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Hydraulic Laboratory Technical Memorandum, PAP-1188

Clark Canyon Reservoir - Acoustic Doppler Profiling Data Collection and Preliminary Analysis, 2017-2018

East Bench Unit, Montana, Pick-Sloan Missouri Basin Program

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

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Purpose

The purpose of the acoustic Doppler profiling in Clark Canyon Reservoir was to support a reservoir water quality study to determine the source and fate of turbidity plumes in the reservoir. An acoustic Doppler profiler (ADP) was deployed near the outlet works intake structure to gain an understanding of surface currents and outlet works withdrawal zone hydraulics during periods of thermal stratification for 2017 and 2018. The ADP data sets will provide information to develop an understanding of the transport of turbidity plumes to the reservoir outlet along with evaluating strong wind events on measured reservoir current profiles.

Introduction

Clark Canyon Dam was constructed at the head of the Beaverhead River from 1961 through 1964. The zoned earth-fill dam has a structural height of 147.5 ft and a crest length of 2,950 ft. The reservoir has a maximum storage capacity of 325,324 acre-ft at full pool elevation, 5,571.9 ft. The spillway structure consists of an approach channel, concrete inlet channel, ungated concrete crest, concrete chute, concrete stilling basin, and an outlet channel. The outlet works, shown in figure 1, consists of an approach channel; concrete intake structure; concrete conduit; a gate chamber with high-pressure gates, two of which serve for emergency closure and are upstream of the regulating gates. Both sets of gates are rectangular slide gates and are 36 inches wide by 78 inches high. The outlet works capacity is about 2,300 ft^3/sec at reservoir water surface elevation 5,547 ft.

Figure 1. Photographs of Clark Canyon Dam and Reservoir.

Methods and Materials

In 2017 and 2018 the Technical Service Center's Hydraulic Investigations & Laboratory Services Group (86-68560) deployed a Sontek ADP in Clark Canyon Reservoir near the river outlet works intake structure. The ADP measurements are part of a larger water quality monitoring project being conducted by the Montana Department of Environmental Quality (MT DEQ) and Reclamation's TSC. The GPS coordinates for the ADP site are: N 44.99878° W 112.86109°. The approximate bottom elevation of the site is 5452 ft and the outlet work intake approach channel is at El. 5454.5 ft. Figure 2 is an aerial photograph with the monitoring site locations discussed in this report.

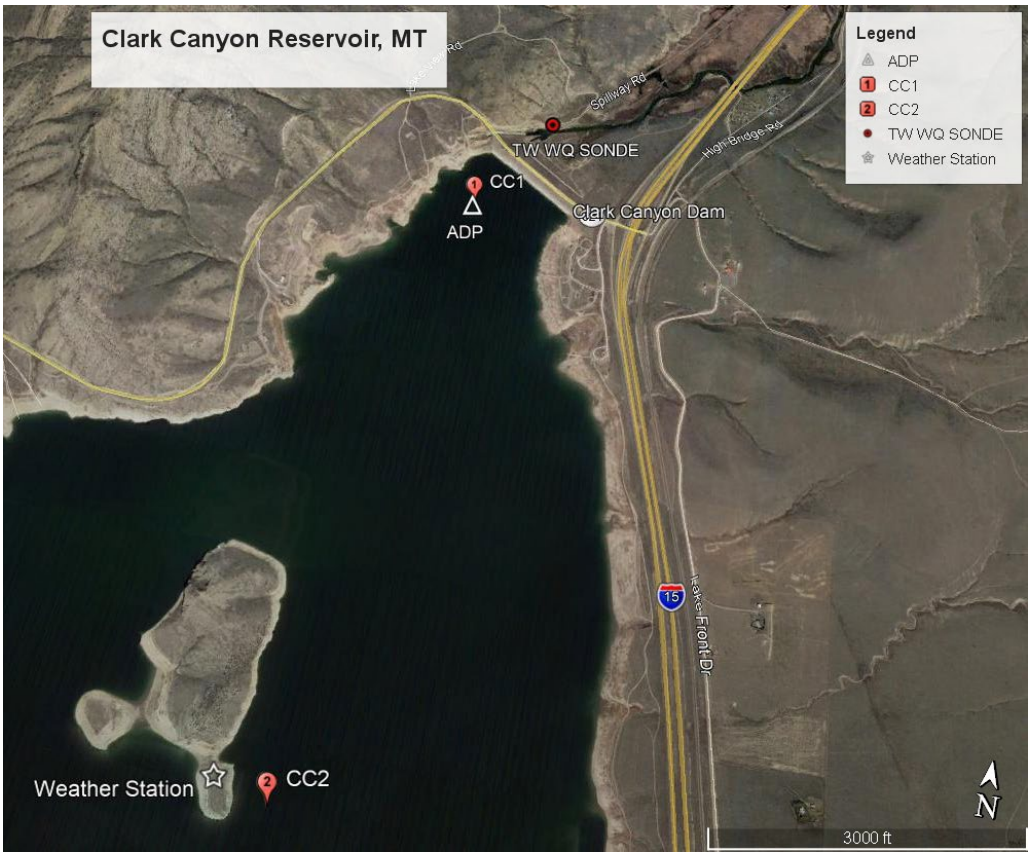


Figure 2. Aerial photograph with the monitoring site locations discussed in this report.

Acoustic Doppler Profiling

2017 field season

The Sontek ADP was initially deployed in Clark Canyon Reservoir on June 27, 2017 and it was removed on September 30, 2017. A test deployment was used to make sure the ADP configuration was optimized for the reservoir conditions. On the morning June 28, 2017 the ADP was removed for a data download and a

cursory review. The ADP was working normally and was re-deployed for 30 days of current profiling. On July 27, the ADP was pulled for service and a data download. The ADP made a single profile measurement and shut down. A Sontek technical support engineer identified the problem as a "2011 clock bug" where the ADP's internal clock gets reset to a default value when the ADP enters AutoSleep mode if the year is later than 2011 (2017 in this case). This bug didn't happen for the overnight test because profiles were being collected continuously and the AutoSleep feature was deactivated for this data collection configuration. Sontek's support engineer suggested the ADP clock be set to a 1995 date and turn the AutoSleep feature off. This configuration was successful, and the ADP worked properly for the second deployment from July 27 to September 23, 2017.

For the 2017 field season, a 500 kHz Sontek ADP was set up to collect 25 depth cells with a 1.06 m cell size. The ADP was configured for an uplooking deployment in a depth of 27.5 meters (90 ft). The profiling schedule was to collect profiles for 300 seconds, then to power down for 600 seconds and repeat. This resulted in a velocity profile averaged over 5 minutes collected every 15 minutes. 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 deployment configuration is in Appendix 1.

A total of 5,565 velocity profiles were collected for this 57-day deployment. For this report, ADP data collected between July 27 and September 23, 2017 will be analyzed and presented.

It is important to note that the ADP's compass calibration utility failed to complete the calibration process for the 2017 deployments. The compass offset was estimated by comparing near surface current directions during sustained high wind events (speeds greater than 10 m/s). This technique is less than ideal but it was the only option available for this data set. The approximate compass offset was estimated to be -122°. It is important to note that while the current direction may have an offset, the relative current direction during any single profile is unaffected by the compass offset.

At the completion of the 2017 field season Sontek technical support was contacted about a compass repair or replacement. The Sontek engineer said our ADP was too old to repair or upgrade because the electronics were obsolete. They suggested taking a field measurement of the compass offset prior to each deployment.

2018 field season

For the 2018 field season, the ADP was redeployed in the same CC1 location with the following configuration parameters. The ADP was configured for an uplooking deployment in a depth of 28 meters (92 ft). The profiling schedule was to collect profiles for 300 seconds, then to power down for 1800 seconds and

repeat. The profiling schedule was changed to extend the battery life to 150 days. This resulted in a velocity profile averaged over 5 minutes collected every 30 minutes. During the August 14, 2018 field visit to replace the batteries, the profiling schedule was to average profiles for 300 seconds, then to power down for 900 seconds and repeat. This resulted in a velocity profile averaged over 5 minutes collected every 15 minutes. The profiling schedule was changed to maximize the number of profiles collected over the remaining field season.

The ADP was initially deployed in Clark Canyon Reservoir on May 22, 2018 and it was removed on October 11, 2018. The GPS coordinates for the ADP profiling site was N44.99878°, W112.86109°. The ADP bottom elevation was measured to be El. 5455.1 ft. The ADP was retrieved on August 14 to replace the batteries and was reset on the reservoir bottom at elevation 5459.3 ft.

It is important to note that the ADP's compass failed to complete the calibration process prior to both 2018 deployments. An approximate compass offset was determined by orientating the ADP to the north and noting the compass reading. For the first deployment the compass offset was measured to be -102° and the second deployment the offset was -68°. These offsets include the local magnetic declination which was12.5° east. These compass offsets were applied to the ADP current direction data during the post processing.

Weather Station

MT DEQ established a weather station on an island in Clark Canyon reservoir. The GPS coordinates for the Clark Canyon weather station shown on figure 2 are: N 44.9798°, W 112.8671°. The weather station was equipped with the following sensors: PAR (photosynthetically active radiation), wind speed and direction, wind gust speed, rainfall, dew point, relative humidity, and air temperature. The sampling interval for the weather data was every 15 minutes. Weather data for the periods of ADP data collection was obtained from the Montana DEQ weather station website. Clark Canyon Reservoir weather station data were collected from June 1 until September 24, 2017. Likewise, the weather station collected data from May 31 through October 11, 2018.

