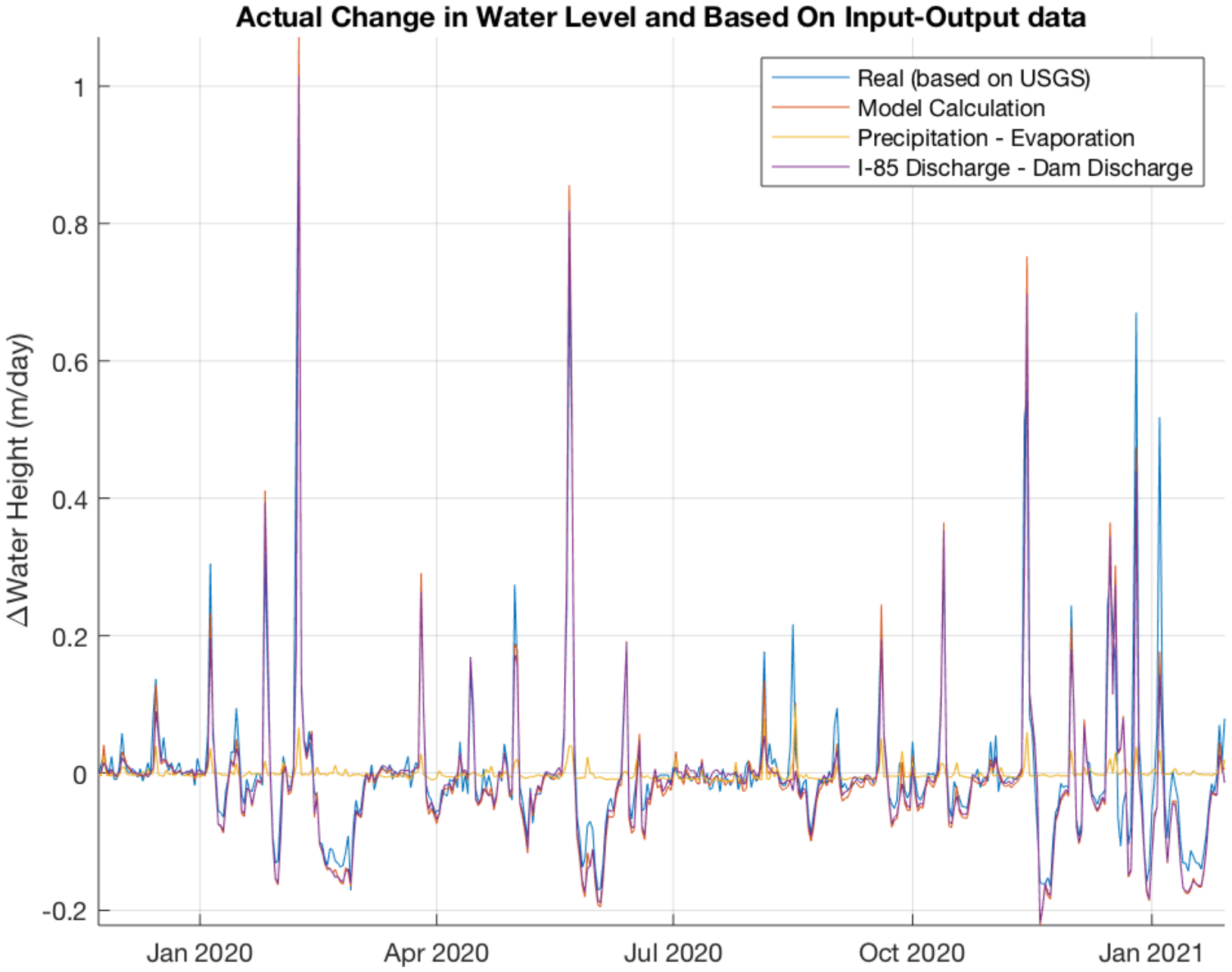
Hwy 98 – July 2020





Basic circulation characteristics

- Simple box model captures depth-integrated transport variations, leads to residence time calculation
- Seasonal thermal variation – vertical stratification and horizontal gradients
- Bi-directional flow – occurs most often during summer stratification, complicates residence time calculation
- Seiches – short-period (hours-long) oscillations are ubiquitous, stir the reservoir, drive mixing at some level



$\partial\eta/\partial t$ = Vout – Vin + P – E

$\partial\eta/\partial t$ = water level change

Vout, Vin = transport out and in

P = precipitation on lake

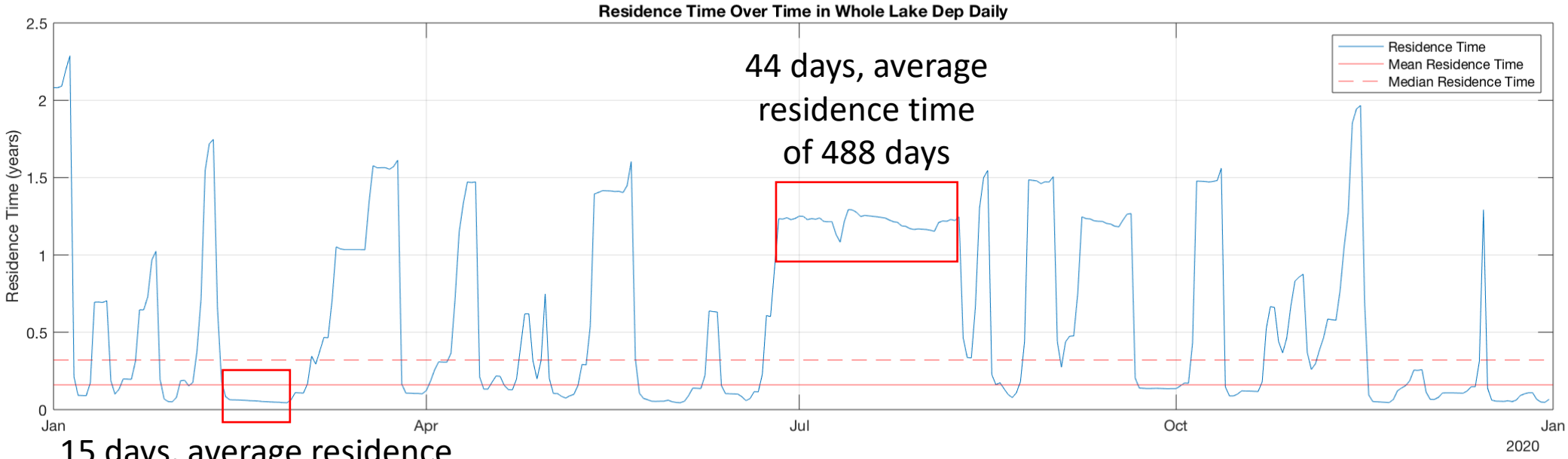
E = Evaporation from lake

R^2 values

	ΔV	model
creeks	0.776	0.775
I-85	0.854	0.873

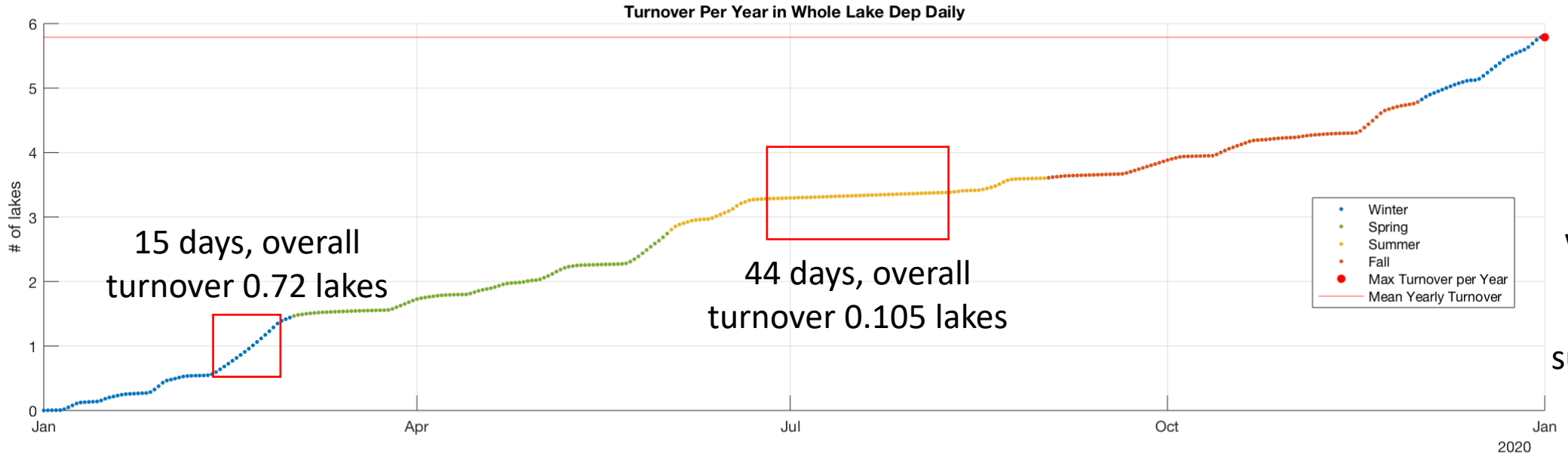
Residence time = T(t) = V(t)/Q(t), where V=lake volume and Q=discharge or inflow, t=time, gives an estimate of time water parcels spend in the lake.

Turnovers = $\Sigma(Q * \Delta t)/\bar{V}$, where $\bar{V}$=average lake volume, Δt=sampling interval, quantifies how many lake volumes have occurred over some time interval.



44 days, average residence time of 488 days

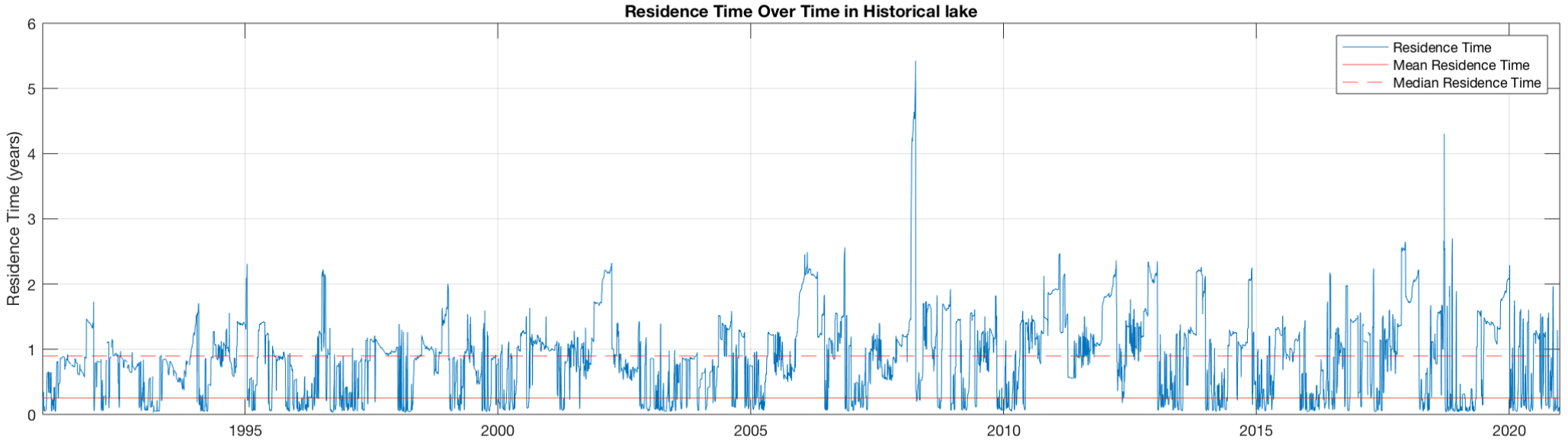
15 days, average residence time of 20 days

