UNC Nutrient Management Study - In Situ Observational Study of Falls Lake Circulation and Physical Characteristics

Final Report

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Executive Summary

This study addressed:

- What are the primary circulation pattern(s) and physical structures in the main along-lake section and in the large side arms (i.e., Little Lick Creek, Ledge Creek and Lick Creeks) over times scales from hourly to seasonal, and how do these properties vary as functions of inflows / outflows, meteorology, physical properties and the seasons?
- How and how significantly do the side arms interact with the flow along the main stem of the lake?

These questions were addressed by collecting long-term observational time series with water current profilers and vertical arrays of temperature/light/conductivity sensors at strategic locations throughout the lake. Phase 1 (years 1-2) focused on the along-lake properties and phase 2 (years 3-4) focused on the side arms.

Results from phase 1 demonstrated that the strongest flows are a response to lake level variations. Rapid increases in water level are accompanied by large but brief currents in the upper portions of the lake; the magnitude of the signal decreases towards the dam. Release of water at the dam produces weaker but more sustained currents that most strongly impact the lower portions of the lake. When the lake level is constant or slowly falling, currents are slower and can vary in magnitude and direction with depth. The surface flow often moves in the same direction as the wind and can be either towards or away from the dam. Currents at mid-depth or below may flow in the direction opposing the surface flow causing the current direction to reverse with depth and creating a wind-driven exchange flow. Super-imposed on the inflow/ release events and the wind-driven flow is a 5.5-hour natural oscillation of the lake. Residence times, formed for the last 30 years using lake level and discharge over the dam, are highly variable, as short as weeks and as long as 5 years. The median value is 4.75 months; for our sampling period the value is 3.3 months, suggesting a period of relatively high through flow.

Analysis of the phase 2 observations found flow in the side arms was substantially different from the main stem and from each other. The side arms did not show a strong response to the 5.5 hr seiche, had variable but largely muted response to discharge events relative to the main stem, but responded strongly to wind forcing. Circulation was strongest in Lick Creek, moderate in Ledge Creek and least in Little Lick Creek. Winds promote exchange of water with the main stem, driving surface currents in the direction of the wind and in the opposite direction in the lower portion of the water column. The strength of this exchange flow was more regular and sustained during months when the lake was thermally stratified. An estimate of residence times in the side arms due to the exchange flow vary between 4.6 to 16.4 days, with the shorter residence times more common during thermally stratified time periods.

These results document the character of circulation in Falls Lake. From a management perspective, as times of slow flow are typically associated with poor water quality, attention to circulation during these times is particularly warranted. Winds were found to efficiently drive a seiche at 5.5 hours, and exchange flows in the main channel and side arms, especially during stratified conditions. The seiche regularly stirs the lake, increasing the background mixing levels. Depending on the degree to which water is retained or released from reaches of the lake by wind-driven exchange flows, they may reduce (as in the case of the side arms) or increase (as may be the case in the main channel) the residence times of these portions of the water body relative to estimates that neglect this effect. These findings have increased our understanding of transport in Falls Lake and can serve as important validation of water quality modeling efforts, such as those sponsored by the UNRBA.

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Background and Objectives

Falls Lake is a man-made reservoir, constructed by the US Army Corps of Engineers (USACE) from 1978 to 1981. The lake is 28 miles long from the confluence of the Eno, Little and Flat rivers to the dam and comprises approximately 12,400 acres of open water. Highway 50 divides the lake's volume approximately in half; the upper section is shallower and wide in comparison to the deeper, narrower lower section that follows the historical river channel, Figure 1. The main stem of the lake is segmented by six bridge causeways: railroad, I85, Fish Dam Rd, Hwy 50, New Light Rd, and Hwy 98 from upstream to downstream.

Net flow through the lake's main stem is principally determined by tributary inputs and the outflow over the dam. The lake has at least 18 tributaries, of which five, the Flat River, Eno River, Little River, Knap of Reeds Creek, and Ellerbe Creek, contribute an average of 78 percent of the annual inflow, (UNRBA 2019). No other tributary delivers more than 3 percent of the annual inflow. All five of the major tributaries enter the lake upstream of the Interstate 85 crossing. Outflow from the lake comprises the Neuse River and is controlled by the USACE for flood control in the Neuse Basin, drinking water supply, recreation, fish and wildlife enhancement and water-quality control, (USACE 2013).

The NC Division of Water Quality (DWQ) has collected water quality data in the lake since its opening. Chlorophyll-a concentrations in excess of 40 micrograms per liter in portions of the lake prompted a modeling study in the 2000s to help identify nutrient reduction targets and the establishment of strategies in 2010 to reduce nutrient input to the lake. To supplement DWQ efforts, in 2014 the Upper Neuse River Basin Association (UNRBA) initiated an extensive data collection and analysis program in the lake and its tributaries (UNRBA 2019) and a re-modeling of the lake (UNRBA 2016a). Water quality data has also been collected in the lake by the City of Durham and by the NC State University Center for Applied Aquatic Ecology (CAAE).

Lake water quality is influenced by multiple factors, including the movement of water and associated constituents (nutrients, sediments, algae, etc.) through the system. Residence time provides a lake-wide average assessment of water movement. From August 2014 – November 2018, the UNRBA found residence times (computed as 15-day average lake volume divided by the 15-day average outflow over the dam) varied from as little as 20 days to nearly 2.5 years, with long residence times occurring when the USACE reduced outflow for downstream flood control (UNRBA 2019). To better document the lake's response to high-flow conditions (which are infrequent but account for a significant portion of the volume inflow to the lake), the UNRBA also sponsored one-hour long flow measurements at the I85 and Hwy 50 causeways, on four days in January and October 2016. Results were converted to daily average discharge and appeared to track predictions based on a mass balance that included changes in lake surface elevation, rainfall, tributary inflows, and evaporation estimates (UNRBA 2016b; UNRBA 2017). While water quality is strongly dependent on the inflows to and outflow from the lake and the associated average transport through the lake, the timescales of nutrient uptake, primary productivity and algal growth are fast compared to average transport timescales. Indeed, the relationship between short-term hydrodynamics and productivity has been identified as having important implications for the lake's water quality model (UNRBA 2015), although no systematic effort has been undertaken to measure water movement in the lake at these scales. Furthermore, no data or analyses has been undertaken to identify circulation and exchange within the lake. Specifically, several substantial tributaries enter the lake below Fish Dam / Cheek Rd. These "side arms" have substantial surface area

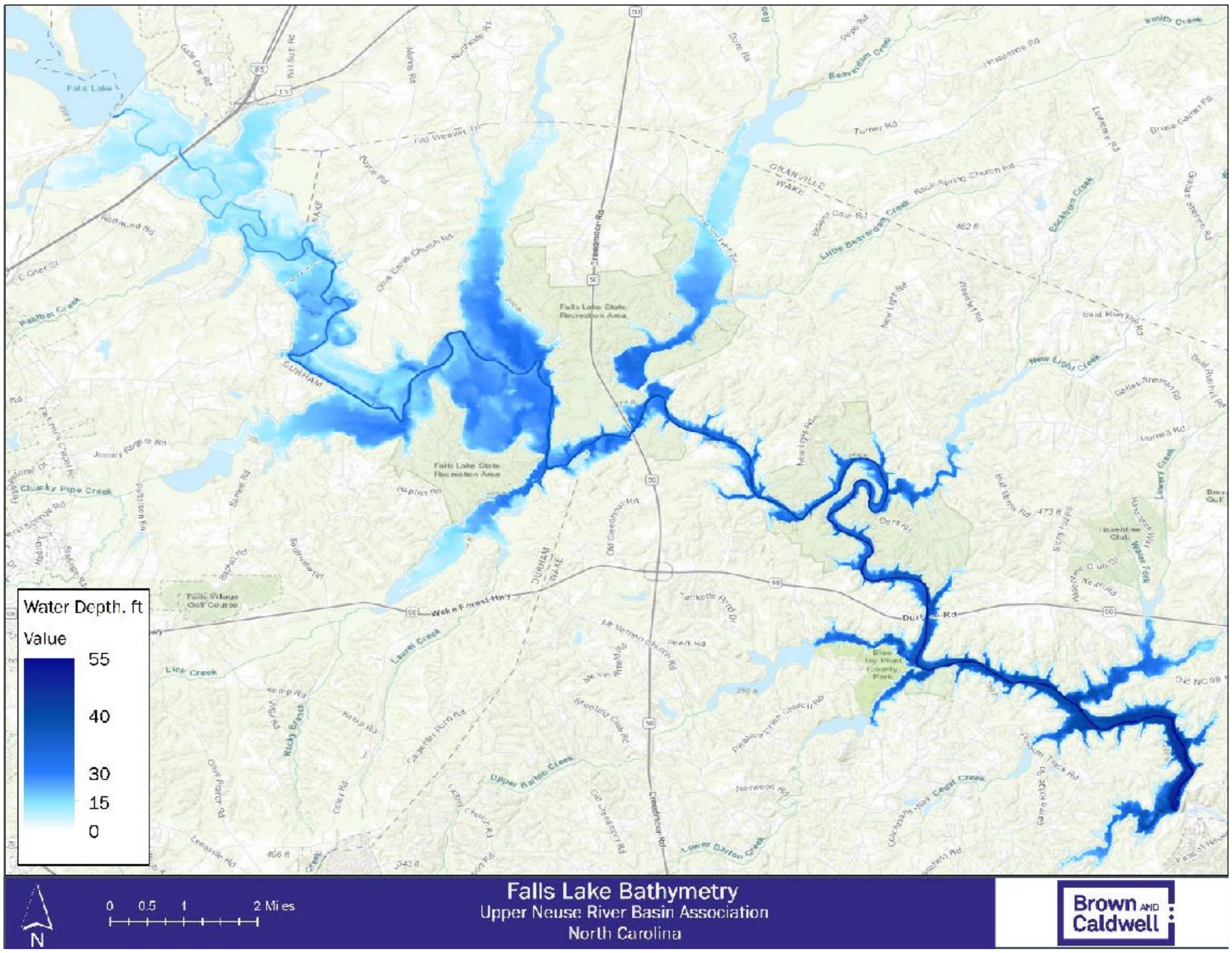


Figure 1. Falls Lake Bathymetry, data collected 2017, (UNRBA 2019)

but relatively low inflow volumes from the watershed. Lacking significant inflow, it is unclear what the dominant circulation drivers, flow structure and resident times are in these portions of the lake and how they interact with the along-lake flow. Thus it is also unclear whether they may have a significant role in nutrient processing, algal growth and water quality in the lake.

To address these data and knowledge gaps, our study was designed around the following questions:

- What are the primary along-lake circulation pattern(s) and physical structures in Falls Lake over times scales from hourly to seasonal?
- How does along-lake circulation vary as functions of:
    - Inflows / Outflows
    - Meteorology
    - Physical Properties
    - Seasons
- What are the primary circulation patterns(s) and physical structures in the large side arms downstream of Fish Dam / Cheek Rd (i.e., Little Lick Creek, Ledge Creek and Lick Creeks?
- How and how significantly do these side arms interact with the flow along the main stem of the lake?

