

RECLAMATION

Managing Water in the West

Hydraulic Laboratory Report HL-2011-02

Glen Canyon Dam Penstock Withdrawal Characteristics, 2007-2008

**MIDDLE RIVER DIVISION – GLEN CANYON UNIT
COLORADO RIVER STORAGE PROJECT**



**U.S. Department of the Interior
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Technical Service Center
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14. ABSTRACT Several recent projects have resulted in detailed current measurements in Glen Canyon Dam's forebay. This collection of current measurements was compiled to describe the seasonal variation in the penstock withdrawal characteristics from Lake Powell. The withdrawal characteristics of the penstock intakes at Glen Canyon Dam are an important factor in accurately modeling Glen Canyon Dam's release water quality and long-term trends in Lake Powell's water quality. Withdrawal zone velocities were measured at several locations across the forebay using an acoustic Doppler current profiler (ADCP) and were independently verified with an acoustic Doppler velocimeter.					
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Glen Canyon Dam Penstock Withdrawal Characteristics, 2007-2008

MIDDLE RIVER DIVISION – GLEN CANYON UNIT
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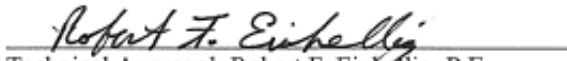
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Cover Photograph: A view of Glen Canyon Dam and its penstock intake structures taken from the safety boom. Photograph was taken by the author.

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Introduction

Technical studies supporting the design of a selective withdrawal system for Glen Canyon Dam resulted in several projects that included the collection of velocity and water quality profile data near the penstock intake structures. In September of 2006, a near-field penstock intake velocity survey (Vermeyen 2006) was conducted for a constructability review (Reclamation 2006). Most recently, far-field water current measurements were collected upstream from 6 penstock intakes on Glen Canyon Dam. The primary purpose of these seasonal surveys was to provide withdrawal zone characteristics for a fish entrainment study. This report on the penstock withdrawal characteristics at Glen Canyon Dam was requested by Upper Colorado Region modelers to support their Lake Powell water quality modeling efforts. This report provides modelers with far-field penstock intake withdrawal zone characteristics that can be used to validate their computer model for seasonal variations in reservoir stratification and powerplant discharges.

Glen Canyon Dam

Glen Canyon Dam and reservoir were constructed to provide the following benefits: power generation, water storage, flood control, sediment retention, fish and wildlife conservation, and recreation. Lake Powell, the reservoir behind Glen Canyon Dam, has a capacity of approximately 27,000,000 acre-feet at a water surface elevation of 3700 feet. The reservoir has an active conservation capacity of 20,876,000 acre-feet above elevation 3490, the minimum reservoir elevation for power generation.

Glen Canyon Dam is a concrete arch structure with a structural height of 710 feet, a hydraulic height of 583 ft, and a crest length of 1,560 ft. The top of the parapet walls are at elevation 3719 ft. The crest of the dam is at elevation 3715 and accommodates a 35-ft-wide roadway which is a service road for the dam and provides access between the spillways. Spillways are located in each abutment. Each spillway consists of an approach channel, a gated intake structure with radial gates, a 41-foot-diameter concrete-lined tunnel, and a deflector bucket. The crests of the spillway control structures are at elevation 3648, and the tops of the closed radial gates are at elevation 3700. The river outlet works, located near the left abutment, consists of two intake structures with trash racks, four 96-inch-diameter steel pipes, ring-follower guard gates, and hollow-jet valves for flow regulation. The centerline of each river outlet intake is at elevation 3374.

Glen Canyon Powerplant

Glen Canyon Powerplant is located immediately downstream from the dam. Eight 15-ft-diameter steel penstocks are embedded in the dam. The centerline of

each penstock intake is at elevation 3470 ft. The minimum water surface elevation for power operation is 3490 ft. See appendix figures D1 and D2 for drawings with plan, elevation, and sections through the dam and powerplant. A reinforced concrete trash rack structure protects each penstock intake. The top of the trash rack structure is at elevation 3652 ft. The penstock intake at the bottom of the trash rack structure is protected by trash racks that extend from elevation 3450 to elevation 3530. Above the trash racks, concrete panels block the flow into the trash rack structure from elevation 3530 to the top of the trash rack structure. See appendix drawing D3 for details of the existing trash rack structures.

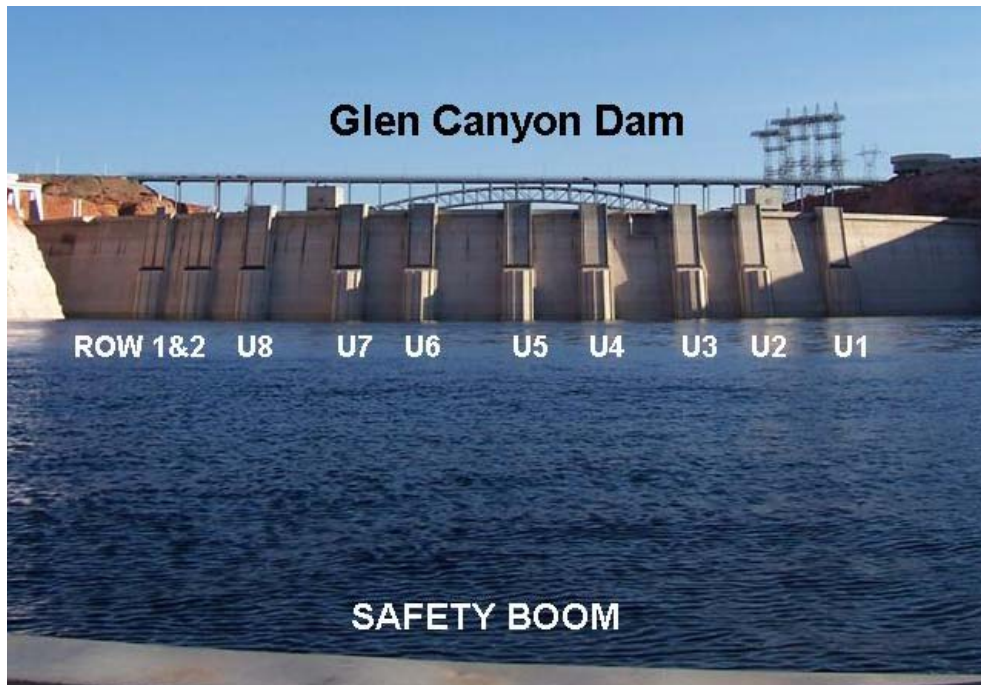


Figure 1. Photograph of Glen Canyon Dam (looking south) with numbered penstock intakes and the river outlet works (ROW) intakes.

Methods and Materials

Two velocity measurement instruments were used for this study. An acoustic Doppler velocimeter (ADV) was used to measure point velocities at the centerline elevation of the penstock intakes (El. 3470 ft). An acoustic Doppler current profiler (ADCP) was used to measure velocity profiles in front of units 2 through 7 (Figure 1). Initial tests showed that ADCP data collected at units 1 and 8 were degraded by acoustic reflections off the canyon walls. As a result, these intakes were excluded from the data collection plan.

Data were collected while positioned in front of units 2 through 7 using a tagline secured between the east and west canyon walls about 420 ft uplake from Glen Canyon Dam (Figure 2). The tagline was fixed between anchors in the canyon

walls and was used to position the boat in the same location for each field visit. Table 1 contains a summary of the tagline stations. Maintaining a fixed position was a critical element for this data collection effort because ADV measurements will include any boat motion in the velocity readings. While an ADCP is capable of removing boat motion from its velocity measurements (using bottom tracking), higher quality data can be obtained from a fixed position. With the exception of boat motion generated by boat wakes and waves, the tagline was very effective at minimizing boat motion during data collection.

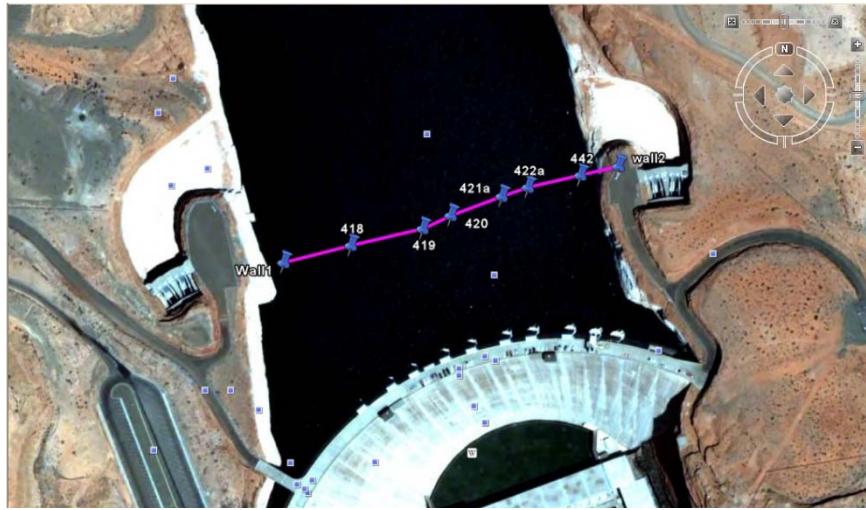


Figure 2. Google™ Earth image with annotations of tagline and velocity measurement locations at Glen Canyon Dam.

Table 1. Locations of sampling sites along the Glen Canyon Dam forebay tagline.

GPS Waypoint	Distance from Wall 1 (ft)	Distance from dam face (ft)
Wall 1 (west)	0	n/a
418/ Unit #2	203	460
424/ Unit #3	269	427
419/ Unit #4	423	433
420/ Unit #5	515	420
421/ Unit #6	673	413
422/ Unit #7	748	420
Wall 2 (east)	1025	n/a

The penstock intake centerline elevation is located at 3470 ft above mean sea level. For these tests the depth to the intake varied from 120 to 140 ft below the reservoir water surface.