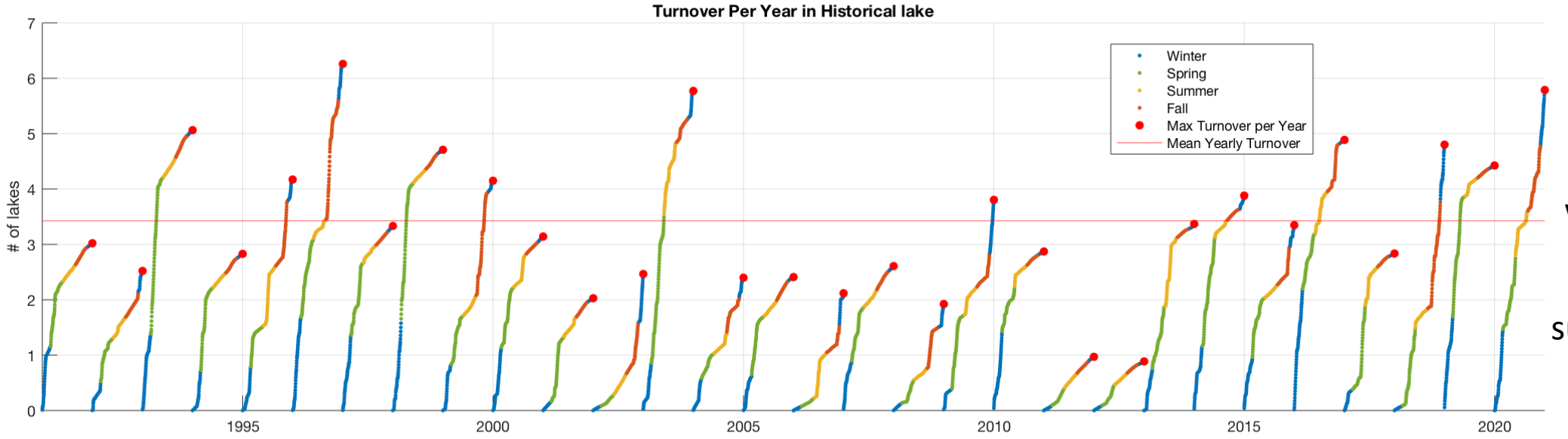


15 days, overall turnover 0.72 lakes

44 days, overall turnover 0.105 lakes

winter	2.46	42%
spring	1.27	22%
summer	0.92	16%
fall	1.16	20%

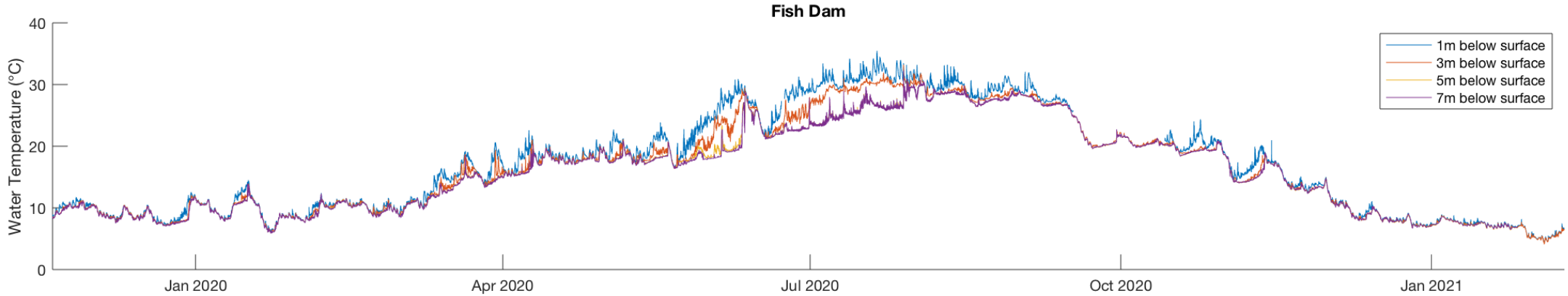


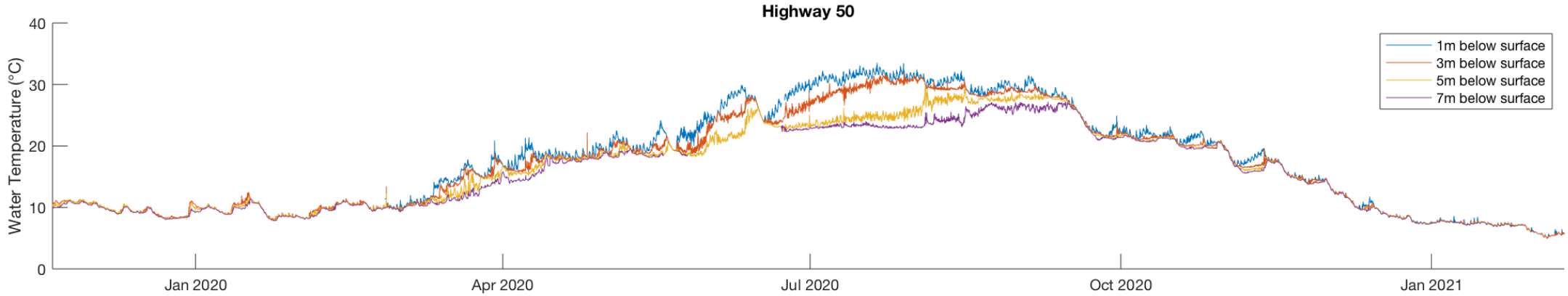


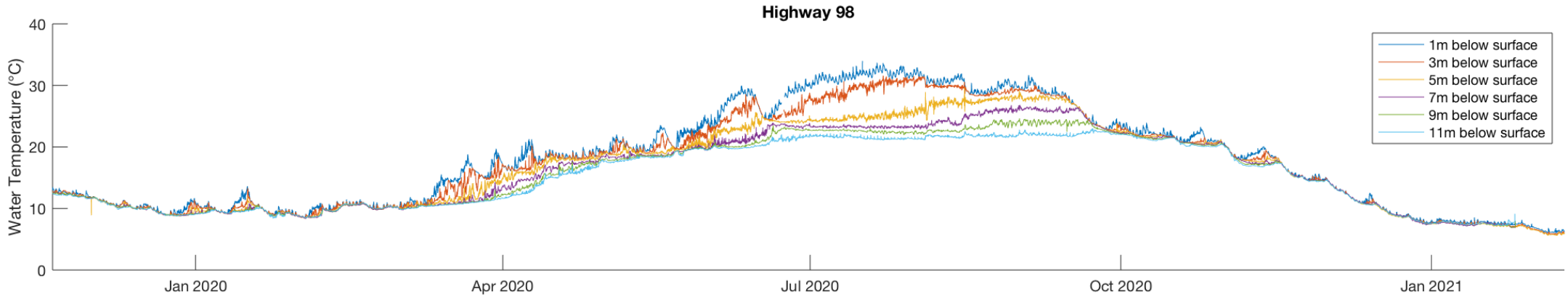
winter	1.13	33%
spring	1.21	35%
summer	0.50	14%
fall	0.61	18%

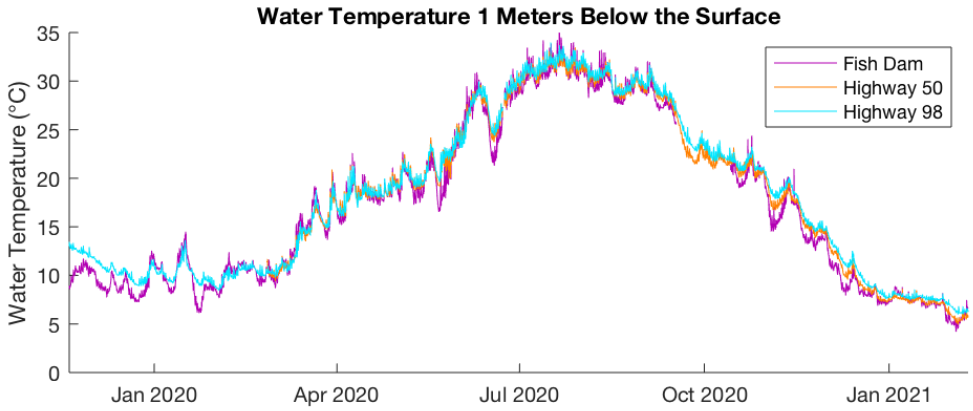
Temperature as a function of depth in the lake

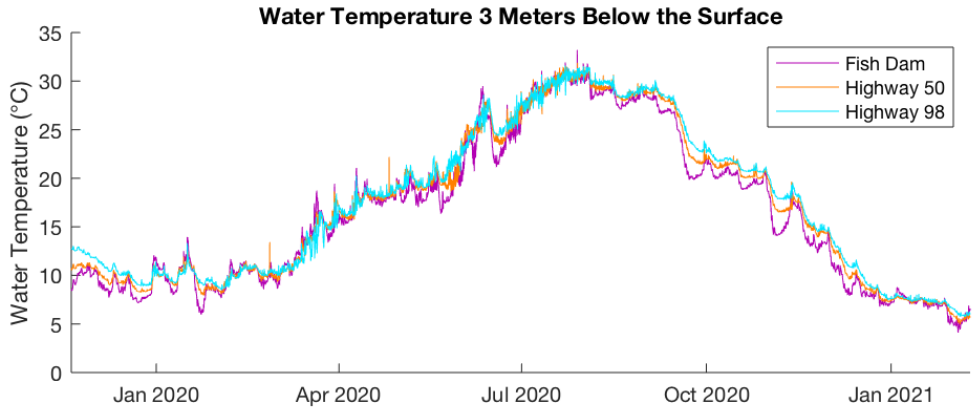
Water Temperature Through Water Column at Each Site