Vertical Temperature Profiles

2017 Field Season

Montana DEQ deployed two temperature profiling buoys in Clark Canyon Reservoir to collect high-resolution vertical temperature profiles. Water temperature profiles were collected every 30 minutes from May 24 to October 11, 2017. One of the profiling buoys (CC1) was located near the ADP site. The other site (CC2) was located mid-lake (see figure 2). The GPS coordinates for the two temperature profiling buoys are: CC1 – N 44.99901°, W 112.86105°, and CC2 – N 44.97942°, W 112.86494°. Both temperature profiling strings were equipped

with HOBO Tidbit temperature loggers with a 1 meter vertical spacing. Temperature string CC1 had 24 loggers and CC2 had 18 loggers. However, 3 loggers from the CC1 temperature string were lost and not recovered.

2018 Field Season

Montana DEQ deployed two temperature profiling buoys in Clark Canyon Reservoir to collect high-resolution vertical temperature profiles. Profiles were collected every 15 minutes from May 30 to October 11, 2018. Profiling buoy CC1 was located near the ADP site. The other profiling site (CC2) was located mid-lake. The GPS coordinates for the two temperature profiling buoys are: CC1 – N 44.99901°, W 112.86105°, and CC2 at N 44.97942°, W 112.86494°. Both temperature profiling strings were equipped with HOBO Tidbit temperature loggers with a 1 meter vertical spacing. Temperature string CC1 was equipped with 27 loggers and the string at CC2 had 22 loggers. additional loggers were added in 2018 to cover the forecasted higher reservoir elevation. No loggers were lost in 2018.

Water Quality Sondes

2017 Field Season

Montana DEQ deployed two YSI/EXO2 water quality sondes in Clark Canyon Reservoir at sites CC1 and CC2 to collect high-resolution water quality readings near the water surface and reservoir bottom. The two WQ sondes were located about 1 meter from the surface and bottom. The WQ sondes collected readings every 15 minutes from May 22 to October 11, 2017. The WQ parameters included pH, turbidity, water temperature, specific conductance, chlorophyll A, dissolved oxygen, and water depth. The GPS coordinates for the two temperature profiling buoys are: CC1 – N 44.99134°, W 112.86047°, and CC2 – N 44.97878°, W 112.85807°. At CC1 the near bottom sonde was at El. 5434 ft which is about 20 ft below the intake elevation, El. 5455.0 ft. Similarly, at CC2 the near bottom sonde was at El. 5484.2 ft which is about 50 ft above the CC1 bottom sonde elevation. A third WQ sonde was deployed in the Beaverhead River below Clark Canyon Dam, also known as the tailwater WQ site (figure 2). The tailwater WQ sonde was located on the left bank about 190 ft downstream from the outlet works. The GPS coordinates for the tailwater WQ site are: N 45.00263° and W 112.85789°.

2018 Field Season

Montana DEQ deployed two YSI/EXO2 water quality sondes in Clark Canyon Reservoir at site CC1 and the Beaverhead River tailwater site. The WQ sondes at CC1 were located about 1 meter from the surface and bottom. The tailwater WQ sonde was moved from the left to right bank and was about 160 ft downstream from the outlet works. The GPS coordinates for the tailwater WQ site are: N45.00246° and W112.85786°. At CC1 the near bottom sonde was at El. 5460.0 ft which is about 5.0 ft above the intake elevation, El. 5455.0 ft. Note: the near-bottom WQ sonde is located above the intake elevation whereas it was 20 ft

below in 2017. The WQ sondes collected readings every 15 minutes from May 30 to October 11, 2018. MT DEQ staff noted there were periods of missing and possibly corrupt data at the CC1 and tailwater WQ sampling sites. From approximately July 31 until August 28, 2018 the CC1 near bottom WQ sonde was recording elevated turbidity values. MT DEQ technicians indicated an intermediate buoy that keeps the sonde 1 m from the reservoir bottom failed which allowed the sonde to periodically contact the bottom sediments. During windy periods, wave action may have caused the bottom WQ sonde to stir up sediments and generate very high turbidity readings. The intermediate buoy was replaced on August 28 to restore flotation and the CC1 bottom turbidity readings returned to more reasonable values. The near surface WQ sonde at CC1 malfunctioned from July 9 until August 28, 2019. The WQ sonde in the Beaverhead River was removed from service from August 15 to August 30, 2018.

It should be noted that the tailwater WQ sonde data for 2017 and 2018 may have been influenced by fisherman wading and launching their drift boats near the sampling site. These impacts were likely reduced in 2018 when the sonde location was moved to the right bank which is opposite from the boat launch.

Water Quality Profiles

Reclamation's TSC collected daily water quality (WQ) profiles at several locations throughout the reservoir including sites CC1 and CC2. The water quality profiles were collected using a Hydrolab water quality sonde. The sonde was equipped with the following sensors: temperature, depth, barometric pressure, specific conductance, pH, turbidity, and dissolved oxygen. Of the several parameters collected, the turbidity profiles were of most interest because they are expected to be strongly correlated to the ADP signal amplitude profiles. During the 2017 field season, WQ profiles were collected almost every day from June 15 to September 30, 2017. For 2018, daily WQ profiling started on August 3 and continued until October 11. When available, CC1 turbidity profile data can be compared with ADP profile data to understand the currents during turbidity events. However, this analysis was beyond this project's scope of work, but was included to document that this data set is available for further analysis.

Clark Canyon Reservoir Operations

For the 2017 and 2018 field seasons, Clark Canyon Reservoir operations data were obtained from Reclamation's Hydromet database using site I.D. CCR. Data collected from the database included: forebay elevation in ft, mean daily computed inflow in CFS, and mean daily total discharge in CFS.

Data Analysis and Results

Reservoir Operations

2017 Field Season

Figure 3 is a plot of the CCR average daily inflow, outflow and reservoir elevation for ADP data collection for calendar days 208 to 266 (July 27 to September 23, 2017). In general, there was a steady decline in the reservoir level (from El. 5535 to 5528 ft), there were periods of small daily reductions in outflows and a few periods of steady outflows. The minimum and maximum outflows were 183 and 667 ft^3/sec, respectively. The reservoir inflows were relatively stable with a few spikes in flow. The minimum and maximum inflows were 120 and 410 ft^3/sec, respectively.

2018 Field Season

Figure 4 is a plot of the CCR average daily inflow, outflow and reservoir elevation for ADP data collection for calendar days 142 to 284 (May 22 to October 11, 2018). In general, there was 35 days of reservoir filling followed by 107 days of steady drawdown of the reservoir level (from El. 5551 to 5537 ft). In general, there was much more flow through Clark Canyon in 2018 when compared to 2017. The minimum and maximum inflows were 150 and 1,324 ft^3/sec, respectively. Likewise, the minimum and maximum outflows were 74 and 800 ft^3/sec, respectively. The reservoir inflows were relatively stable with a few spikes in flow. Reservoir releases into the Beaverhead River were very stable for weeks at a time except for a week in late May where the outflow was reduced from 600 to 300 ft^3/sec.

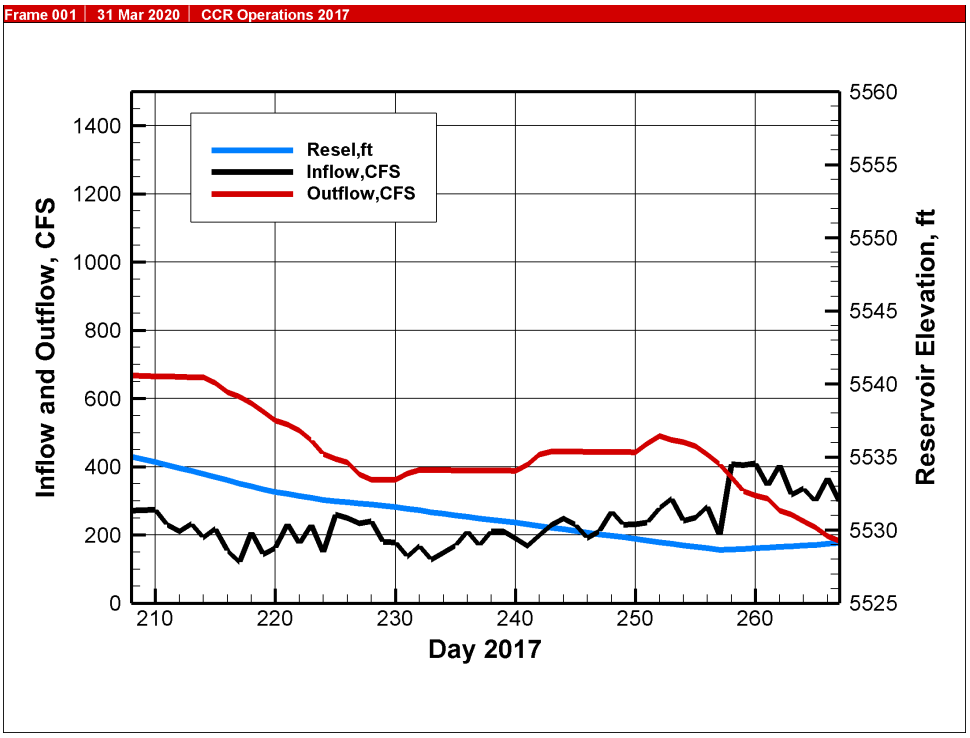


Figure 3. Clark Canyon Reservoir operations during the ADP data collection period for calendar days 208 to 266 (July 27 to September 23, 2017).