- How does side arm circulation, structure and exchange with the main stem depend on:
    - Inflows / Outflows
    - Physical Properties
    - Meteorology
    - Seasons
- Can a comprehensive in situ data set be collected for use in validating the circulation and physical structure represented in water quality models (e.g., ongoing under the sponsorship of the UNRBA), thereby providing additional confidence in the modeling as well as additional understanding of processes controlling lake water quality. We note that the model validation and increased understanding will depend on integration with other components of the Falls Lake study including the UNRBA modeling team.

Our study was comprised of two phases. Phase one (years 1 and 2) delineated the primary circulation drivers, water column and flow structures, and residence times along the elongated, river-like main stem of the lake. Phase two (years 3 and 4) focused on flow in and through three side arms located in the mid to upper, nutrient sensitive portion of the lake. Details of the instrument deployments for each study are described in Appendix - Data Collection Methods, Main Stem and Side Arm Observations. A comprehensive presentation of the data are presented in the remaining appendices and summarized in the body of this report. The data itself has been archived in Hydroshare as presented at the end of this report.

Results

Main Stem Study

The successful collection of more than a year of observations along the main axis of Falls Lake allows examination of the circulation on a range of time scales and as well as its spatial variation between I85 and the dam. The strongest flows observed were associated with large lake level variations. This behavior reflects operations of the reservoir, with lake levels typically rising abruptly following an inflow event from the tributaries, because flow over the dam is restricted; a more gradual reduction in lake level is seen as flow over the dam is increased at prescribed rates following the inflow events (Figure 2). Currents in the lake exhibit a clear response to these inflow/release cycles (Figure 3). Rapid increases in water level are accompanied by large but brief current pulses in the upper portions of the lake; currents are often 0.5 m/s and can exceed 1 m/s (Figure 3, upper right). The magnitude of the inflows decreases towards the dam; notice how in Figure 3 that dark red stripes, indicating currents greater than 0.2 m/s, are most prominent in I-85, less so at Fish Dam, and not present at Hwy 50 or Hwy 98. Conversely, release of water at the dam most strongly impacts the lower portions of the lake, with a weaker but still noticeable signal in the upper portions of the lake. The currents associated with release of water over the dam are smaller in magnitude (typically 0.1-0.2 m/s) but are sustained over a longer period than those associated with inflows. A strong inflow event in February 2020 typifies this behavior; see monthly graphics in Appendix - Monthly Plots of Mooring and Velocity Data, Main Stem Observations for this period (Appendix Figures 13-16) for a more detailed presentation. The currents during these inflow events, both during rising and falling lake levels, are unidirectional and nearly uniform with depth.

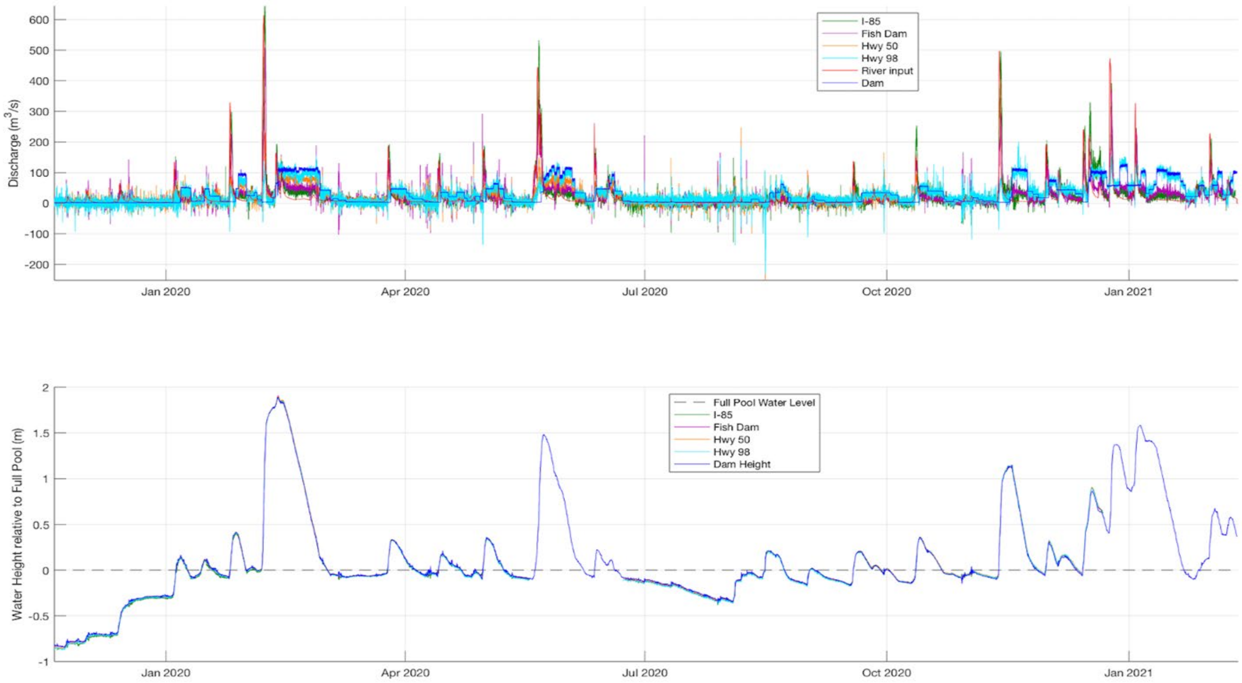


Figure 2. Top) discharges measured at I-85, Fish Dam Rd, Hwy 50, Hwy 98 and the dam; and bottom) water level relative to full pool.

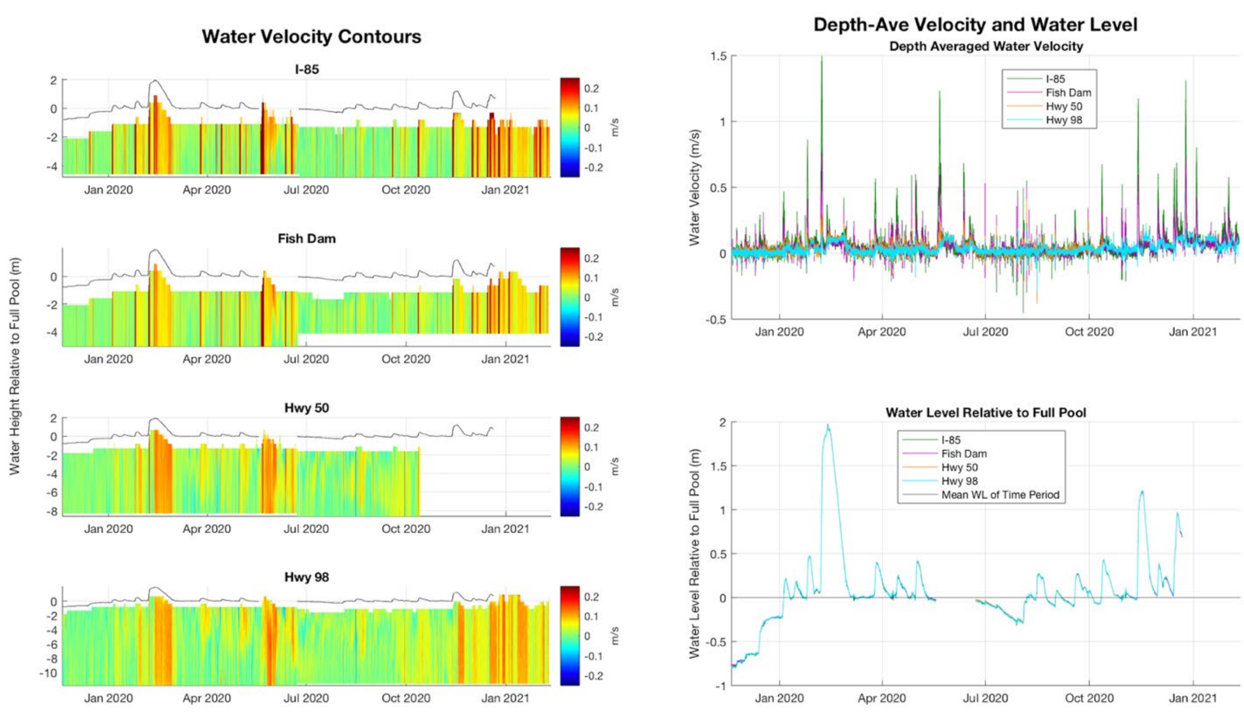


Figure 3. Left) along-channel currents as a function of time and depth at (from top to bottom) I-85, Fish Dam Rd, Hwy 50 and Hwy 98; top right) depth-averaged currents at the 4 measurement sites; lower right) water level time history over the collection period.

In contrast to the strong currents associated with inflow/release events, there were periods of limited inflow, when there was little rainfall in the watershed. These are periods when the lake level is relatively constant or slowly falling, such as July-September of 2020 (Figure 2). Currents during these times are typically < 0.1 m/s but can vary in magnitude and direction with depth. When the lake is thermally stratified, as in summer, the surface flow often moves in the same direction as the wind and can be either downstream towards the dam or upstream away from the dam. Most notably at Hwy 50 and Hwy 98, the current at mid-depth or below may flow in the direction opposing the surface flow (and wind), such that current direction reverses with depth.

In Figure 4, which shows conditions at Hwy 98 during part of April 2020, periods of bi-directional flow are marked with black boxes; note the correspondence of flow direction with that of the winds. During fall and winter when the lake temperatures were most often uniform with depth, there can still be instances of reversing flow with depth but the magnitudes of the currents are less than during stratified time periods. An example of the role of stratification in supporting stronger wind-driven currents occurred in March 2020. There was little stratification at the beginning of the month but starting about March 10 the lower lake began to stratify and current speeds increase in response (see Appendix - Monthly Plots of Mooring and Velocity Data, Main Stem Observations, Figures 19 and 20). Because the winds force this bi-directional flow, the temporal variability of the flow is largely in the weather band, between 2-8 days. Bi-directional flow is more common at Hwy 50 and Hwy 98, being observed roughly 40% of the time at these locations, compared to 10-15% of the time at I-85 and Fish Dam.