ADV Measurements

A Sontek/YSI[®] Argonaut-ADV was used to measure three-dimensional water velocities at the penstock intake centerline elevation for Units 2 through 7 (Figure 3). The manufacturer's specifications for the Argonaut-ADV are listed in Table 2.

Table 2. Sontek/YSI[®] Argonaut-ADV specifications

Three-dimensional velocities were measured in earth coordinates, that is, velocities were referenced to east, north, and up directions using an internal flux-gate compass. The ADV is equipped with a pressure sensor and tilt sensors that are used to determine the ADV's depth and orientation, respectively. The pressure transducer was calibrated before each measurement to remove the influence of atmospheric pressure from the depth measurement. Throughout the velocity profiling, an integral temperature sensor was used to measure water temperature to perform real-time speed-of-sound corrections.

Velocity

- Range: ± 0.003 to 15 ft/sec
- Resolution: 0.0003 ft/sec
- Accuracy $\pm 1\%$ of measured velocity, ± 0.003 ft/sec

Compass/Tilt Sensor

- Resolution Heading, Pitch, Roll 0.1°
- Heading Accuracy $\pm 2^\circ$
- Pitch & Roll Accuracy $\pm 1^\circ$

Temperature Sensor

- Resolution 0.01°C
- Accuracy $\pm 0.1^\circ\text{C}$

Pressure Sensor

- Strain Gage Accuracy $\pm 0.1\%$

The ADV was lowered down using a graduated line to facilitate repeatable depths during the velocity measurements. In general, this profiling system was effective at positioning the ADV at known elevations. An Argonaut-ADV samples at a frequency of 10 Hz and accumulates 1-second averages over a user-defined averaging interval. The averaging interval for this project was 30 seconds, but data were collected for at least 15 minutes at each station. ADV readings were filtered to remove data collected during periods of boat motion (as described by the standard deviation of the average pressure reading). Typically, 15 to 25 ADV readings were averaged to describe the water velocity at each sampling location.

Data were collected and monitored on a laptop computer. During post processing, the measurement depths were verified using data from the ADV's internal pressure transducer. Likewise, velocity directions were corrected for a local magnetic variation of 11.7 degrees east.

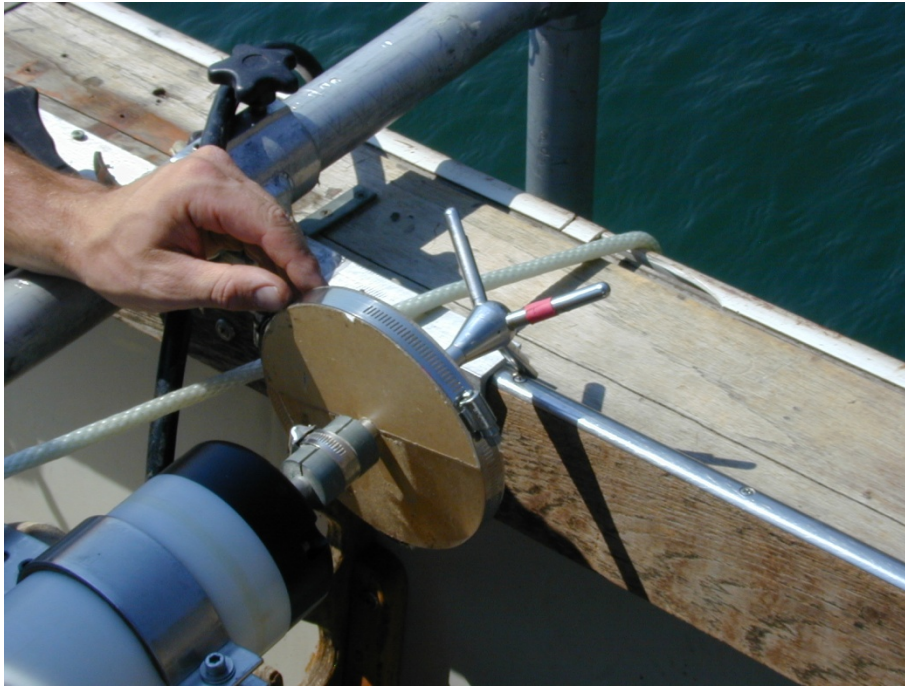


Figure 3. Photograph of the ADV with a 6-inch diameter disk attached to protect the transducer arms from damage.

ADCP Measurements

Velocity profile data were collected using an ADCP manufactured by RD Instruments. A 300 kHz Workhorse ADCP system was selected for this project because it is capable of measuring profiles for depths up to 450 ft. Figure 4 is a photograph of the ADCP mounted on the work boat. The ADCP uses the Doppler shift principle to measure velocities along four acoustic beams projected downward below the boat. The instrument transmits precise acoustic pulses (called pings) and then listens for backscattered acoustic signals reflected from scatterers in the water column (e.g., organic or inorganic particles). The frequency change of the Doppler-shifted backscattered signal is proportional to the velocity of the scattering particles (which are moving the same speed as the water). The ADCP receives and processes the backscatter signals. Each reflected signal is separated from the next ping by a fixed time. The reflected signals are used to compute velocities from uniformly spaced volumes commonly referred to as depth cells. The four acoustic beams are positioned 90 degrees apart and are angled 20 degrees from vertical. Trigonometric relationships for the acoustic beam configuration are used to resolve the three-dimensional velocity components for each depth layer. Velocities reported by the instrument are the resultant of velocities measured along each of four acoustic beams, rather than a measurement at a single point beneath the instrument. As a result, the accuracy of this measurement technique depends on the homogeneity of horizontal currents in layers of constant depth. In other words, the velocities detected by each beam

must be similar in both magnitude and direction for each beam. Typically, the horizontal homogeneity assumption for currents in oceans, rivers, and lakes is a reasonable assumption. For this study, ADCP measurements were collected at a distance upstream from the dam that was at least 26 times the penstock diameter (15 ft) which is sufficient to assure the horizontal homogeneity assumption was valid. Current research on flow upstream of two-dimensional intakes (Islam and Zhu, 2011) showed a uniform and steady far-field velocity field is established within 2 or 3 times the penstock diameter upstream from the dam face.



Figure 4. Photograph of ADCP mounted to the gunwhale (foreground). The black transducer (background) was used to survey fish distribution in the forebay.

The ADCP was configured to profile the water column at 3 m depth cells yielding a velocity profile from about 5 m below the water surface to about 8 m above the reservoir bottom. Velocities cannot be measured near the water surface because the transducer must be submerged, and there is a time delay between transmit and receive modes of operation. This unmeasured depth is called the blanking distance and for this project was 5 m below the water surface. Likewise, velocities cannot be measured near the bottom (approximately the last 6 to 10 percent of the depth) due to a phenomenon called side-lobe interference. Side-lobe interference occurs when a lobe of secondary acoustic energy reflects off the bottom and interferes with backscatter echoes coming from depth cells close to the bottom. Side-lobe interference was not a concern for this project because the currents of interest were above this zone of interference.

Three orthogonal components of velocity (x, y, z) are measured by the ADCP; an internal compass allows the velocities to be referenced to an earth coordinate system (east, north, and up). Tilt sensors are used to correct for any pitch/roll errors in depth measurements. A heave sensor was not available for this project, so no heave corrections were made.

In addition to the velocity data, the ADCP measures the depth where each beam hits the bottom. Velocity profiling from a moving boat requires dedicated bottom tracking pings to track the boat motion relative to the reservoir bottom using the same Doppler shift technique that is used to measure water velocity. Bottom tracking allows the water velocity measurements to be corrected to remove the boat's velocity from the current velocity, and permits tracking the position of the instrument throughout the measurement. A tag line was used to minimize the boat velocity and allow the collection of high quality current measurements.

The ADCP configuration settings and commands are listed in an appendix to this report. The most notable difference from a typical ADCP configuration was the use of the narrow bandwidth processing instead of broadband. The narrow bandwidth processing (WB1 command) was required to gain extended profiling range in the deep and low backscatter water at Glen Canyon Dam forebay. While narrow bandwidth processing allows the ADCP to profile deeper, the consequence is that the standard deviation of a velocity measurement is increased by as much as 2.5 times that of a broadband measurement. This limitation was overcome by collecting several hundred profiles at each site to compute a mean velocity profile. According to PlanADCP version 2.04, which models ADCP performance for ideal conditions, velocity measurement would have an uncertainty (standard error) of ± 0.014 ft/sec (0.42 cm/sec) for an average of 400 ensembles. For this configuration, 0.014 ft/sec is the lowest velocity magnitude the ADCP can reliably measure. A listing of the PlanADCP output for this configuration is provided in an appendix to this report.

A laptop computer was used to configure the ADCP, control data collection, and store data. A GPS receiver was connected to the laptop computer so continuous GPS positions were recorded simultaneously with the velocity data. GPS positions stored in the ADCP data files were measured using WAAS (wide area augmentation system) differential corrections. WAAS is a system of earth stations and satellites that improves the tracking accuracy of the GPS navigation to approximately ± 10 ft. GPS data were not used in lieu of bottom tracking, but were used to document profile location.

Water Quality Profiles

Water quality (WQ) profiles were measured concurrently with ADCP data at a station near the middle of the forebay tagline (typically at the Unit 4 intake centerline). WQ profiles used for this project were collected by staff from Reclamation's Technical Service Center (TSC) or the USGS's Grand Canyon

Monitoring and Research Center (GCMRC). The following WQ parameters were sampled using a Hydrolab water quality sonde: temperature, specific conductance, dissolved oxygen, and pH. In general, data were collected at 1 m depth intervals from the surface through the thermocline, then every 2 to 5 m in the hypolimnion. There were two instances when TSC WQ profiles were unavailable and GCMRC WQ profiles were used instead. The GCMRC WQ profiles were collected at a sampling station in Wahweap Bay (Site: LPCR0024) and were collected within one week of the ADCP data collection. The Wahweap Bay station is located about 1.5 miles upstream from Glen Canyon Dam. A few comparisons of WQ profiles collected at the forebay and in Wahweap Bay showed they have reasonably similar WQ characteristics.

