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Lake Arrowhead Acoustic Doppler Profiling Data Collection and Preliminary Analysis, 2019

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulics Investigations and Laboratory Services Group
Denver, Colorado **December 2020**

Hydraulic Laboratory Technical Memorandum PAP-1194

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Purpose

The purpose of the acoustic Doppler profiling in Lake Arrowhead was to provide water current profile data to support hydrodynamic modeling and tracer studies that will be used to assess risks associated with proposed indirect potable reuse (IPR) for surface water augmentation (SWA) at Lake Arrowhead. The purpose of this Reclamation Science and Technology funded project (ST-19-7100) is to develop best practices for conducting data collection, hydrodynamic modeling and tracer studies that can provide guidance to water utilities as they conduct IPR-SWA studies in their reservoirs.

Acoustic Doppler profilers (ADPs) were deployed at two locations in Lake Arrowhead to develop an understanding of reservoir currents during periods of thermal stratification for 2019. The ADP data sets will provide information to develop an understanding of reservoir current patterns during mixing events caused by wind, inflows, and pumping station withdrawals.

Introduction

Lake Arrowhead and its dam are located in the San Bernardino National Forest in San Bernardino County, California. The reservoir is located on Little Bear Creek about 30 miles east of Redlands. Lake Arrowhead was originally named Lake Little Bear with initial development in the 1890's to provide a diverted water supply for the San Bernardino area. These water diversions were never approved, so the completed reservoir was renamed Lake Arrowhead and became a popular resort community. Recreational use of the privately-owned reservoir is controlled by the Arrowhead Lake Association (ALA). The Lake Arrowhead Community Services District (LACSD) withdraws water from the reservoir for treatment and distribution to local residents for potable use.

In 2019, the Technical Service Center's Hydraulic Investigations and Laboratory Services Group (86-68560) deployed two ADPs in Lake Arrowhead at locations selected to provide calibration/validation data for a 3-D hydrodynamic reservoir model that is being developed for Science and Technology project ST-19-7100. The project team leader is Dr. David James from the University of Nevada Las Vegas (UNLV).

Methods and Materials

Acoustic Doppler Profiling Locations

A Sontek 500 kHz ADP was initially deployed mid-lake on April 25, 2019. Likewise, a Sontek 1,500 kHz Pulse Coherent ADP (PC-ADP) was deployed from a dock in Meadow Bay (MB) on April 24, 2019. Figure 1 is a map of Lake Arrowhead with the approximate locations of the two ADP deployments. On April 25, 2019 a test deployment of the ADP was conducted during a preliminary test of the UNLV drifters. Several current profiles were measured at 5 different sites in Lake Arrowhead. These data were provided to UNLV for comparison to their drifter data.

The GPS coordinates for the mid-lake ADP site are N34.25744°, W117.185510°. The approximate reservoir bottom elevation of the ADP site was computed to be 5001.02 ft (ALA 1917 datum[1]). The GPS coordinates for the Meadow Bay PC-ADP are N34.256355°, W117.197749°. Note: all GPS coordinates in this report are for the NAD83 datum. The PC-ADP reservoir bottom elevation was computed by subtracting the PC-ADP depth from the reservoir elevation on April 24, 2019. The reservoir bottom elevation at the PC-ADP location is approximately 5,079.1 ft.

ADP deployments and retrievals

Divers retrieved the mid-lake ADP on July 26, 2019 around 2:00 p.m. The divers reported the ADP was lying on its side when they found it. The ADP's tilt sensor data confirmed the ADP tipped over just after it was set on the bottom. It is likely the ADP was pulled over when the intermediate anchor was being deployed. Consequently, no usable current profiles were collected from the mid-lake ADP for the first deployment. Both ADPs were serviced on August 13 to replace their battery packs.

The PC-ADP was re-deployed on August 13, 2019 at 10:00 a.m. at the same location as the previous deployment. The reservoir bottom elevation was computed to be 5080.47 ft. The second mid-lake ADP deployment was delayed until September 26, 2019 because of scheduling conflicts between UNLV and the divers. The ADP was placed on the bottom and leveled by the divers after the intermediate anchor was set. For the second deployment, the computed reservoir bottom elevation for the mid-lake ADP was 5001.0 ft.

On Jan 16, 2020 the PC-ADP was retrieved from the Meadow Bay dock by the ALA-UNLV crew. On January 17, 2020, divers and the ALA-UNLV crew

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[1] Bureau of Reclamation, Lake Arrowhead 2008 Reservoir Survey, Technical Report No. SRH-2009-9. On page 2 it states that the 1917 Lake Arrowhead vertical datum, established during construction, is about 8.0 feet lower than NGVD29 and 11.2 feet lower than NAVD88.

retrieved the mid-lake ADP. Both ADPs were stored in an Arrowhead Lake Association shed until they could be serviced by Reclamation staff. Both ADPs were serviced on February 6, 2020. The ADPs were packed up and shipped back to Denver on February 7, 2020.

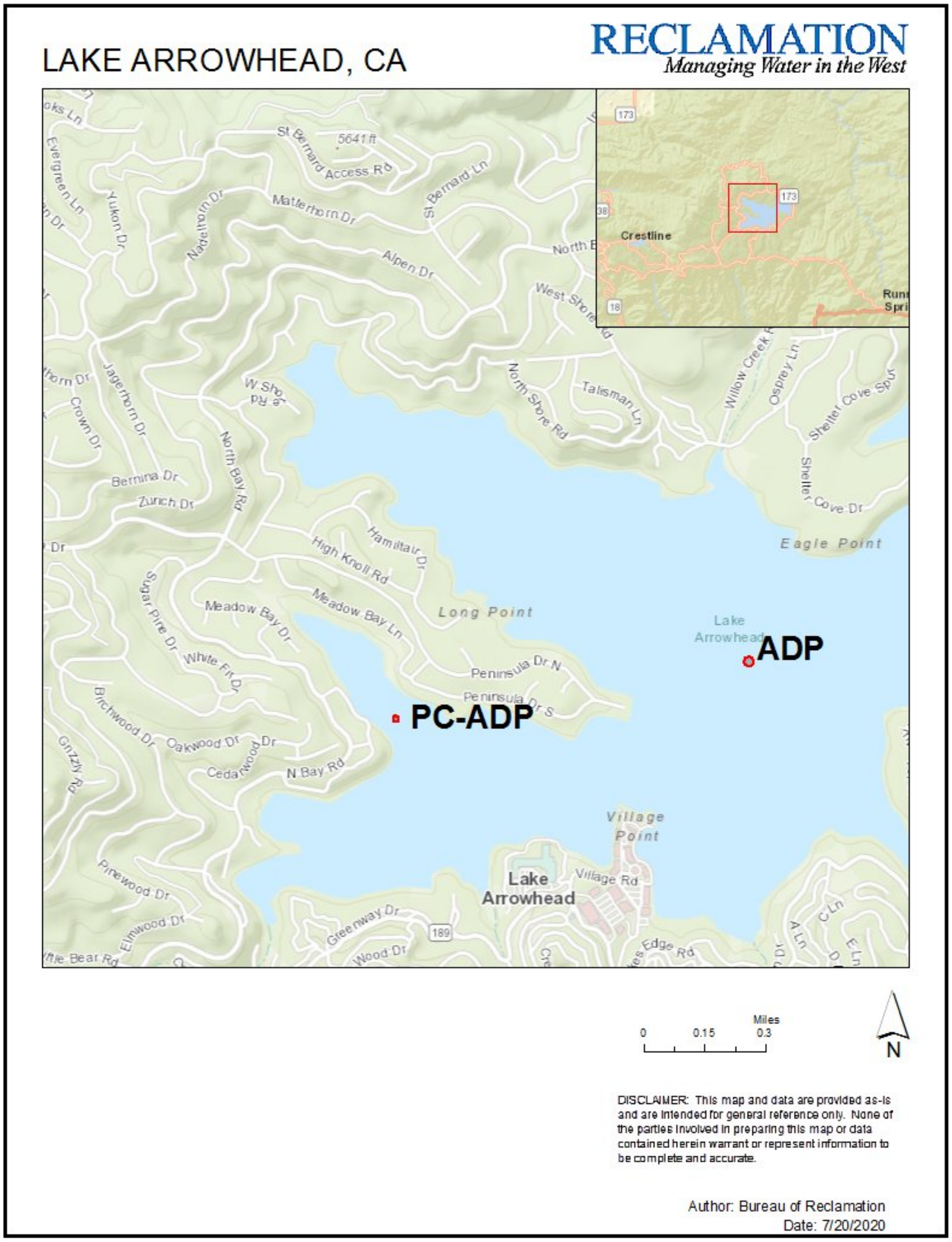

Figure 1. Lake Arrowhead map showing the Meadow Bay PC-ADP and mid-lake ADP sites.

Mid-Lake ADP Configuration

For the 2019 field season, the 500 kHz ADP (serial number C34) was set up for 30 depth cells with a 1.0 m cell size. The ADP was configured for an uplooking deployment for a depth of 30.0 meters (98.4 ft). The blanking distance was 1.0 m while the sensor depth was set to 0 m. For the first deployment, the profiling schedule was to measure current profiles with an averaging interval of 300 seconds and a profiling interval of 1200 seconds. This resulted in a velocity profile averaged over 5 minutes collected every 20 minutes. For the second deployment, the profiling schedule was to measure current profiles with an averaging interval of 300 seconds and a profiling interval of 900 seconds. This resulted in a velocity profile averaged over 5 minutes collected every 15 minutes. For this sampling configuration, the uncertainty in the horizontal velocity measurement was about ±1.0 cm/sec. Note: the second deployment was started on August 13, 2019, but the ADP wasn't deployed by divers until September 26, 2019 due to problems with scheduling the divers. As a result, the first 4220 velocity profiles were measured in air and are meaningless.

This ADP was equipped with a pressure sensor to measure depth, a temperature probe for water temperature measurements and sound speed calculation, and a compass so the 3D velocities can be referenced to east, north, and up coordinates. A complete listing of the ADP system and second deployment configuration is in Appendix 1.

Note: Reclamation's ADP is an older model with firmware that has the "2011 clock bug" where the ADP's internal clock gets reset to a default value if the year is later than 2011 (2019 in this case) and the ADP enters AutoSleep mode. A Sontek support engineer suggested setting the ADP date with a 2009 year instead of 2019. As a result, the raw ADP data will have time-stamped profiles with the year 2009 instead of 2019. This clock bug was not an issue with the PC-ADP deployments.

It is important to note that the mid-lake ADP's compass calibration utility failed to complete the calibration process for the 2019 deployments. The compass offset was estimated by comparing the ADPs compass reading with the digital compass on a mobile phone. When the ADP was oriented due north its compass reading was 242° or the offset was -118°. Similarly, when the ADP was oriented due south its compass reading was 71.5° or the offset was -108.5°. When the ADP was deployed on September 26, 2019 the compass reading after the divers positioned the ADP mount was 177°. To correct the ADP current direction data the value was reduced by -108.5°. This compass calibration technique is less than ideal, but it was the only option available for this data set. It is important to note that while the current direction may have a calibration offset, the relative current direction during any single profile is unaffected by the compass offset.