Super-imposed on the inflow/release events and the wind-driven flow is a 5.5-hour natural oscillation of the lake, or seiche. Water levels rise at one end of the lake while falling at the other end, then force flow down-gradient along the length of the lake until the lake surface slope is reversed, and the process repeats, driving flow in the opposite direction. We find a signature of the seiche in the water level records from I-85, Fish Dam Rd, Hwy 98 and the dam but not at Hwy 50, indicating that the node of the oscillation must be near the Hwy 50 causeway. Using spectral analysis, the average amplitude of the water level variation is found to be approximately 1 cm near the dam. The velocity response at the 5.5 hour period was measured at all 4 sites, with average amplitudes of up to 0.05 m/s. Because the measurement sites are near causeways that form constrictions to flow in the lake, currents away from the causeways associated with the seiche are expected to be weaker. However, the nearly constant presence of the seiche (it is the source of short-period variation in the depth-averaged current in the monthly plots – Appendix - Monthly Plots of Mooring and Velocity Data, Main Stem Observations) suggests it may play an important role in stirring the lake and promoting a base level of mixing. An example of this type of behavior, and a particularly large amplitude seiche, is illustrated in Figure 5, which displays 5 days of observations from April 2020. Water levels at I-85 and Hwy 98 are mirror images of each other for several oscillations in the first half of the time period, while depth averaged currents vary in concert, at times >0.1 m/s. The depth-dependence of the flow varies across the stations, with I-85 and Fish Dam exhibiting little depth-dependence whereas Hwy 50 and Hwy 98 show a more complicated response to the seiche, presumably because of thermal stratification in the lower portion of the lake. Results of spectral and cross-spectral analyses that document the seiche are presented in Appendix - Spectral Analysis Documenting Seiches, Main Stem Observations.

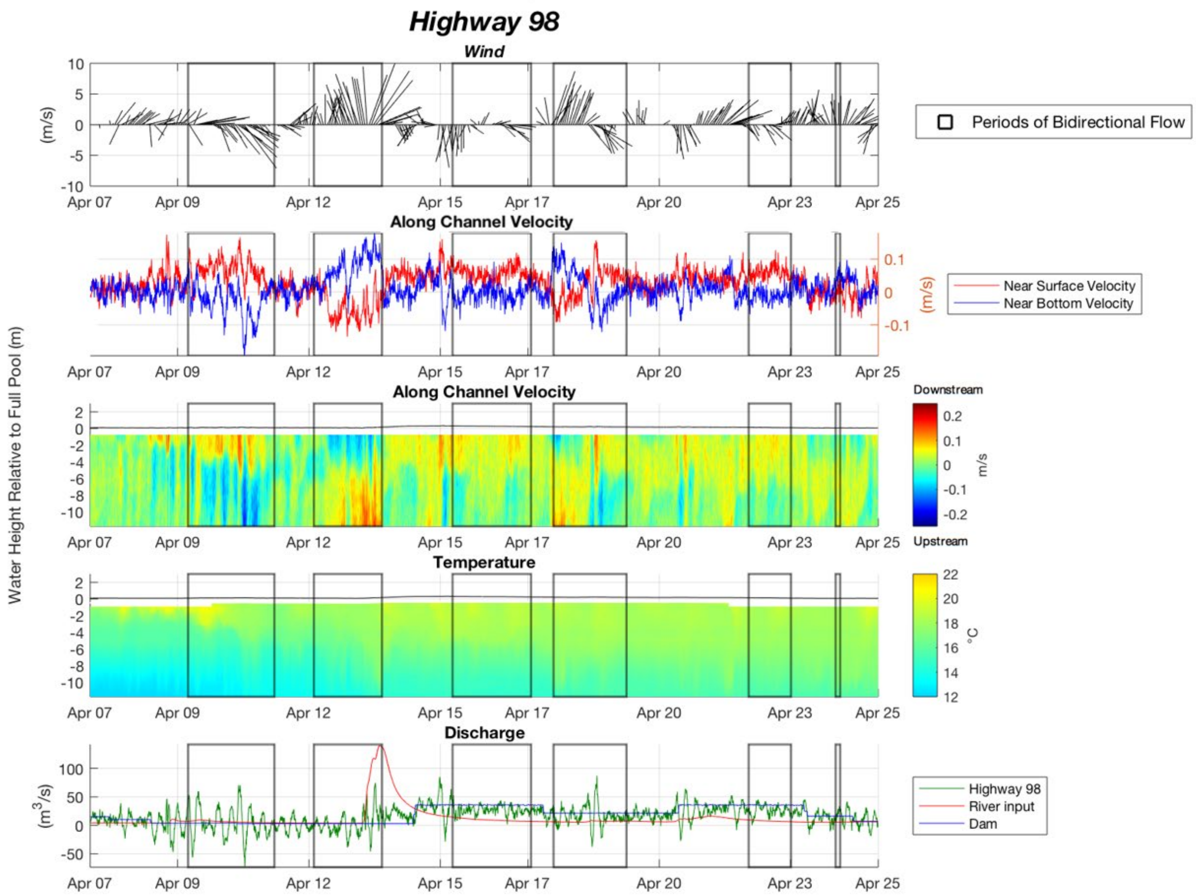


Figure 4. An example of wind-driven bi-directional flow at Hwy 98 from April 2020. From top to bottom: winds, near-surface (red) and near-bottom (blue) along-channel flow speeds, depth-time plot of along-channel velocity, and discharges into the lake (red), at Hwy 98 (green) and over the dam (blue). Black boxes mark times of bi-directional flow.

The moorings provide a detailed record of the thermal structure in the lake. At least for the year observed, stratified conditions began in March and persisted until late September (Figure 6 and Appendix - Monthly Plots of Mooring and Velocity Data, Main Stem Observations). The timing was quite similar at the 3 sites monitored, though Fish Dam, being shallower, de-stratified earliest. It is notable that once stratification was well established in late April the bottom temperature at Hwy 98 remained nearly constant throughout the summer months, implying very little vertical mixing or deep circulation at this location (Figure 6).

The strength of stratification (the rate of change of temperature with depth), averaged seasonally, was remarkably consistent between the 3 mooring sites (Figure 7). In summer the gradient reached a maximum and was approximately 1 °C/m. Interestingly the temperature in the surface waters was consistently lowest at Fish Dam; while this might be expected in fall, when the shallower waters of the upstream portion of the lake would cool faster than the deeper regions closer to the dam, the reverse would be expected in spring, but that was not observed. One possible explanation could be springtime inflows are cooler than ambient lake temperatures and offset the warming experienced from solar radiation.

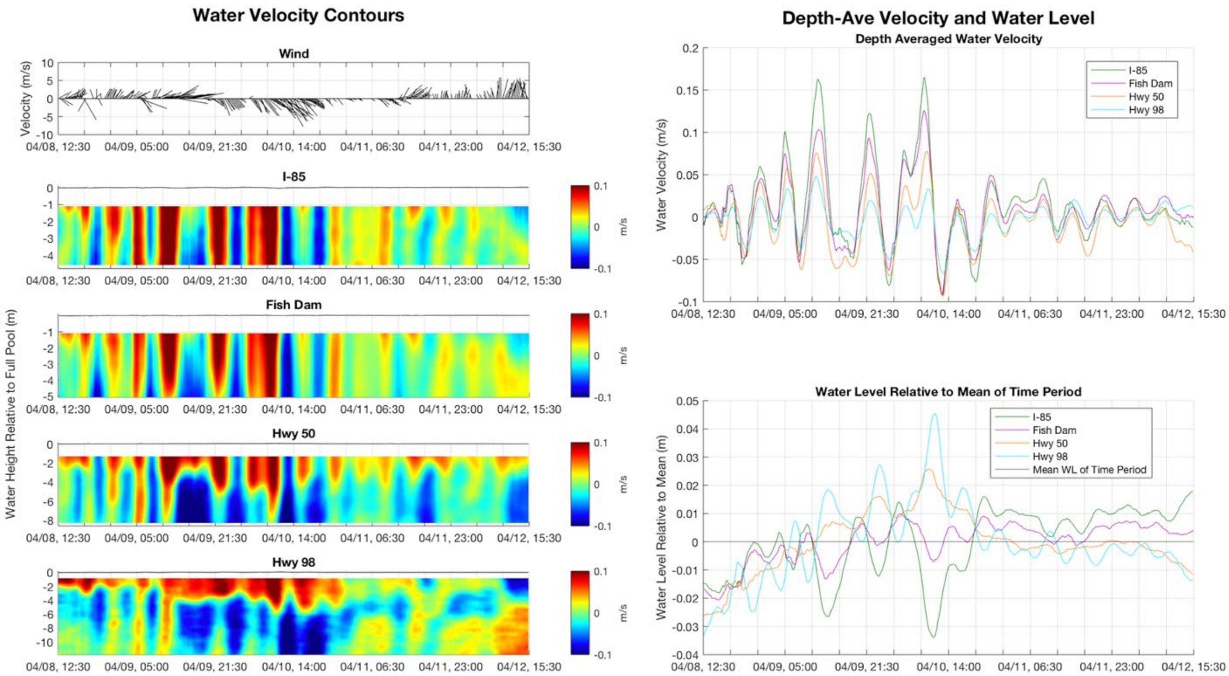


Figure 5. An example of the 5.5 hr period seiche. Left panel) top to bottom: winds, time-depth currents at I-85, Fish Dam, Hwy 50 and Hwy 98. Right panel) top: depth averaged along-channel velocities from the 4 sites; bottom: water levels at the 4 sites.

While the quality of the in situ light sensor data was generally impacted by biofouling and missing data due to several failed sensors on the Fish Dam mooring, these data nevertheless show a strong pattern that we believe is robust, Figure 8. We've quantified this by fitting exponential curves to vertical profiles from the *in situ* sensors and the shipboard-based PAR sensor to calculate the 1 percent light penetration depth at each location over time, Figure 9. Together these indicate that light penetration increases significantly along the axis of the lake moving toward the dam. Median 1 percent light levels from the moorings were 1.8m, 2.5m, and 3.4m at Fish Dam, Hwy 50 and Hwy 98, respectively. This trend is confirmed by the shipboard profiles, although the 1 percent light levels were slightly different, Figure 9. Given that most of the freshwater inputs are upriver of the Fish Dam site, the majority of the sediment influx associated with runoff and high river flow also enters the system upriver of this location. In addition, the upriver half of the lake is wider and shallower (c.f. bathymetry in Figure 1) and has historically higher Chl-a levels. We expect that these factors all contribute to higher turbidity / lower light penetration toward the upper end of the lake and the along lake light gradient we observed.

A commonly used measure of flushing of reservoirs is the residence time, and we examine it here to put our observations in a longer-term context. Residence time is defined as lake volume divided by the inflow or outflow rate. We use the time-varying lake volume and discharge over the dam to form a daily value. A similar but maybe more intuitive measure of flushing is turnovers, the number of lake volumes that leave the lake in a particular time frame. We look at the number of turnovers in a year in the text below.