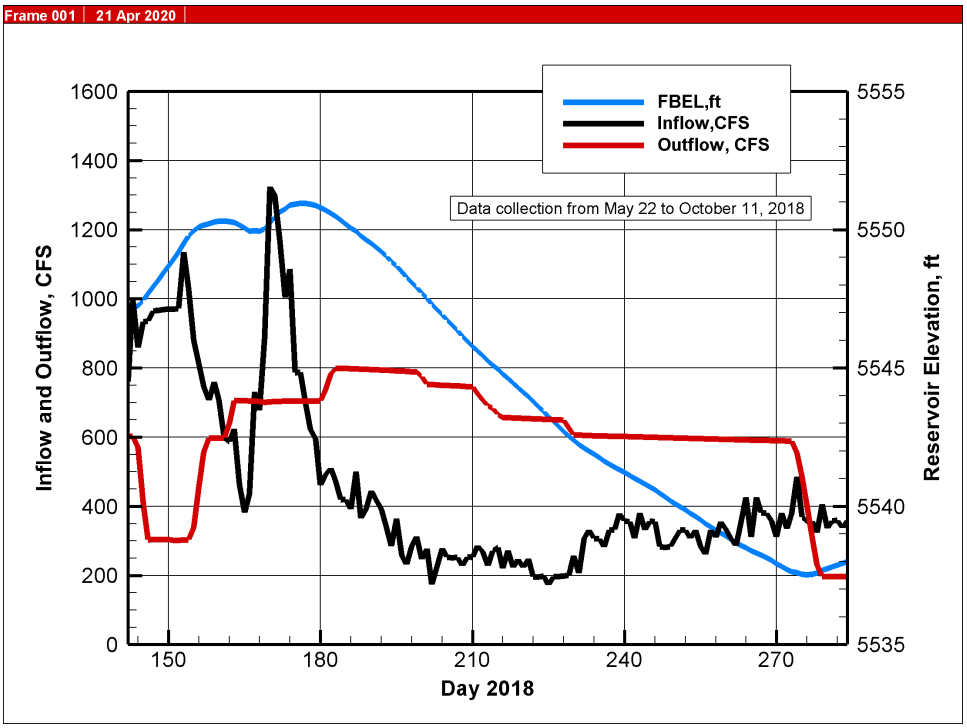


Figure 4. Clark Canyon Reservoir operations during the ADP data collection for calendar days 142 to 284 (May 22 to October 11, 2018).

Clark Canyon Reservoir Wind Data Analysis

For this project, the wind data were analyzed to determine the predominant wind directions for sustained high wind events during the ADP data collection period. For this analysis, wind direction was converted to the direction toward which the wind is blowing to match the convention used for ADP current direction. For example, a sustained north wind toward Clark Canyon Dam should produce surface water currents to the north.

Clark Canyon reservoir's fetch is about 4 miles along a north-to-south axis which is from the dam to the Red Rock River delta. Where fetch is defined as the maximum length of open water over which the wind can blow. Fetch is an important factor in determining the size and energy of waves.

Table 1 and its associated bar chart contains a summary of the 2017 wind direction distributions for the WQ data collection period, from May 23 to September 23, 2017 (this period of record was selected to allow for a direct comparison to the 2018 ADP data set). For sustained wind events (greater than 10 m/sec) the predominant wind direction is towards the S-SW about 33% of the time. Whereas, for periods when the wind speed was between 0-10 m/sec the direction was along the N-NE fetch about 27% of the time. Winds toward the east were also quite common in 2017.

Table 1. Summary of 2017 wind toward direction data from May 23 to September 23, 2017.

Wind TO Dir	0-10 m/s	>10 m/s
N	16%	3%
NE	11%	14%
E	26%	38%
SE	11%	2%
S	10%	3%
SW	12%	30%
W	3%	3%
NW	11%	7%

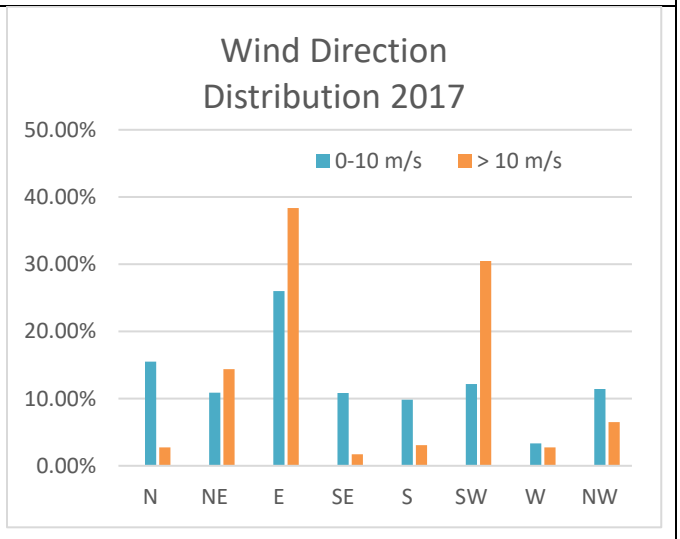
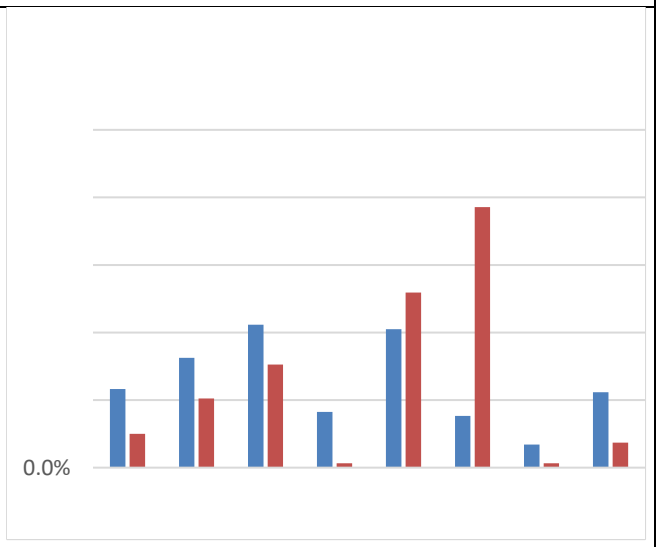


Table 2 and its associated bar chart contains a summary of the 2018 wind direction distributions for WQ data collection period from May 31 to October 11,

2018. For sustained wind events (greater than 10 m/sec) the predominant wind direction is towards the S and to the SW about 26% and 39% of the time, respectively. Whereas, for periods when the wind speed was between 0-10 m/sec the direction was towards N-NE and S-SE 28% and 29% of the time, respectively.

The wind direction patterns are similar for 2017 and 2018 with the predominant wind direction along the S-SW fetch for high wind events. This feature may be an important factor in wave-generated turbidity events along the south shoreline of Clark Canyon reservoir where the Red Rock River delta is located especially in the fall when the more shoreline is exposed as the reservoir is drawn down.

Table 2. Summary of 2018 wind toward direction data from May 31 to October 11, 2018.

WIND TO Dir	0-10 m/s	>10 m/s	
N	11.6%	5.0%	
NE	16.3%	10.2%	
E	21.1%	15.3%	
SE	8.3%	0.7%	
S	20.5%	25.9%	
SW	7.6%	38.6%	
W	3.4%	0.7%	
NW	11.2%	3.7%	

ADP Analysis

2017 field season

Acoustic Doppler current profile data are inherently noisy and usually require averaging to dampen out the acoustic noise. ADP data were collected with a 5-minute averaging interval and a 15-minute profiling interval. Depth averaging and temporal averaging were used to smooth the data which can help with data interpretation. For example, averaging three near surface cells (e.g. ADP cells 22-24) was used to examine the relationship between wind stress and near-surface water velocity. Similarly, temporal averaging data from four consecutive profiles created an average hourly value which also helped smooth the current profile data.

Another data processing consideration was to exclude ADP cells near the water surface because they are biased by sidelobe interference. For this application the interference occurs at the water surface. The sidelobe energy from each 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.

At Clark Canyon, the reservoir elevation was dropping throughout the field season. As a result, the ADP data had to be processed to account for sidelobe interference occurring in different depth cells as the water surface elevation changed. There isn't a way in post-processing to remove the bias from the sidelobe interference. Consequently, the ADP velocity profiles do not contain the surface water velocity generated by the wind. It is possible to model the surface velocity using the ADP velocity profile, using a mathematical model for the near-surface velocity profile.

Figure 5 shows the complete ADP data record for 2017 along with a plot of the wind speed and direction data from the Clark Canyon reservoir weather station. In general, these plots show the dynamic currents with many wind mixing events in the epilimnion that generate water currents up to 10 cm/sec. In contrast, the currents within the hypolimnion are most often below 3 cm/s which is the lower threshold for valid ADP current measurements. For currents below 3 cm/s the acoustic noise is greater than the Doppler shift signal which results in a poor current measurement. The average current direction for a poor measurement is usually around 180 degrees which is why the direction contours in figure 5 are mostly around 180 degrees. Later in the data record, there are several events where the near bottom currents were around 5 to 7 cm/sec in both north and south directions.