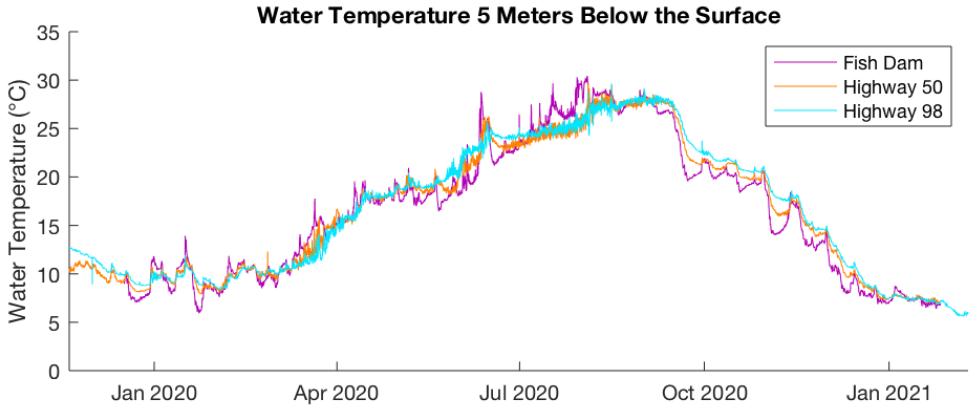


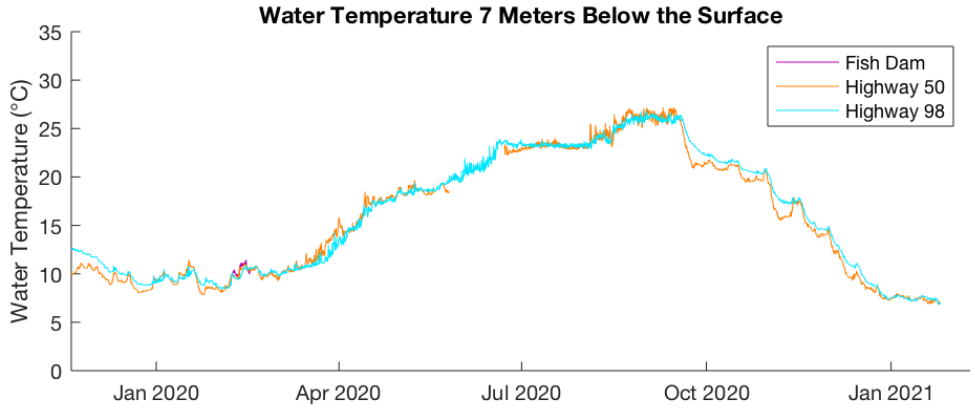


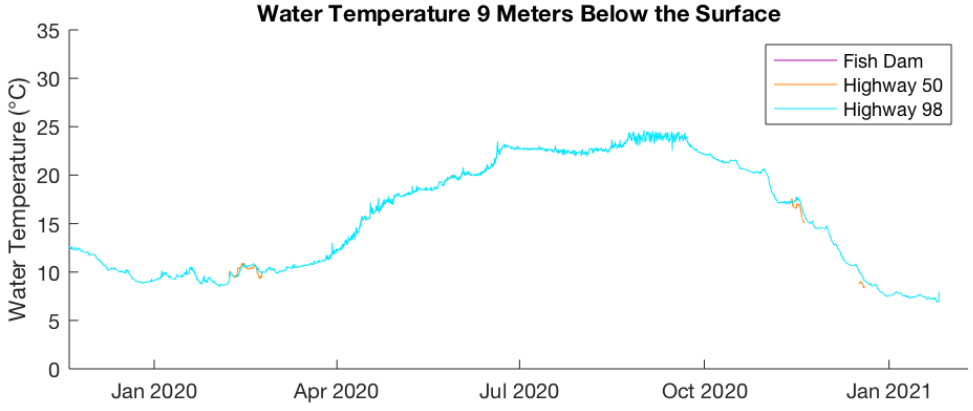


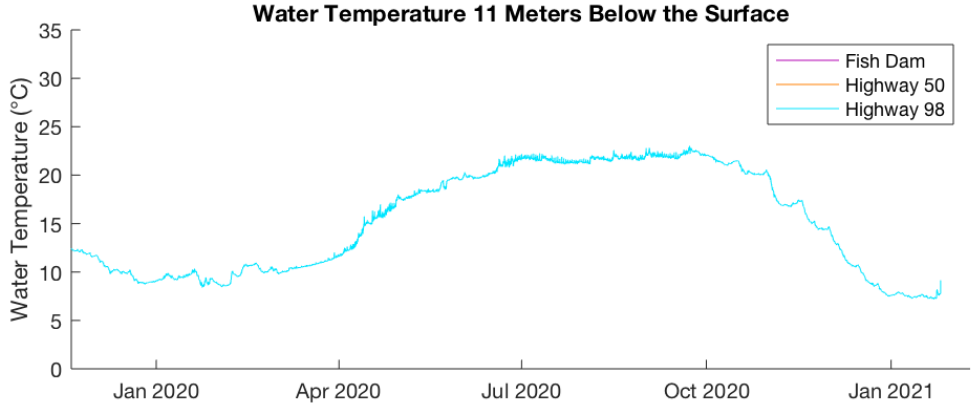

Water Temperature 1 Meters Below the Surface
Water Temperature (°C)
0
5
10
15
20
25
30
35
Jan 2020
Apr 2020
Jul 2020
Oct 2020
Jan 2021
Fish Dam
Highway 50
Highway 98


Water Temperature 3 Meters Below the Surface
Water Temperature (°C)
0
5
10
15
20
25
30
35
Jan 2020
Apr 2020
Jul 2020
Oct 2020
Jan 2021
Fish Dam
Highway 50
Highway 98

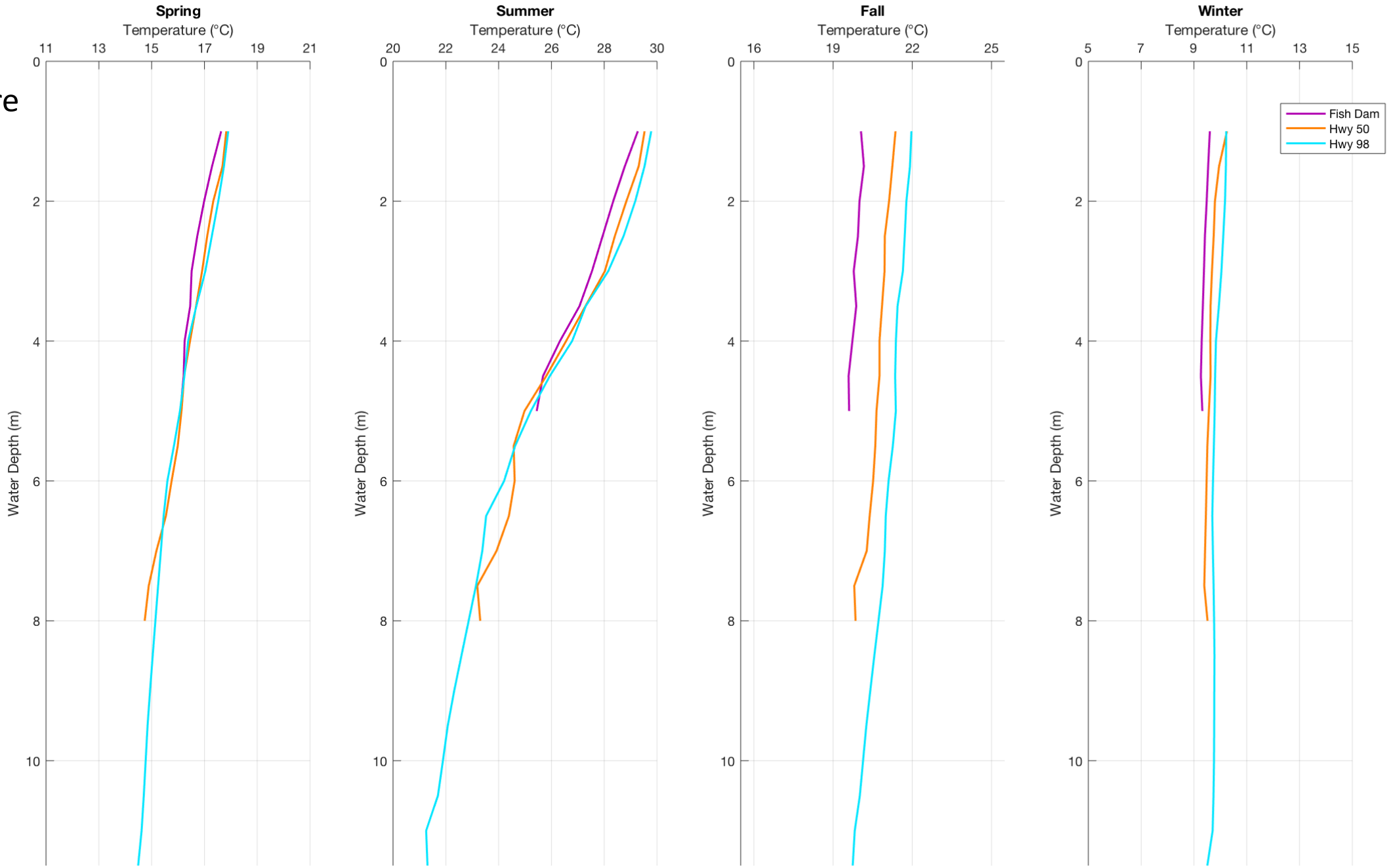

Water Temperature 5 Meters Below the Surface
Water Temperature (°C)
0
5
10
15
20
25
30
35
Jan 2020
Apr 2020
Jul 2020
Oct 2020
Jan 2021
Fish Dam
Highway 50
Highway 98


Water Temperature 7 Meters Below the Surface
Water Temperature (°C)
0
5
10
15
20
25
30
35
Jan 2020
Apr 2020
Jul 2020
Oct 2020
Jan 2021
Fish Dam
Highway 50
Highway 98

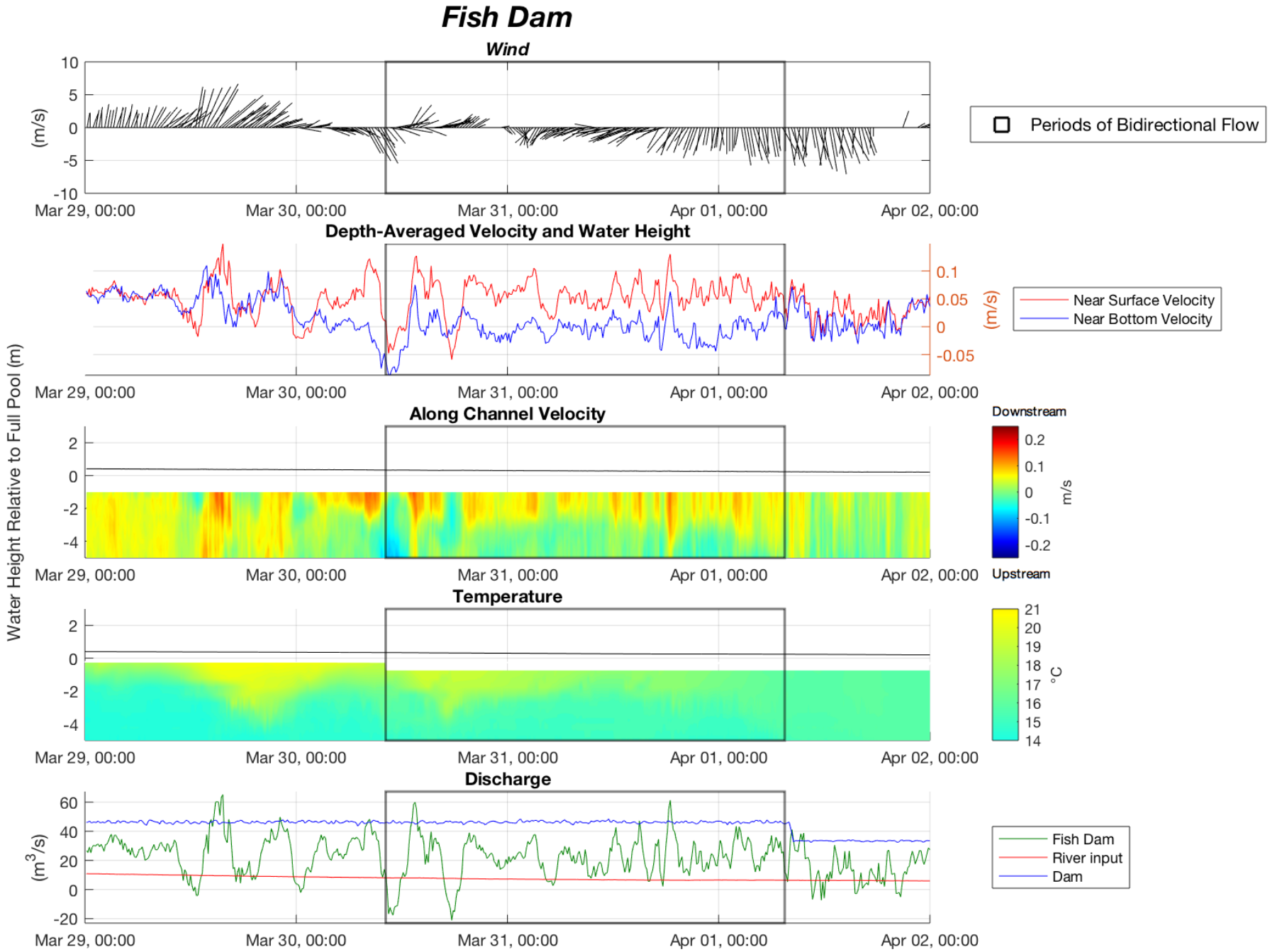

Water Temperature 9 Meters Below the Surface
Water Temperature (°C)
0
5
10
15
20
25
30
35
Jan 2020
Apr 2020
Jul 2020
Oct 2020
Jan 2021
Fish Dam
Highway 50
Highway 98