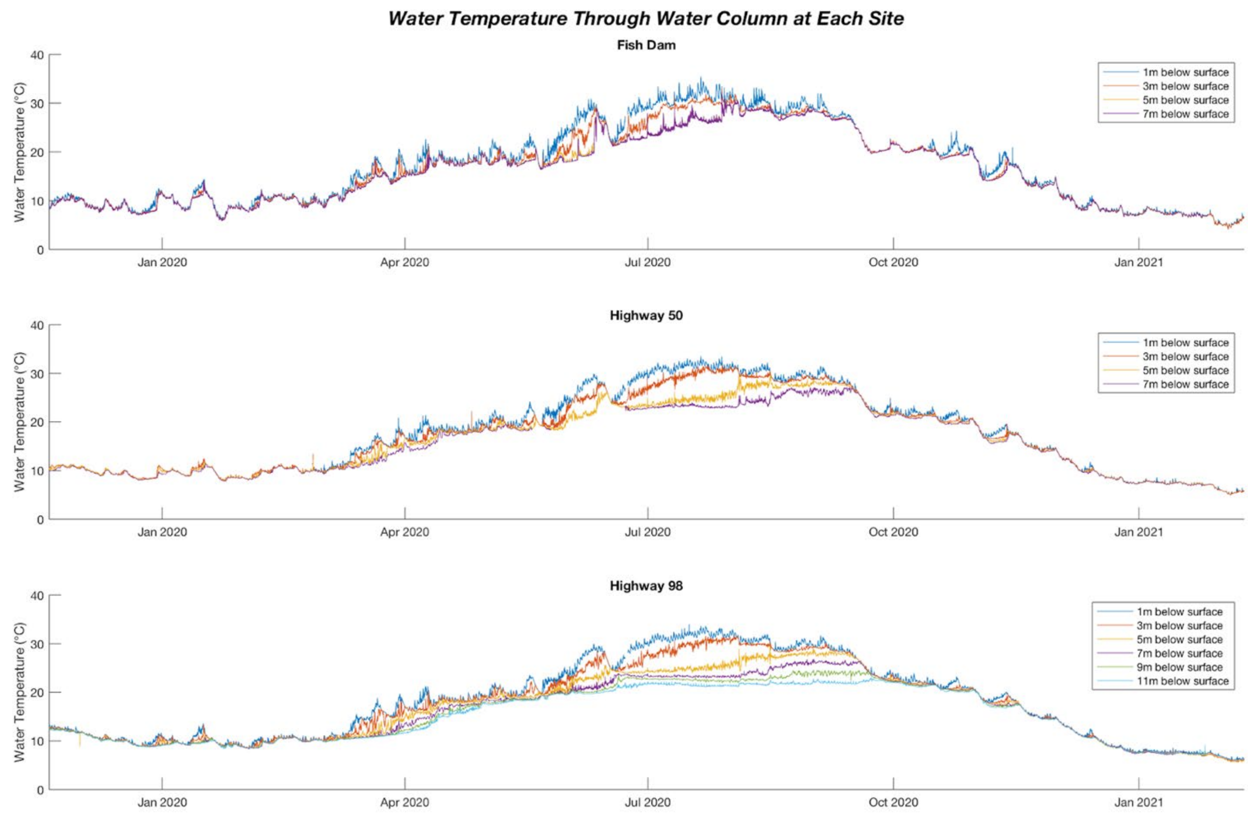


Figure 6. Temperature time series from 1 m depth downward in 2 m increments at (top to bottom) Fish Dam, Hwy 50 and Hwy 98. During stratified conditions the individual time series separate from each other.

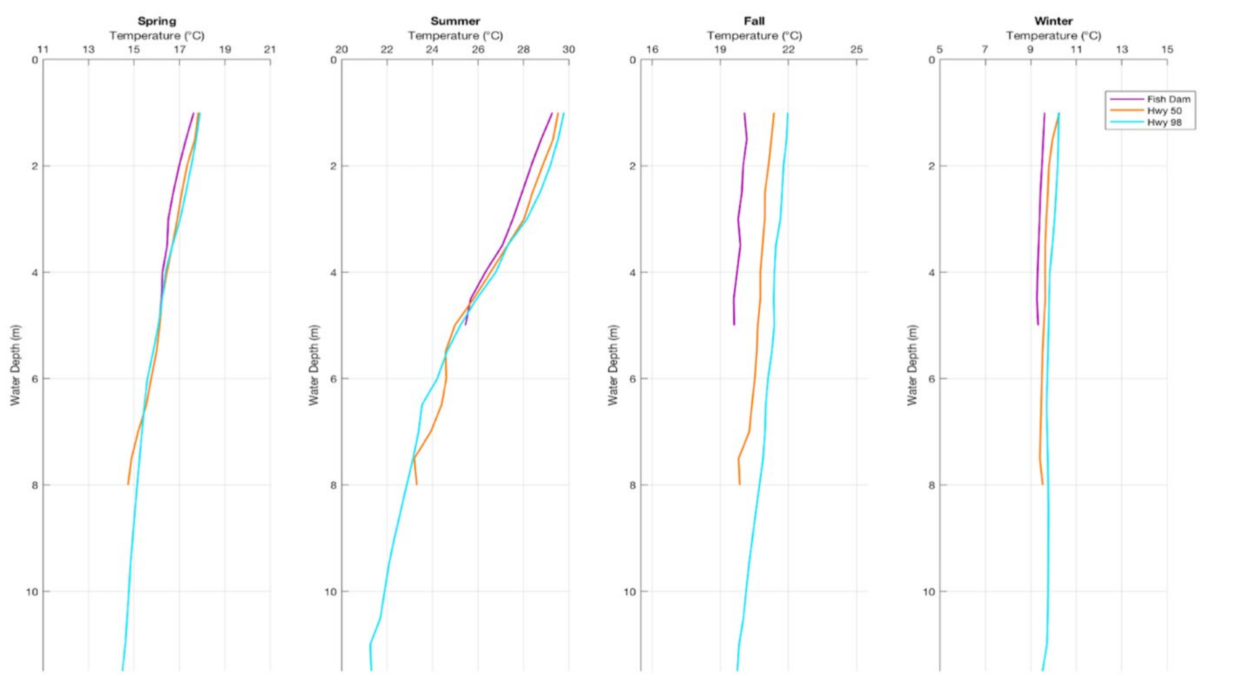


Figure 7. Season-averaged temperature profiles at the 3 mooring sites, where spring=MAM, summer=JJA, fall=SON and winter=DJF.

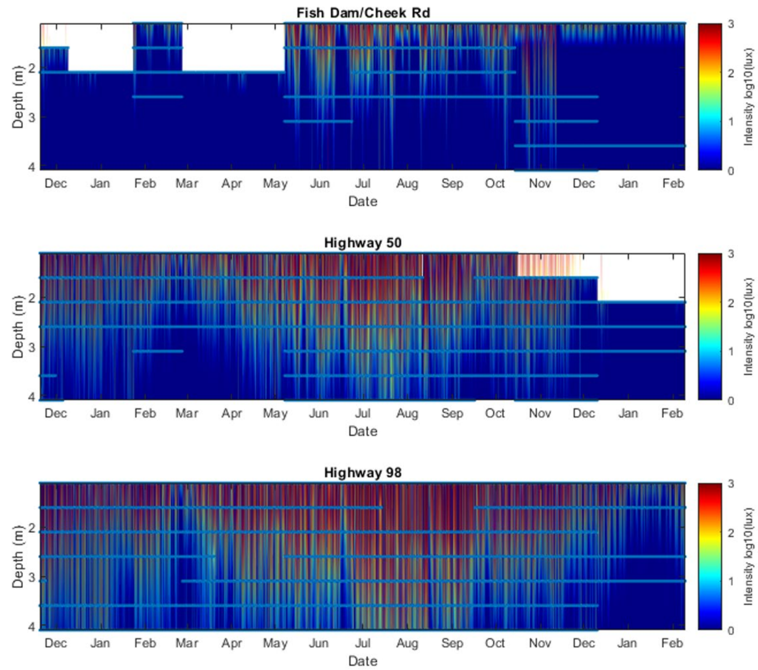
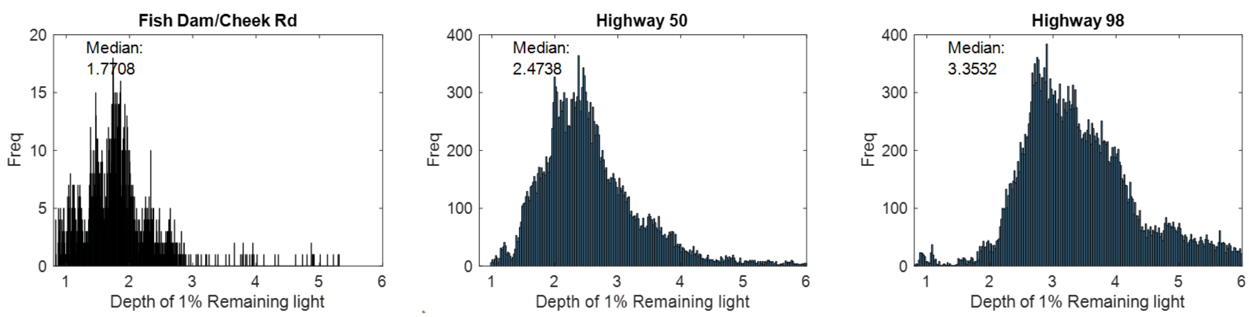


Figure 8. In situ light sensor data in log10(lux) from each of the three sites. Areas with a white background have been extrapolated. Horizontal lines represent locations in the water column with data.

In Situ 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**

Figure 9. 1 % light penetration depths computed from the in situ moorings and the shipboard profiles.

We use measured daily averaged lake level at the dam, converted to lake volume using the UNRBA hypsometry, and measured daily averaged discharge over the dam since 1991 to examine variations in residence time and turnovers over the last 30 years (Figure 10). Residence times are highly variable, as short as weeks and as long as 5 years, when formed in this fashion. The median value over the last 30 years is 4.75 months; for our sampling period the value is 3.3 months, suggesting our sampling was during a time of shorter than typical residence time. Turnovers give a similar impression – the long-term mean number of lake turnovers in a year is about 3.3, but for our sampling period it is 5.85. This finding, that we sampled a 'wet' year with higher-than-normal inflow to the lake suggests the mean velocities (0.03-0.08 m/s, see Figure 4) may be larger than is typical. Otherwise, we would expect the flow variability to be consistent with the findings above.