Meadow Bay PC-ADP Configuration

For the 2019 field season, a 1,500 kHz PC-ADP (serial number H33) was set up for 18 depth cells with a 0.50 m cell size. The ADP was configured for an uplooking deployment in a depth of 9.0 meters (29.5 ft). The blanking distance was 0.50 m while the sensor depth was set to 0 m. Assuming minimal settlement of the PC-ADP mount, the sensor distance from the reservoir bottom is 0.38 meters. For the first deployment, the profiling schedule was to measure current profiles with an averaging interval of 300 seconds and a profiling interval of 1,200 seconds. This resulted in a velocity profile averaged over 5 minutes collected every 20 minutes. For the second deployment, the averaging interval was 300 seconds and a profiling interval of 1,800 seconds. This resulted in a velocity profile averaged over 5 minutes collected every 30 minutes. The profiling interval was set to 1800 seconds to prolong the battery life for the second deployment. For this sampling configuration, the uncertainty in the horizontal velocity measurement is less than ±1.0 cm/sec.

The PC-ADP was equipped with a pressure sensor to measure depth, a temperature probe for water temperature measurements and sound speed calculation, and a compass so the 3D velocities can be referenced to east, north, and up coordinates. The compass calibration was successfully completed before each deployment. A complete listing of the PC-ADP system and deployment configuration is in Appendix 1.

Vertical Temperature Profiles

Vertical temperature profiles are used to monitor the thermal stratification of a water body. Stratification can influence reservoir currents and inflow and outflow mixing processes. High-resolution temperature profiles can detect short-term events, like seiches or destratification (turnover).

Mid-Lake Profiles

UNLV deployed a temperature profiling string in Lake Arrowhead near the mid-lake ADP site to collect high-resolution vertical temperature profiles. Temperature logger spacing varied from 1m near the water surface to 3m near the reservoir bottom. The GPS coordinates for the temperature profiling buoy are N34.25825°, W117.18494°. The temperature profiling string was equipped with 18 Onset HOBO® U22-001 water temperature loggers which used the Onset factory calibration with ±0.21°C from 0°C to 50°C. Profiles were collected every 5 minutes from April 24, 2019 until January 31, 2020. Note: the mid-lake temperature profiling buoy was vandalized and sank to the lake bottom on July 7. The temperature profiling string wasn't repaired and redeployed until September 26, 2019. As a result, temperature profiling data are not available at this location from July 7 through September 26, 2019.

Meadow Bay Profiles

Reclamation was responsible for deploying the temperature profiling string at the Meadow Bay PC-ADP location. The string was located directly above the PC-ADP location shown in Figure 1. Profiles were collected every 5 minutes from April 24, 2019 to January 11, 2020. The temperature profiling string was equipped with HOBO Tidbit® temperature loggers with a 1 meter vertical spacing. The GPS coordinates for the Meadow Bay temperature profiling string are N34.256355° and W117.197749°. The Meadow Bay temperature string had 10 loggers which were calibrated in Reclamation's hydraulics laboratory in Denver, Colorado prior to the initial deployment. All Tidbit® temperature loggers were calibrated to within the manufacturer's specified accuracy of ±0.2°C.

Lake Arrowhead Reservoir Operations

For the 2019 field seasons, Lake Arrowhead Reservoir operations data were collected by Arrowhead Lake Association and were provided to UNLV. For this report, the reservoir surface elevation was used to convert the temperature logger depths to elevations.

Weather Stations

UNLV established a network of weather stations around Lake Arrowhead to support this project. Reclamation was not involved with collecting or analyzing weather station data. Weather station wind speed and direction data can be used to analyze the vertical temperature profile data to understand the influence of wind on the stratification and the formation of seiches. Likewise, wind data are also a key driver in reservoir water currents.

Data Analysis and Results

Reservoir Operations

Figure 2 is a plot of the Arrowhead Lake reservoir elevations during the ADP measurements and vertical temperature profiling. Reservoir elevations are necessary for data analysis to exclude ADP depth cell data that are biased by boundary (water surface) interference. Other reservoir operations data pertinent to this report are the Grass Valley Tunnel inflows to Meadow Bay, especially during a storm event on December 4, 2019 when UNLV was conducting a dye tracer experiment in Lake Arrowhead. UNLV deployed a water temperature and specific conductance logger in the Grass Valley Tunnel inflow channel just upstream from Lake Arrowhead. Figure 3 shows the USGS gage (10260855) inflow hydrograph for Grass Valley Lake Tunnel releases into Meadow Bay at Lake Arrowhead. The peak discharge during the dye tracer study was 30 cubic feet per second (CFS) on December 4, 2019.

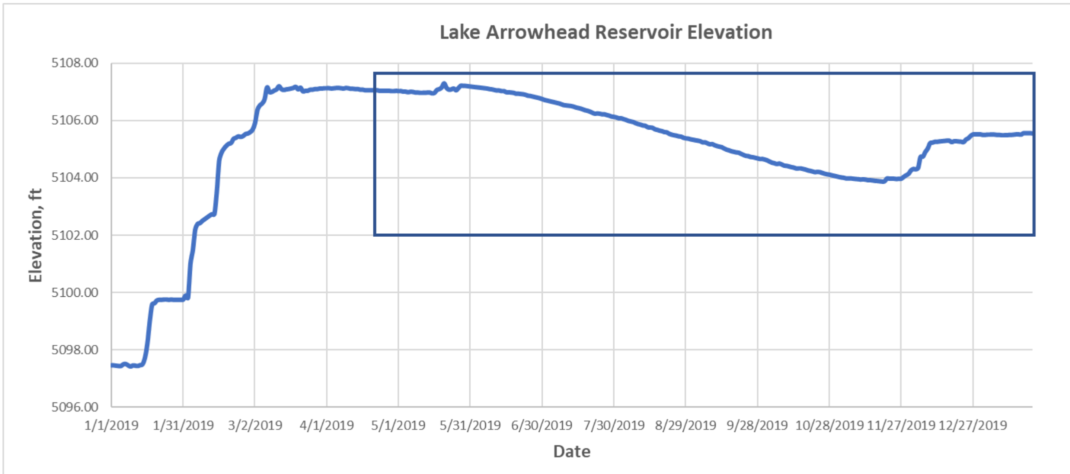

Figure 2. Lake Arrowhead reservoir elevation from January 1, 2019 to January 21, 2020 (ALA vertical datum 1917). The rectangle illustrates the study period, April 24, 2019 to January 15, 2020.

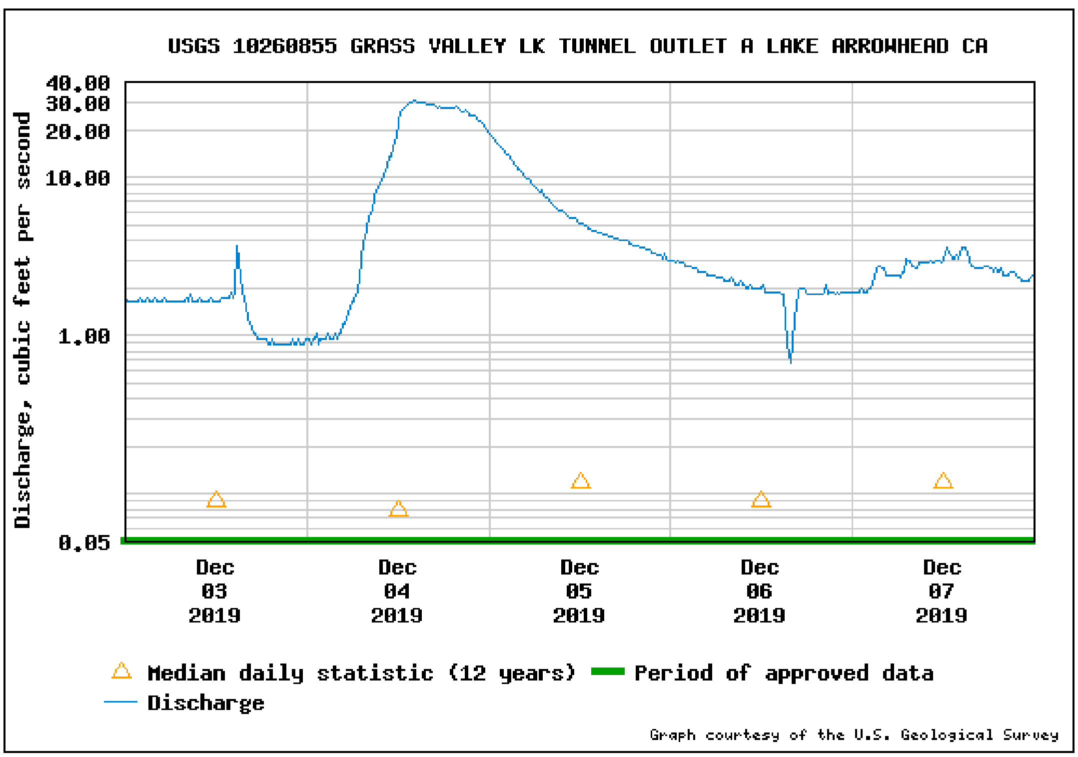

Figure 3. Plot of USGS Grass Valley Lake tunnel outlet that discharges into Lake Arrowhead's Meadow Bay during a storm event that coincided with UNLV's dye tracer study. Source: USGS website.

Arrowhead Lake Wind Data Analysis

UNLV was responsible for the collection and analyses of the wind data. The wind field over Lake Arrowhead is an important input to the computer model used for modeling the reservoir. UNLV used wind data from several weather stations to define the wind field over the entire reservoir. In this report, wind data from LACSD pump station No. 8, McKay Park (BR1) and Tavern Bay (BR3) weather stations will be presented to support understanding of reservoir currents and thermal stratification (vertical temperature profiles) for Meadow Bay and mid-lake sites, respectively. Note: wind directions presented are converted from the direction the wind was blowing from to the direction the wind was blowing towards. This change was made so the wind direction would be consistent with the water current direction. For example, a sustained wind from the north should produce surface water currents in a southerly direction.

ADP Analysis

A detailed analysis of the ADP data collected at Lake Arrowhead was not included as part of the technical assistance to UNLV. However, a brief presentation of the ADP data and some general observations will be covered in this section. In general, the analysis for each ADP profiling site will be for the same time period.

Acoustic Doppler profile data are inherently noisy and usually require averaging to dampen out the acoustic noise. Lake Arrowhead ADP data were collected with a 5-minute averaging interval and a 20-minute profiling interval. Depth averaging and temporal averaging can be used to smooth the data which can assist with data interpretation.

Another data processing consideration was to exclude ADP cells near the water surface because they are biased by sidelobe interference. For this uplooking application the interference occurs at the water surface. The sidelobe energy from each 25° slant angle acoustic beam will encounter the water surface before the primary acoustic beam does because it travels a shorter path (vertically). Because the water surface is a strong acoustic reflector and these sidelobe returns occur in the same range (with respect to travel time) where the main lobe depth cell is located, they bias the backscattered signal in these near-surface depth cells. Unfortunately, there isn't a way to remove the bias from the sidelobe interference. Note: the PC-ADP has a 15° slant angle so it is not as susceptible to sidelobe interference.

At Lake Arrowhead, the reservoir water surface elevation dropped slowly throughout the data collection period (see figure 2). As a result, the ADP data have to be processed to account for sidelobe interference occurring in different depth cells as the water surface elevation drops. Consequently, the ADP velocity profiles do not contain the surface water velocity generated by the wind.

However, the near-surface velocity measurements should behave similarly to the wind-driven surface velocities.

Mid-Lake ADP Analysis

ADP data were collected continuously between September 26, 2019 and January 9, 2020. A total of 10,060 velocity profiles were collected for this 105-day deployment. For the data shown in this section the ADP current directions have been adjusted in an attempt to correct for the compass offset, as previously described.