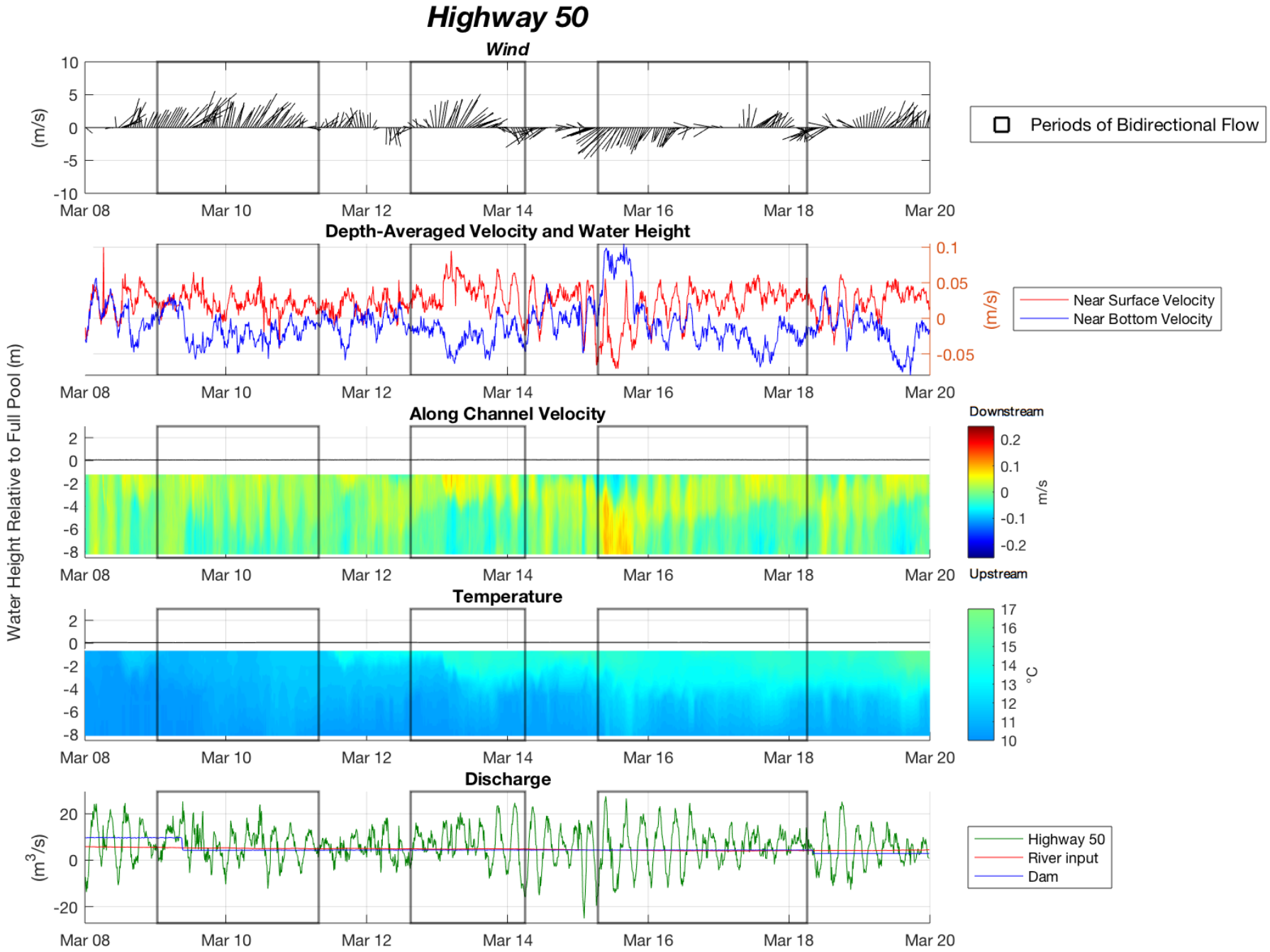

Water Temperature 11 Meters Below the Surface
Water Temperature (°C)
0
5
10
15
20
25
30
35
Jan 2020
Apr 2020
Jul 2020
Oct 2020
Jan 2021
Fish Dam
Highway 50
Highway 98

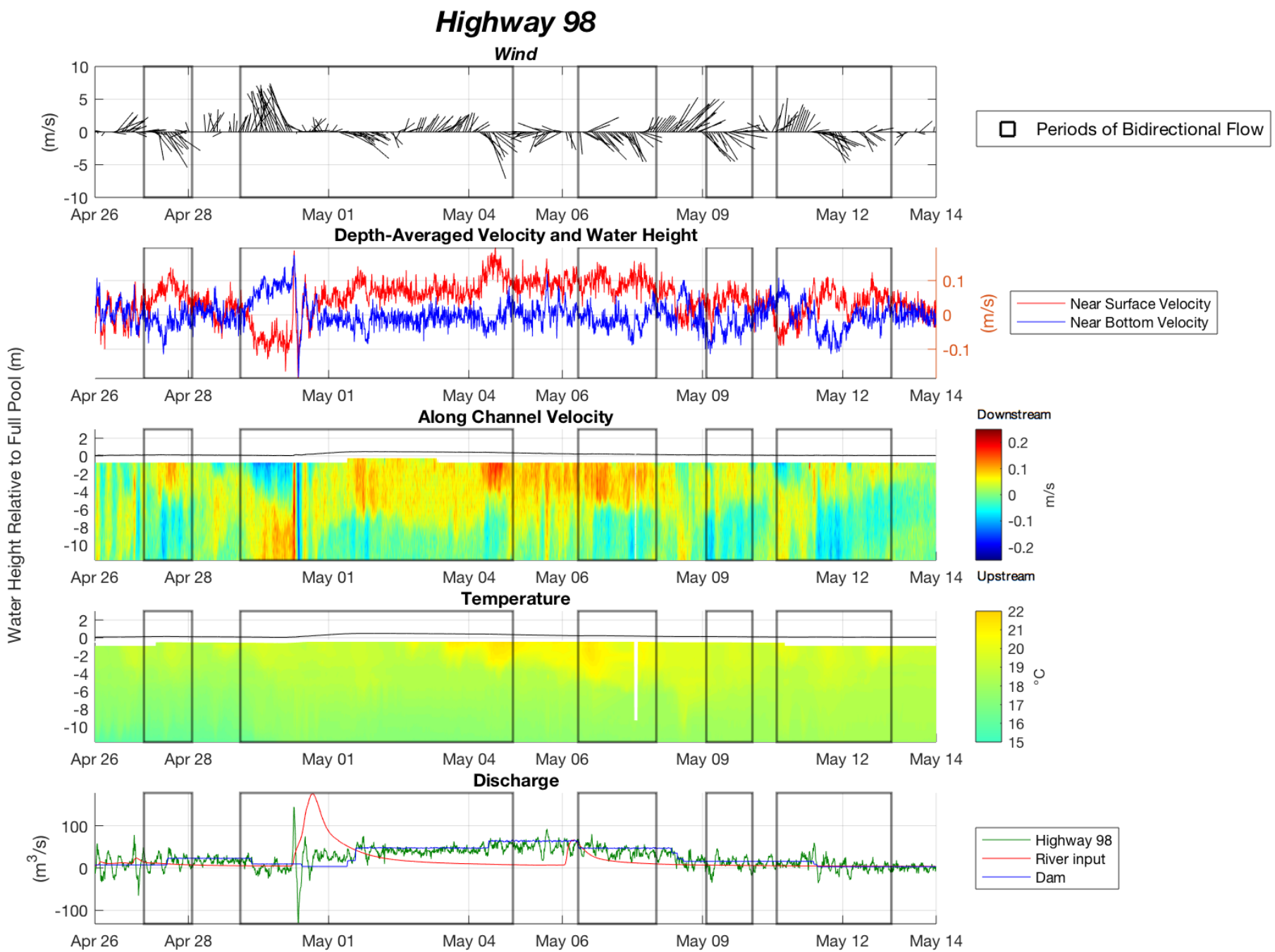
Average vertical temperature structure, plotted by season.



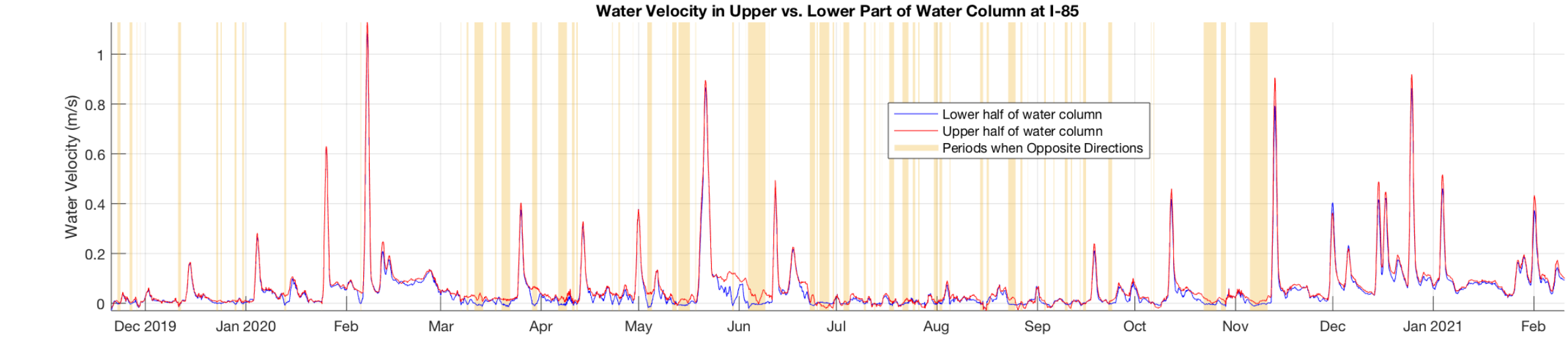
Bidirectional Flow

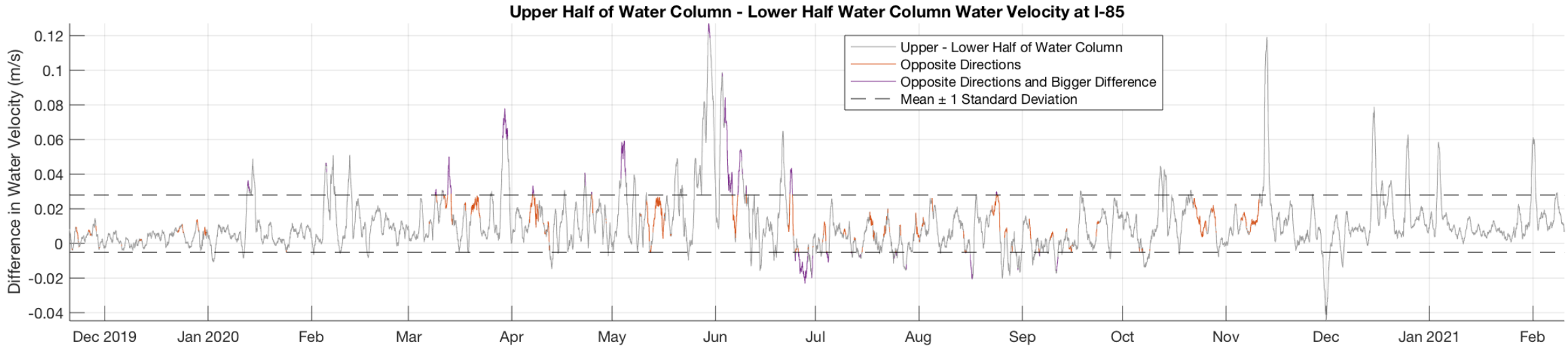

Fish Dam
Wind
(m/s)
10
5
0
-5
-10
Mar 29, 00:00
Mar 30, 00:00
Mar 31, 00:00
Apr 01, 00:00
Apr 02, 00:00
Periods of Bidirectional Flow
Depth-Averaged Velocity and Water Height
0.1
0.05
0
-0.05
(m/s)
Near Surface Velocity
Near Bottom Velocity
Water Height Relative to Full Pool (m)
Along Channel Velocity
2
0
-2
-4
Downstream
0.2
0.1
0
-0.1
-0.2
m/s
Upstream
Temperature
21
20
19
18
17
16
15
14
°C
Discharge
60
40
20
0
-20
(m3/s)
Fish Dam
River input
Dam