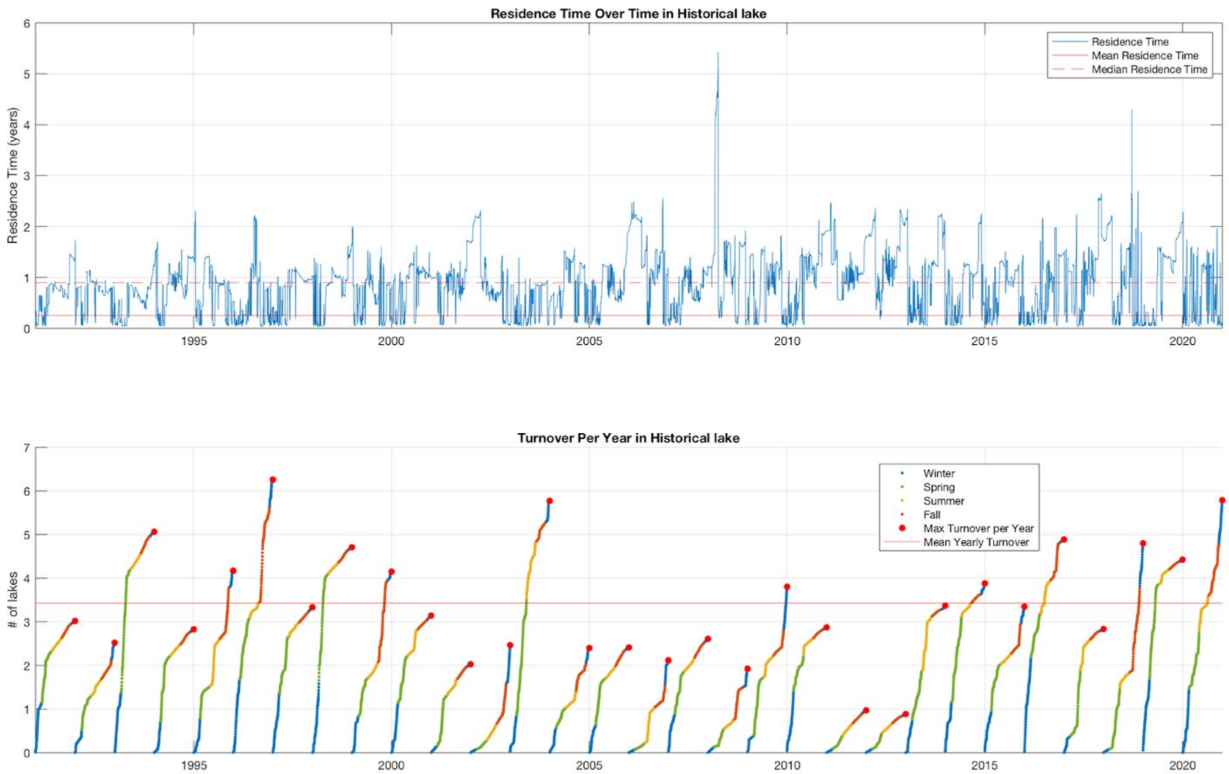


Figure 10. (top) daily estimate of residence time for Falls Lake, with mean and median values shown as horizontal lines; (bottom) turnovers in a year, shown as a cumulative curve for each year.

Side Arm Study

Data collected for this phase of the study has helped to clarify the structure, circulation and connection between the side arms and main stem portion of the lake. The side arm study was conducted during a relative dry period in comparison to the main stem study; maximum total gauged inflows were less than 1/3 of those during the main stem study resulting in smaller fluctuations in lake level, Figure 11.

The first four months of the deployment (September – December) had low inflows and outflow. During this period lake levels dropped by approximately 0.6 m as outflows exceeded inflows. A major inflow event occurred in early January followed by additional events into early March. The large January event returned the lake level to full pool; outflow over the dam was subsequently increased to maintain the lake level at approximately that level, Figure 11.

At each of the sites, the water column temperature was generally uniform over the depth during the fall and winter months. Persistent vertical temperature stratification began in late March to early April at four of the sites (Fish Dam, Hwy 50, Ledge Creek, Lick Creek) but was minimal throughout the deployments in Little Lick Creek due to its substantially shallower water depth, Figure 12.

Along channel water velocities at Fish Dam and Hwy 50 showed similar behaviors to those identified during the main stem study, including response to inflows and releases over the dam and a 5.5 hr along-channel seiche. However, flow in the side arms was substantially different from the main stem and from each other. In particular, the side arms do not show a strong response to the 5.5 hr seiche, Figure 13, and their response to discharge varies as discussed below.

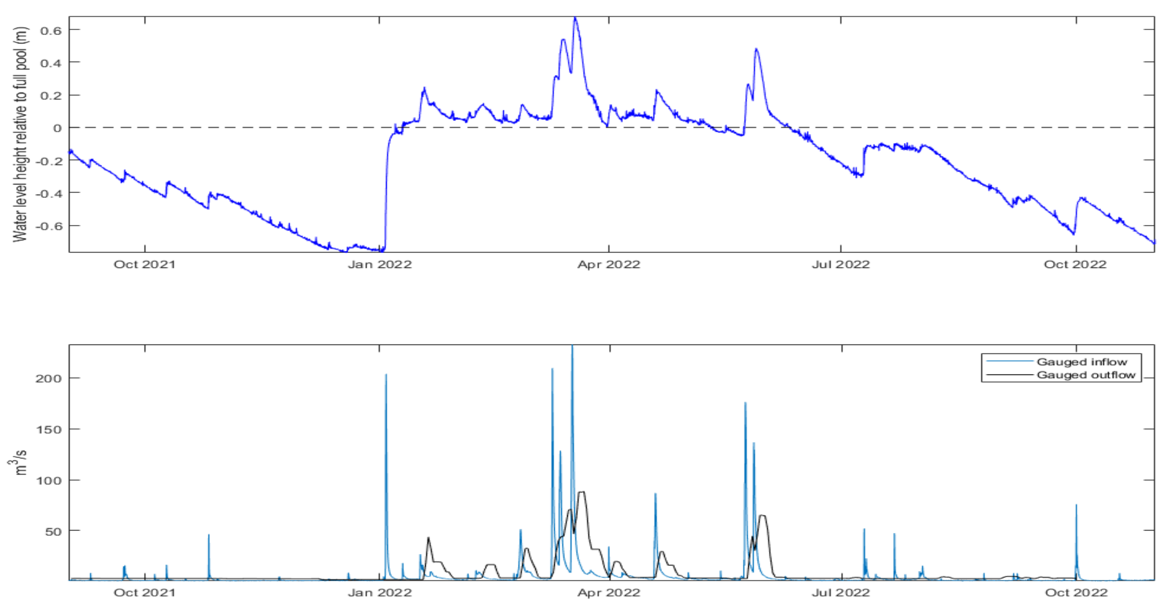


Figure 11. Water level at the dam and discharge (total gauged inflows and gauged outflow over the dam) during the side arm study.

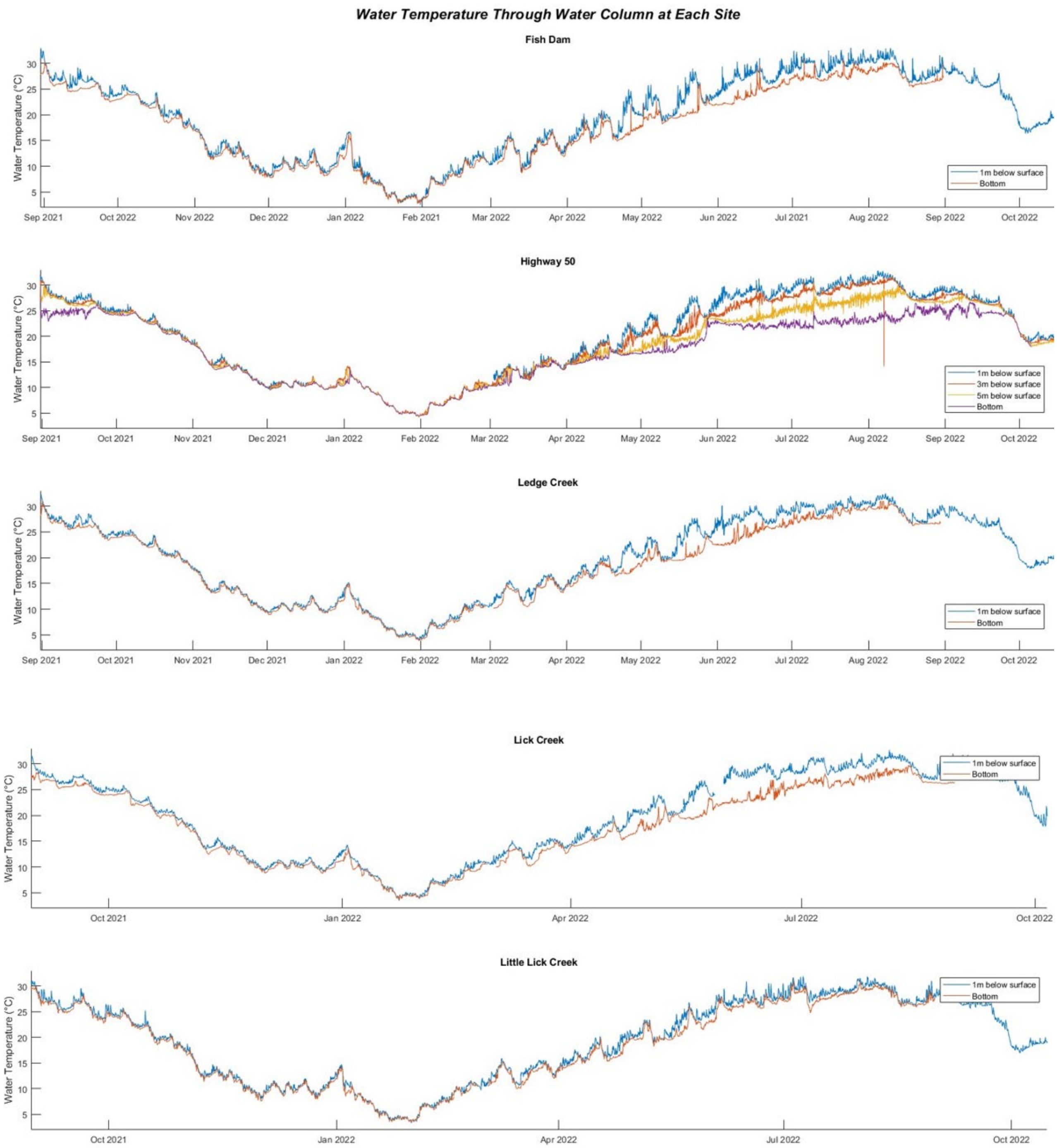


Figure 12. Temperature time series starting from 1 m depth below surface (near surface) to the bottom at the five in situ observations sites used in the side arm study. Due to their shallow depths, only the near surface and bottom temperatures are reported at four of the sites. During stratified conditions the individual time series separate from each other.