Powerplant Operations

A summary of Glen Canyon powerplant operations during field data collection are provided in Table 3. During the March 6, 2008 field visit a high flow experiment was underway with a steady flow of 41,000 ft³/sec. The total dam release consisted of 15,500 ft³/sec from the river outlet works and 25,500 ft³/sec through the powerplant.

Table 3. Summary of powerplant operations for the seven forebay velocity data sets.

Date - Data Set	Total Flow (ft ³ /sec)	Unit Schedule	Water surface Elevation (ft)	Comments
7/23/2007- night	14,800	2,3,4,5,7	3609	
7/24/2007-day	15,800	2,3,5,6,7	3609	unit 4 replaced by unit 6
9/25/2007- night	12,000	2,4,5,7	3602	
9/26/2007- day	12,400	2,4,5,7	3602	
3/6/2008- day and night	41,000	1,2,3,4,6,7,8	3590	High flow test
5/29/2008- night	15,750	1,2,4,6,7	3610	
6/25/2008- day	15,500	1,2,4,6,8	3629	

Data Collection

Five field trips were made to Glen Canyon Dam to measure velocity profiles in the forebay. Trips were planned to span four seasons so a wide range of reservoir stratification could be sampled. To support the fish entrainment study, day and night velocity profiles were collected. Data for each field trip are summarized below.

July 23-24, 2007

On July 23, 2007, velocity profiles and fish density profiles were collected in the forebay at Glen Canyon Dam. A tagline was placed across the canyon uplake from Glen Canyon Dam and was used to position the boat in front of each penstock intake. A night time data set was collected from 2100 to 2300 for clear and warm conditions with little to no wind. On July 24 a daytime data set was collected from 1030 to 1600 in clear and hot conditions. A forebay temperature profile was collected while moored to the safety boom. A more detailed description of the data collection and preliminary data are presented below.

A summary of Lake Powell operations is contained in Table 4. Outflow and release temperature data were obtained from the USGS gage at Lees Ferry (gage 09380000). Outflows were provided by powerplant operators. Inflow and reservoir elevation data were obtained from the Upper Colorado Region's reservoir operations website.

Table 4. Lake Powell operations data for July 23-24, 2007

Reservoir Elevation (ft)	3608.2
Glen Canyon Dam Outflow (ft ³ /sec) 7/23 from 1900 to 2200	14,800
Release Temperature (°C) on 7/23	10.4
Colorado River Inflow (ft ³ /sec) on 7/23	5,200
Glen Canyon Dam Outflow (ft ³ /sec) 7/24 from 1000 to 1500	16,800
Release Temperature (°C) on 7/24	10.2
Colorado River Inflow (ft ³ /sec) on 7/24	6,230

ADCP profiles

A summary of the six forebay velocity profiles collected at units 2 through 7 are plotted in Figure 5. Velocity profile data were very similar regardless of whether the units were online or offline. The maximum velocity was 0.28 ft/sec at elevation 3466 ft in front of Unit 7. The velocity profiles indicate the upper limit of withdrawal is near elevation 3520 ft. The lower limit of withdrawal was estimated to be about elevation 3430 ft. Data quality was poor below elevation 3430 ft because low signal strength resulted in a poor correlation between pings. Furthermore, when velocity magnitudes approach zero the velocity direction data become very erratic because the ADCP is measuring acoustic noise which is random in both magnitude and direction.

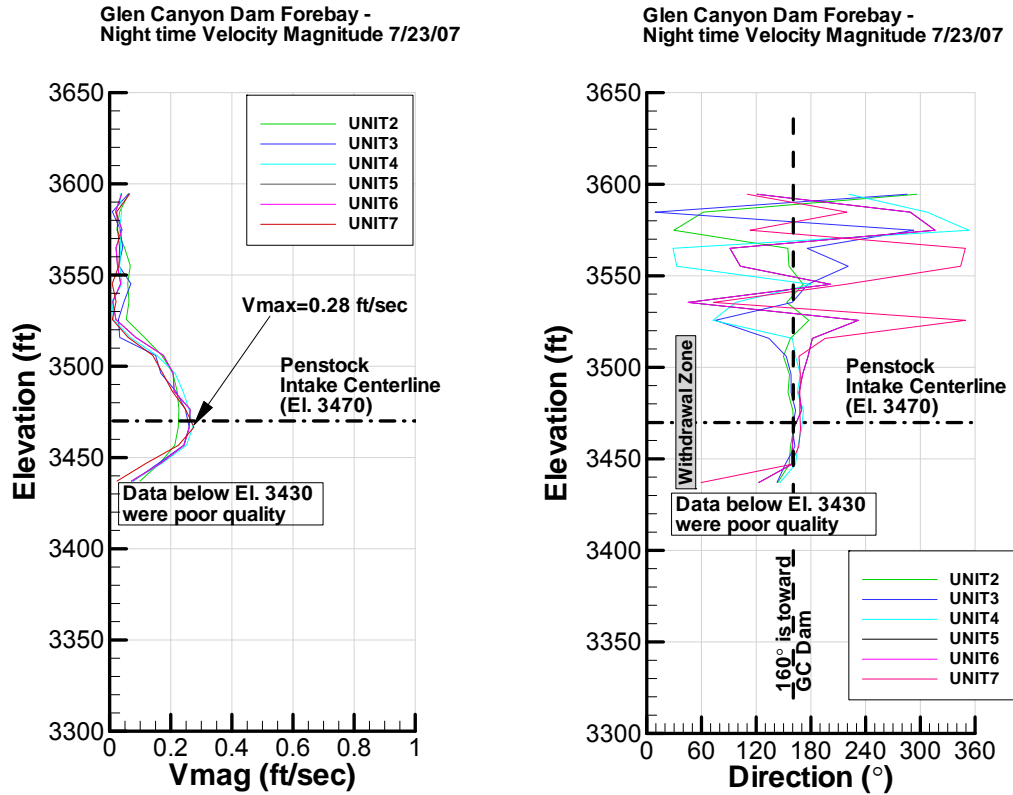


Figure 5. Plots of night time velocity magnitude and direction for Units 2 through 7 for July 23, 2007. Note: data collected below El. 3430 ft were of poor quality so they were not plotted.

Argonaut ADV Profile

An Argonaut ADV velocity profile was collected in the upper 200 ft of the water column for comparison with ADCP velocities measured. A profile consisting of 28 point velocities was collected while moored at the Unit 4 station. Argonaut ADV data are shown in Figure 6. The ADV probe contains a temperature sensor that was used to measure a temperature profile.

A comparison of ADV and ADCP velocities showed the two instruments measured very similar withdrawal zone velocities. For example, at Unit 4's intake centerline elevation, 3,470 ft, the ADCP measured 0.27 ft/sec while the ADV measured 0.26 ft/sec. Furthermore, the velocity directions measured by both instruments were about 160 degrees from north.

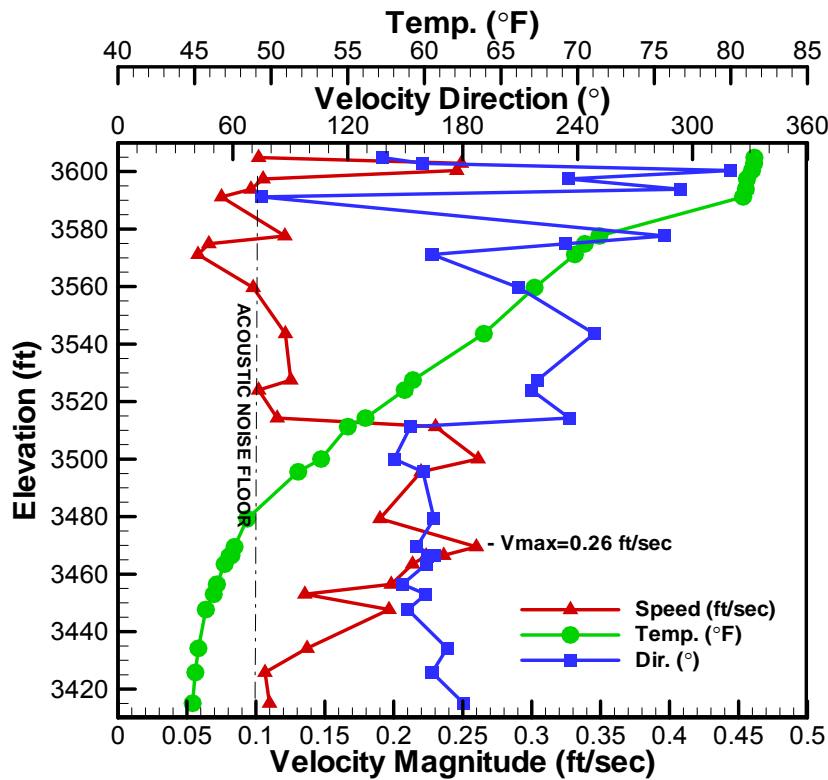


Figure 6. Plots of ADV velocity and temperature (°F) profiles at Unit 4 collected on July 24, 2007 at 1400. The lower range of ADV velocity detection (acoustic noise floor) is about 0.10 ft/sec.

Water Quality Profile

The ADV probe contains an integral temperature sensor that was used to measure a partial temperature profile because the Hydrolab sonde was damaged during shipment. Figure 6 contains a plot of the forebay temperature profile. A complete set of water quality profiles were collected five days earlier on July 19, 2007 by the USGS-GCMRC at the Wahweap Bay sampling site (Site I.D. LPCR0024). The GCMRC data show the forebay was strongly thermally stratified and there were strong gradients in the DO and specific conductance profiles, see Figure 7. The water quality profile data are in appendix Table WQ1.