Figure 6 shows a 7-day period from calendar day 257 to 264 (September 14 to 20, 2017) which helps to visualize the effects of sustained wind events on surface and bottom currents at site CC1. This type of plot can assist with the calibration and validation of the CE-Qual-W2 reservoir model to evaluate if the model current profiles are representative of the field measurements. For example, on day 257 there was a sustained wind towards the N-NE which produced 4 to 5cm/s near-surface currents in a NE direction. On day 263 there was a sustained wind towards the S-SW that produced 7 cm/s near-surface currents S-SE direction, which illustrates that winds toward the south creates stronger surface currents at CC1. This wind event also generated 10 cm/s hypolimnetic (bottom) currents in a N-NE direction. It is a rare occurrence when the bottom currents are stronger than the surface currents.

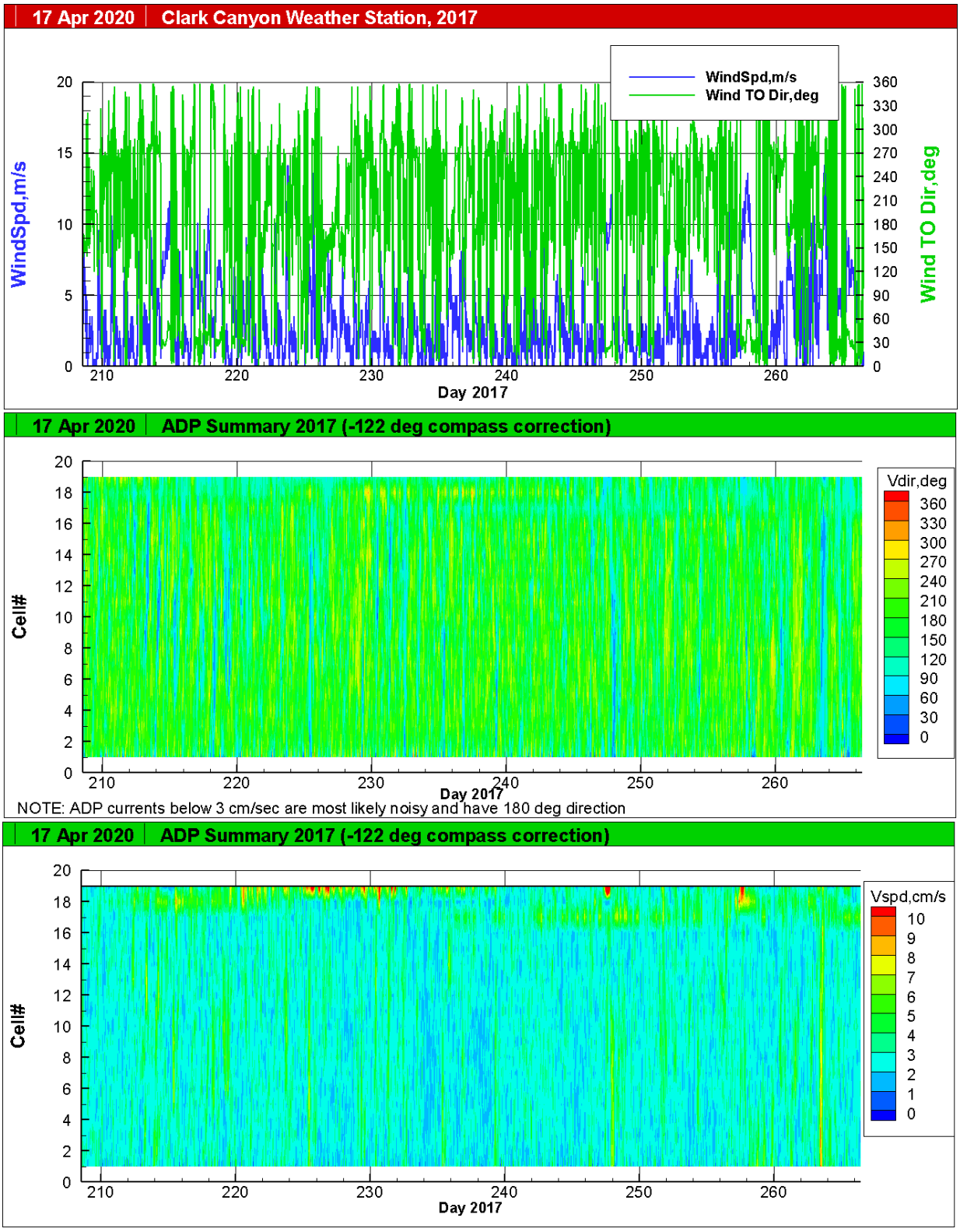


Figure 5. Complete record of ADP current speed and direction from calendar day 208 to 266 (July 27 to September 23, 2017). The CCR weather station's wind speed and direction (toward) data for the same time period are included in the top plot.

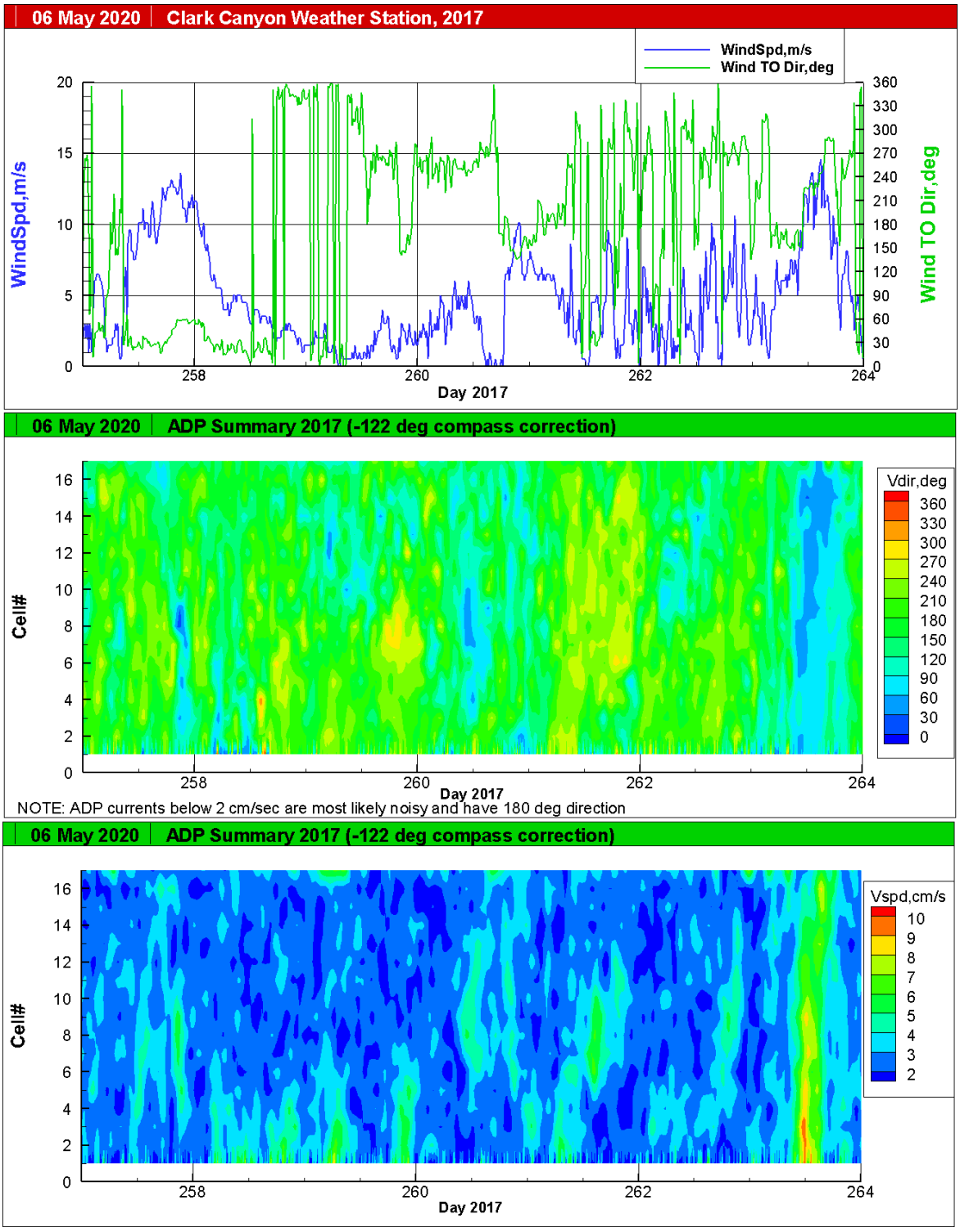


Figure 6. Seven-day record of ADP current speed and direction for calendar day 257 to 264 (September 14 to September 21, 2017). This shorter window of time allows for a detailed inspection of surface and bottom currents for a range of wind events.

An analysis of the near surface currents showed that currents greater than 10 cm/s occurred when wind events were primarily aligned with the reservoir fetch. Table 3 summarizes the results of the near surface velocity analysis. Of the 290 profiles with surface currents greater than or equal to 10 cm/s, 17% were in the NE direction (towards the dam) while 43% were in the SE-S direction (towards Red Rock Creek). The remaining 40.0% of the profiles were in the E direction. The maximum surface current was 23.8 cm/s to the NE on 9/4/2017 at 14:53. The maximum surface current toward the SE was 16.2 cm/s on 8/18/2017 at 15:38. The maximum surface current off fetch was toward the E and was 18.9 cm/s on 9/4/2017 18:08.