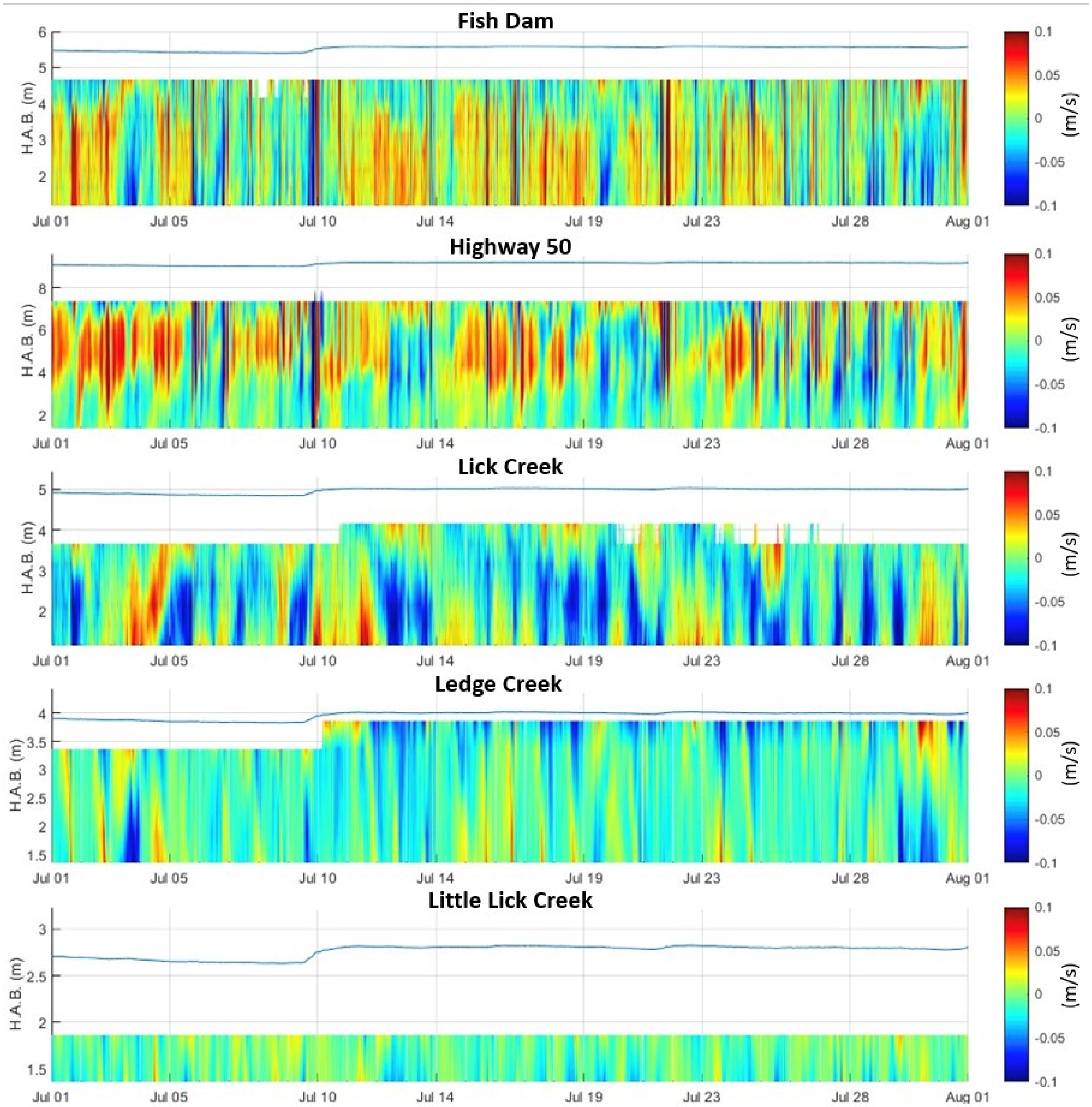


Figure 13. Along stream velocity at the five in situ side arm observational sites during July 2022. Positive velocity is toward the dam, negative velocity is away from the dam. H.A.B stands for height above bottom.

Of the three side arms, Lick Creek had the strongest along channel circulation. During well-mixed conditions, along channel velocities responded primarily to wind events, although in approximately the opposite direction from the wind, i.e., winds from the NE created outflow and winds from the SW created inflow. The associated transport per unit width (velocity multiplied by water column depth) was relatively low with spikes corresponding to significant wind events, Figure 14. During stratified conditions, along channel velocities were similarly driven by the wind, however, the inflow and outflow were typically stronger (~0.1 m/s) and a surface layer was more apparent moving in the direction of the wind and a return layer moving against the wind near the bottom. There was also a significant daily oscillation in the along channel flow that appears to be closely related to daily variations in the strength of the wind, Figure 15. The strong inflow event that occurred in early January and raised the water level in the lake by approximately 0.7 m was accompanied by a strong outflow from the Lick Creek toward the main stem, indicating that runoff into Lick Creek was rapidly sourced to the main stem of the lake. Similarly, the lesser inflow event near mid-January created a brief outflow to the main stem of the lake followed by a strong inflow into the side arm, presumably aided by a change in the wind direction to one favorable for inflow.

Ledge Creek experienced weaker currents than Lick Creek, but a similar pattern with the wind and along channel velocity being approximately 180 deg out of alignment (Appendix - Monthly Plots of Mooring and Velocity Data, Side Arm Observations). Wind from the N created inflow and wind from the S created outflow from the sidearm. Stratification increased the along-channel velocity in the sidearm. The strong inflow event in early January created inflow from the main stem into Ledge Creek as did the lesser event near mid-January suggesting that runoff into Ledge Creek was less significant than into Lick Creek.

Due to its shallow water depth, stratification and currents were typically weaker in Little Lick Creek than in Lick and Ledge Creeks (see Appendix - Monthly Plots of Mooring and Velocity Data, Side Arm Observations). During unstratified conditions, the correlation between wind direction and along channel velocity was less clear, however, when stratification was present the circulation responded similarly to that in Lick Creek with surface flow in the direction of the wind and return bottom flow. The large inflow in early January created outflow from the side arm to the main stem, whereas the mid-January inflow was initially accompanied by a weak outflow and then a stronger inflow into the side arm.

The high-resolution bathymetry collected by the Upper Neuse River Basin Authority (UNRBA 2019) was used to compute the volume of each side arm, assuming a full pool water level, and to recreate the cross section at the observation locations in Lick and Ledge Creeks. The along channel velocity was recorded in 0.5 m vertical bins through the water column (except near the surface and bottom where larger bins were used). Assuming the velocity in each bin is uniform across the side arm, it can be multiplied by its corresponding side arm width and the vertical bin thickness and summed over the vertical to obtain an estimate of the total water flux towards (side arm outflow) and away from (side arm inflow) the main stem of the lake. Due to the shallow depth in Little Lick Creek, often only a single 0.5 m velocity bin was available and therefore this calculation could not be performed reliably for this side arm. Since along channel water movement was frequently bi-directional, water fluxes toward and away from the main stem were accumulated separately. If the assumptions used to calculate these fluxes are reasonable, then inflows and outflows should balance unless there was a significant change in water level or there was significant upstream discharge, either of which may have caused a net inflow to

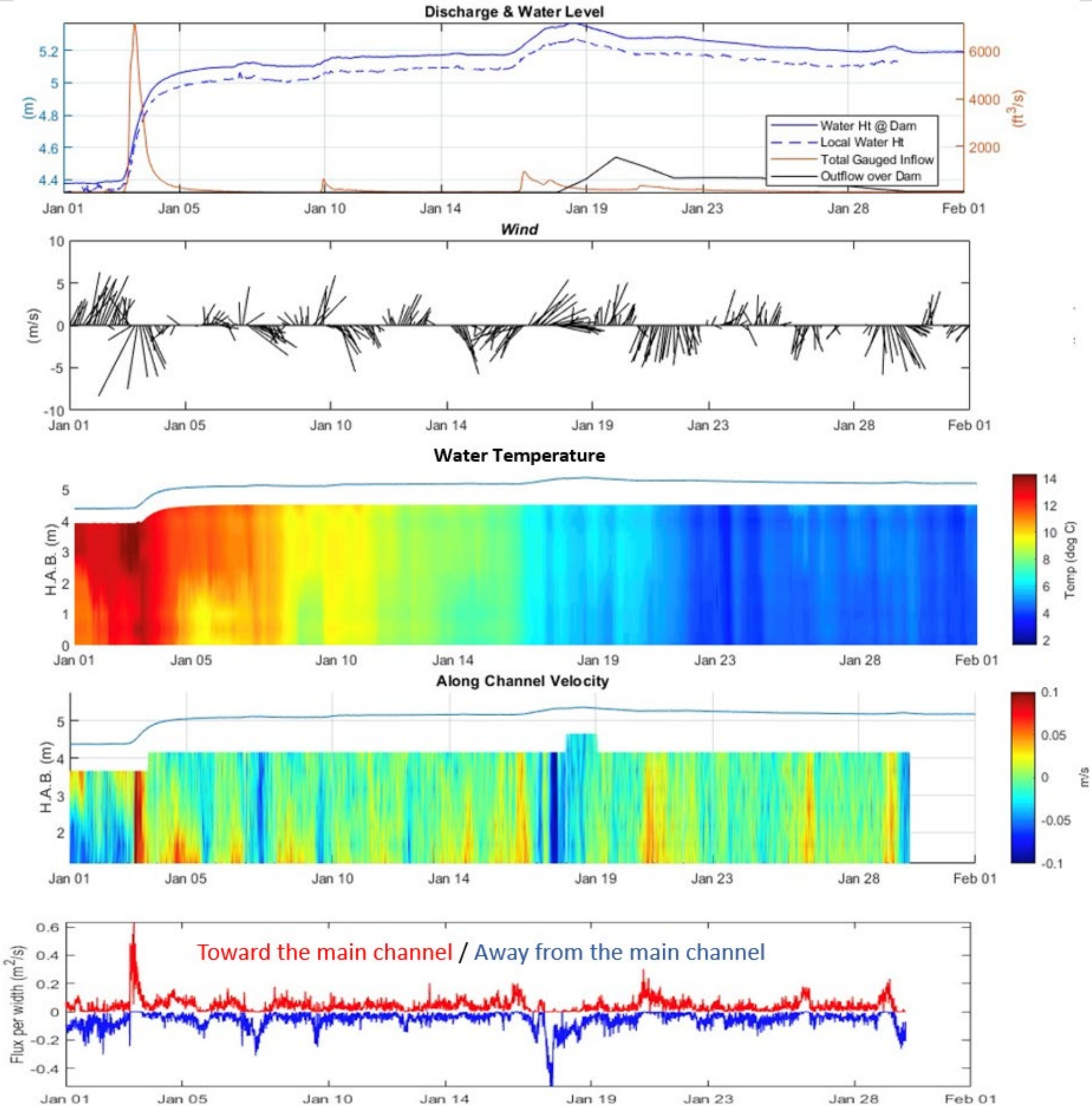


Figure 14. An example of physical conditions and along channel exchange in Lick Creek during an unstratified period, January 2022. From top to bottom: water level change and total gauged inflows and outflows; wind velocity; water temperature; along-channel velocity (positive outflow towards the main stem, negative inflow away from the main stem), and water flux per unit toward / away from the main stem. H.A.B stands for height above bottom.