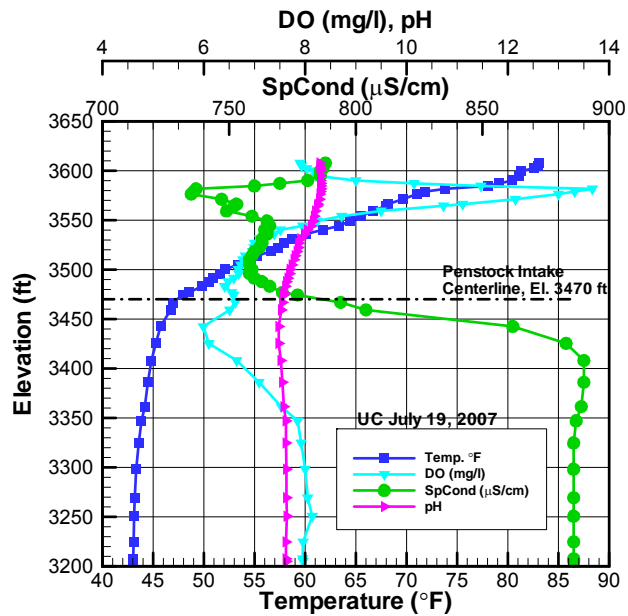


Figure 7. Plot of water quality profile data collected by GCMRC on July 19, 2007 at Wahweap Bay (LPCR0024). This profile was collected 5 days prior to measuring forebay velocity profiles.

September 25-26, 2007

After consulting with RD Instruments concerning the limited ADCP profiling range experienced during the July 2007 field trip, a modified instrument configuration was implemented on this field visit in an attempt to measure velocities for the entire water column. The ADCP was configured with a narrow bandwidth, rather than a wide bandwidth setting. This configuration worked very well and extended the profiling range to over 390 ft. The maximum forebay depth was about 425 ft.

Table 5 contains a summary of Lake Powell operations during the September 25-26, 2007 field data collection. Powerplant units 2, 4, 5, and 7 were in use during data collection.

Table 5. Lake Powell operations data for September 25-26, 2007

Reservoir Elevation (ft)	3601.9
Glen Canyon Dam Outflow (ft ³ /sec) 9/25/07 1830 to 2300	11,000
Release Temperature (°F) on 9/25	52.0
Colorado River Inflow (ft ³ /sec) 9/25	12,262
Glen Canyon Dam Outflow (ft ³ /sec) 9/26/07 1000 to 1500	12,500
Release Temperature (°F) on 9/26	52.0
Colorado River Inflow (ft ³ /sec) 9/26	15,294

ADCP profiles

On September 25, 2007, night time velocity profiles were collected along the forebay tagline. The weather was clear, calm and cool. A night time data set was collected from 1900 to 2300. Daytime ADCP data were collected September 26, 2007 from 1030 to 1415 in clear, calm, and warm conditions.

Figure 8 contains a plot of the daytime forebay velocity profiles for Units 2-7. While not shown, velocities were very repeatable for the day and night data sets. The maximum velocity was measured in front of Unit 4 and was 0.37 ft/sec at elevation 3,456 ft which is 14 ft below the intake centerline. However, this peak velocity was an outlier; peak velocities of 0.34 ft/sec were measured near the intake centerline for other profile locations. The velocity profile data indicate the upper and lower limits of withdrawal are at elevations 3,520 and 3,410 ft, respectively. Note: When velocity magnitudes approach zero the velocity direction data become very erratic because the ADCP is measuring acoustic noise which is random.

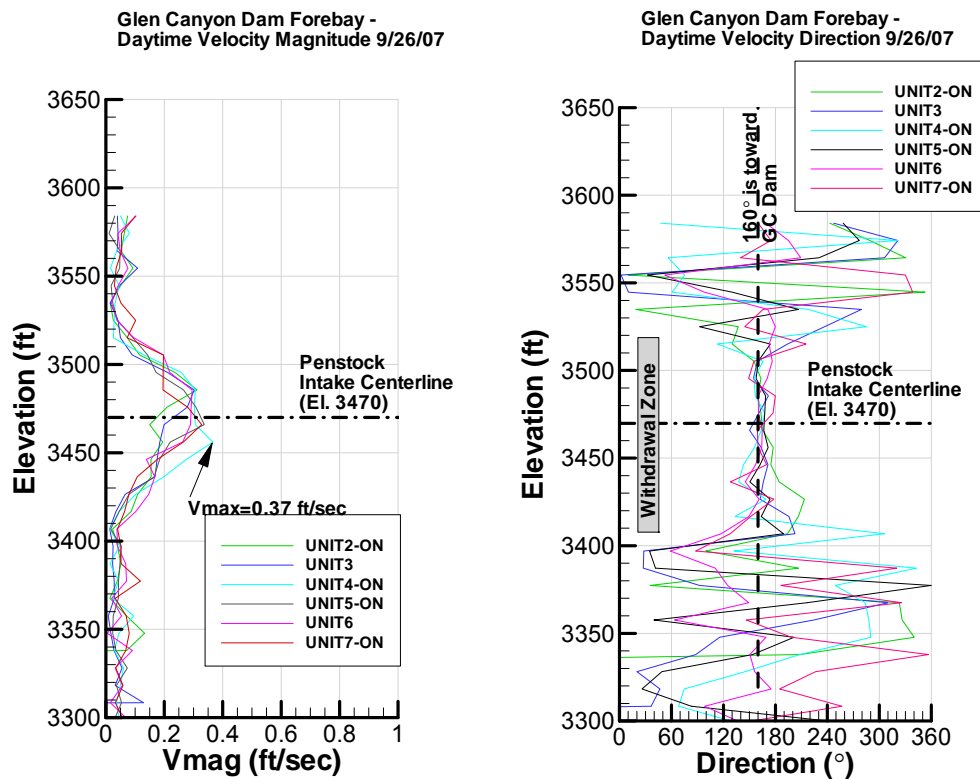


Figure 8. Plots of daytime velocity magnitude and direction for Units 2 through 7 on September 26, 2007.

Argonaut ADV Data

No ADV data were collected during this field visit.

Water Quality Profile

Figure 9 contains a plot of TSC water quality profile data collected on September 26, 2007 at Glen Canyon Dam. This profile was collected to a depth of 50 meters because a longer communication cable was not available. The data show the forebay was strongly thermally stratified and there were strong gradients in the DO and specific conductance profiles. The TSC water quality profile data are in appendix Table WQ2.

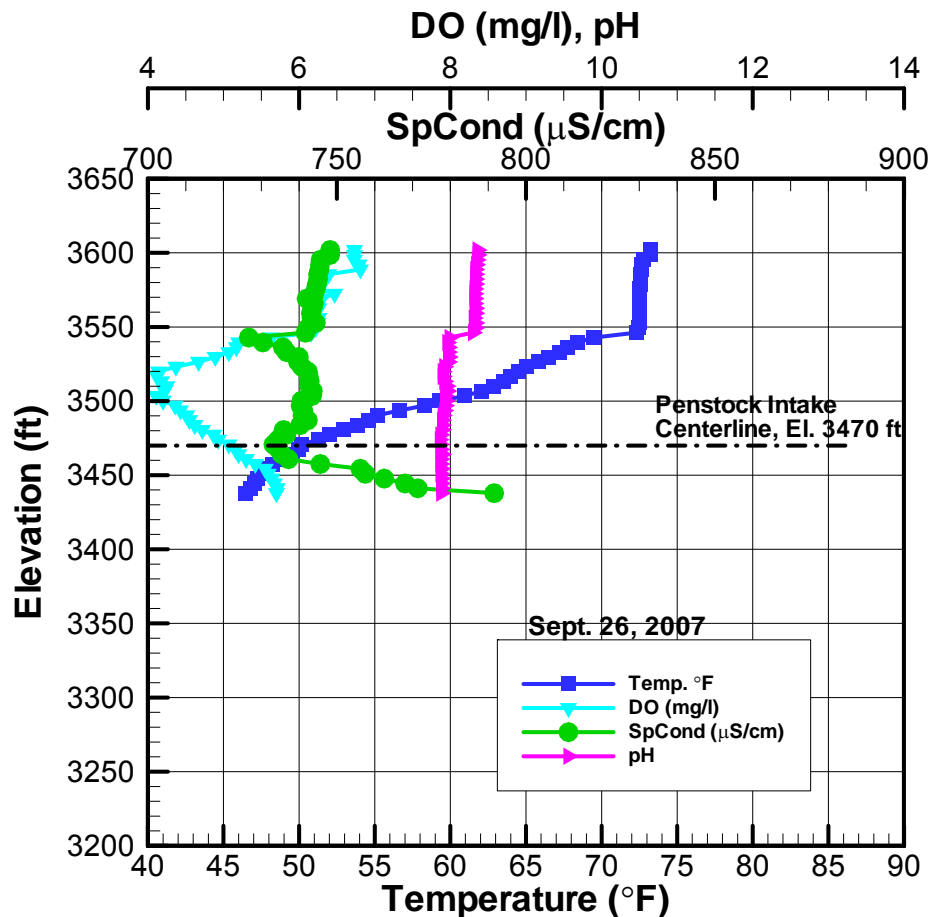


Figure 9. Plot of TSC water quality profile data collected on September 26, 2007 at Glen Canyon Dam.

March 6, 2008

On March 6, 2008, day and night time velocity profiles were collected along the forebay tagline at Glen Canyon Dam. The weather was clear, calm and cool during data collection. We collected a daytime data set from 1045 to 1430. The night time data set was collected from 1900 to 2230. This field visit was during a

high-flow experiment where dam releases of 41,000 ft³/sec were maintained for 60 hours.

ADCP data were collected at the typical six locations. An additional velocity profile was collected in front of Unit 8 in an effort to document the influence of the river outlet releases on the forebay velocity distribution. The Unit 8 profile was collected 866 ft from the canyon wall (Wall 1).