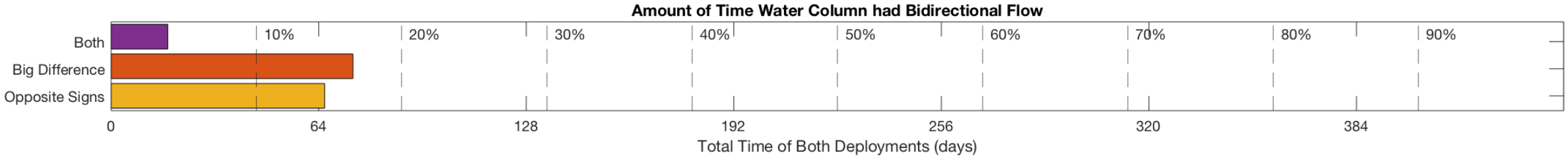

Highway 50
Wind
(m/s)
Periods of Bidirectional Flow
Depth-Averaged Velocity and Water Height
Near Surface Velocity
Near Bottom Velocity
Water Height Relative to Full Pool (m)
Along Channel Velocity
Downstream
Upstream
m/s
Temperature
°C
Discharge
(m3/s)
Highway 50
River input
Dam
Mar 08
Mar 10
Mar 12
Mar 14
Mar 16
Mar 18
Mar 20


Highway 98
Wind
(m/s)
10
5
0
-5
-10
Apr 26
Apr 28
May 01
May 04
May 06
May 09
May 12
May 14
Periods of Bidirectional Flow
Depth-Averaged Velocity and Water Height
0.1
0
-0.1
(m/s)
Near Surface Velocity
Near Bottom Velocity
Water Height Relative to Full Pool (m)
Along Channel Velocity
2
0
-2
-4
-6
-8
-10
Downstream
0.2
0.1
0
-0.1
-0.2
m/s
Upstream
Temperature
22
21
20
19
18
17
16
15
°C
Discharge
100
0
-100
(m3/s)
Highway 98
River input
Dam

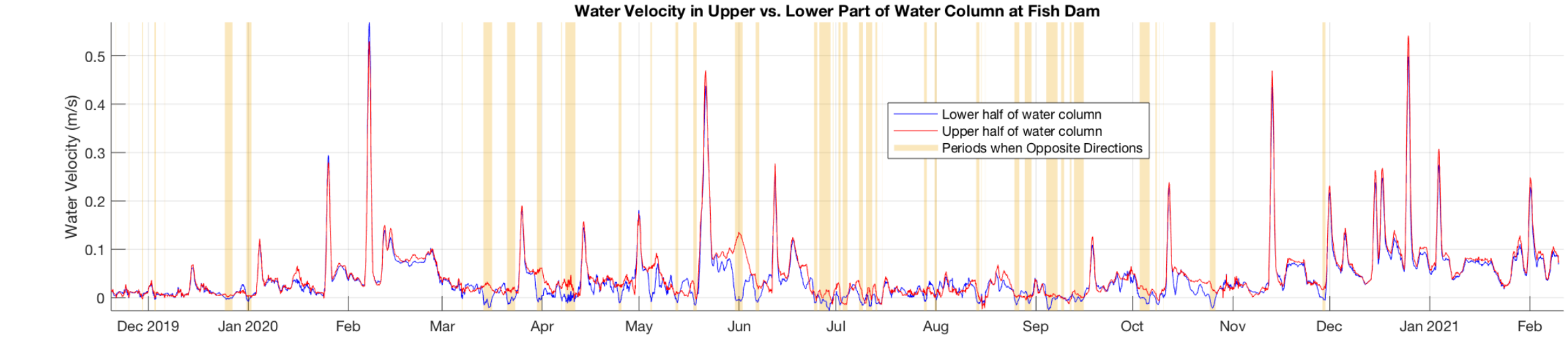
I-85

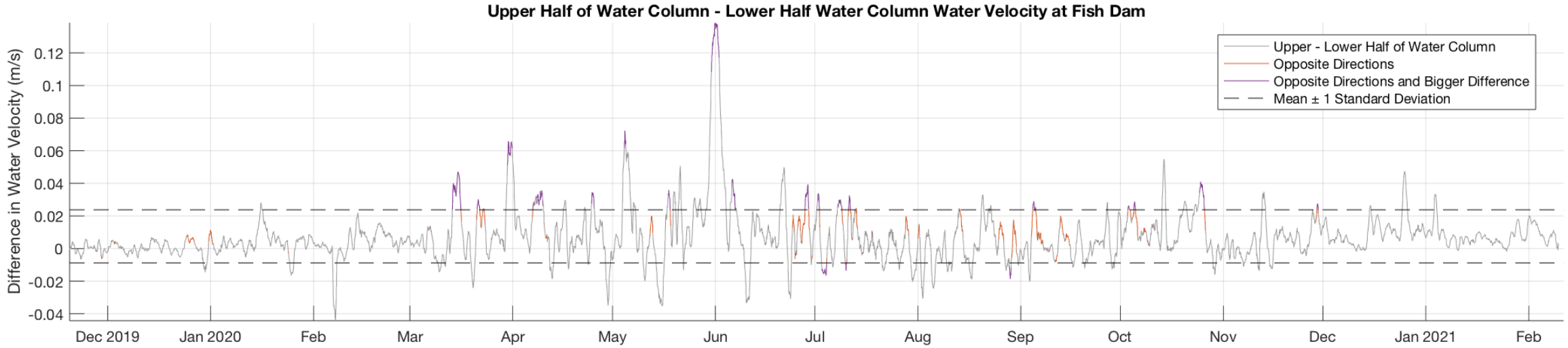

Water Velocity in Upper vs. Lower Part of Water Column at I-85
Water Velocity (m/s)
0
0.2
0.4
0.6
0.8
1
Lower half of water column
Upper half of water column
Periods when Opposite Directions
Dec 2019
Jan 2020
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan 2021
Feb

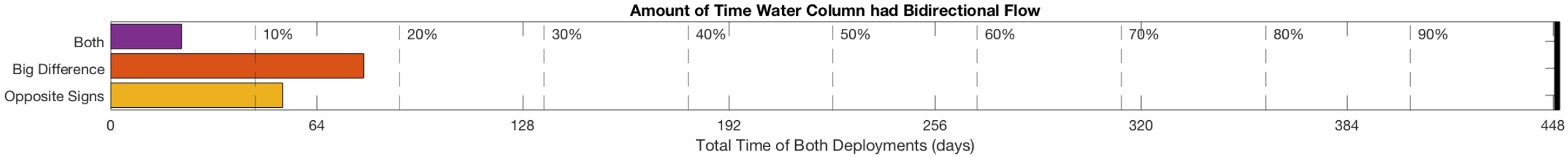

Upper Half of Water Column - Lower Half Water Column Water Velocity at I-85
Difference in Water Velocity (m/s)
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
Upper - Lower Half of Water Column
Opposite Directions
Opposite Directions and Bigger Difference
Mean ± 1 Standard Deviation
Dec 2019
Jan 2020
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan 2021
Feb


Amount of Time Water Column had Bidirectional Flow
Both
Big Difference
Opposite Signs
10%
20%
30%
40%
50%
60%
70%
80%
90%
0
64
128
192
256
320
384
Total Time of Both Deployments (days)

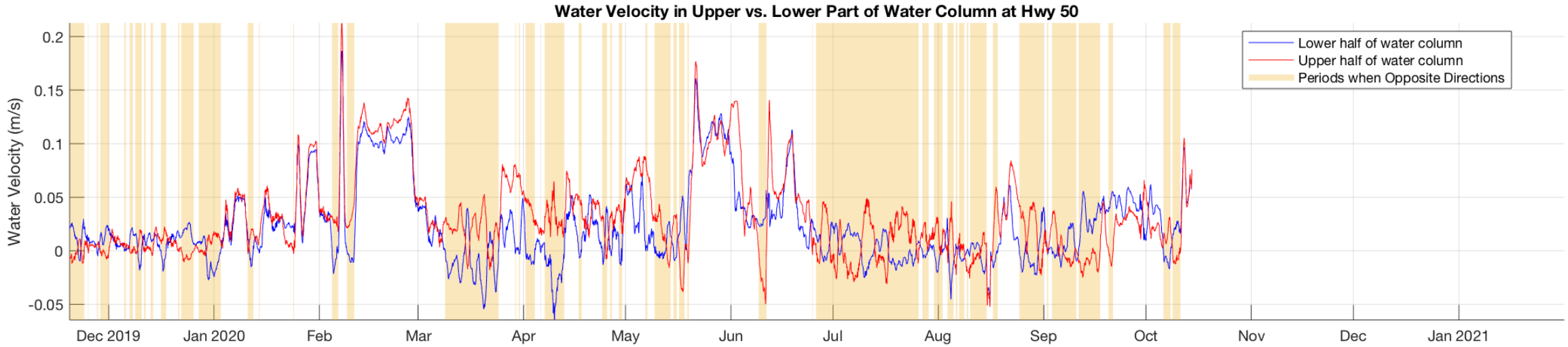
Fish Dam

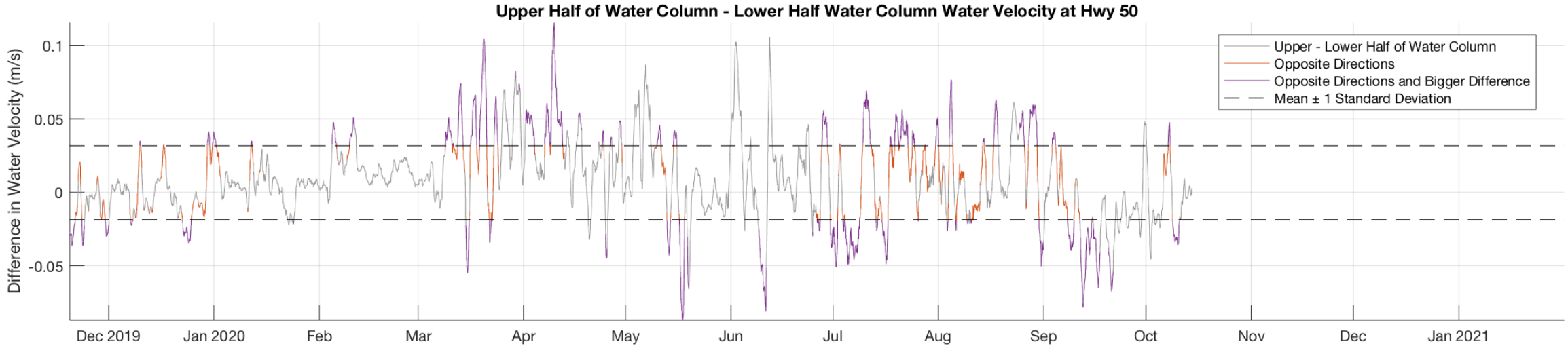

Water Velocity in Upper vs. Lower Part of Water Column at Fish Dam
Water Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
Lower half of water column
Upper half of water column
Periods when Opposite Directions
Dec 2019
Jan 2020
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan 2021
Feb