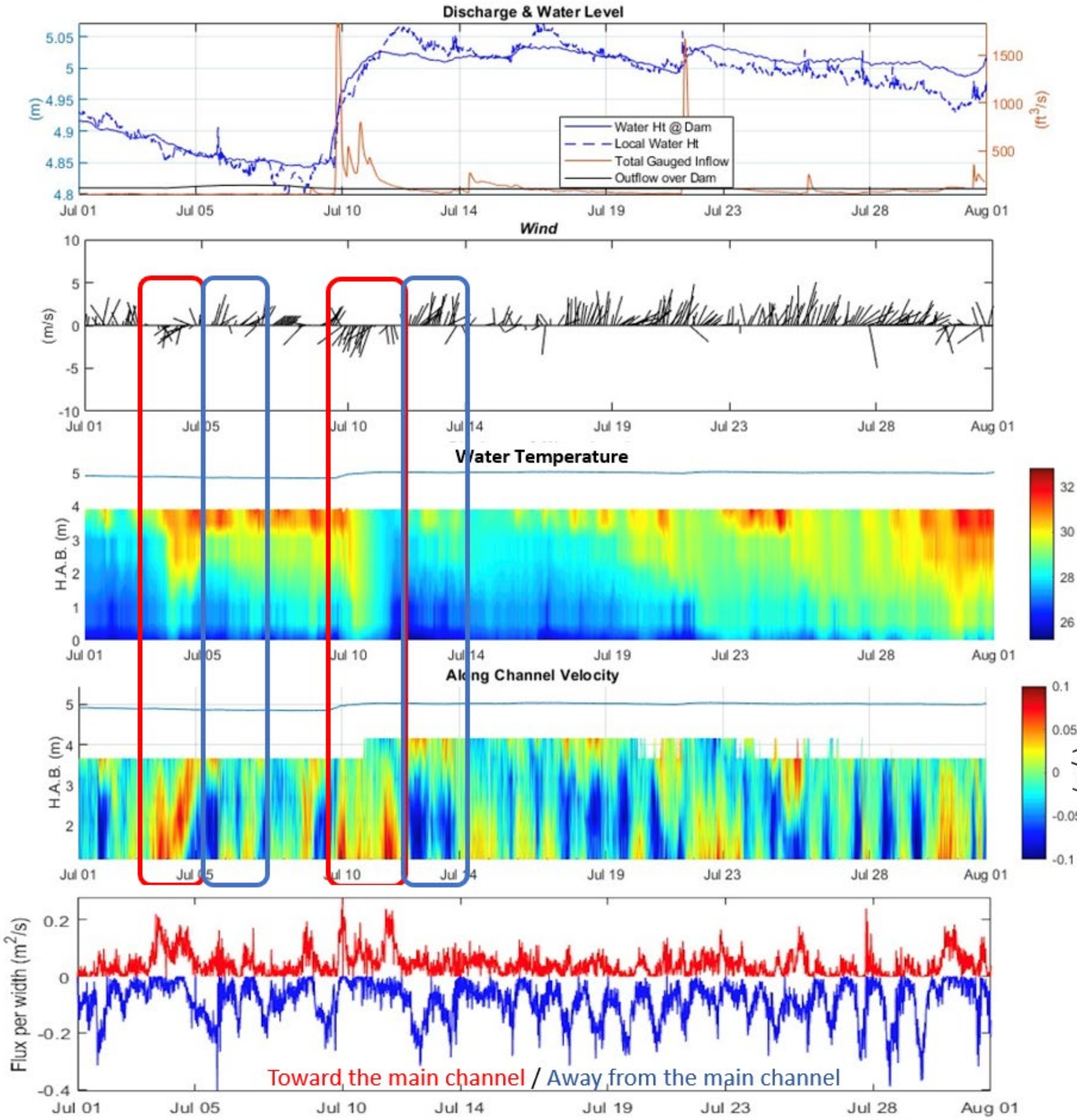


Figure 15. An example of physical conditions and along channel exchange in Lick Creek during a stratified period, July 2022. From top to bottom: water level change and total gauged inflows and outflows; wind velocity; water temperature; along-channel velocity (positive outflow toward the main stem, negative inflow away from the main stem), and water flux per unit toward / away from the main stem. Red (blue) boxes identify examples of near bottom flow toward (away from) the main stem. H.A.B stands for height above bottom.

or outflow from the side arm.

Despite these potential sources of error, inflows and outflows match remarkably well in Lick Creek during most months, Figure 16. The average monthly fluxes are typically between 1.5 – 2 x10^7 m^3 during unstratified months and ~2.5 x10^7 m^3 during stratified months, Table 1. Inflows and outflows in Ledge Creek showed good agreement during unstratified months but were further apart during stratified months. Average fluxes, 1.5 – 2.5 x10^7 m^3 were slightly higher than Lick Creek during unstratified months, and much greater, 4 – 6 x10^7 m^3, during stratified months, Table 1.

Using the volume of each side arm and the average flux through the side arm, residence times, representing the average time it takes to replace the water in the side arm, were computed for each month, Table 1. In Lick Creek these range from 5.6 to 8 (avg 6.7) days during unstratified to weakly stratified conditions to 4.8 to 5.8 (avg 5.3) days during strongly stratified conditions. In Ledge Creek they range from 10 – 16 (avg 12.4) days during unstratified conditions to 4.6 – 7.1 (avg 5.6) days during stratified conditions. Thus, the primarily wind driven circulation is capable of flushing both side arms 3-6 times per month. The residence time may be as much as twice as long during unstratified conditions as during stratified conditions, although this will depend both the presence of stratification and on the strength of the wind forcing. This approach to estimating residence time in the side arms provides lower bounds because it assumes no reflux, and because velocity likely slows near the shoreline, another factor that will cause the transport estimates to be biased high.

Table 1. Monthly volume inflows to and outflows from the Lick Creek and Ledge Creek side arms. Residence time in days is computed as the volume of the side arm (Lick Creek = 4.17 x 10^6 m^3; Ledge Creek = 8.71 x 10^6 m^3) divided by the average of the inflow and outflow multiplied by the number of days in the month.

Month	**Lick Creek inflow (m^3) x 10^7**	**Lick Creek outflow (m^3) x 10^7**	**Lick Creek average (m^3) x 10^7**	**Lick Creek residence time (days)**	**Ledge Creek inflow (m^3) x 10^7**	**Ledge Creek outflow (m^3) x 10^7**	**Ledge Creek average (m^3) x 10^7**	**Ledge Creek residence time (days)**
Sep ‘21	2.49	1.55	2.02	6.2	3.36	1.87	2.62	10.0
Oct ‘21	2.43	1.33	1.88	6.9	3.13	1.49	2.31	11.7
Nov ‘21	1.88	1.67	1.78	7.0	2.42	1.45	1.94	13.5
Dec ‘21	1.85	1.96	1.91	6.8	1.86	1.43	1.65	16.4
Jan ‘22	2.80	1.78	2.29	5.6	3.16	1.60	2.38	11.3
Feb ‘22	2.49	1.50	2.00	5.9	2.20	2.15	2.18	11.2
Mar ‘22	3.11	2.00	2.56	5.1	4.64	2.96	3.80	7.1
Apr ‘22	2.99	2.22	2.61	4.8	5.04	3.35	4.20	6.2
May ‘22	2.42	2.79	2.61	5.0	9.23	2.58	5.91	4.6
Jun ‘22	2.56	1.85	2.21	5.7	6.28	3.56	4.92	5.3
Jul ‘22	2.88	1.58	2.23	5.8	8.97	2.10	5.54	4.9
Aug ‘22	2.35	1.12	1.74	7.5				
Sep ‘22	1.58	1.54	1.56	8.0				
Oct ‘22	1.18	1.80	1.49	7.3				

Lick Creek

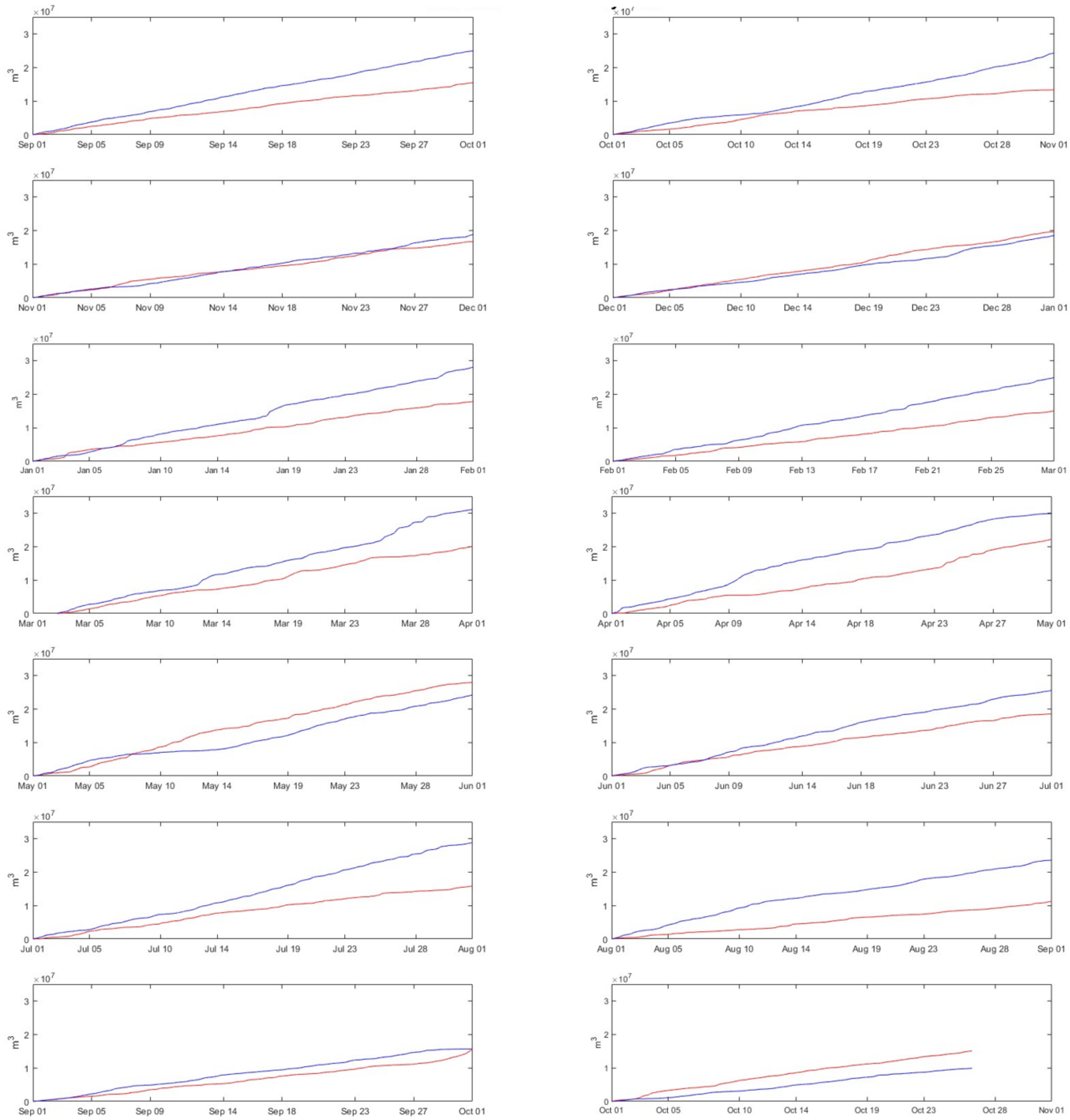


Figure 16. Cumulative inflow (blue) and outflow (red) over each month of the side arm study past the Lick Creek in situ observation location.