Figure 4 shows the complete 2019 mid-lake ADP data record along with a plot of the wind speed and direction data from the McKay Park weather station (BR1). In general, these contour plots show mostly low currents with some near-bottom currents which appear to be expanding upward with time. It is important to note that the mid-lake current speeds are biased high by about 1 to 2 cm/sec because the mid lake ADP has a higher measurement standard deviation when compared to the PC-ADP data (Figure 4). In other words, the ADP current measurements cannot accurately resolve water currents less than 1 to 2 cm/sec because of the random acoustic noise that is inherent with the ADP signal processing. It appears on figure 7 that on or around day 330 (November 26, 2019) there was a strong wind event that changed the bottom currents. It is likely that this wind event caused the reservoir stratification to break down.

Figure 5 contains plots for days 329 to 332 which confirms that a strong wind event blowing towards the northwest disrupted the relatively stable current pattern at the mid-lake location. Winds of over 12 m/sec toward the northwest created near-surface current speeds up to 8 cm/sec on November 27, 2019 (day 331). However, these currents dissipated quickly when the wind slowed and changed direction.

Figure 6 shows a 6-day period for calendar days 336 to 342 (December 2-7, 2019) which includes the December 3-7 UNLV dye tracer study period. These ADP contour plots help visualize the effects of a December 4 (day 238) storm event on surface and bottom currents at the mid-lake site. On day 338 there was increased current speed mid depth (El. 5040 ft), but it was short lived. It is interesting that the strong winds at BR1 did not create stronger surface water currents. It is also important to note the reservoir stratification was breaking down and Lake Arrowhead was essentially iso-thermal during the dye tracer study.

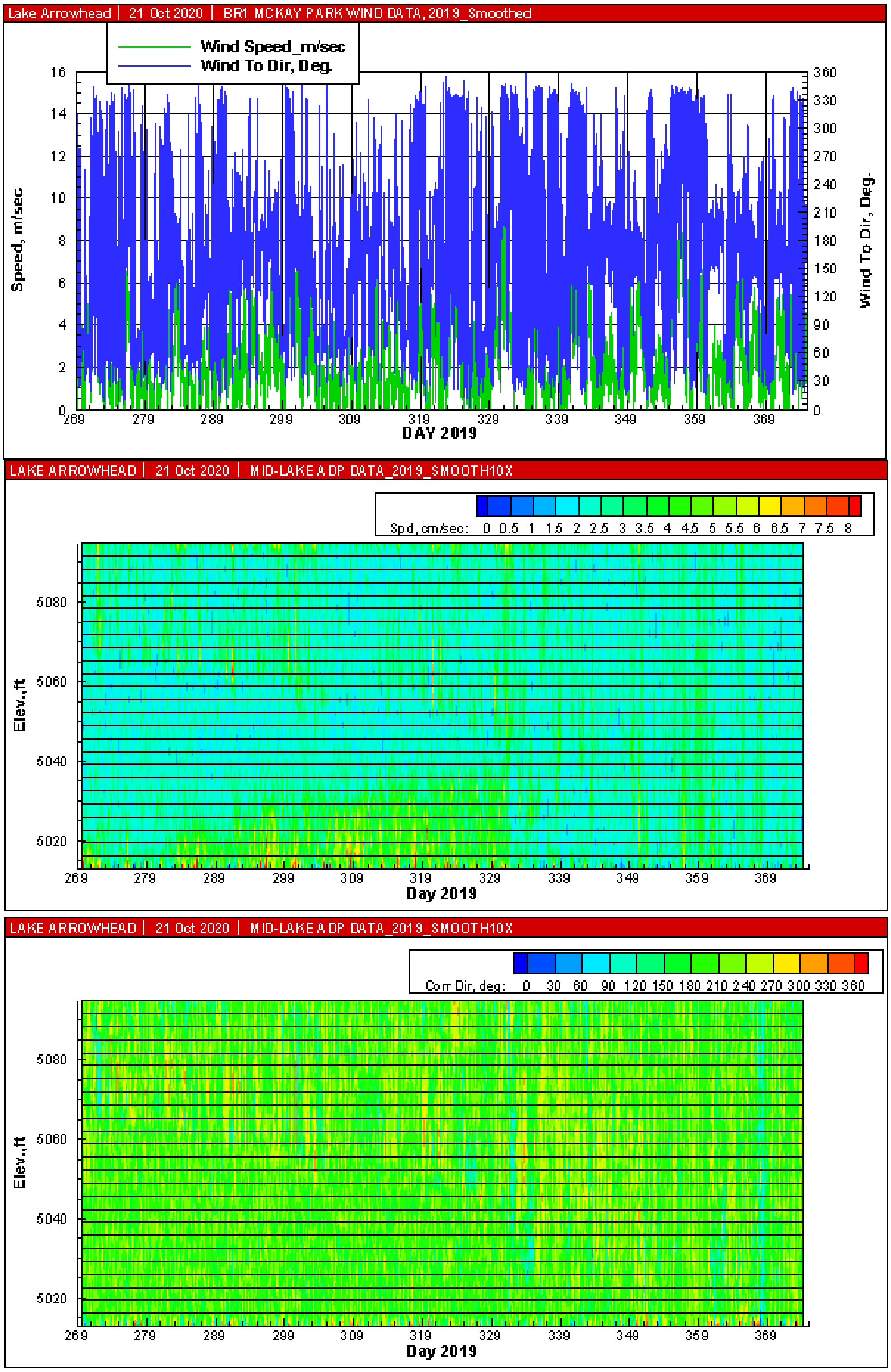

Figure 4. Complete record of ADP current speed and direction contour plots from calendar day 269 to 374 (September 26, 2019 to January 9, 2020). The BR1 weather station's wind speed and direction (toward) data for the same time period are included in the top plot. The black dots represent ADP depth cell locations.

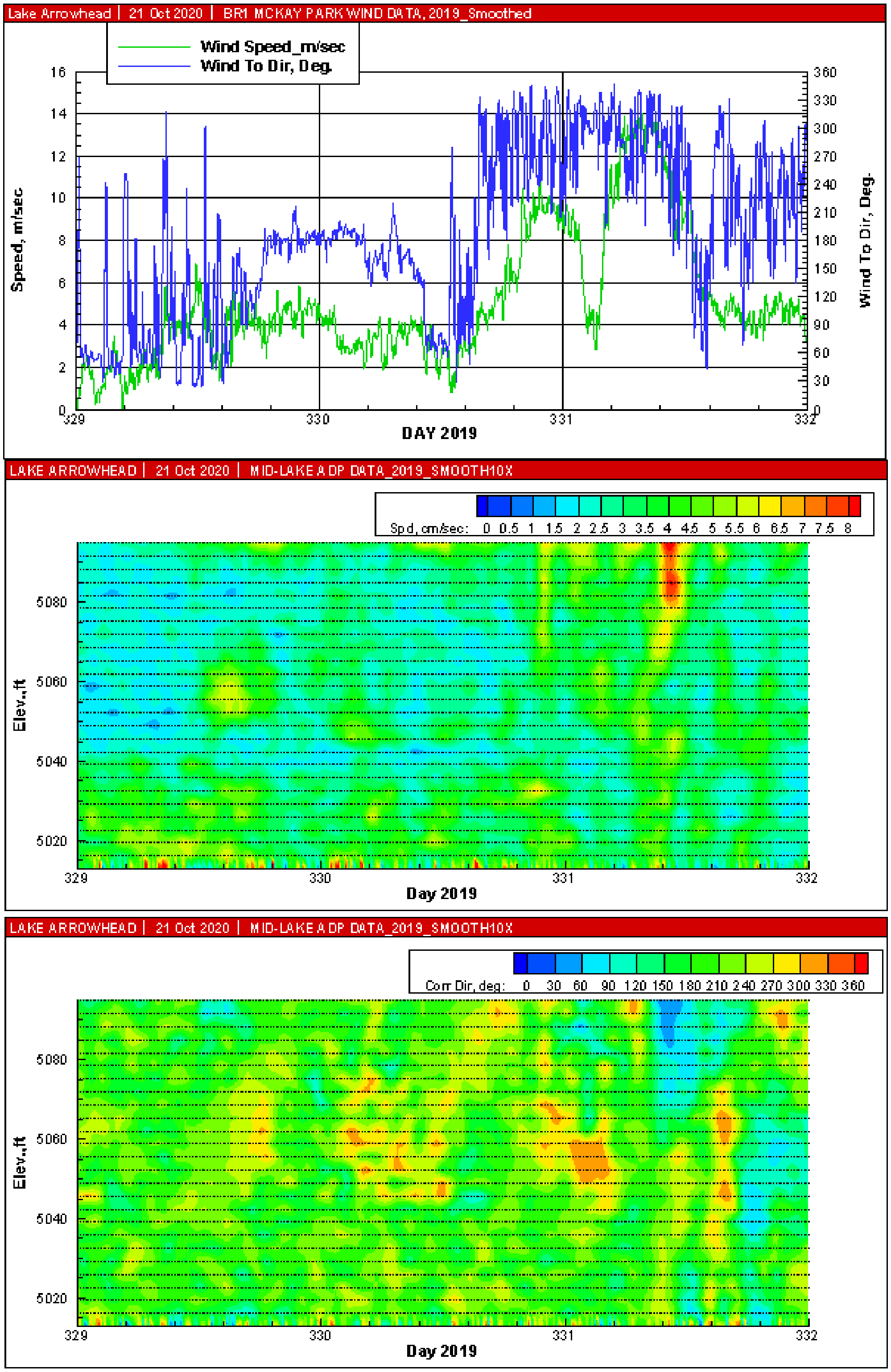

Figure 5. Three-day record of ADP current speed and direction contour plots for calendar day 329 to 331 (November 25-27, 2019). This shorter window of time allows for a detailed inspection of surface and bottom currents during a strong wind event measured at the BR1 weather station. The black dots represent ADP depth cell locations.