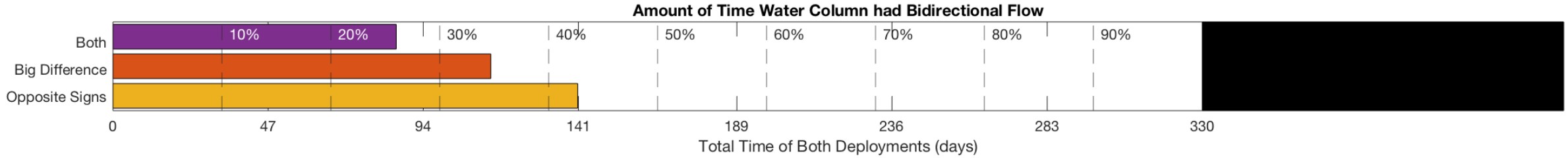

Upper Half of Water Column - Lower Half Water Column Water Velocity at Fish Dam
Difference in Water Velocity (m/s)
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
Upper - Lower Half of Water Column
Opposite Directions
Opposite Directions and Bigger Difference
Mean ± 1 Standard Deviation
Dec 2019
Jan 2020
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan 2021
Feb


Amount of Time Water Column had Bidirectional Flow
Both
Big Difference
Opposite Signs
10%
20%
30%
40%
50%
60%
70%
80%
90%
0
64
128
192
256
320
384
448
Total Time of Both Deployments (days)

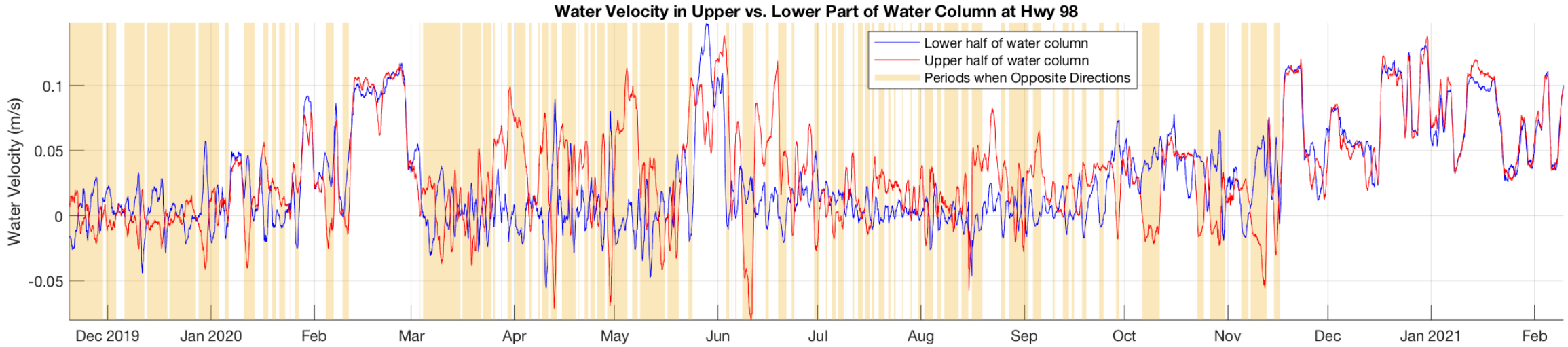
Hwy 50

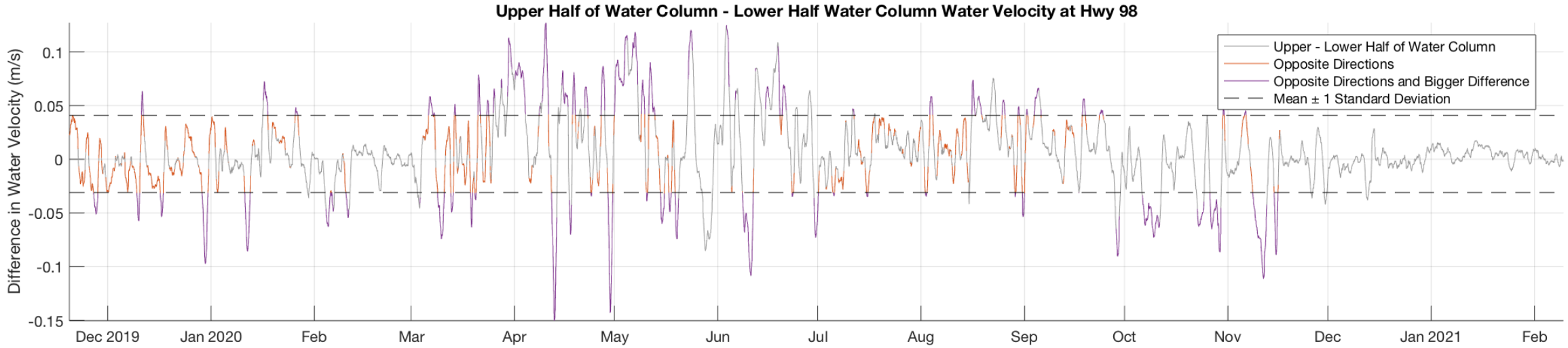

Water Velocity in Upper vs. Lower Part of Water Column at Hwy 50
Water Velocity (m/s)
0.2
0.15
0.1
0.05
0
-0.05
Lower half of water column
Upper half of water column
Periods when Opposite Directions
Dec 2019
Jan 2020
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan 2021

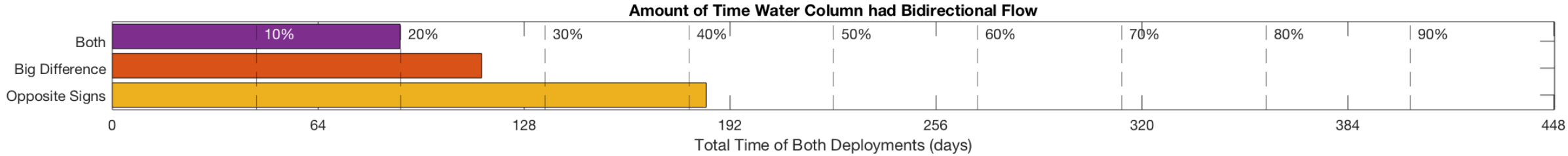

Upper Half of Water Column - Lower Half Water Column Water Velocity at Hwy 50
Difference in Water Velocity (m/s)
0.1
0.05
0
-0.05
Upper - Lower Half of Water Column
Opposite Directions
Opposite Directions and Bigger Difference
Mean ± 1 Standard Deviation
Dec 2019
Jan 2020
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan 2021


Amount of Time Water Column had Bidirectional Flow
Both
Big Difference
Opposite Signs
10%
20%
30%
40%
50%
60%
70%
80%
90%
0
47
94
141
189
236
283
330
Total Time of Both Deployments (days)

Hwy 98

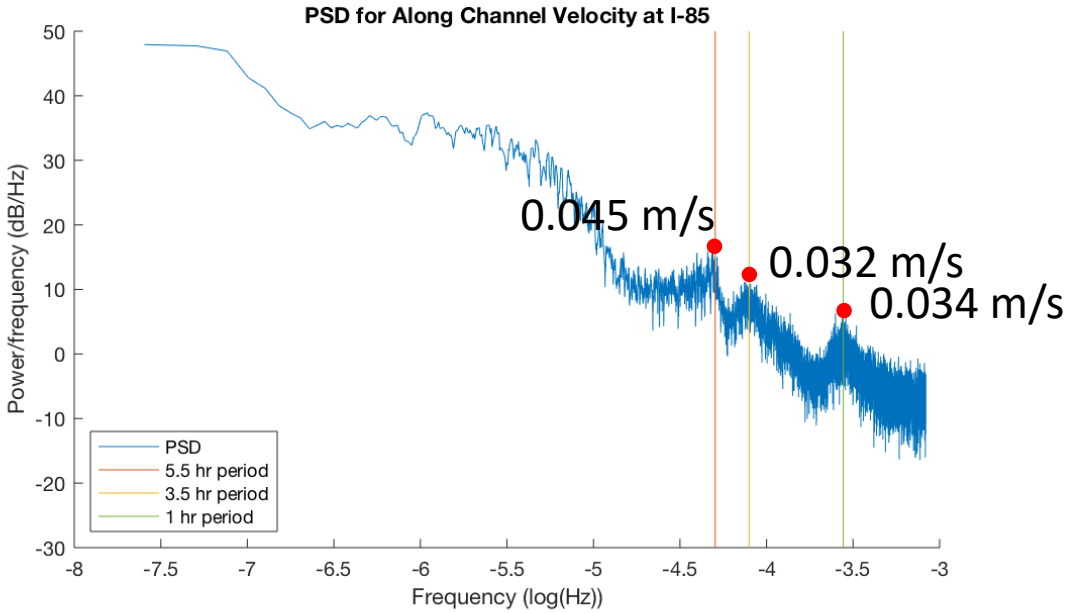

Water Velocity in Upper vs. Lower Part of Water Column at Hwy 98
Lower half of water column
Upper half of water column
Periods when Opposite Directions
Water Velocity (m/s)
0.1
0.05
0
-0.05
Dec 2019
Jan 2020
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan 2021
Feb

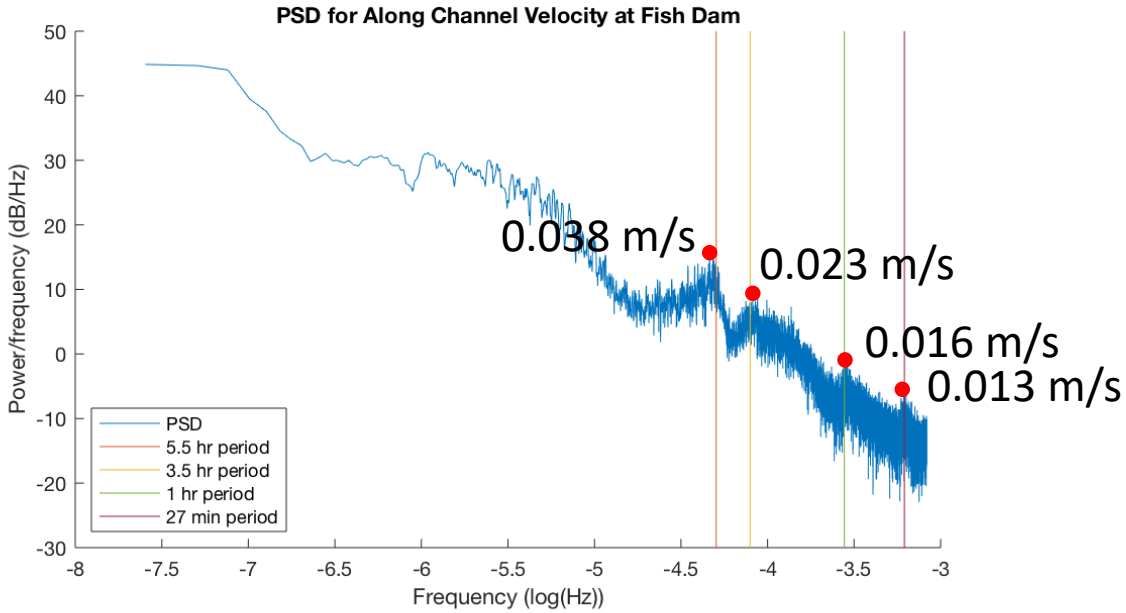

Upper Half of Water Column - Lower Half Water Column Water Velocity at Hwy 98
Upper - Lower Half of Water Column
Opposite Directions
Opposite Directions and Bigger Difference
Mean ± 1 Standard Deviation
Difference in Water Velocity (m/s)
0.1
0.05
0
-0.05
-0.1
-0.15
Dec 2019
Jan 2020
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan 2021
Feb