A summary of Lake Powell operations is contained in Table 6. Outflow and release temperature data were obtained from the USGS gage at Lees Ferry. Inflow and reservoir elevation data were obtained from the Upper Colorado Region's website. Glen Canyon Dam releases were steady at 41,000 ft³/sec for the duration of our data collection. The river releases were split between the river outlets and powerplant, and the flow distribution was 15,500 and 25,500 ft³/sec, respectively. Powerplant Units 1, 2, 3, 4, 6, 7, and 8 were operating at maximum capacity during the high flow test.

Table 6. Lake Powell operations data for March 6, 2008

Reservoir Elevation (ft)	3589.8
Glen Canyon Dam Outflow (ft ³ /sec)	41,000
Release Temperature (°C)	7.6
Release Specific Conductance (µS/cm)	820
Colorado River Inflow (ft ³ /sec)	10,617

ADCP profiles

Stationary ADCP velocity profiles were collected in front of Units 2 through 8. However, the profiling range at Unit 8 was much less than the other units because the canyon walls limited the ADCPs profiling range. The Glen Canyon Dam release flow had been steady for four hours prior to the start of data collection at 1045.

Daytime velocity profiles at six locations are plotted for comparison in Figure 10. The profile plots show the velocity magnitudes were similar at all locations. The maximum current speed measured in the penstock withdrawal zone was 0.41 ft/sec in front of Units 5 and 7. The peak velocity was measured at El. 3,483 ft which is 13 ft higher than the intake centerline elevation of 3,470 ft. It is interesting that a peak velocity was measured in front of a non-operating unit. This observation indicates that ADCP measurements were collected outside of the near-field withdrawal zone generated by individual penstock intakes. The velocity direction was very consistent at 121 degrees from north which was significantly different from the 160 degrees measured during previous field visits. The reason for this apparent change in velocity direction was found to be an

uncorrected bias in the ADCP compass calibration. A -39 degree compass bias was confirmed from the difference between the ADCP's boat heading and the tagline heading which was measured using GPS.

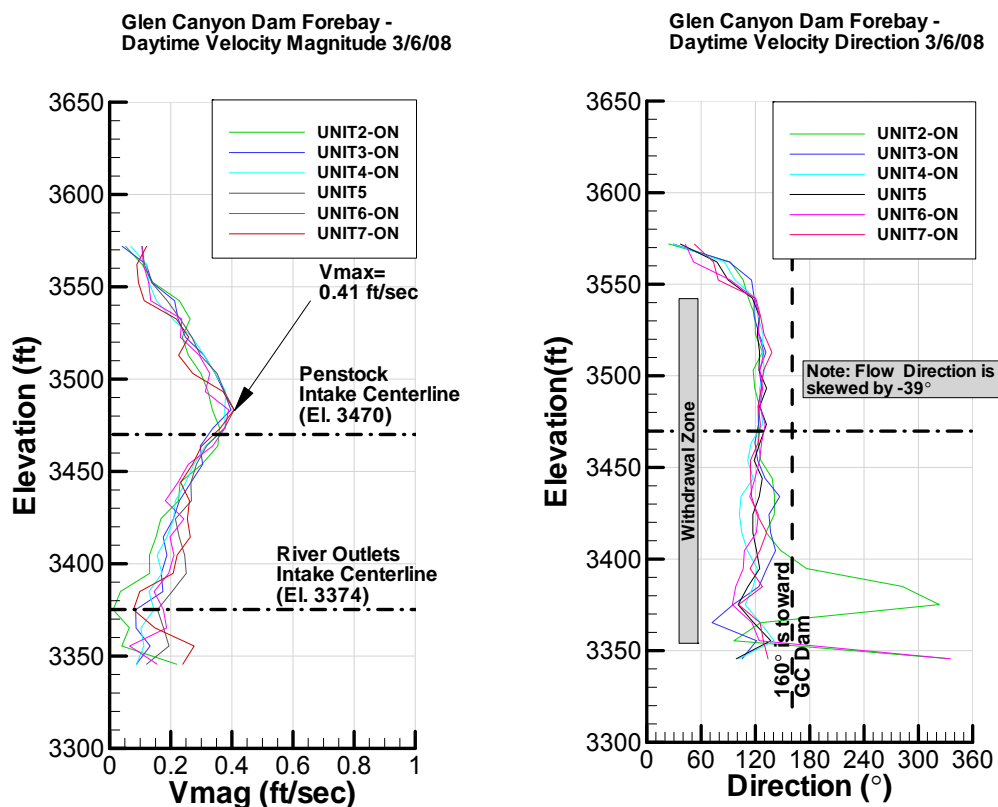


Figure 10. Plots of daytime velocity magnitude and direction for Units 2 through 7 on March 6, 2008. These profiles were collected during an experimental high flow that included river outlet works releases.

The velocity profiles indicate the approximate upper and lower limits of withdrawal are at elevations 3,540 and 3,355 ft, respectively. The withdrawal zone is considerably larger during the high flow test because of large releases from penstock and river outlet intakes at El. 3,470 and El. 3,374, respectively. The profile data also show velocities in the lower portion of the withdrawal zone are more variable in both speed and direction, with somewhat higher magnitudes near the river outlet intakes. ADCP data quality begins to degrade below El. 3,380 as illustrated by the increased variability in velocity directions. The variation in direction is likely influenced by local topographic features.

Night time data collection started at 1830 and was completed at 2250. ADCP data were only collected in front of unit 5 because of time constraints. The maximum current speed was measured to be 0.35 ft/sec at El. 3,483 ft. A comparison of the day and night time velocity profiles at the Unit 5 profiling site are plotted in Figure 11. The two velocity profiles are similar in shape, but the peak velocity was 0.06 ft/sec higher during the day. The reason for the difference

is unknown and is peculiar because the dam releases were steady during the entire high-flow test. It is also interesting that the peak velocities for both profiles were measured above the intake centerline.

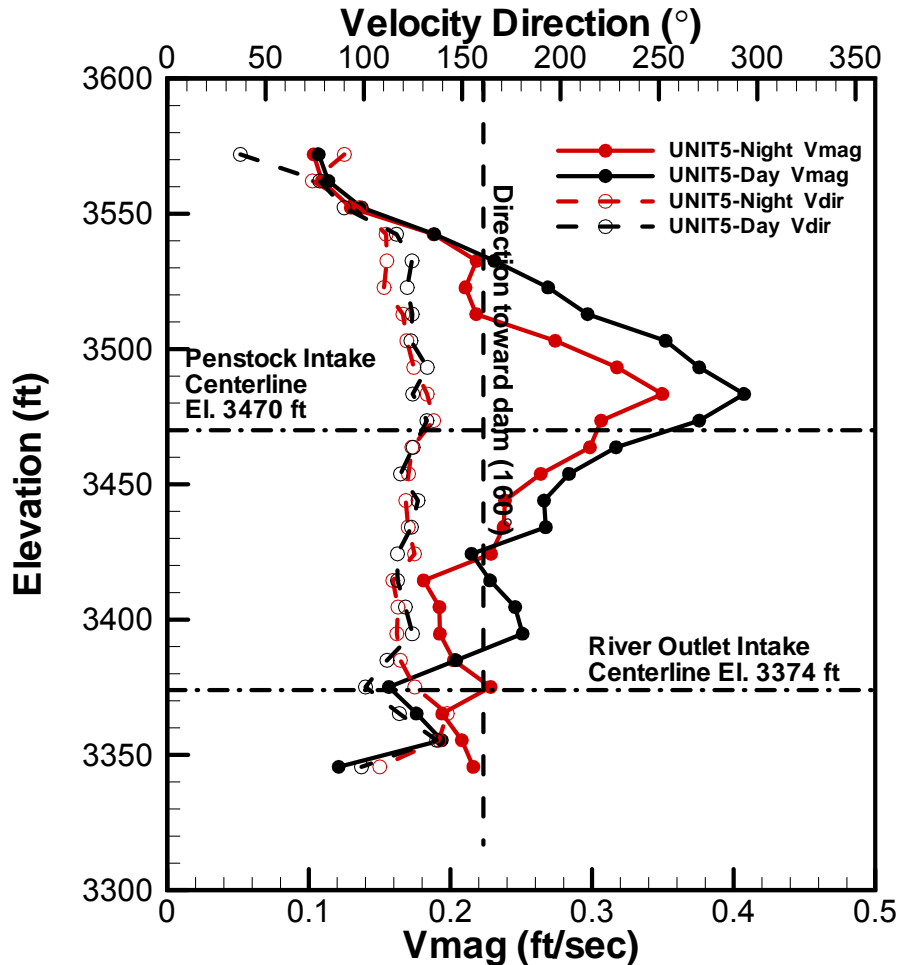


Figure 11. Comparison of day and night velocity profiles collected at Unit 5 on March 6, 2008.

Argonaut ADV Profile

No Argonaut ADV data were collected during this field visit.

Water Quality Profile

A Hydrolab sonde was used to collect a partial water quality profile at the Unit 5 station at 1600 on March 6, 2008. Data were collected with a 1 meter interval for the first 10 meters, then at a 5 m interval to a maximum depth of 50 meters. The profiling depth was limited by a 50-meter communications cable. Parameters collected were temperature, dissolved oxygen, specific conductivity, and pH. A complete set of water quality profiles were collected on March 8, 2008 by the USGS-GCMRC at the Wahweap Bay sampling site (Site I.D. LPCR0024), see

Figure 12. The temperature profile data show a weak thermal stratification in the forebay, but there was a strong gradient in the specific conductance and DO profiles at the penstock intake centerline, El. 3,470. The GCMRC water quality profile data are in appendix Table WQ3. The USGS-GCMRC has produced a report on the effects of the high flows on the water quality of Lake Powell and Glen Canyon Dam releases ([Vernieu 2010](#)). This open-file report describes water quality studies that were conducted before, during, and after the high flow experiment to determine the effects on Lake Powell's stratification in the forebay, and water quality of combined Glen Canyon Dam releases and changes that occurred in the stretch of tailwater below the dam.