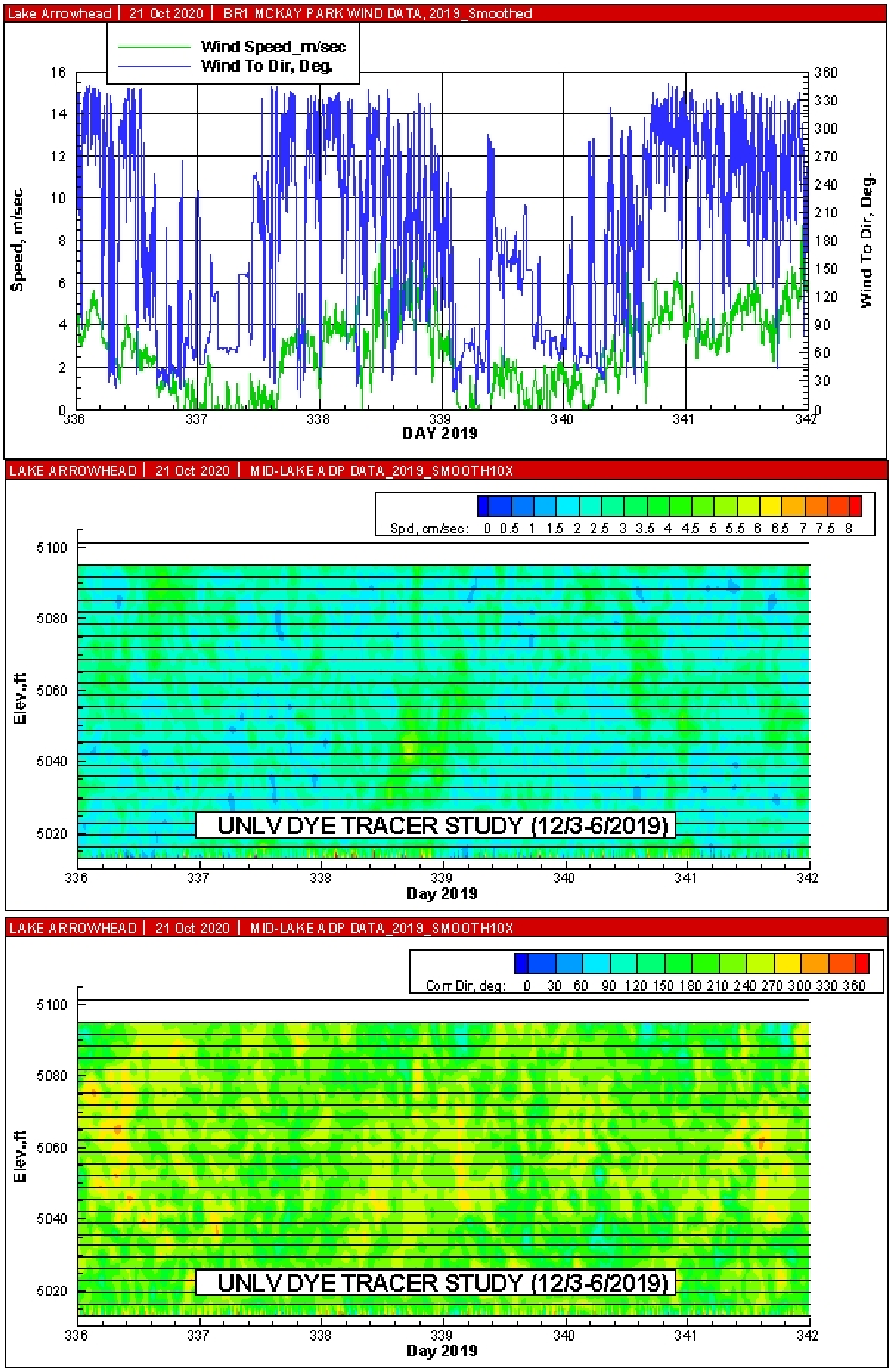

Figure 6. Plots of PC-ADP current speed and direction collected during the UNLV Dye Tracer Study on days 336-341 (December 2 -7, 2019). The McKay Park wind speed and direction (toward) data for the same time period are included in the top plot. The current direction data shows several reversals in direction near the reservoir surface and bottom. The current speed data do not show any strong currents generated by the storm events.

Meadow Bay PC-ADP Analysis

Meadow Bay PC-ADP data were collected continuously between April 24, 2019 and January 15, 2020. A total of 16,033 velocity profiles were collected for this 266-day deployment. For this report, Meadow Bay PC-ADP data collected between April 24, 2019 and January 15, 2020 will be presented.

Figure 7 shows the complete 2019 PC-ADP data record along with a plot of the wind speed and direction data from the LASCD pump station No. 8 wind sensor. In general, these plots show the dynamic currents with many wind events that generate near surface water currents up to 4 to 5 cm/sec. In contrast, the currents measured near the reservoir bottom only occasionally exceeded 4 cm/sec. The velocity direction data is the most informative as it shows frequent reversals in current direction throughout the water column.

Figure 8 shows a 1-day period for calendar day 186 (July 5, 2019) which helps to visualize the effects of sustained wind events on surface and bottom currents at the Meadow Bay site. This type of plot can assist with the calibration and validation of the reservoir model to evaluate if the model current profiles are representative of the field measurements. The PC-ADP data shows reversals in current direction as the wind picks up in the afternoon and subsides in the evening. The near-surface currents pick up to 7 cm/sec when the Meadow Bay average wind speeds increase to 4 m/sec during the middle of the day.

Figure 9 shows a 6-day period for calendar days 336 to 341 (December 2-7, 2019) which includes the dye tracer test conducted by UNLV. These plots help visualize the effects of a December 4 (day 238) storm event on surface and bottom currents at the Meadow Bay site. It is important to note that the reservoir stratification was breaking down and Meadow Bay was essentially iso-thermal during the dye tracer study. When interpreting the PC-ADP data the current direction contours are red/orange when water is moving into Meadow Bay. Conversely, the contours are light blue when water is moving out of Meadow Bay and into Lake Arrowhead.

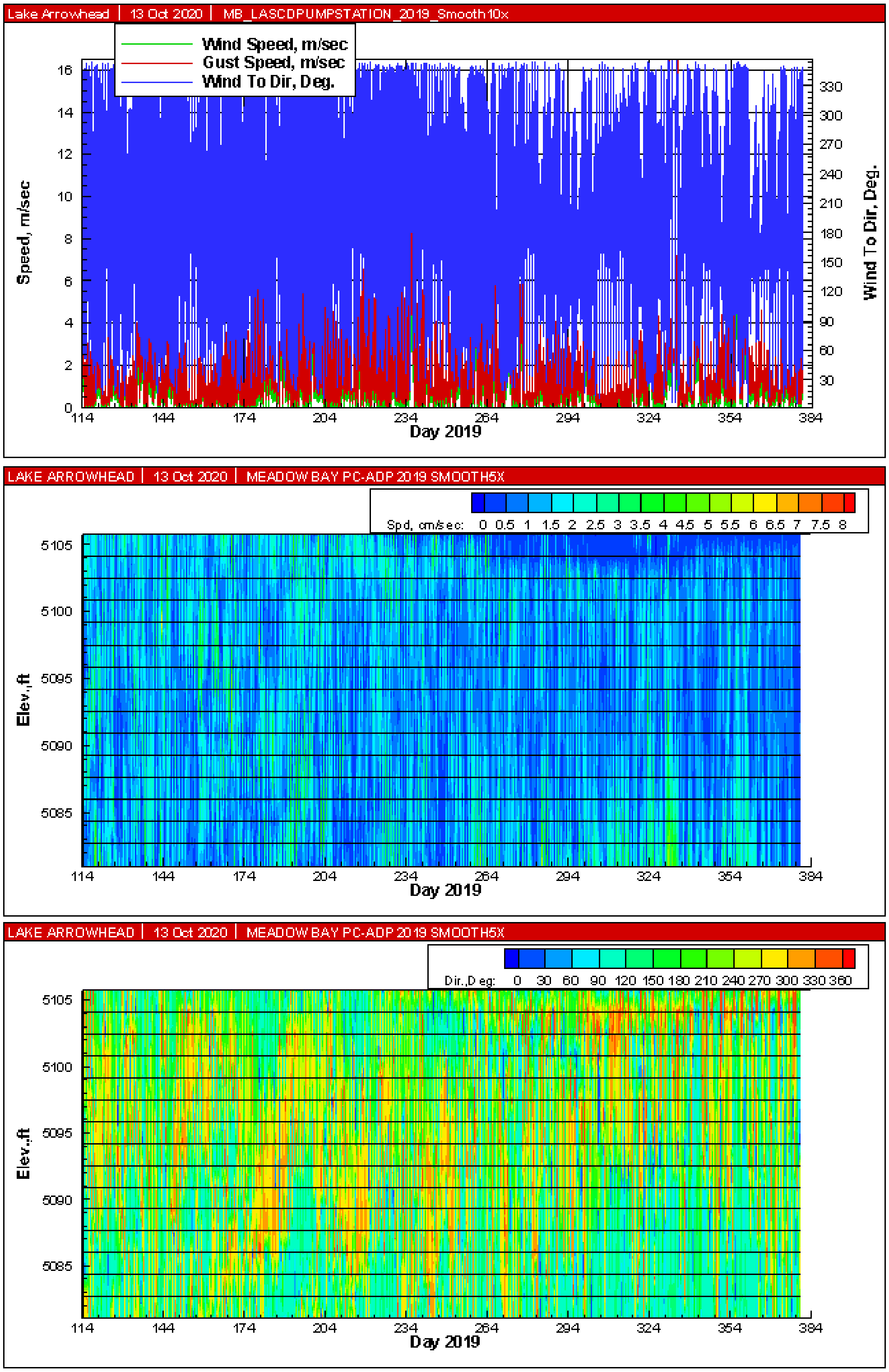

Figure 7. Plots of wind speed and direction (top panel) and PC-ADP current speed and direction contour plots at the Meadow Bay site. The period of data collection was from April 24, 2019 (day 114) to January 15, 2020 (day 380). Both wind and PC-ADP data were smoothed to remove spikes from the data. The black lines on the PC-ADP plots are the depth cell elevations. The black dots represent PC-ADP depth cell locations.

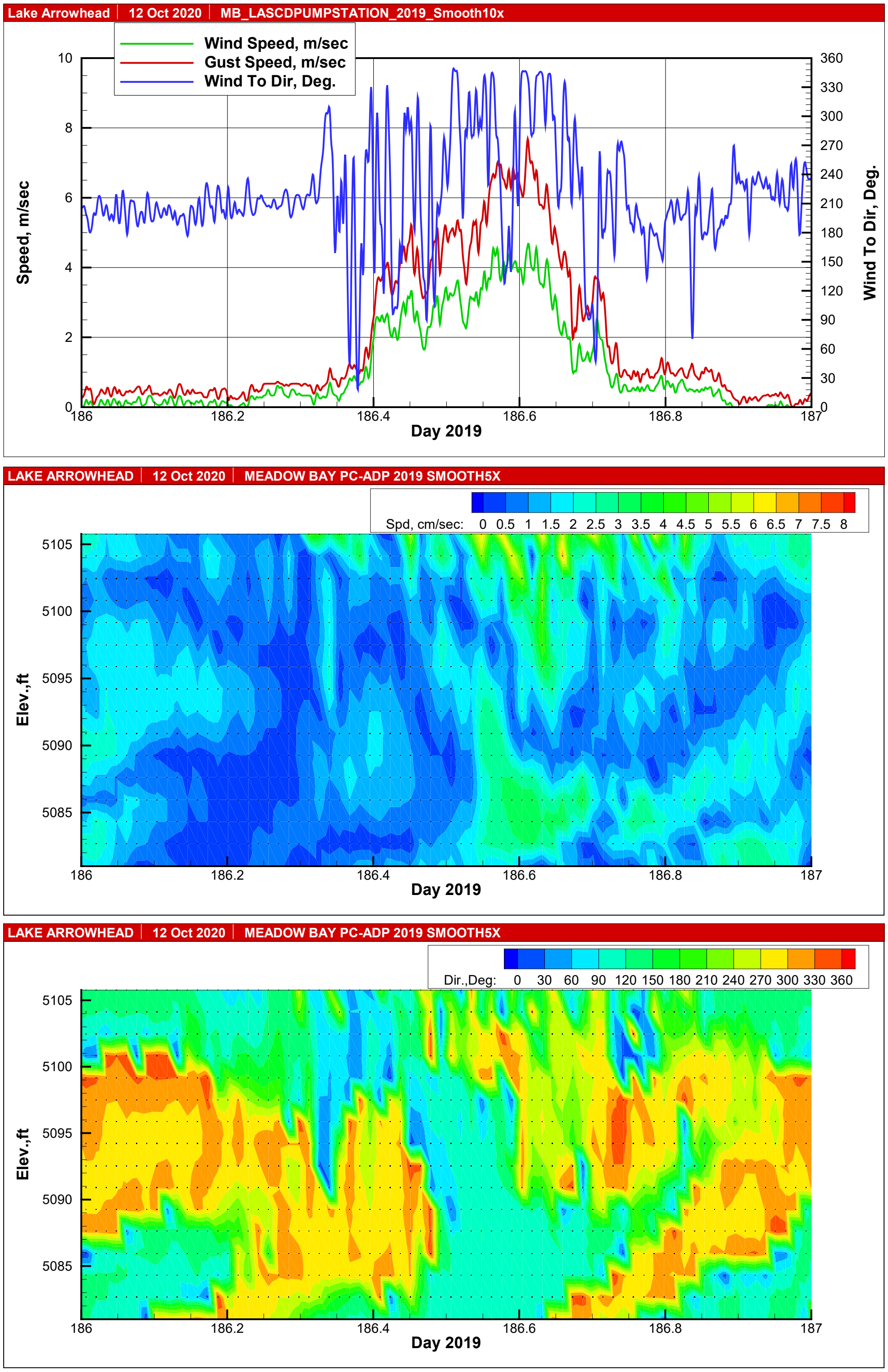

Figure 8. Plots of PC-ADP current speed and direction contour plots for calendar day 186 (July 5, 2019). The Meadow Bay wind speed and direction (toward) data for the same time period are included in the top plot. The current direction shows several reversals in direction near the reservoir bottom. The current speed near the water surface increases when the wind speed increases in the middle of the day.