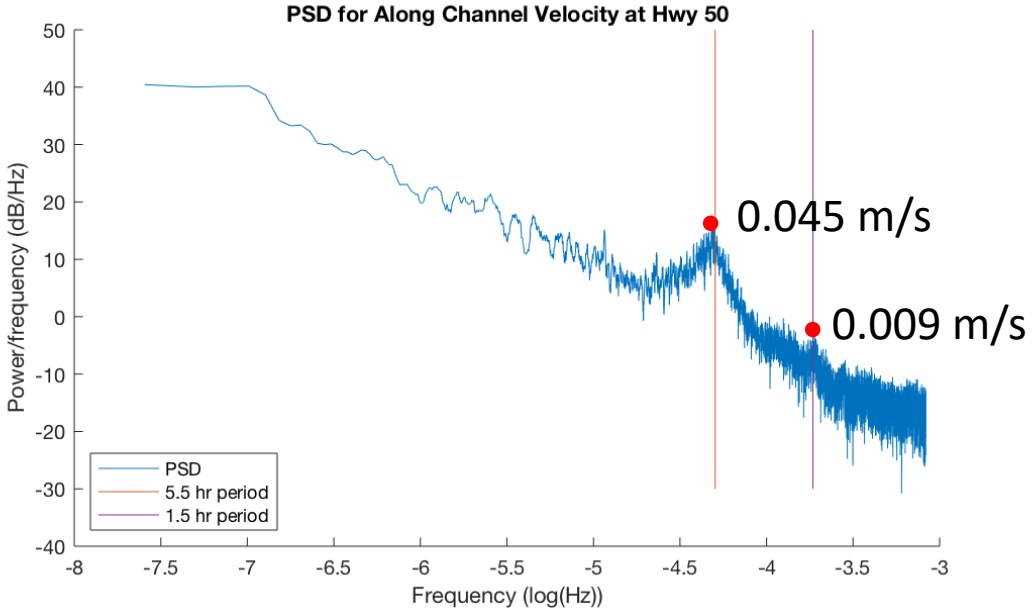

Amount of Time Water Column had Bidirectional Flow
Both
Big Difference
Opposite Signs
10%
20%
30%
40%
50%
60%
70%
80%
90%
0
64
128
192
256
320
384
448
Total Time of Both Deployments (days)

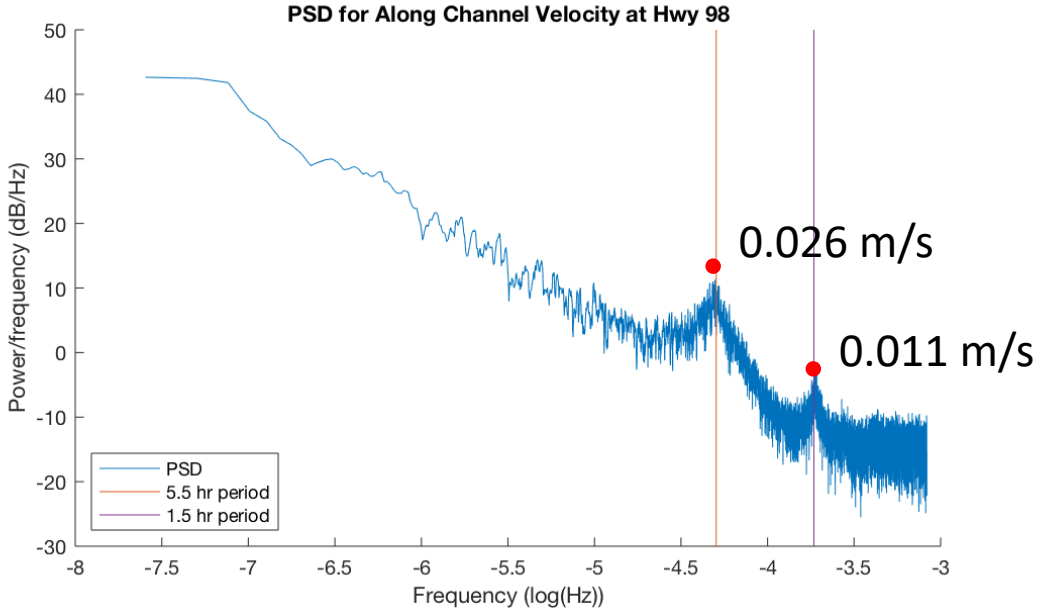
Seiche (PSDs and cross PSDs, formula, contour examples)

Along Channel Velocity

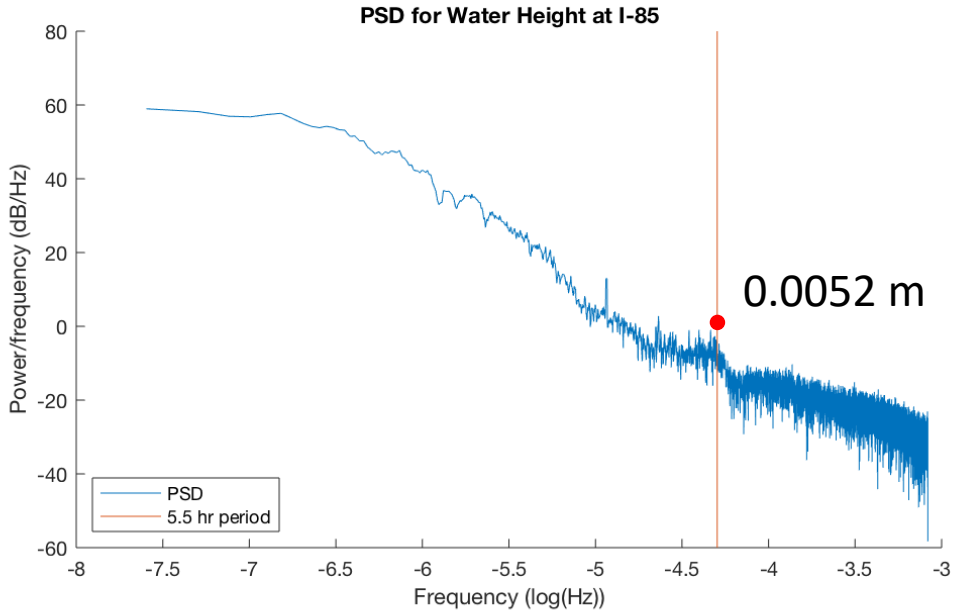


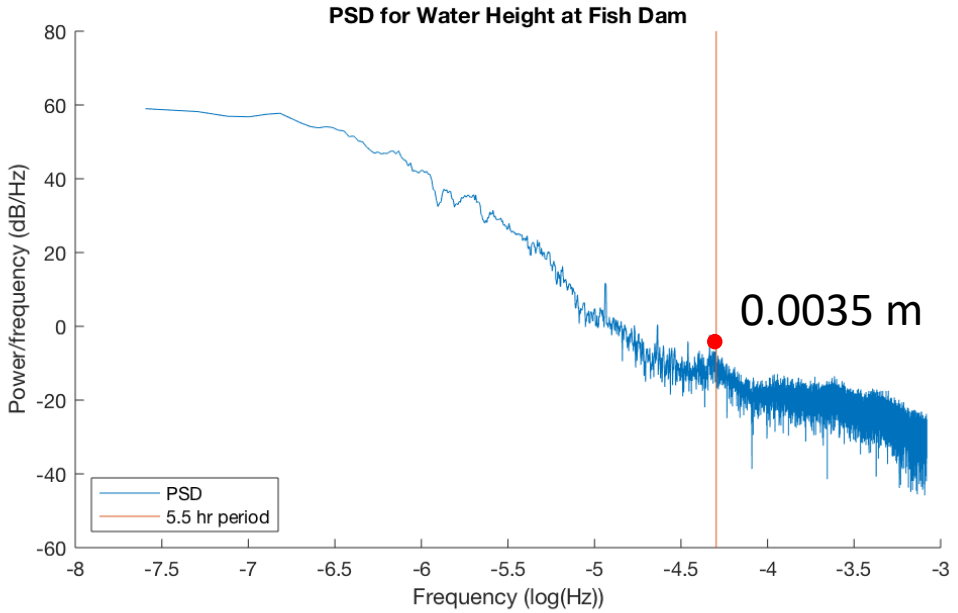


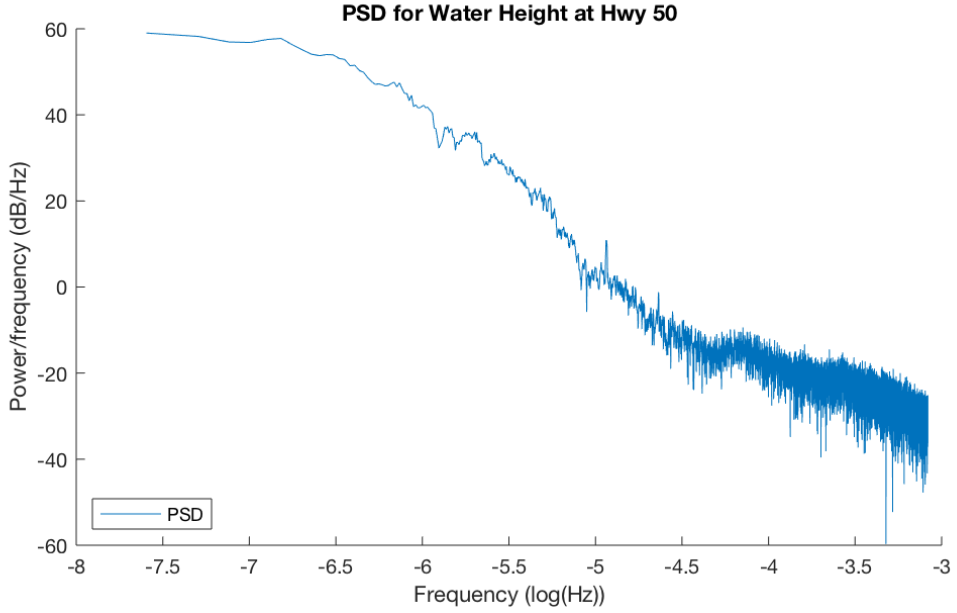


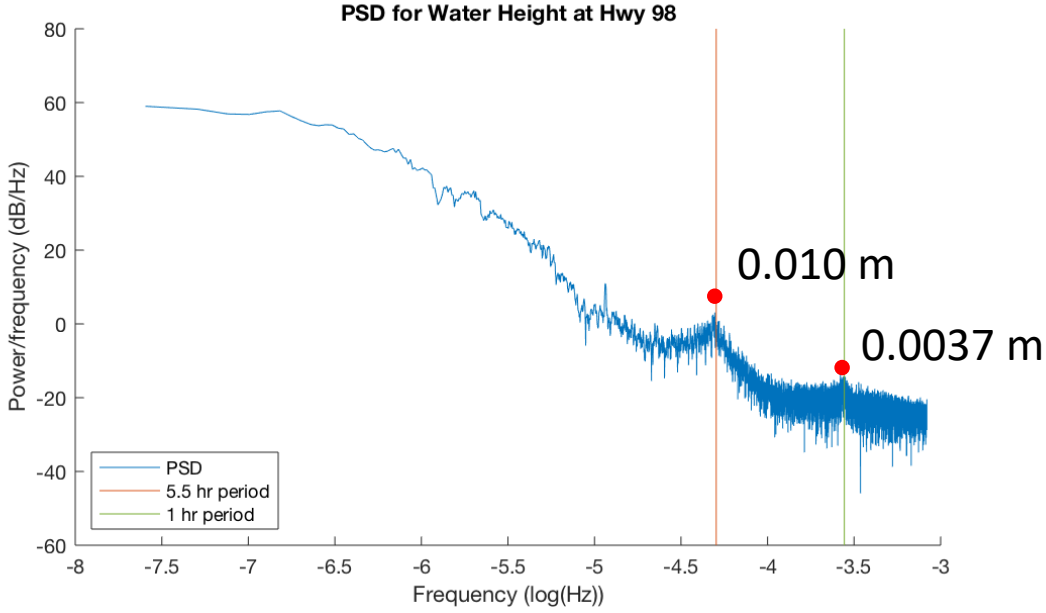


Water Levels (detrend and demean)