Near Surface Velocities (cell#19) >=10 cm/s				
n=	290	%	Max Spd	Day
NE	49	16.9%	23.8	9/4/17 14:53
E	116	40.0%	18.9	9/4/17 18:08
S	2	0.7%	10.6	8/16/17 16:53
SE	123	42.4%	16.2	8/18/17 15:38
Total	290	100%		

Similarly, an analysis of the near bottom currents (using cell#1) showed that currents greater than 7 cm/s occurred when wind events were typically aligned with the fetch and when the reservoir's thermal stratification was breaking down. Table 4 presents a summary of the near bottom current analysis. Of the 68 profiles with bottom currents greater than 7 cm/s, 35% were in the N-NE (toward the intake structure) direction while 17% were in the S-SW direction. The remaining 20% and 7% of the profiles were in the E and SE direction, respectively. The maximum bottom current was 11 cm/s to the NE on 9/5/2017 at 1:38. The maximum bottom current to the SW was 8.6 cm/s on 9/16/2017 at 6:38. The maximum off fetch bottom current was toward the E and was 10.5 cm/s on 9/20/2017 13:08. It is interesting to note that near surface currents are 3 to 6 times higher in magnitude than bottom currents which is indicative a thermally stratified reservoir where the thermocline acts as a barrier which isolates the hypolimnion from wind driven surface currents.

Comparison of surface and bottom velocities with the wind data shows they move in opposite directions especially when the thermal stratification breaks down. During sustained high wind events along the reservoir fetch when thermal

stratification is weak, a seiche is created which completely displaces the epilimnion. During these events, a single circulation cell develops which increases the magnitude of the near bottom currents. Another observation was that the bottom velocity magnitudes are usually much less than surface velocity. Rarely were bottom velocities greater than 10 cm/sec. When they occurred, they were brief and were in both north and south directions.

Table 3. Near bottom velocity analysis of when the current magnitudes exceeded 7 cm/s for the 2017 ADP data set.

Current Direction	Occurrences	Percent of total	Max Speed (cm/s)	Date & time
S-SW	17	25.0%	8.6 to SW	9/16/17 6:38
N-NE	24	35.3%	11 to NE	9/5/17 1:38
E	20	29.4%	10.5 to E	9/20/17 13:08
SE	7	10.3%	8.2 to SE	8/4/17 9:53
Total	68	100%		

2018 Field Season

Figure 7 shows the complete ADP data record for 2018. This data record covers 142 days compared to 58 days in 2017. The 2018 data set contains current measurements from the onset of thermal stratification in late spring through the breakdown in stratification in the fall. In general, the ADP data show dynamic conditions with many seiches and mixing events in the epilimnion. In contrast, the currents within the hypolimnion are most often below 2 to 3 cm/s which is the threshold where accurate ADP profiles can be collected. For currents below 2 cm/s the acoustic noise is greater than the Doppler shift signal which results in a poor current measurement. The current direction of a poor measurement is usually around 180 degrees which is why the direction contours in figure 7 are mostly green.

Figure 8 shows a 7-day record of ADP current speed and direction for calendar days 232 to 239 (August 20 to 26, 2018). This shorter window of time allows for a detailed inspection of surface and bottom currents during a sustained 1-day wind event and days with typical wind fluctuations. This type of plot can assist with the calibration and validation of the CE-Qual-W2 reservoir model to evaluate if the model current profiles are representative of the field measurements. For example, on day 232 there was a sustained wind towards the S-SW which produced 10 cm/s near-surface currents in a N-NE direction. Again, the current directions do not match the wind directions because the compass calibration was

not successfully completed. A compass correction was attempted, but it did not produce satisfactory results.

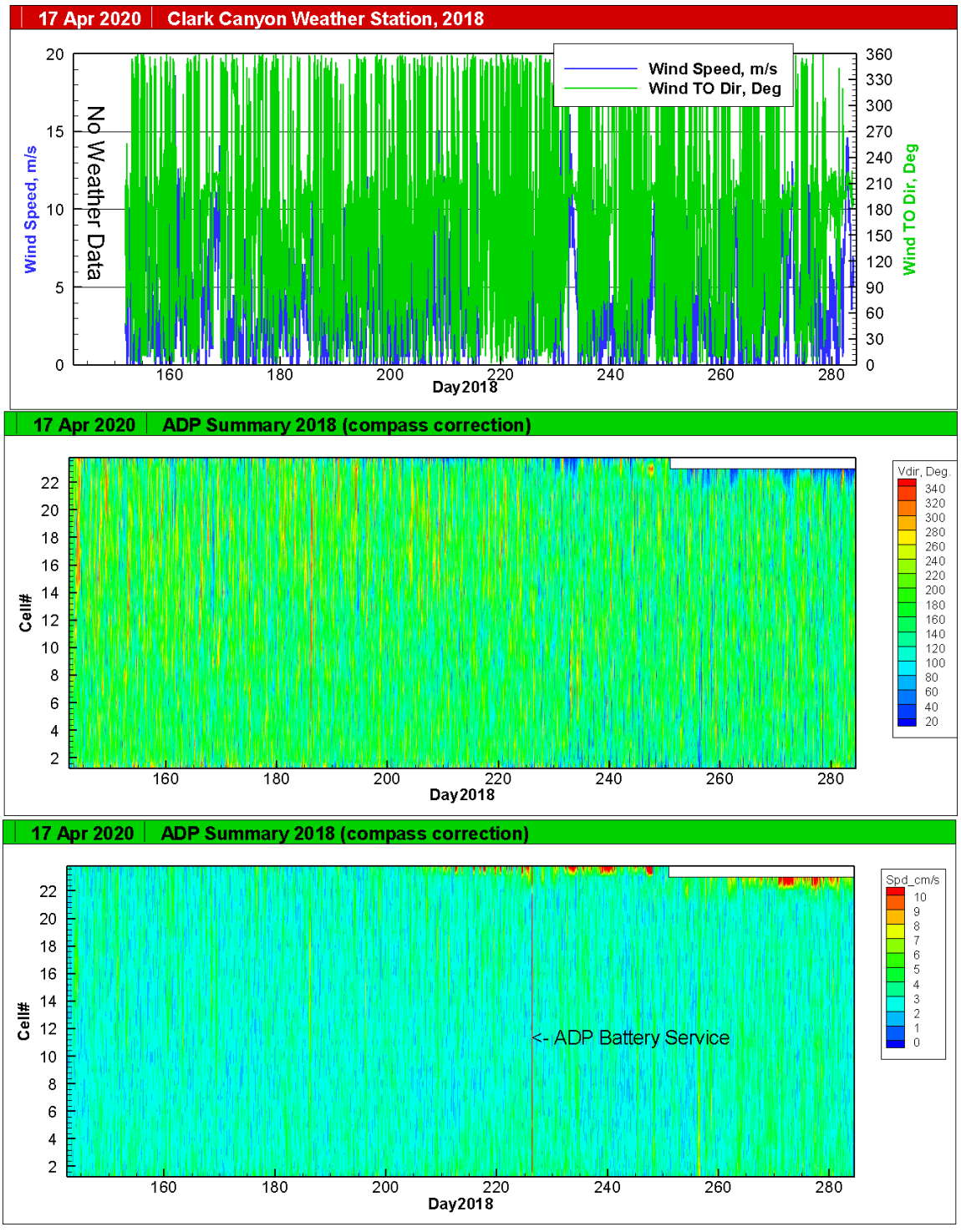


Figure 7. Complete record of ADP current speed and direction for calendar days 142 to 284 (May 22 to October 11, 2018). The CCR weather station's wind speed and direction (toward) data are also included.