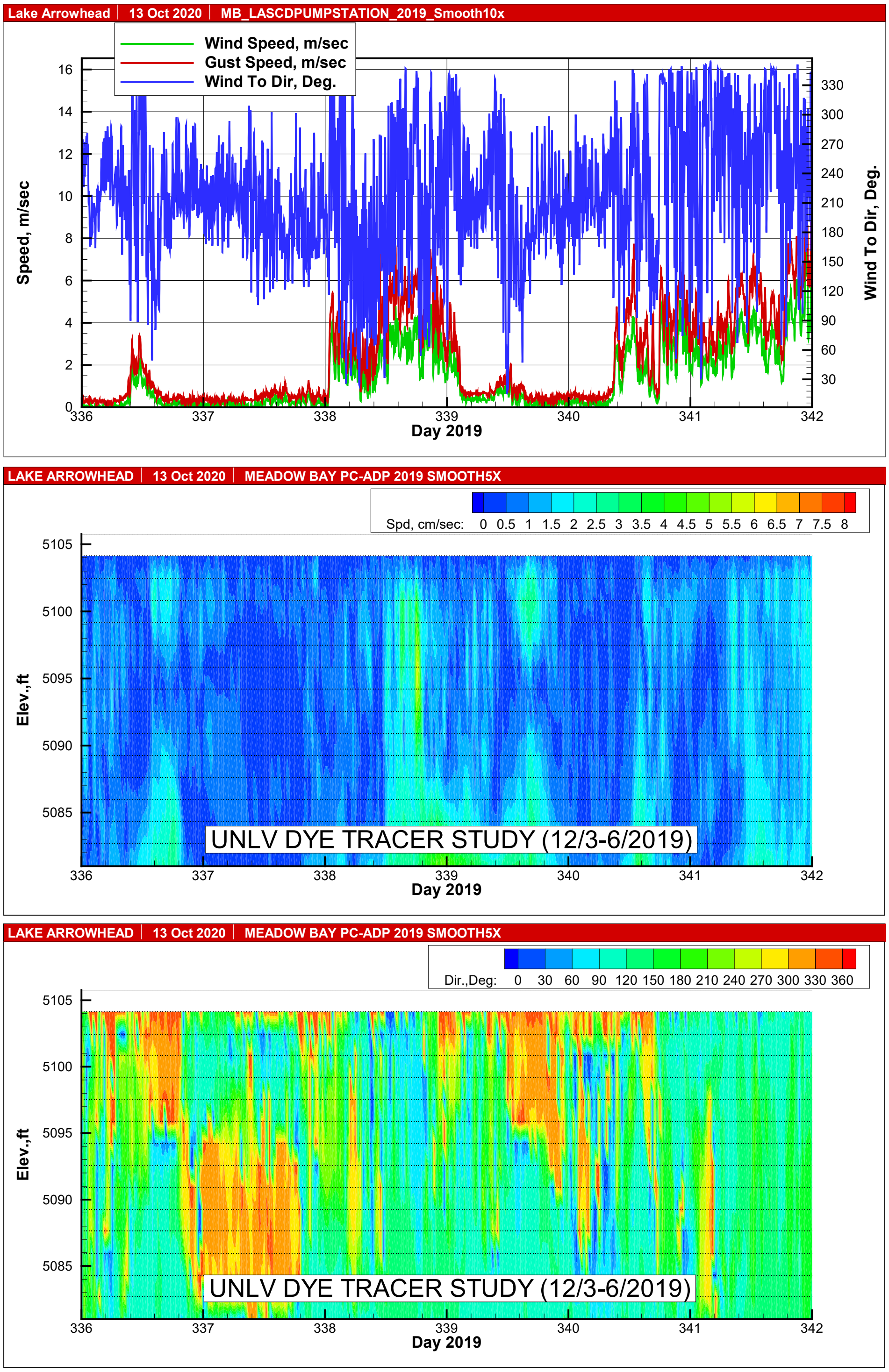

Figure 9. Plots of PC-ADP current speed and direction contour plots for data collected during the UNLV Dye Tracer Study days 337-341 (December 3 - 7, 2019). The Meadow Bay wind speed and direction (toward) data for the same time period are included in the top plot. The current direction contours show flow reversals near the reservoir surface on days 336, 338 339 and 340 and bottom on days 337 and 341. Likewise, the current speed contours show a circulation forms when the wind speed increases during the high wind events on days 338 and 341.

ADP Signal Amplitude Analyses

ADP signal strength amplitudes can provide an indication of the suspended particle density and distribution in the water column at the time of each profile measurement. The signal amplitude unit is in counts which can range from 0 to 255 counts. Particles can be suspended sediments, organic matter, or fish. There is no simple way to differentiate the composition or size of the particles. However, signal amplitudes can be used to identify suspended particle events that occur in the water column in Meadow Bay or the mid-lake sites. Signal amplitudes were measured for each depth cell in the three acoustic beams. The depth cell signal amplitudes for each beam were averaged to obtain the values used in this analysis.

As an example, figures 10 and 11 show the of signal amplitude profiles collected during the UNLV dye tracer study at Meadow Bay and mid-lake profiling sites, respectively. These contour plots of signal amplitude indicate there were more significant events at Meadow Bay where suspended particles increase throughout most of the water column during the storm events. In contrast, most of the higher signal amplitudes at the mid-lake location were confined to the lower half of the water column. It is likely the increase in signal amplitudes in Meadow Bay were related to increased inflows from Grass Valley tunnel (see figure 3) and higher inflow turbidities. At the mid-lake site, signal amplitudes increased closer to the reservoir bottom during the winter storm event of December 3-5, 2019 which may indicate a density current of sediment laden water coming from stormwater inflow or particles resuspended from the reservoir bottom.

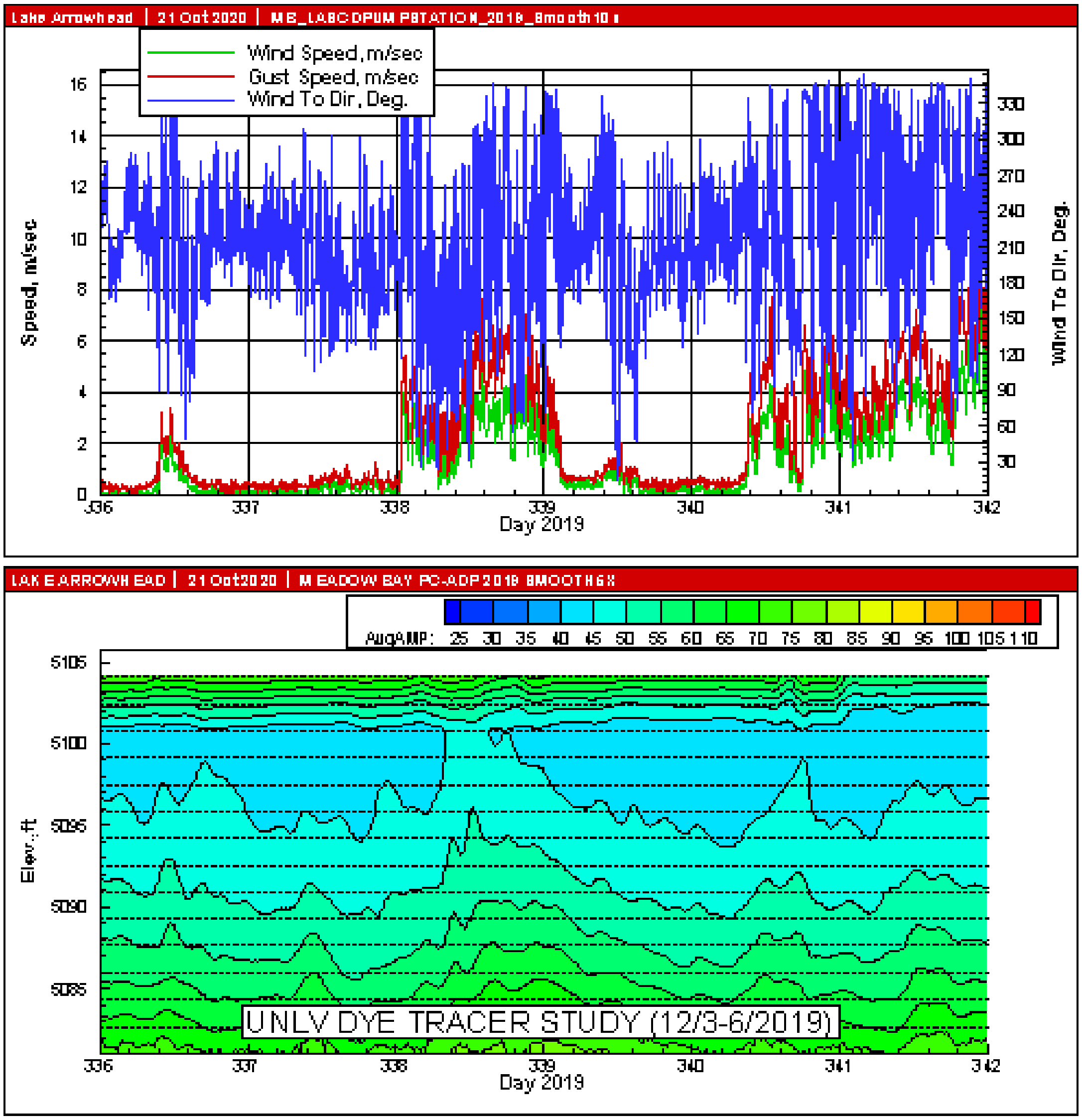

Figure 10. Plots showing six days of wind speed data and signal amplitude contours at the Meadow Bay PC-ADP site. Signal amplitudes increased through most of the water column during the winter storm event of December 4, 2019 (day 338) and again on December 6 (day 340).