Simple seiche period calculation

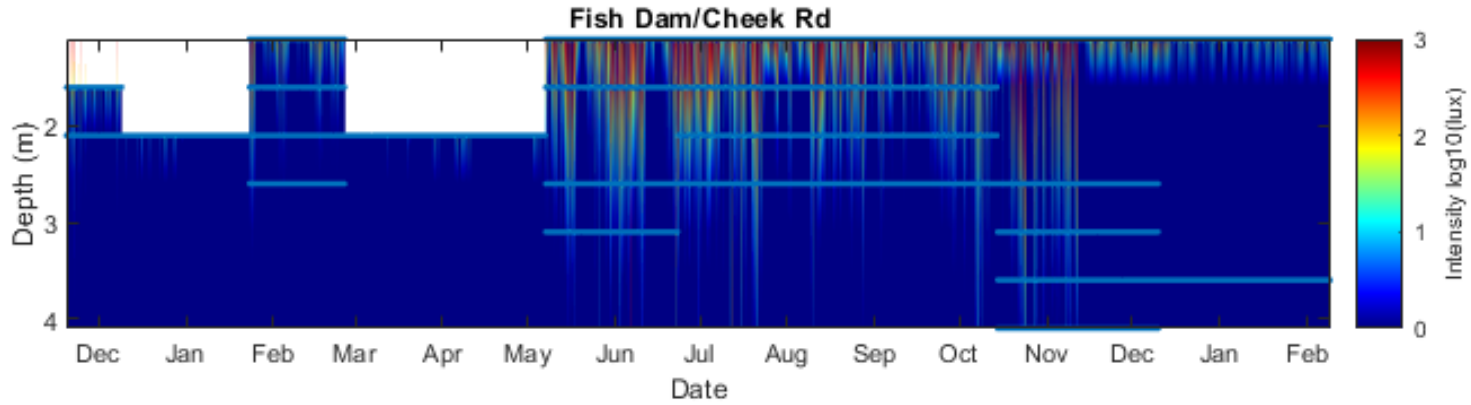
$$T = \frac{2l}{n(gh)^{\frac{1}{2}}}$$

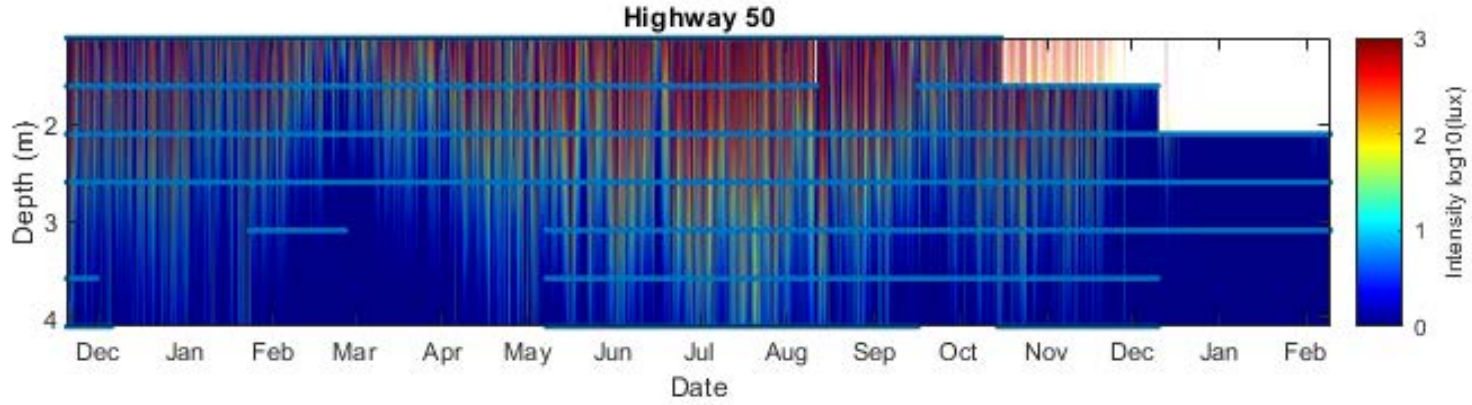
Length of the lake ~ 40,100 meters
h (based on bathymetry data) ~ 3.66 meters
n = 1
Estimated seiche = 3.7 hours

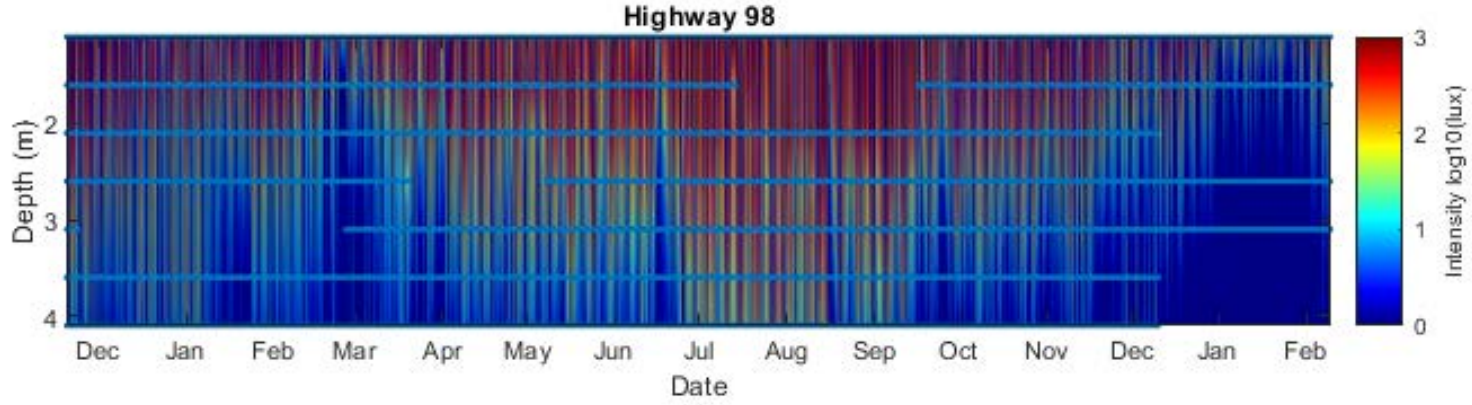
Length of the lake ~ 40,100 meters
h (to get observed seiche time) ~ 1.67 meters
n = 1
Estimated seiche = 5.5 hours

In-water light levels

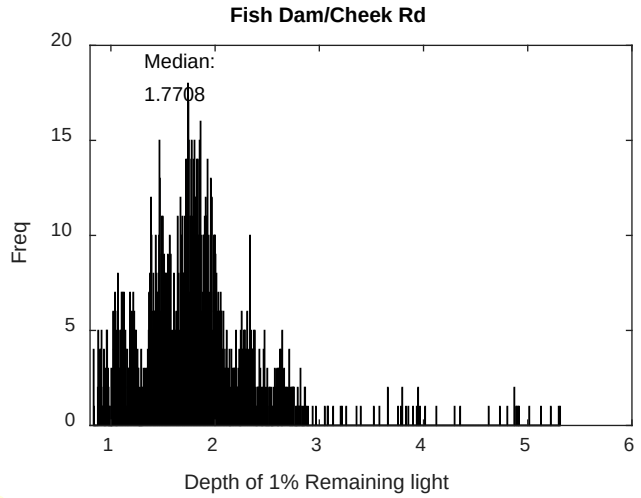
- Visible light sensors were deployed on surface moorings (intensity in lux)
- Despite cleaning once a month, biofouling impacts measurements
- Assuming similar rate of fouling at all depths, can estimate light penetration
- Express as k, extinction coefficient ($I(z) = I_0 e^{kz}$, z=-h,0) or 1% light level

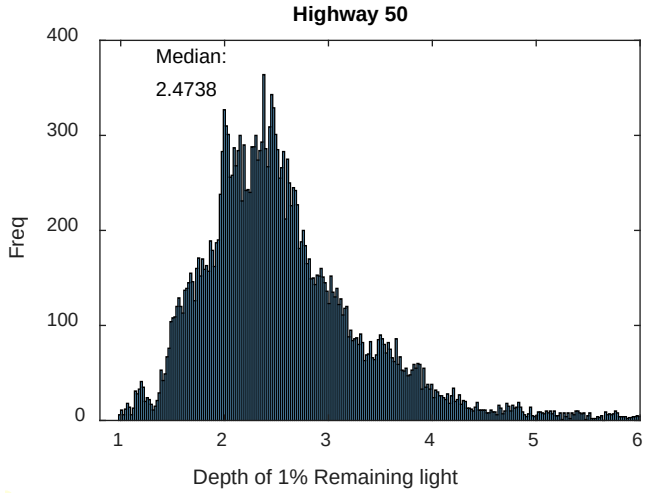

Fish Dam/Cheek Rd
Depth (m)
2
3
4
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Date
Intensity log10(lux)
0
1
2
3

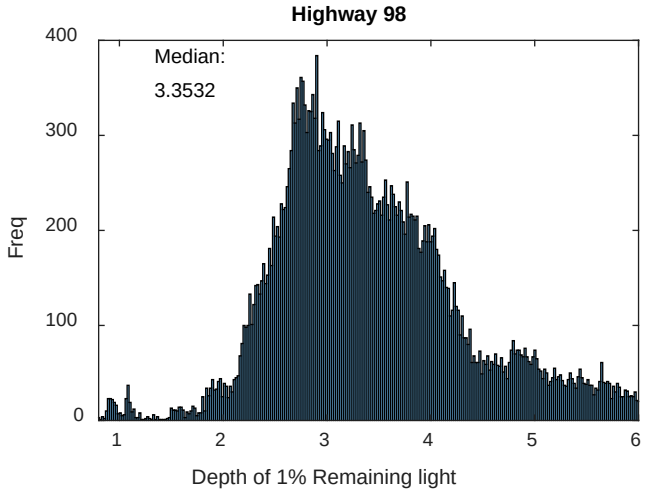

Highway 50
Depth (m)
2
3
4
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Date
Intensity log10(lux)
0
1
2
3


Highway 98
Depth (m)
2
3
4
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Date
Intensity log10(lux)
0
1
2
3

Hobo Light Sensor Data







LiCor Shipboard Casts

Depth of 1% Remaining Light

Fish Dam		
2/26/2020 10:19		1.06
5/7/2020 10:16		1.35
6/23/2020 11:12		1.58
8/11/2020 9:20		1.48
9/16/2020 9:52		1.47
10/14/2020 9:20		1.37
12/10/2020 10:12		1.84
	Mean	**1.45**

Highway 50		
1/23/2020 13:56		2.1
2/26/2020 11:27		0.95
5/7/2020 12:21		2.04
6/22/2020 15:50		2.49
8/11/2020 10:46		2.68
9/16/2020 11:43		2.24
10/14/2020 11:07		2.78
12/10/2020 11:54		1.72
	Mean	**2.125**

Highway 98		
1/23/2020 15:14		2.34
2/26/2020 12:25		1.28
5/7/2020 13:50		2.56
6/22/2020 13:31		2.34
8/11/2020 12:21		4.52
9/16/2020 13:04		1.97
10/14/2020 12:41		2.9
12/10/2020 13:06		1.81
	Mean	**2.465**

Summary

- Key Findings - much more complete picture of circulation in Falls Lake
  - Strong along lake flow in response to inflows and dam operation
  - Episodic two-layer flow in lower lake when temperature stratified
  - Whole lake residence time – highly variable, from days to months, affected by two-layer flow?
  - A 5.5hr oscillation frequently occurs along the lake, excited by inflow, wind?, outflow?
  - Light data quality unclear, however greater penetration down lake
- Ongoing activities – continued analysis and synthesis
  - Full presentation of results and synthesis, data archival
- Policy - Implications for Water Quality
  - Synthesis with other researchers
  - Dataset provides a substantial challenge for hydrodynamic / water quality modeling!