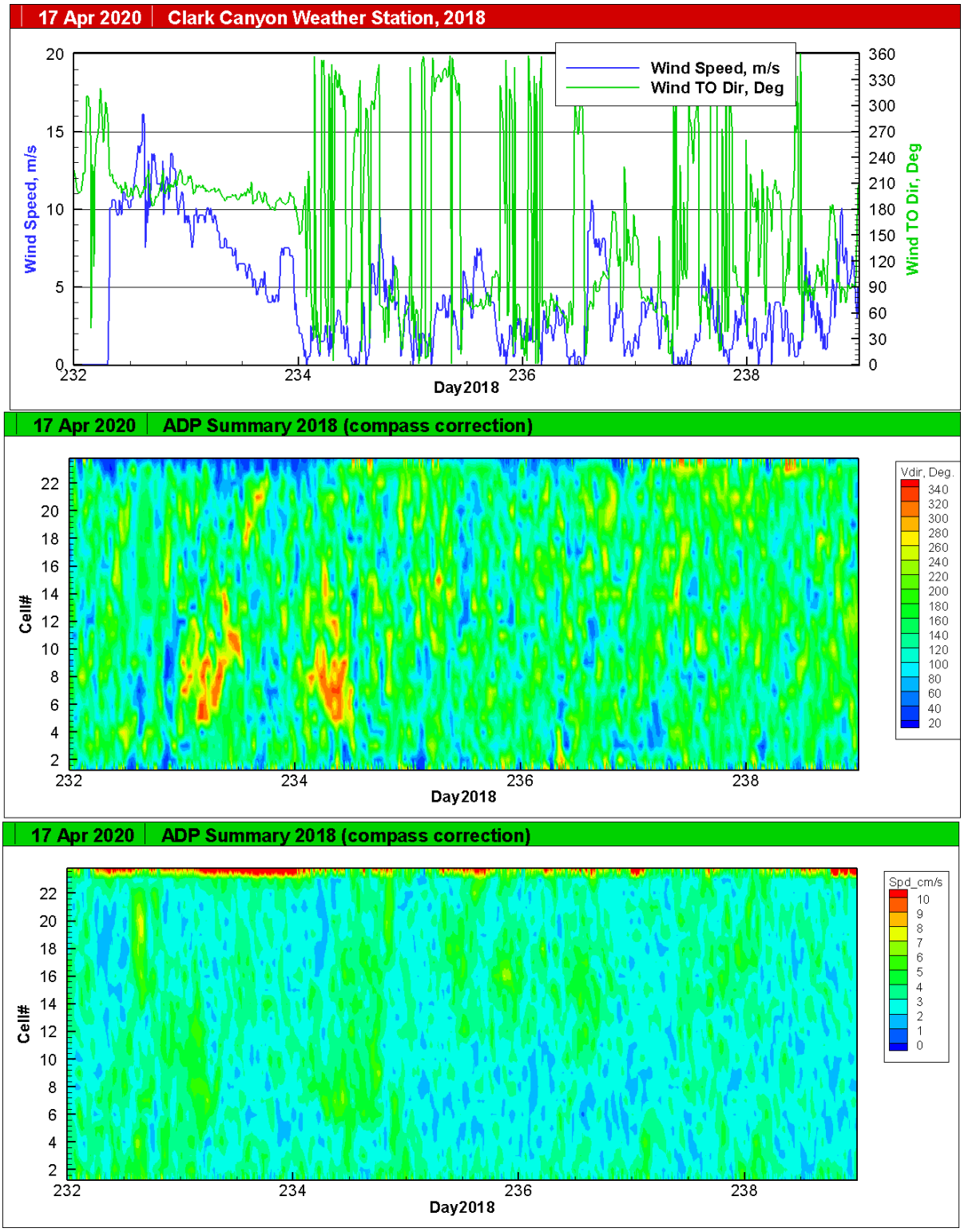


Figure 8. Seven-day record of ADP current speed and direction for calendar days 232 to 239 (August 20 to 26, 2018). This shorter window of time allows for a detailed inspection of surface and bottom currents during a sustained 1-day wind event and days with typical wind fluctuations.

An analysis of the near surface currents during strong wind events was inconclusive given the uncertainty in the ADP compass calibration. When compared to the wind direction data the ADP surface current directions did not align during high wind events which should be the case.

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 at CC1. Signal amplitudes are measured for each depth cell in the three acoustic beams. The signal amplitudes for each beam were averaged for this analysis.

Figures 9 and 10 show the complete record of signal amplitude profiles collected in 2017 and 2018. These color contour plots of signal amplitude clearly indicate that there are many events at CC1 where suspended particles increase both near the water surface and reservoir bottom. It is interesting that the frequency and strength of near-bottom suspended particle events occur more often later in the data record when the reservoir stratification begins to break down. Figure 11 is a plot of the 2018 water temperature profiles at CC1 which illustrates the breakdown in thermal stratification which begins around day 232 (August 20, 2018).

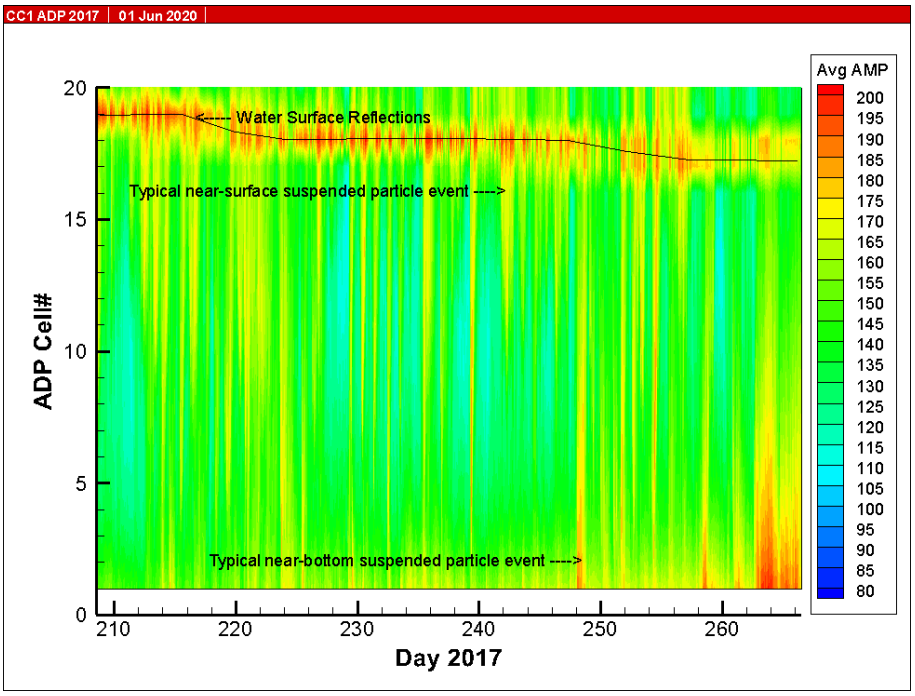


Figure 9. Complete 2017 record of average signal amplitude profiles for site CC1. Typical near-surface and near-bottom suspended particle events were a common occurrence in 2017.

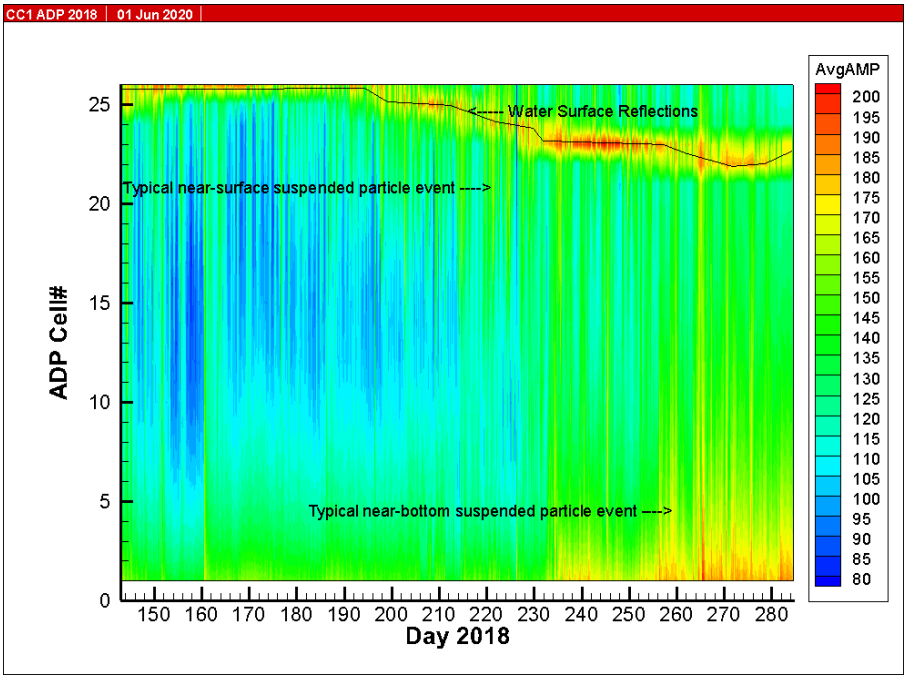


Figure 10. Complete 2018 record of average signal amplitude profiles for site CC1. Typical near-surface and near-bottom suspended particle events were a common occurrence in 2018.

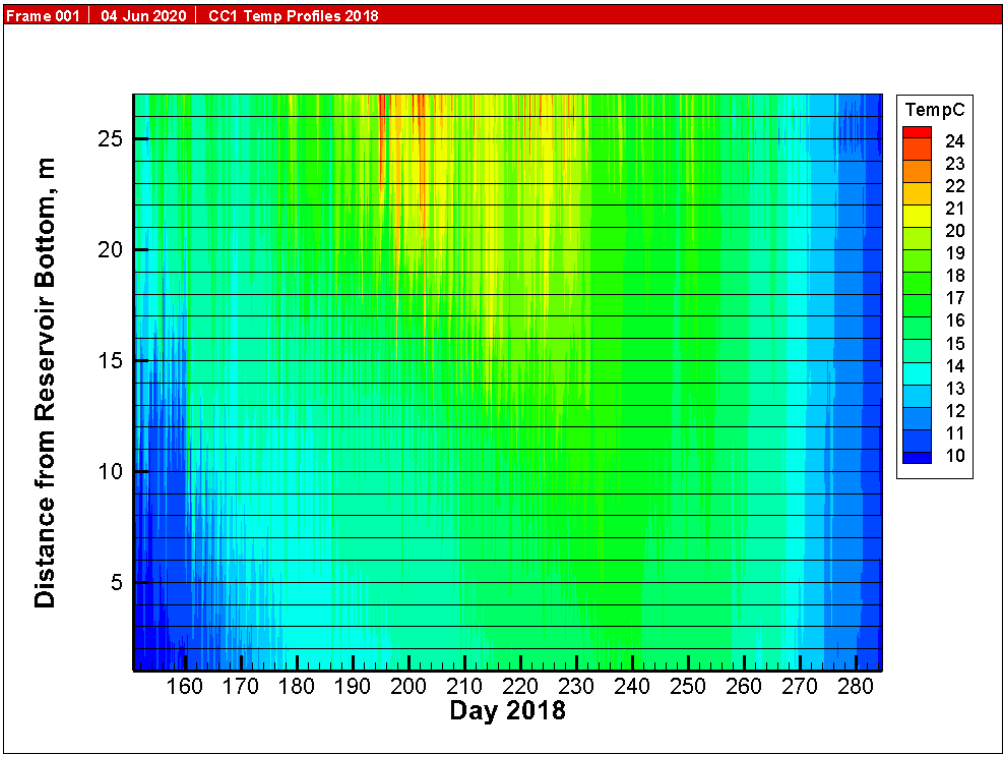


Figure 11. 2018 water temperature profiles measured at site CC1. The temperature contours illustrate the breakdown in thermal stratification which begins on day 232 (August 20, 2018). The onset of thermal destratification corresponds with increased frequency of suspended particle events at CC1 as shown in figure 10.