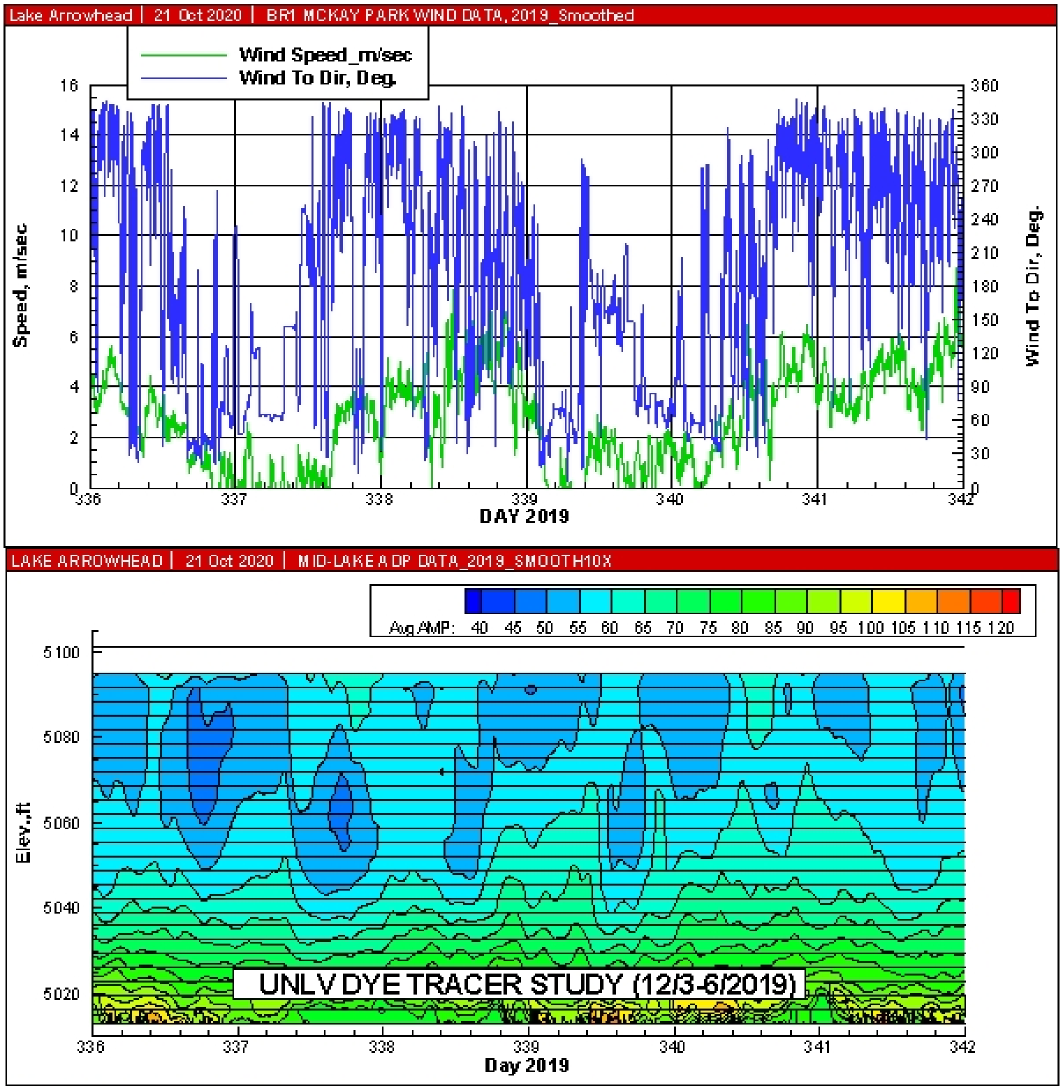

Figure 11. Plots showing six days of wind speed data and signal amplitude contours at the mid-lake ADP site. Signal amplitudes increased closer to the reservoir bottom during the winter storm event of December 3-5, 2019 (day 337-339) which may indicate a density current of sediment-laden water or particles were suspended from the reservoir bottom.

Analysis of Temperature Profiling Sites

A detailed analysis of the vertical temperature profiles collected at Lake Arrowhead was not included in the scope of work for the technical assistance to UNLV. However, temperature profile data were processed to aid in the visualization of Lake Arrowhead's thermal stratification over the course of the study. A brief presentation of the vertical temperature profile data that supplements the ADP date presented earlier will be covered in this section.

Mid-Lake Vertical Temperature Profiles

Mid-Lake temperature profiles were collected every 5 minutes between April 24, 2019 and January 31, 2020. However, profile data were interrupted when the surface buoy sunk on July 7, 2019 and the profiling string was dropped to the lake bottom. The profiling string was re-deployed on September 26, 2019. A total of 57,660 temperature profiles were collected over the 201-day deployment. For this report, mid-lake temperature profiles collected between April 24, 2019 and January 11, 2020 will be briefly discussed.

High-resolution temperature profiling data are useful for understanding the current dynamics in a reservoir or lake. These temperature profile data, along with the wind data from a nearby weather station (Tavern Bay, BR3) allows the analysis of seiches and wind mixing events during high wind events. Even though mid-lake ADP data were not collected from late April to September 26, 2019 the mid-lake temperature profiles (when available) can be used to infer surface currents and seiches generated by strong wind events.

Figure 12 shows the complete 2019 temperature profile record for the mid-lake site and the time periods of lost data. Note: the black horizontal lines are the temperature sensor depths. The temperature contours illustrate the onset of strong thermal stratification which begins around June 6th (day 157). In early July (around day 185) the thermal stratification stabilized with an epilimnion thickness of 7.5 meters with a temperature of 20.2°C. When the profiling string was re-deployed in late September the epilimnion had increased to 11.5 meters thick with an average temperature of 19.1°C. Throughout autumn, the thermal stratification slowly broke down until about the end of November (day 332) when the thermocline rapidly dissipated during a strong wind event – sustained 10 m/sec wind from the north.

Figure 13 shows a 1-day period for calendar day 186 (July 5, 2019) which helps to visualize the how a sustained wind to the NNW does little to change the stable thermal stratification at the mid-lake profiling site. This high-resolution temperature profile data shows the epilimnion warms from 19.9 to 20.4°C during the wind event with speeds up to 6 m/sec. However, the wind event creates no discernable displacement of the thermocline.

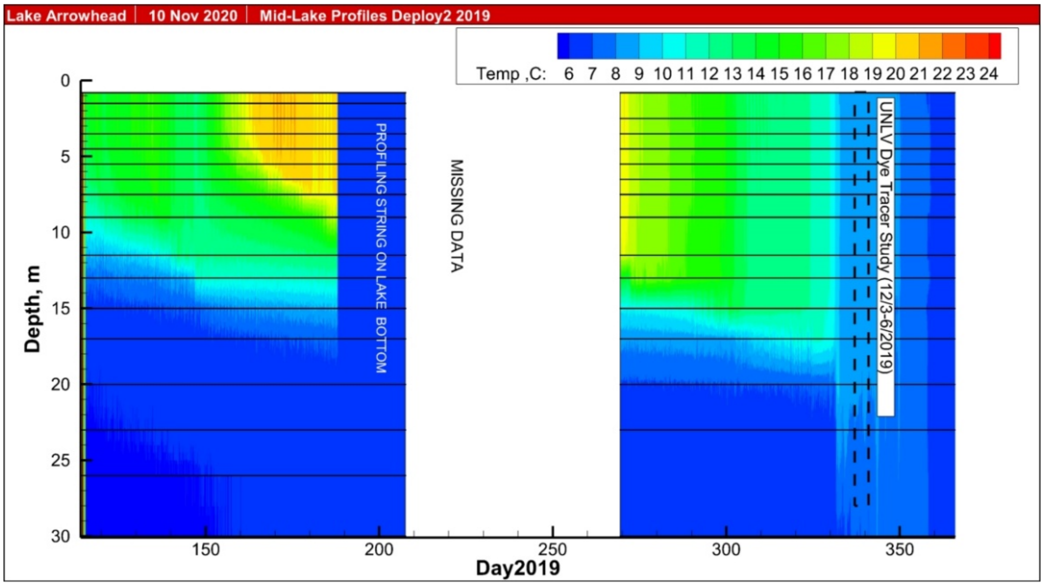

Figure 12. Water temperature profiles measured near the mid-lake ADP site. The temperature contours illustrate the strong thermal stratification which begins around June 6th (day 157). Near the end of November (day 332) the thermal stratification begins to break down after a strong wind event.

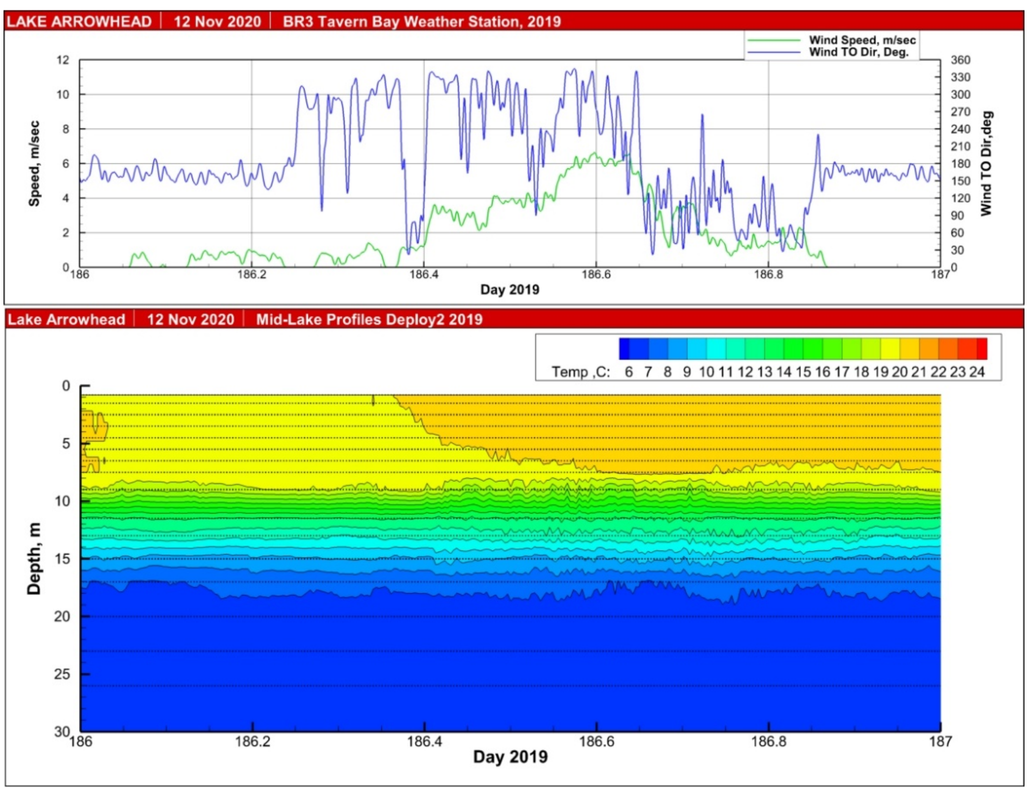

Figure 13. Plots of mid-lake temperature profile contours for calendar day 186 (July 5, 2019). The Tavern Bay (BR3) wind speed and direction (toward) data for the same time period are included in the top plot. The temperature profiles show that the wind toward the NNW warms the surface water at the mid-lake location but has no discernable impact on the stability of the thermocline.

Figure 14 shows a plot of temperature profile contours during the UNLV dye tracer study in early December 2019. The Tavern Bay (BR3) wind speed and direction (toward) data for the same time period are included in the top plot. The temperature profiles show that when the wind speed increases (day 338) the epilimnion is mixed to a depth of 20 meters but the weak thermal stratification from 20 to 30 meters remains unaffected. It is interesting to note that there is a short period of time when cool water (6.8°C) shows up near the reservoir bottom (as detected by the logger at 30 meters depth) on December 4, 2019 (day 338) around 1:00 pm. This could be the same cool water underflow related to the releases from the Grass Valley Lake tunnel or other ungauged inflows. According to UNLV's instream temperature logger the inflow water temperature was about 3°C when the inflow peaked at 30 CFS (see figure 3).