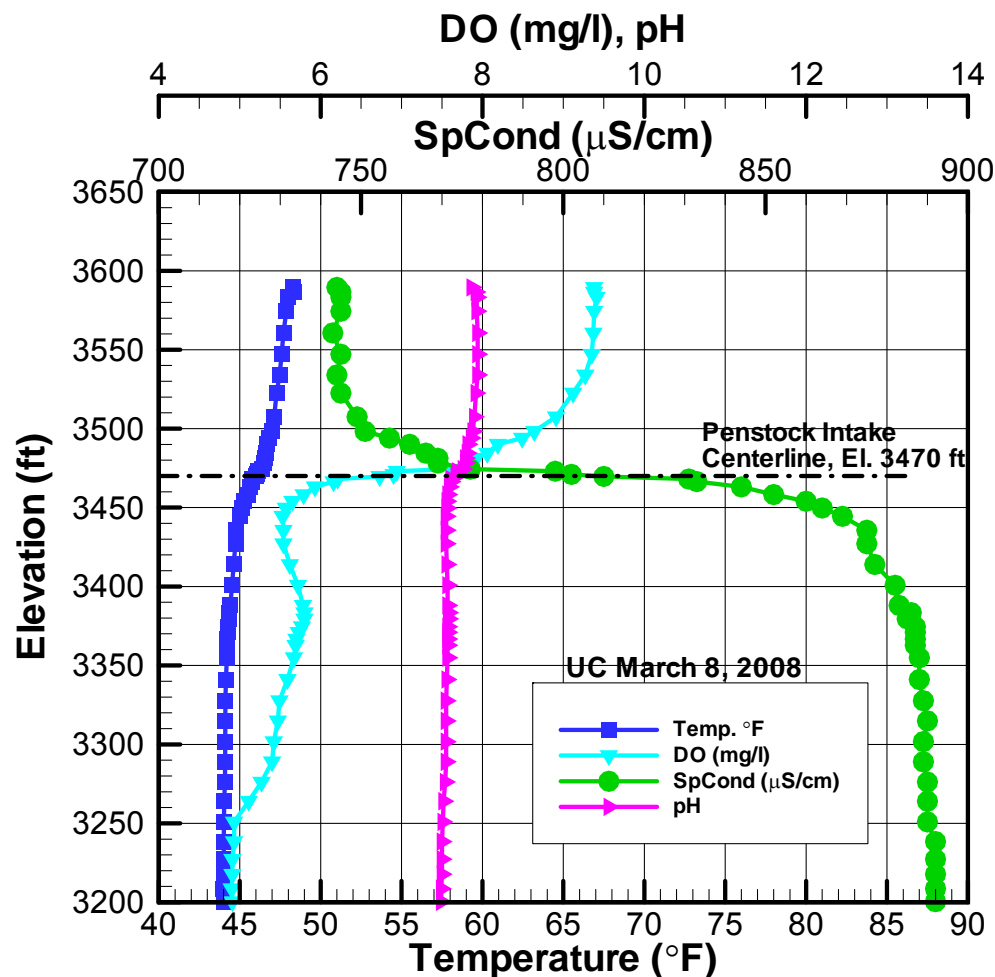


Figure 12. Plot of GCMRC water quality profile data collected on March 8, 2008 at Wahweap Bay near Glen Canyon Dam. These WQ data were collected near the end of the high flow test and should be representative of March 6 conditions.

May 29, 2008

On Thursday, May 29, 2008, night time velocity profiles and a water quality profile were collected in the forebay to Glen Canyon Dam. Data were collected from 2000 to 2240. The weather was clear, windy (from the SW) and warm during data collection. ADCP data were collected at Units 2 through 7. An additional profile in front of Unit 8 was collected because time permitted; however, the canyon walls interfered with acoustic profiler's data quality.

A summary of Lake Powell operations is contained in Table 7. Glen Canyon Dam releases were 15,700 ft³/sec during the night time data collection. Powerplant Units 1, 2, 4, 6, and 7 were running during data collection. Water temperature and specific conductance values were obtained from the Lees Ferry gage.

Table 7. Lake Powell operations data for May 29, 2008

Reservoir Elevation (ft)	3609.5
Glen Canyon Dam Outflow (ft ³ /sec)	15,700
Release Temperature (°F)	48.7
Release Specific Conductance (µS/cm)	798.3
Colorado River Inflow (ft ³ /sec)	55,416

ADCP profiles

Night time velocity profiles at seven locations are plotted for comparison in Figure 13. The profile plots show the velocity magnitudes were similar at all locations. The maximum current speed measured in the penstock withdrawal zone was 0.27 ft/sec in front of Unit 5 at El. 3,473 ft which is 3 ft above the intake centerline elevation of 3,470 ft. Another 0.27 ft/sec reading was measured at Unit 3 at El. 3,503.

The velocity profiles indicate the upper and lower limits of withdrawal are at elevations 3,530 and 3,420 ft, respectively. Note: When velocity magnitudes approach zero the direction data become very erratic because the ADCP is measuring acoustic noise which is random.

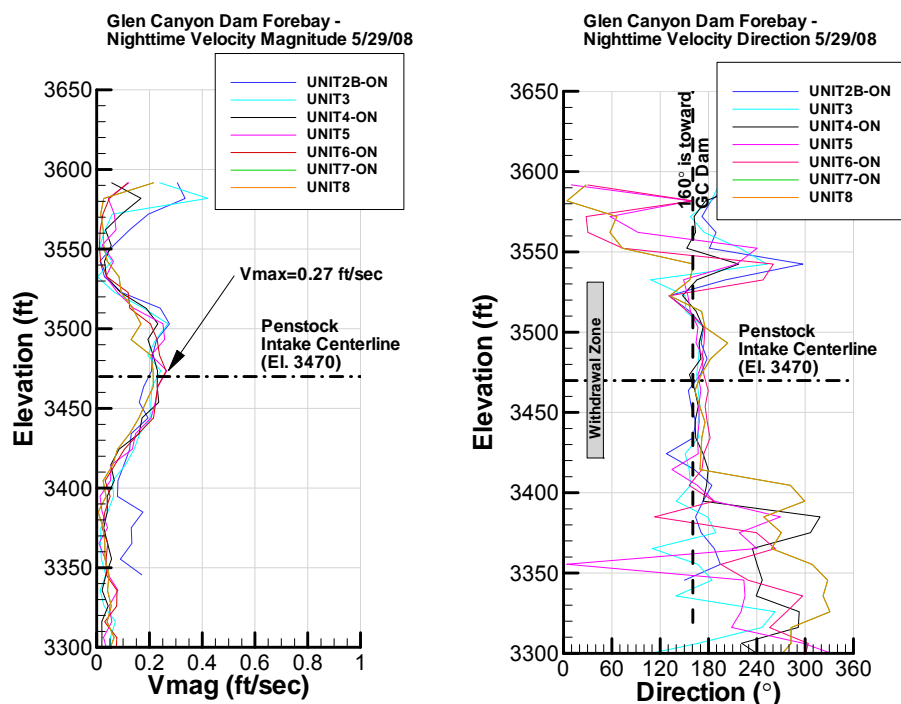


Figure 13. Plots of night time velocity magnitude and direction for Units 2 through 8 on May 29, 2008.

Argonaut ADV Profile

ADV data were collected at the centerline elevation of intakes 2 through 8 at Glen Canyon Dam while simultaneously collecting ADCP data. The data were collected during the evening of May 29, 2008 with Units 1, 2, 4, 6, and 7 releasing about 3,140 ft³/sec each.

A comparison of ADV and ADCP velocities showed the two instruments measured very similar withdrawal zone velocities at the intake centerline elevation. For example, at Unit 6's intake centerline elevation the ADCP measured velocities of 0.26 ft/sec at 174 degrees from north while the ADV measured 0.23 ft/sec at 163 degrees.

Water Quality Profile

A Hydrolab sonde was used to collect a high resolution water quality profile at Unit 5 profiling site at 1600 on May 29, 2008. Parameters collected were temperature, dissolved oxygen, specific conductivity, salinity, and pH. Figure 14 contains the profile plots of the water quality data. The TSC water quality profile data are in appendix Table WQ4.

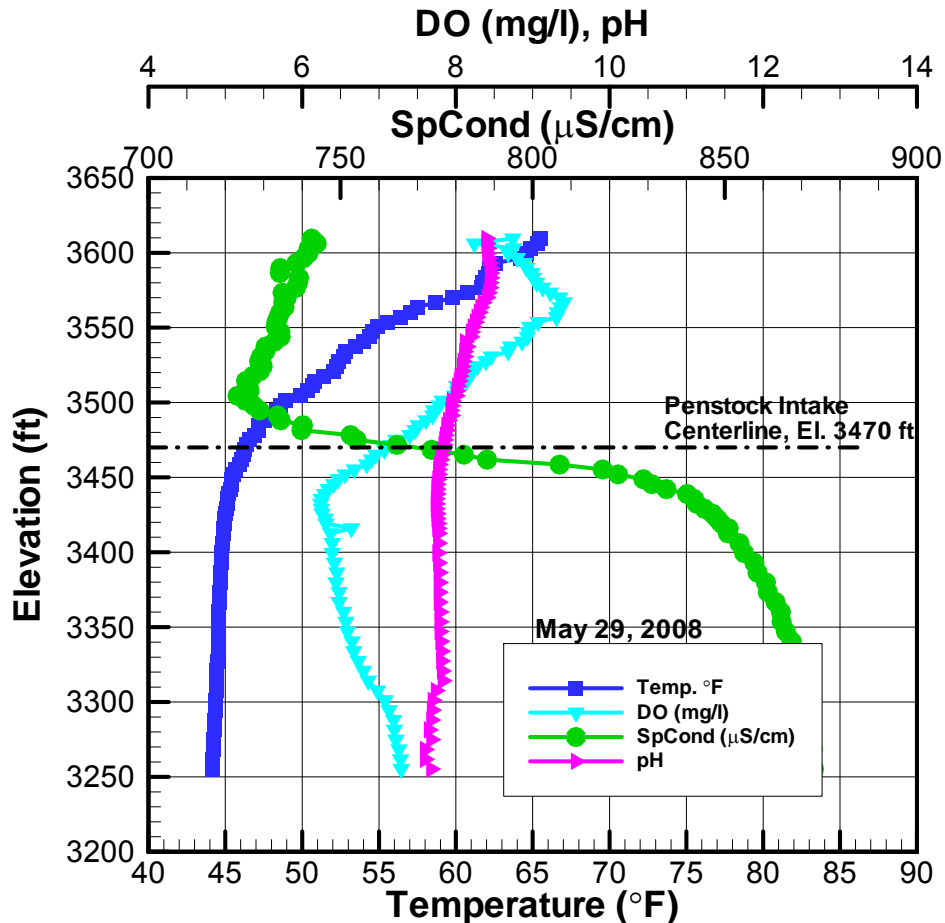


Figure 14. Plot of water quality profile data collected on May 29, 2008 at the forebay tagline at Glen Canyon Dam.