ADP signal amplitudes may be used to ground truth turbidities measured by MT DEQ at CC1. A comparison of ADP signal amplitude strength near the reservoir bottom and CC1 near-bottom WQ sonde turbidity measurements show a strong correlation in mid-August to early October when the reservoir's thermal stratification was breaking down. Figure 12 presents ADP signal amplitudes along with CC1 and Beaverhead River turbidity measurements for calendar day 230 to 268 (August 18 to September 23, 2017). Likewise, figure 13 presents ADP signal amplitudes and turbidity measurements for calendar day 230 to 284 (August 18 to October 11, 2018). These data show that when the ADP signal amplitudes would increase when bottom turbidity at CC1 would increase. However, there were a few high turbidity events in 2017 that did not coincide with high AvgAMPs, e.g. on day 253 (September 10, 2017). The reason for these anomalies is not clear. The Beaverhead River turbidity readings would typically increase after a several hour delay and be a lower value. The time delay is most likely related to the travel-time it takes the water to move from CC1 to the Beaverhead River WQ Sonde location. It is important to note that there is also a travel time delay between the CC1 WQ sonde location and the CC1 ADP location, i.e. they were not co-located.

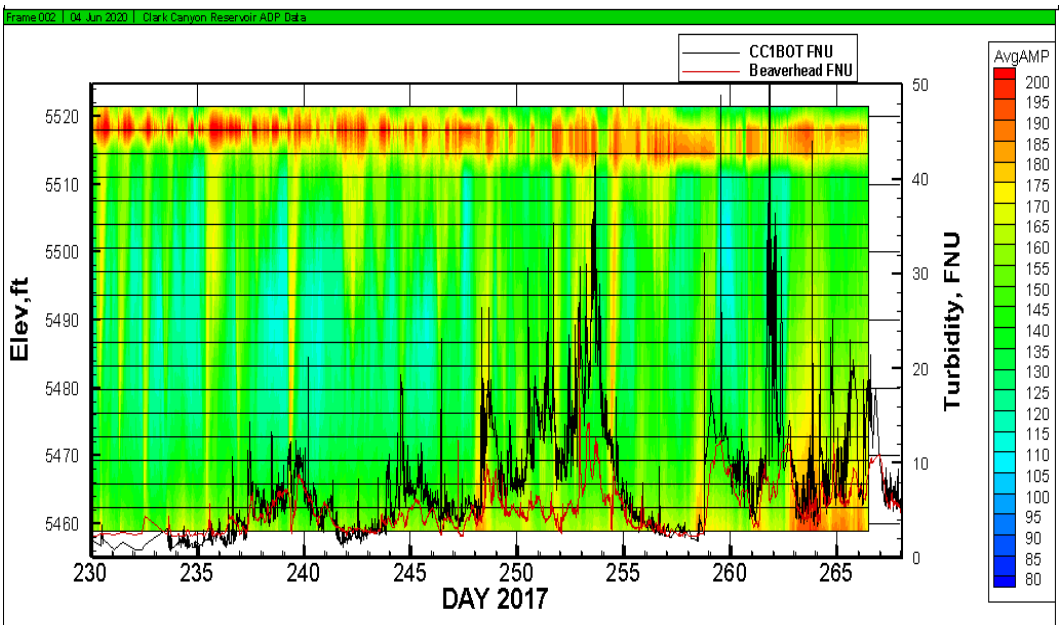


Figure 12. Example of ADP signal amplitude contours compared to near bottom turbidity measurements at CC1 and release water turbidities in the Beaverhead River below Clark Canyon Dam. The time period is for calendar days 230 to 268 (August 18 to September 23, 2017).

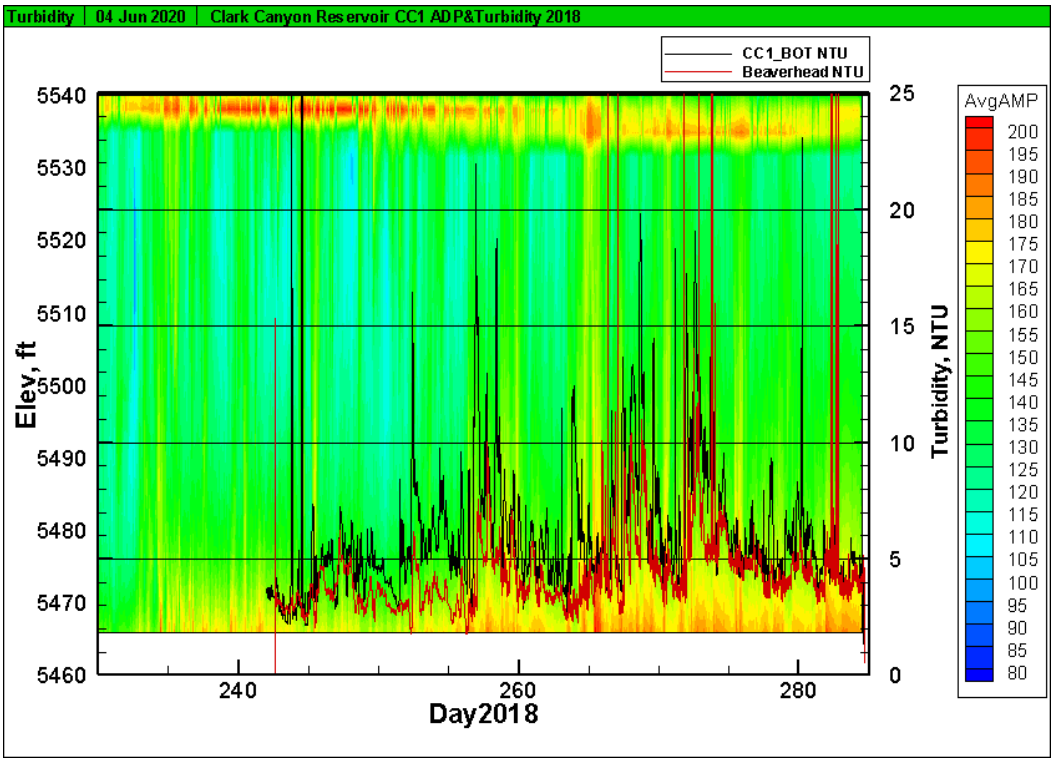


Figure 13. Example of ADP signal amplitude contours compared to near bottom turbidity measurements at CC1 and release water turbidities in the Beaverhead River below Clark Canyon Dam. The time period is from calendar day 230 to 284 (August 18 to October 11, 2018). Note: WQ sonde turbidity readings prior to calendar day 242 were of poor quality and not plotted.

Analysis of Temperature Profiling Sites

High resolution temperature profiling data collected at two sites (CC1 and CC2) are available for calendars days 144 to 284 (May 24 to October 11, 2017). Similar data were collected again from May 30 to October 11, 2018. These data sets along with the wind data from the reservoir weather station allows the analysis of seiches and wind mixing events during high wind events. Even though ADP data are not available for June and most of July 2017, the temperature profiles can be used to infer surface currents and bottom currents. These temperature profile data also show the very dynamic nature of the reservoir stratification due to meteorological conditions in June and July. In general, strong winds from the north or south along the longest fetch (fetch is defined as the longest unbroken stretch of open water on a lake) create the most change to the reservoir stratification. The wind effects on the depth and strength of the thermocline can indicate the vertical extent of the circulation in the epilimnion. When a wind event breaks down the reservoir stratification it allows wind driven currents to interact with bottom sediments which may create a turbidity plume. It appears that the fate of a turbidity plume depends on the strength and direction of the bottom currents.

An example of thermal profiles at CC1 and CC2 for a strong wind event on calendar day 159 (June 8, 2017) is presented in figure 14. Figure 14 shows that on day 159 a wind from the S wind created a thickened epilimnion and a much stronger thermocline at CC1. Later in the day a strong NW wind causes the epilimnion to shrink and the hypolimnion thickens at CC1. Furthermore, during a N-NE wind event at the end of the calendar day 160 there was a near total destratification at CC2.