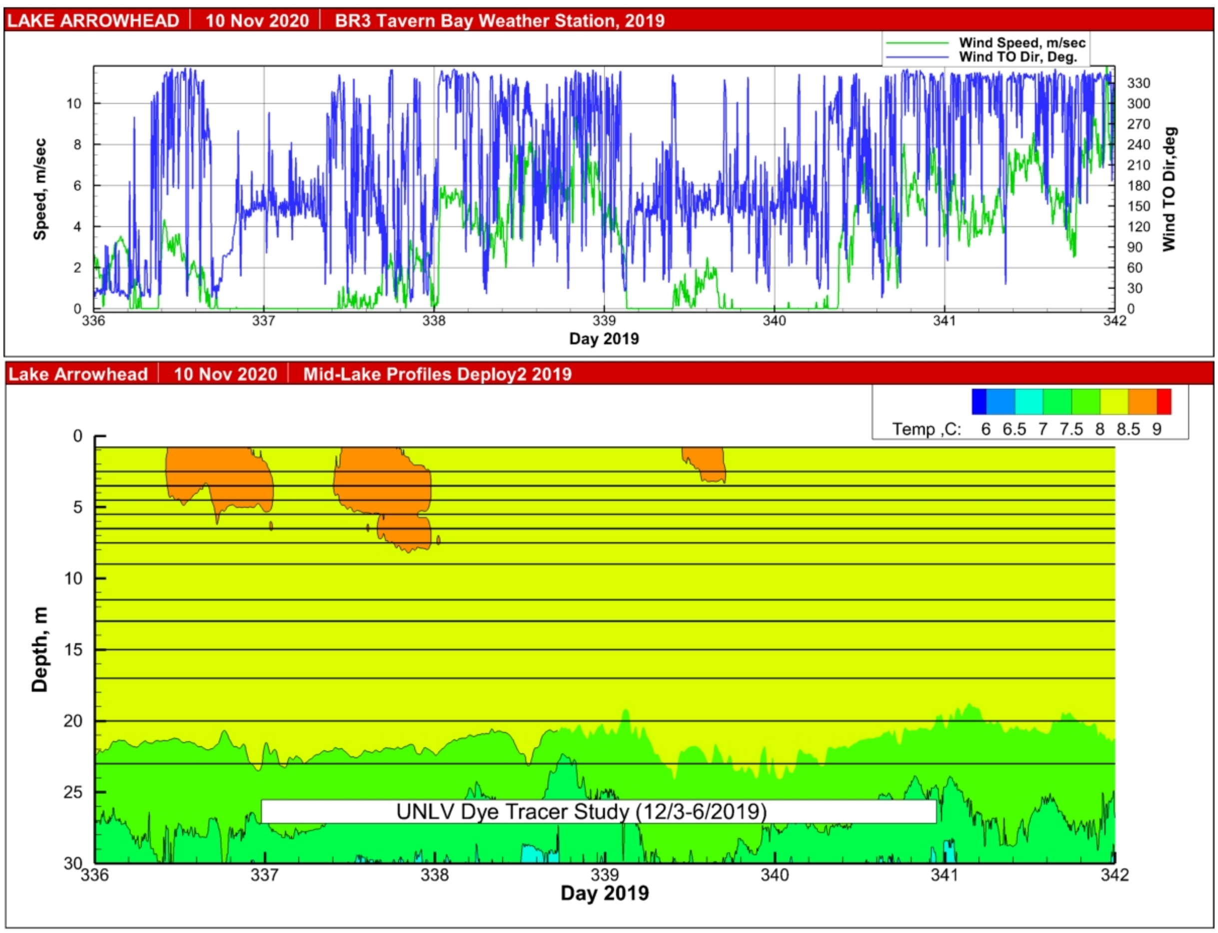

Figure 14. Plots of mid-lake temperature profile contours during the UNLV dye tracer study December 2-7, 2019. The Tavern Bay (BR3) wind speed and direction (toward) data for the same time period are included in the top plot. The temperature profiles show that when the wind speed increases there is some mixing in the surface layer, but the thermal stratification is not completely broken down. The cool water measured near the bottom on day 338.6 could be an underflow produced by Grass Valley Lake Tunnel inflows or other inflows.

Meadow Bay Vertical Temperature Profiles

Meadow Bay temperature profiles were collected continuously (every 5 minutes) between April 24, 2019 and January 11, 2020. A total of 75,320 temperature profiles were collected for this 263-day deployment. For this report, Meadow Bay temperature profiles collected between April 24, 2019 and January 11, 2020 will be briefly discussed.

Figure 15 shows the complete 2019 data record for the Meadow Bay site. The temperature contours illustrate the relatively weak thermal stratification which begins around June 1st (day 152). Later in the summer the water column at the Meadow Bay site is primarily in the epilimnion or the well-mixed surface layer.

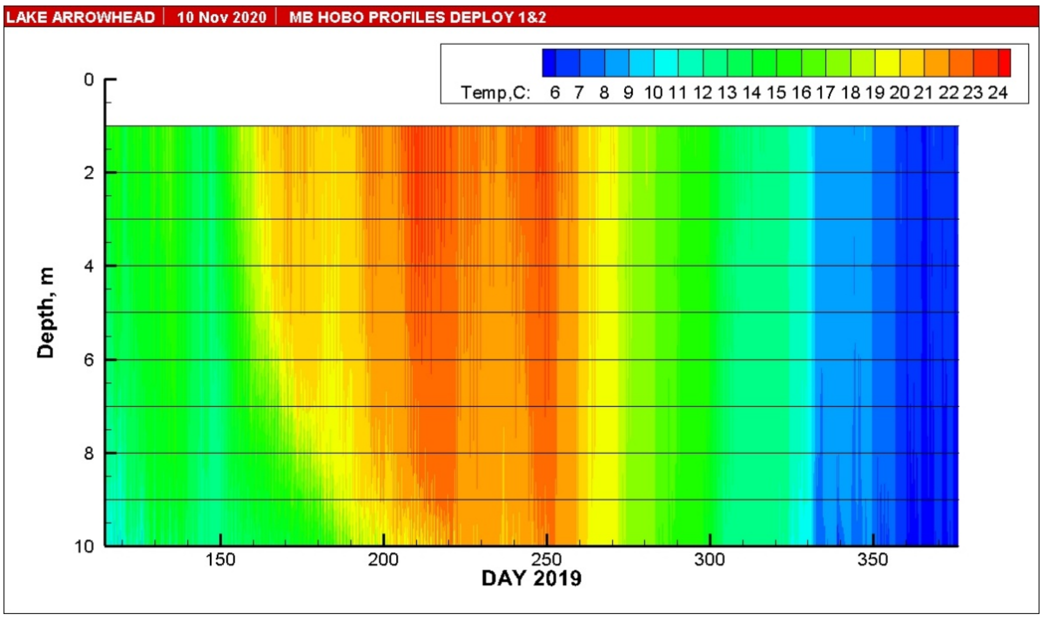

Figure 15. Water temperature profiles measured at the Meadow Bay PC-ADP site. The temperature contours illustrate the weak thermal stratification which begins around June 1st (day 152). Later in the summer the entire water column at the Meadow Bay site is within the epilimnion, or the well-mixed surface layer.

Figure 16 shows a 1-day period for calendar day 186 (July 5, 2019) which helps to visualize the how a sustained wind to the north changes the thermal stratification at the Meadow Bay site. This high-resolution temperature profile data shows warm surface water moving into the Meadow Bay that creates a stronger stratification in the surface layer as a cooler water layer moves in near the reservoir bottom. When the wind subsides, the unstable temperature gradient returns to a weakly stratified condition as the cooler water flows away from the Meadow Bay temperature profiling site. The change in the temperature stratification at this site agrees with the PC-ADP current speed and direction as presented in figure 8. For example, when cooler water moves along the reservoir bottom the current direction changes from southeast to northwest and back to southeast.

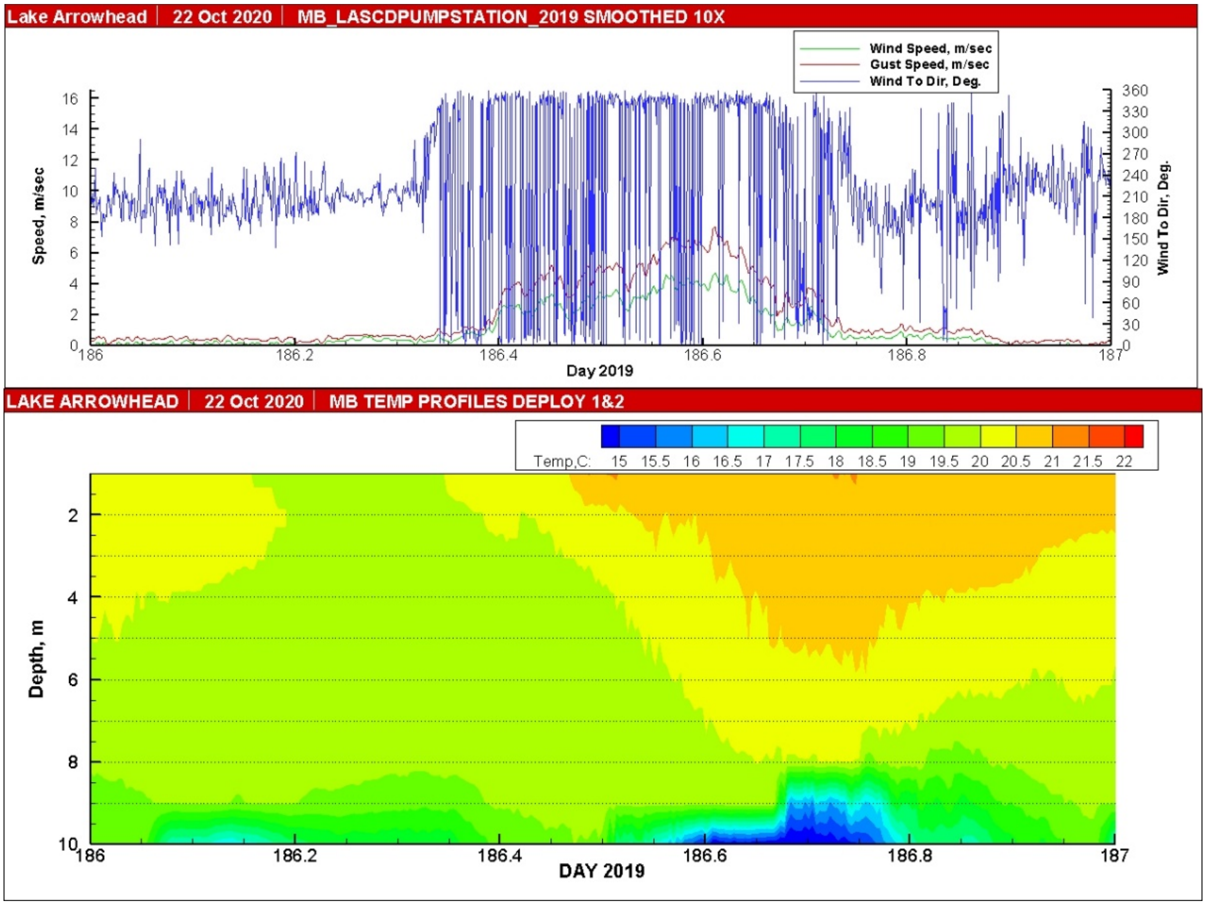

Figure 16. Plots of temperature profile contours for calendar day 186 (July 5, 2019). The Meadow Bay wind speed and direction (toward) data for the same time period are included in the top plot. The temperature profiles show that the wind toward the north creates a current that moves warm surface water into Meadow Bay and cooler water moves in near the bottom.