June 25, 2008

On June 25, 2008, daytime velocity profiles and a water quality profile were collected. The weather was clear, calm and warm during data collection. The data were collected from 1500 to 1630. No night time data were collected on this visit because of time constraints.

A summary of Lake Powell operations is contained in Table 8. Outflow, release temperature, and specific conductance data were obtained from the USGS gage at Lees Ferry. Outflows were also obtained periodically from powerplant operators. Inflow and reservoir elevation data were obtained from the Upper Colorado Region's website. Glen Canyon Dam releases were steady at 16,200 ft³/sec for the duration of data collection. The releases were from the powerplant only. Powerplant Units 1, 2, 4, 6, and 8 were in operation during data collection.

Table 8. Lake Powell operations data for June 25, 2008

Reservoir Elevation (ft)	3629.1
Glen Canyon Dam Outflow (ft ³ /sec)	16,200
Release Temperature (°F)	49.8
Release Specific Conductance (μS/cm)	760
Colorado River Inflow (ft ³ /sec)	46,744

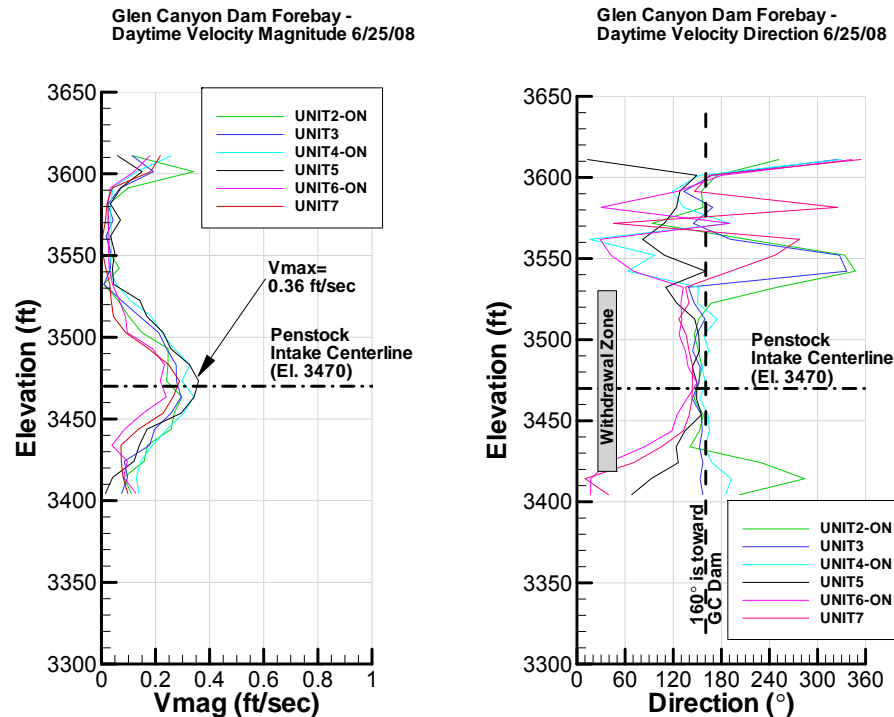


Figure 15. Plots of daytime velocity magnitude and direction for Units 2 through 7 on June 25, 2008.

ADCP profiles

Day time velocity profiles at six locations are plotted for comparison in Figure 15. The profile plots show the velocity profiles had similar shapes, but velocity magnitudes were more variable than previous measurements. The maximum current speed measured in the penstock withdrawal zone was 0.36 ft/sec in front of Unit 5 at El. 3,473 ft which is 3 ft above the intake centerline elevation of 3,470 ft.

The velocity profiles indicate the upper and lower limits of withdrawal are at elevations 3,530 and 3,420 ft, respectively.

Argonaut ADV Measurements

ADV data were collected at the centerline elevation of intakes 2 through 7. The data were collected from 1450 to 1640 on June 25, 2008 with Units 1, 2, 4, 6, and 8 releasing 3,100 ft³/sec each. A comparison of ADV and ADCP velocities showed the two instruments measured very similar withdrawal zone velocities at

the intake centerline elevation. For example, at Unit 7's intake centerline elevation the ADCP measured velocities of 0.29 ft/sec at 144 degrees from north while the ADV measured 0.25 ft/sec at 160 degrees.

Water Quality Profile

A Hydrolab sonde was used to collect a high resolution water quality profile at the Unit 5 station on June 26, 2008 at 1400. Data were collected with a 1-m interval for the first 60 m, then at a 2 m interval to a maximum depth of 100 m. Water quality parameters collected were temperature, dissolved oxygen, specific conductivity, salinity, and pH. Figure 16 contains a profile plot of the water quality data. The TSC water quality profile data are in appendix Table WQ5.

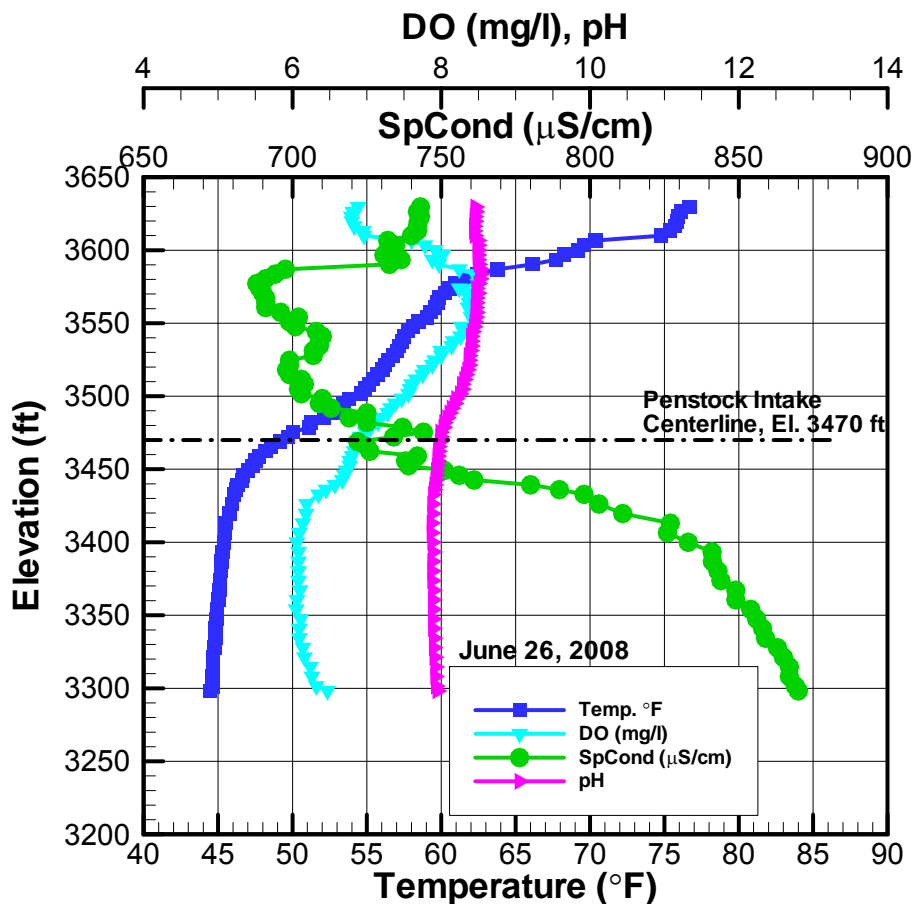


Figure 16. Plot of water quality profile data collected on June 26, 2008 at the forebay tagline at Glen Canyon Dam.

ADCP and ADV Velocity Comparisons

May 29, 2008

In an effort to validate the accuracy of the ADCP data, ADV data were collected at the centerline elevation of intakes 2 through 8 at Glen Canyon Dam. The data were collected during the evening of May 29, 2008 with Units 1, 2, 4, 6, and 7 releasing 3,000 ft³/sec per unit. Table 9 contains average ADV velocity data, elevation and temperature for the seven locations sampled. Table 10 contains average ADCP velocity data collected simultaneously with the ADV data. There is good agreement between these independent velocity measurements. However, ADV velocity directions appear to have a bias of about -11 degrees.