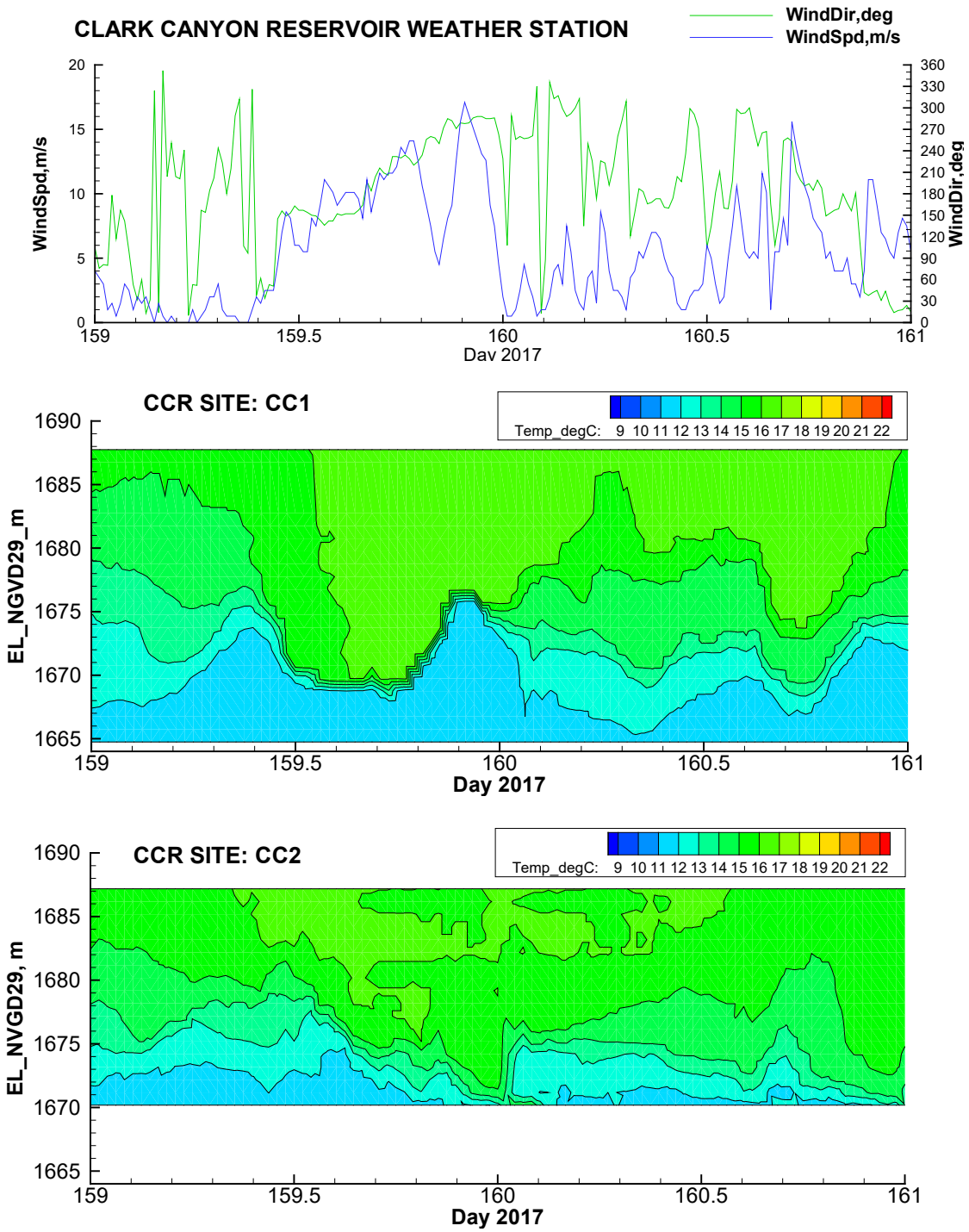


Figure 14. On calendar day 159 (June 8, 2017) a sustained strong wind from the south created a seiche characterized by thickened epilimnion and a very strong thermocline at CC1. Later, near the end of day 160 a N-NE wind causes near destratification at CC2 which displaces the thermocline upwards at CC1.

Conclusions and Recommendations

A Sontek ADP was successfully deployed in Clark Canyon Reservoir and collected 57 and 142 days of continuous velocity profiles in 2017 and 2018, respectively. A preliminary analysis of the velocity profile data was useful for ground truthing supporting data like wind speed and direction, turbidity measurements, and reservoir temperature profiles.

The ADP profiles illustrated very dynamic reservoir currents in response to sustained high wind events which caused seiching, especially when the wind was aligned with the reservoir fetch.

While ADP measurements were impacted by compass calibration problems this only affects the current direction measurements with respect to magnetic north. The relative current direction data can provide information on flow reversals and overall circulation patterns in the reservoir. Measurement of current speed profiles was not affected and should provide a good indication velocity distribution throughout the water column.

It appears that high turbidity releases from Clark Canyon reservoir occur in the late spring and late summer during sustained wind events when the reservoir's thermal stratification is weak.

At times, ADP signal amplitudes appeared to agree with near-bottom turbidity measurements. However, there were several instances where elevated ADP signal amplitudes did not agree with turbidity spikes and vice versa.

If future studies are warranted, it is recommended that ADP data be collected at other locations in the reservoir to better understand how wind events impact reservoir stratification and near bottom current speeds in shallower water. Likewise, ADP data should be collected in an open-water area that is not affected by the dam or abutments. These measurement sites may shed some light on the impacts of E/W winds affect reservoir water quality and thermal stratification.

It is recommended that daily water quality profiles be collected more frequently at the ADP site to capture more turbidity plume events.

References

Sontek, 2000, Acoustic Doppler Profiler – Technical Documentation Manual, San Diego, CA (www.sontek.com)

Appendix 1

HARDWARE CONFIGURATION PARAMETERS FOR 2017

Sensor serial # ---------- C34
Sensor type -- (kHz) --------- 500
Number of beams ---------- 3
Beam Geometry ---------- 3_BEAMS
Slant angle -- (deg) --------- 25.0
Orientation ---------- UP
Compass/Tilt sensor ---------- YES
Recorder sensor ---------- YES
Temperature sensor ---------- YES
Pressure sensor ---------- YES
PressOffset - (dbar) --------- -1.949000
PressScale -- (dbar/count) --- 0.002436
PressScale_2 (pdbar/count^2) - 0
External sensors ---------- NO
External Pressure Sensor ----- NO
Microcat CTD ---------- NO
Bottom Track Option ---------- YES
Waves Option ---------- NO

CURRENT SYSTEM PARAMETERS

CPU Ver ---- ADP 5.8
DSP Ver ---- DSP 4.0
Board Rev. - REV D
Date ------- 1995/10/02
Time ------- 09:41:13
AutoSleep -- NO
OutFormat -- ASCII
OutMode ---- AUTO
Recorder --- ON
RecMode ---- NORMAL
BottomTrack - NO
SyncMode ---- DISABLE

CURRENT ADP SETUP PARAMETERS

Temp ---------- (deg C) - 15.00
Sal ---------- (ppt) --- 0.10
TempMode ---------- MEASURED
Sound Speed ---- (m/s) --- 1465.20
CellSize ------- (m) ----- 1.06
BlankDistance -- (m) ----- 1.06
PulseLength ---- (m) ----- 1.06
Ncells ---------- 25
AvgInterval ---- (s) ----- 300
ProfileInterval- (s) ----- 900
PingInterval --- (s) ----- 0.0
CoordSystem ---------- ENU

CURRENT DEPLOYMENT PARAMETERS

Deployment ---------- CLARK
StartDate ---------- 2017/07/27
StartTime ---------- 10:45:00
AvgInterval ----- (s) - 300
ProfileInterval - (s) - 900
PingInterval ---- (s) - 0.0

BurstMode ---------- DISABLED
BurstInterval --- (s) - 1200
ProfilesPerBurst ------ 1
Comments:

HARDWARE CONFIGURATION PARAMETERS FOR 2018

Sensor serial # ---------- C34
Sensor type -- (kHz) --------- 500
Number of beams ---------- 3
Beam Geometry ---------- 3_BEAMS
Slant angle -- (deg) --------- 25.0
Orientation ---------- UP
Compass/Tilt sensor ---------- YES
Recorder sensor ---------- YES
Temperature sensor ---------- YES
Pressure sensor ---------- YES
PressOffset - (dbar) --------- -1.949000
PressScale -- (dbar/count) --- 0.002436
PressScale_2 (pdbar/count^2) - 0
External sensors ---------- NO
External Pressure Sensor ----- NO
Microcat CTD ---------- NO
Bottom Track Option ---------- YES
Waves Option ---------- NO

CURRENT SYSTEM PARAMETERS

CPU Ver ---- ADP 5.8
DSP Ver ---- DSP 4.0
Board Rev. - REV D
Date ------- 2008/05/22
Time ------- 10:37:46
AutoSleep -- YES
OutFormat -- ASCII
OutMode ---- AUTO
Recorder --- ON
RecMode ---- NORMAL
BottomTrack - NO
SyncMode ---- DISABLE

CURRENT ADP SETUP PARAMETERS

Temp ---------- (deg C) - 15.00
Sal ---------- (ppt) --- 0.00
TempMode ---------- MEASURED
Sound Speed ---- (m/s) --- 1465.10
CellSize ------- (m) ----- 1.00
BlankDistance -- (m) ----- 1.00
PulseLength ---- (m) ----- 1.00
Ncells ---------- 28
AvgInterval ---- (s) ----- 300
ProfileInterval- (s) ----- 1800
PingInterval --- (s) ----- 0.0
CoordSystem ---------- ENU

CURRENT DEPLOYMENT PARAMETERS

Deployment ---------- CCR18
StartDate ---------- 2008/05/22
StartTime ---------- 10:25:00
AvgInterval ----- (s) - 300
ProfileInterval - (s) - 1800
PingInterval ---- (s) - 0.0
BurstMode ---------- DISABLED
BurstInterval --- (s) - 1200
ProfilesPerBurst ------ 1