Figure 17 shows a plot of temperature profile contours during the UNLV dye tracer study in early December 2019. The Meadow Bay wind speed and direction (toward) data for the same time period are included in the top plot. The temperature profiles show that when the wind speed increases (day 338) the weak thermal stratification breaks down. The cool water that shows up near the reservoir bottom on December 4, 2019 (day 338) is a cool water underflow related to the releases from the Grass Valley Lake tunnel. According to UNLV's instream temperature logger the inflow water temperature was about 3°C when the inflow peaked at 30 CFS (see figure 3).

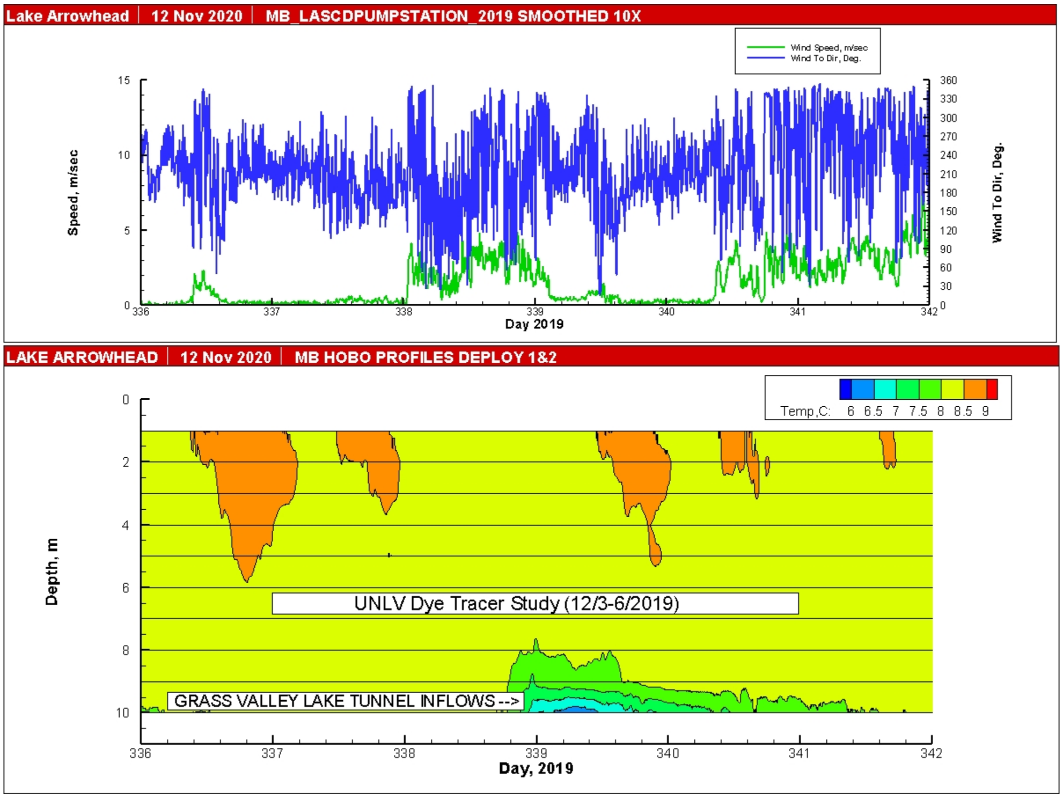

Figure 17. Plots of temperature profile contours during the UNLV dye tracer study in early December 2019. The Meadow Bay wind speed and wind direction (toward) data for the same time period are included in the top plot. The temperature profiles show that when the wind speed increases on day 338 weak thermal stratification was broken down (orange 8.5-9°C surface water shifts to yellow 8-8.5°C water). The cool water measured near the bottom on days 338-339 is likely an underflow produced by Grass Valley Lake Tunnel inflows (and possibly other ungaged inflow) which were about 3°C (see figure 3).

Conclusions and Recommendations

Two acoustic Doppler profilers were successfully deployed in Arrowhead Lake and collected continuous velocity profiles from late spring through late fall 2019. This current profile data will be useful for ground-truthing supporting data like nearby wind speed and direction and vertical temperature profiles.

The mid-lake ADP velocity profiles illustrated very weak reservoir currents within the hypolimnion during periods of strong thermal stratification. This observation was supported by mid-lake vertical temperature profile data that showed a very stable thermocline throughout the summer months. There were periods when currents were below the threshold where the ADP could accurately resolve water currents (1 to 2 cm/sec) because of the random acoustic noise that is inherent with the ADP signal processing. Using a PC-ADP instead of an ADP would allow for these low currents to be measured accurately.

Mid-lake ADP measurements were impacted by compass calibration problems. However, this only affects the current direction measurements with respect to magnetic north. A compass correction was applied in an attempt to correct the uncalibrated readings. The relative current direction data can provide information on flow reversals and overall circulation patterns in the reservoir. Measurements of current speed profiles were not affected and should provide a good indication the vertical current distribution throughout the water column. If future studies are warranted, it is recommended that the outdated Sontek 500 kHz ADP be replaced with a newer model with a fully functional compass.

Future deployments at a mid-lake location should be made with the assistance of divers to make sure the ADP is oriented properly and does not sink into the bottom sediment layer.

The Meadow Bay PC-ADP collected velocity profiles for almost 9 months without any issues. However, the location was too shallow to measure currents in the thermocline and hypolimnion during periods of strong thermal stratification because the epilimnion was thicker than the 9-meter depth at the deployment location.

The Meadow Bay PC-ADP velocity profiles illustrated periods of circulation (mixing) in the epilimnion in response to frequent mid-afternoon wind events. This observation was supported by vertical temperature profiles which showed seiching during the daily wind events.

If future ADP measurements are to be collected in Lake Arrowhead, it is recommended that high-resolution vertical temperature profiles be collected in close proximity to the ADP sampling sites to providing supporting data on currents which may be too weak to be measured accurately using the ADP, as well as, changes in lake stratification due to seiching events. The PC-ADP is capable of measuring much slower currents, but it is still prudent to have both sets of vertical temperatures profile data when interpreting velocity profile data.

Appendix 1

Configuration Parameters for Mid-Lake ADP Deployment

Filename ---------------------> LKARW007.ctl
File Size --------------------> 6313646 bytes
Number of profiles -----------> 14283
Time of first profile --------> 2009/08/13 15:17:12
Time of last profile ---------> 2010/01/09 09:47:09

ADP Hardware Configuration

CPUSoftwareVerNum ------------> 5.8
DSPSoftwareVerNum ------------> 4.0
BoardRev ---------------------> D
SerialNumber -----------------> C34
AdpType ----------------------> 500 kHz
Nbeams -----------------------> 3
BeamGeometry -----------------> 3_BEAMS
Slant Angle ------------------> 25.0 deg
Sensor Orientation -----------> UP
Compass Installed ------------> YES
Recorder Installed -----------> YES
Temperature Installed --------> YES
Pressure Installed -----------> YES
Pressure Offset --------------> -1.949000 dbar
Pressure Scale ---------------> 0.002436 dbar/count
Pressure Scale 2 -------------> 0.000000 pdbar/c^2
Ext Sensor Installed ---------> NO
Ext Pressure Sensor Installed > NONE
CTD Sensor Installed ---------> NO
Transformation Matrix

1.577	-0.789	-0.789
0.000	-1.366	1.366
0.368	0.368	0.368

ADP User Setup

Default Temperature ----------> 15.00 deg C
Default Salinity -------------> 0.10 ppt
Default Speed of Sound -------> 1465.20 m/s
No. of Cells -----------------> 30
Cell Size --------------------> 1.00 m
Blank Distance ---------------> 1.00 m
Sensor Depth -----------------> 0.00 m
Temperature Mode -------------> MEASURED

Averaging Interval -----------> 300 s
Profile Interval -------------> 900 s
Ping Interval ----------------> 0.00 s
Burst Mode--------------------> DISABLED
Burst Interval ---------------> 1200 s
Profiles per Burst -----------> 1
Coordinate System ------------> ENU
Pulse Coherent Mode ----------> NO
Bottom Track -----------------> NO
Magnetic Declination ---------> 0.00
Out Mode ---------------------> AUTO
Out Format -------------------> ASCII
Recorder Enabled -------------> ENABLED
Recorder Mode ----------------> NORMAL
Deployment Mode --------------> ON
Deployment Name --------------> LKARW
Deployment Start Date/Time ---> 2009/08/13 15:17:09

Configuration Parameters for Meadow Bay PC-ADP Deployment

Filename ---------------------> LAHMB003.ctl
File Size --------------------> 2666738 bytes
Number of profiles -----------> 7983
Time of first profile --------> 2019/04/24 12:09:32
Time of last profile ---------> 2019/08/13 08:49:29

ADP Hardware Configuration

CPUSoftwareVerNum ------------> 17.4
DSPSoftwareVerNum ------------> 4.0
BoardRev ---------------------> F
SerialNumber -----------------> H33
AdpType ----------------------> 1500 kHz
Nbeams -----------------------> 3
BeamGeometry -----------------> 3_BEAMS
Slant Angle ------------------> 15.0 deg
Sensor Orientation -----------> UP
Compass Installed ------------> YES
Recorder Installed -----------> YES
Temperature Installed --------> YES
Pressure Installed -----------> YES
Pressure Offset --------------> -2.171380 dbar
Pressure Scale ---------------> 0.000478 dbar/count
Pressure Scale 2 -------------> -44.000000 pdbar/c^2
Ext Sensor Installed ---------> NO
Ext Pressure Sensor Installed > NONE
CTD Sensor Installed ---------> NO
Transformation Matrix

2.576 -1.288 -1.288
0.000 -2.230 2.230
0.345 0.345 0.345
ADP User Setup

Default Temperature ----------> 20.00 deg C
Default Salinity -------------> 0.00 ppt
Default Speed of Sound -------> 1481.60 m/s
No. of Cells -----------------> 18
Cell Size --------------------> 0.50 m
Blank Distance ---------------> 0.50 m
Sensor Depth -----------------> 0.00 m
Temperature Mode -------------> MEASURED
Averaging Interval -----------> 240.0 s (300s for 2nd Deployment)
Profile Interval -------------> 1200.0 s (1800s for 2nd Deployment)
Ping Interval ----------------> 0.00 s
Burst Mode--------------------> DISABLED
Burst Interval ---------------> 1200 s
Profiles per Burst -----------> 1
Coordinate System ------------> BEAM
Pulse Coherent Mode ----------> YES

Pulse Coherent Setup:
Pulse length --- (m) ------> 1.00
Max range ----------- (m) ------> 9.55
User Prof Lag ------- (m) ------> 9.00
System Lag ---------- (m) ------> 10.71
MaxVertVel (ProfLag) - (m/s) ----> 0.03
MaxHorizVel (ProfLag) -(m/s) ----> 0.13
User Res Lag --------- (m) ------> 4.00
System Res Lag ------- (m) ------> 4.01
MaxVertVel (ResLag) -- (m/s) ----> 0.09
MaxHorizVel (ResLag) - (m/s) ----> 0.35
MinCorrLevel --------- (%) ------> 25

Bottom Track -----------------> NO
Magnetic Declination ---------> 0.00
Out Mode ---------------------> AUTO
Out Format -------------------> ASCII
Recorder Enabled -------------> ENABLED
Recorder Mode ----------------> NORMAL
Deployment Mode --------------> ON
Deployment Name --------------> LAHMB
1st Deployment Start Date/Time ---> 2019/04/24 12:00:00
(2nd Deployment Start Date/Time ---> 2019/08/13 10:02:01)