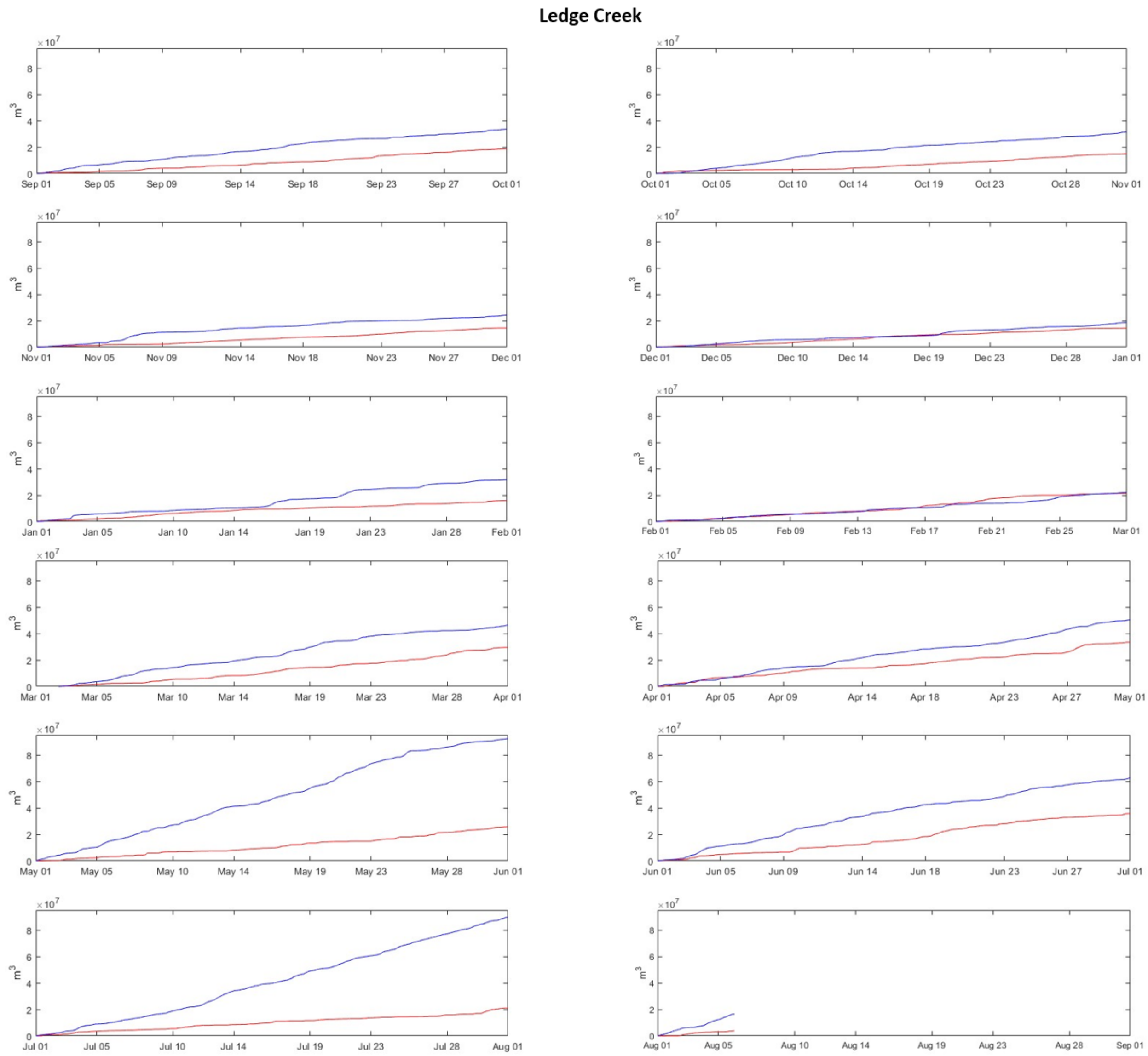


Figure 17. Cumulative inflow (blue) and outflow (red) over each month of the side arm study past the Ledge Creek in situ observation location.

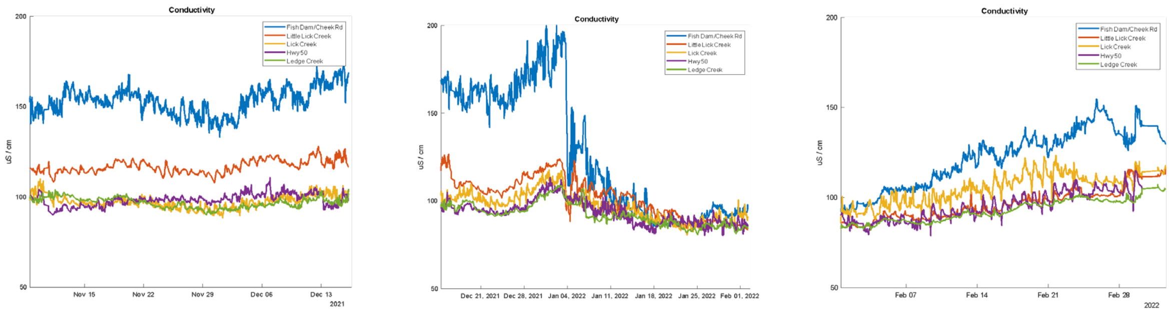


Figure 17. Surface conductivity measured at the five in situ mooring sites during (a) November 2021, (b) December 2021 – January 2022, (c) February 2022.

Light sensors were located at multiple depths on each in situ mooring allowing the calculation of light penetration into the water column. Light penetration was generally greatest at Hwy 50 and Ledge Creek; least at Fish Dam and Little Lick Creek; and intermediate at Lick Creek, (Appendix - Vertical Light Penetration, Side Arm Observations).

Water conductivity was also measured near surface at all of the *in situ* moorings and near bottom at all of the moorings except Little Lick Creek (Appendix - Surface and Bottom Conductivity, Side Arm Observations.) During low flow periods, conductivity was highest at Fish Dam, reflecting a concentration of salts due to evaporation in the large shallow area upstream of this location. Moving toward the dam, conductivity decreased which is consistent with the dilution of the upstream water by inflow in the lower lake, Figure 17a. The major discharge event that occurred in early January, rapidly lowered the conductivity at Fish Dam from nearly 200 µS/cm to approximately 100 µS/cm; conductivity was also rapidly lowered at the Little Lick mooring. Conductivity dropped at the other three sites, albeit more slowly, Figure 17b. Throughout much of the month of January, there was little difference in conductivity among the sites, reflecting the influence of the early January event as well as a smaller event near the middle of the month. Absent significant inflows during the latter part of January and most of February, conductivity increased at all sites, although most rapidly at Fish Dam, Figure 17c.

The shipboard flow through system measurements provided additional insight on connectivity between the main stem and side arms in the study area (Appendix - Flow through surface sampling, Side Arm Observations). The clearest signal appears in surface conductivity which on most trips indicated that water in Little Lick Creek and the area west of the constriction lying north of the Rolling View State Recreational Area was closely coupled with that coming past Fish Dam. To the east of the constriction, including Ledge Creak, Lick Creek and Hwy 50, water had substantially lower conductivity and was presumably influenced by local runoff, Figure 18a. A similar pattern can be seen in some months in turbidity, Figure 18b, although this was often disrupted by local turbidity sources such as resuspension or water column biomass. Spatial patterns of pH and dissolved oxygen distributions along the lake were similar to each other suggesting these may both have been strongly controlled by local primary productivity, Figure 19.

Temperature and *in vivo* fluorescence (a measure of chl-a and related biomass) showed significant spatial variability, however, there were no discernable patterns that we were able to identify.

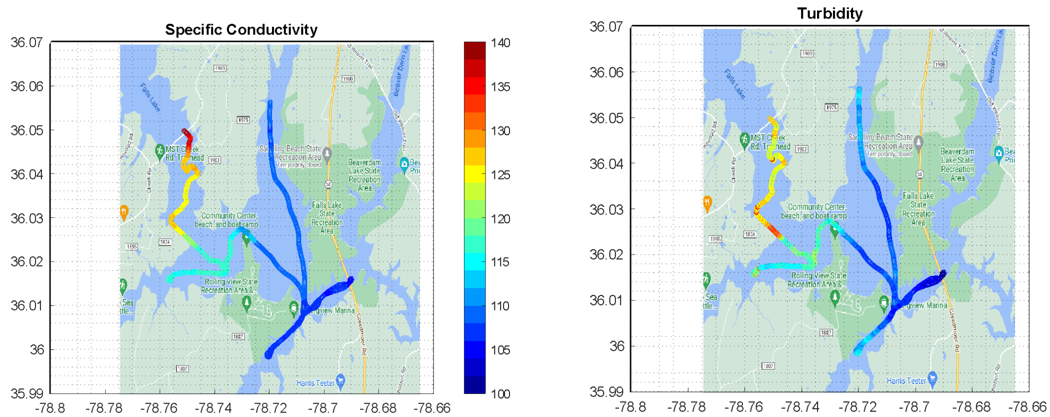


Figure 18. (a) Surface conductivity and (b) turbidity from the flow through system measured on 8/23/2022.

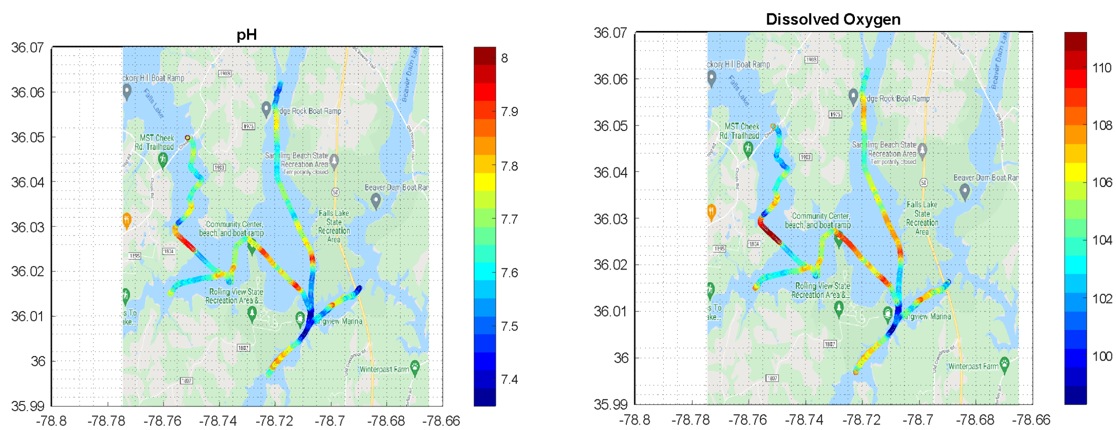


Figure 19. (a) pH and (b) dissolved oxygen (% saturation) from the flow through system measured on 12/16/2021.

Data Archive

Data from the Jordan and Falls Lake observational study are available at the Jordan and Falls Lakes and Watersheds group on Hydroshare https://www.hydroshare.org/groups. Hydroshare provides a robust and convenient means for archiving and exchanging data with other interested groups, such as the modeling team working with the Upper Neuse River Basin Association.

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