In general, velocity directions reported by both instruments were variable for the five data sets. From the alignment of the forebay, water moving toward the penstocks should be directed parallel to the canyon walls (160 degrees clockwise from north). Compass calibrations were performed as per the manufacturer's instructions, but the ADCP compass calibration method is not suited for on-the-water calibration because the tilt angle has to be constant during the calibration procedure. As a result, the ADCP compass calibration was performed on the dock near the boat. The Sontek compass calibration was usually performed on the boat where magnetic fields from the boat, motor, or other equipment can affect the compass calibration. However, these magnetic fields will not be present at the depths where ADV velocities are being measured. For future reservoir velocity measurements, the ADV's compass should be calibrated on-shore in an area away from any stray magnetic fields.

Table 9. Summary of far-field penstock intake velocities collected with an ADV from 2000 to 2240 on May 29, 2008.

Unit No. (Status)	ADV Velocity Magnitude (ft/sec)	ADV Velocity Direction (° from north)	Elev. (ft)	Water Temperature (° F)
1 (on)	n/a	n/a	n/a	n/a
2 (on)	0.17	166	3482	46.4
3 (off)	0.22	170	3481	46.8
4 (on)	0.23	154	3480	46.6
5 (off)	0.19	159	3478	46.5
6 (on)	0.23	163	3478	46.4
7 (on)	0.21	164	3478	46.5
8 (off)	0.15	151	3478	46.5

Table 10. Summary of far-field penstock intake velocities collected with an ADCP from 2000 to 2240 on May 29, 2008. The velocity magnitudes compare closely with ADV data collected simultaneously. The bias in velocity direction is attributed to the ADV compass calibration.

Unit No. (Status)	ADCP Velocity Magnitude (ft/sec)	ADCP Velocity Direction (° from north)	Elev. (ft)	Water Temperature (° F)
1 (on)	n/a	n/a	n/a	n/a
2 (on)	0.19	171	3483	n/a
3 (off)	0.19	168	3483	n/a
4 (on)	0.21	171	3483	n/a
5 (off)	0.21	174	3483	n/a
6 (on)	0.24	172	3483	n/a
7 (on)	0.21	183	3483	n/a
8 (off)	n/a	n/a	n/a	n/a

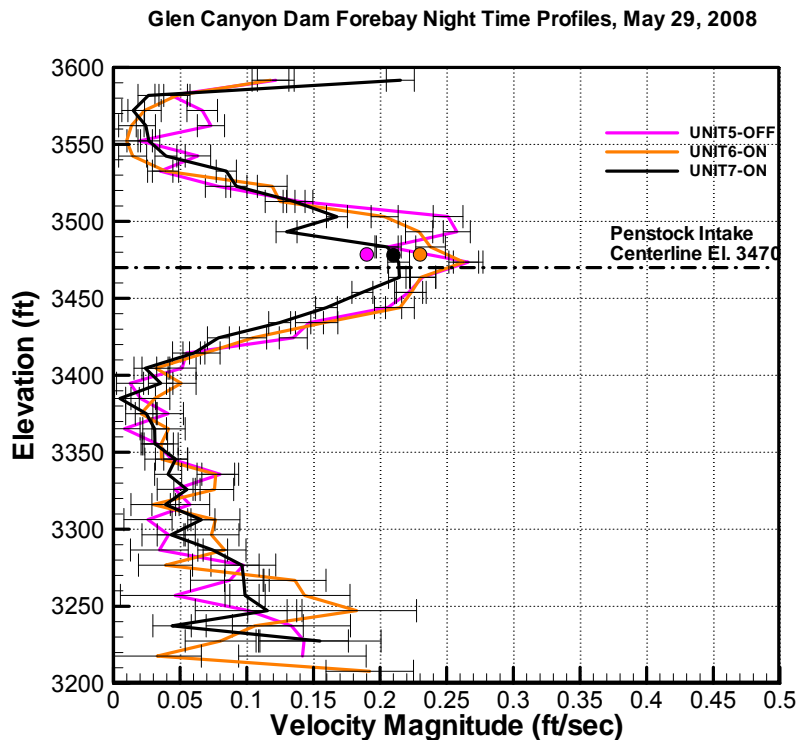


Figure 17. Comparison plot of ADCP profiles collected 420 ft upstream from the penstock intakes for units 5, 6, and 7 and corresponding ADV velocity (colored circles) measured near the intake centerline elevation.

A comparison of ADV and ADCP velocity magnitudes showed good agreement considering the ADV measurement includes minor boat motion that adds a bias to velocity magnitudes. Wavy conditions will increase the bias in ADV measurements because of increased boat motion. Figure 17 is a plot of the average ADCP profiles (horizontal error bars represent the standard error range of each average velocity) and average ADV measurements collected at Units 5, 6, and 7 on May 29, 2008. The ADV velocities were typically within the standard error range of their corresponding ADCP velocity

June 25, 2008

A second velocity comparison for daytime velocities collected on June 25, 2008 verified the close agreement between ADCP and ADV velocity measurements. The average penstock centerline velocities measured by the ADV and ADCP are summarized in Tables 11 and 12, respectively. Table 13 contains a summary of the average of the six forebay velocities collected at the intake centerline elevation using an ADV and ADCP. In general, agreement between the average velocities is very good.

Table 11. Summary of far-field penstock intake velocities collected with an ADV from 1510 to 1635 on June 25, 2008. Units 1,2,4,6, and 8 were releasing a total of 15,500 ft³/sec.

Unit No. (Status)	ADV Velocity Magnitude \pm SE (ft/sec)	ADV Velocity Direction \pm SE (° from north)	Elev. (ft)	Water Temperature (° F)
1 (on)	n/a	n/a	n/a	n/a
2 (on)	0.25 \pm 0.012	146 \pm 1	3472.6	48.1
3 (off)	0.28 \pm 0.026	156 \pm 4	3472.8	48.1
4 (on)	0.33 \pm 0.024	150 \pm 1	3472.8	47.9
5 (off)	0.28 \pm 0.020	161 \pm 5	3472.6	48.0
6 (on)	0.32 \pm 0.019	159 \pm 1	3472.6	47.3
7 (off)	0.25 \pm 0.016	160 \pm 1	3472.4	47.1
8 (on)	n/a	n/a	n/a	n/a

Table 12. Summary of far-field penstock intake velocities collected with an ADCP from 1510 to 1635 on June 25, 2008.

Unit No. (Status)	ADCP Velocity Magnitude \pm SE (ft/sec)	ADCP Velocity Direction \pm SE (° from north)	Elev. (ft)	Water Temperature (° F)
1 (on)	n/a	n/a	n/a	n/a
2 (on)	0.24 \pm 0.013	152 \pm 5	3473.1	n/a
3 (off)	0.28 \pm 0.011	152 \pm 4	3473.1	n/a
4 (on)	0.30 \pm 0.015	160 \pm 5	3473.1	n/a
5 (off)	0.36 \pm 0.016	150 \pm 4	3473.1	n/a
6 (on)	0.22 \pm 0.010	150 \pm 4	3473.1	n/a
7 (off)	0.29 \pm 0.012	144 \pm 4	3473.1	n/a
8 (on)	n/a	n/a	n/a	n/a

Table 13. Comparison of average forebay ADV and ADCP velocities collected near the penstock intake centerline elevation (El. 3470) on June 25, 2008. The agreement between velocity data is acceptable and within the measurement uncertainty range of each instrument.

Profile Location	ADV			ADCP		
	Depth (ft)	Vmag (ft/sec)	Vdir (°)	Depth (ft)	Vmag (ft/sec)	Vdir (°)
Overall forebay average	156.5	0.27	156.7	155.9	0.28	151.1

Penstock Intake Withdrawal Zone Analysis

Withdrawal zone characteristics of a penstock intake depends upon the discharge, density stratification, intake geometry, forebay bathymetry, and ambient reservoir currents. Any variation of these factors could change the flow field and the release water quality. Penstock intakes can be characterized as either a point or line sink. Typically, a single intake at a given elevation is characterized as a point sink. Conversely, a series of penstock intakes at the same elevation will approximate a line sink. The eight penstock intakes at Glen Canyon will approximate a line sink under most flow conditions. This concept is supported by previous studies which have reported that no significant difference in water quality exists in discharges from the various penstocks across the face of Glen Canyon Dam (Hart and Sherman, 1996).

In general, the vertical extent of the withdrawal zone will not vary greatly in response to moderate changes in discharge. The presence of a strong density gradient (a thermocline) can create an asymmetrical withdrawal zone. On the other hand, regions with little or no density gradient allow an unrestricted expansion of the withdrawal zone. In general, the withdrawal zone will be fully established within one withdrawal zone thickness upstream from the intake. If physical obstructions like reservoir bathymetry or canyon walls are present near the intakes, the development of the withdrawal zone characteristics may be altered.

For Glen Canyon's powerplant intakes, the withdrawal zone is on-average about 100 ft thick, so the near-field acceleration zone is within about 100 ft from the face of the dam. Beyond 100 ft upstream, the withdrawal zone's vertical extent will remain nearly constant for as long as the flow and stratification is unchanged. Daily fluctuations in powerplant releases will alter the withdrawal zone to some degree and can result in minor changes to the release water quality (e.g. temperature, DO and specific conductance). Furthermore, withdrawal zone extents will vary seasonally with changes to the reservoirs density stratification or can vary with strong wind events. Strong winds can create seiches which can dramatically alter the thickness of the epilimnion for several hours at a time. Depending on wind direction, seiches can increase or decrease the epilimnion thickness.

Near-Field Penstock Intake Velocities

In September 2006, a grid of near-field penstock intake velocities were collected in front of the intake trash racks for a single unit with flows of 2,600 and 3,600 ft³/sec (Vermeyen 2006). The strongest horizontal velocities in the forebay were measured near the penstock intake centerline elevation, El. 3,470. Under steady

flows, the maximum near-field velocity (measured adjacent to the trashrack bars) was 1.64 ft/sec at El. 3,459 ft as unit 7 was releasing 3,600 ft³/sec. Velocity magnitudes quickly dropped with distance from the operating unit's trash rack. Currents decreased to less than 0.4 ft/sec at a distance of 20 ft from the operating intake for high flows (3,600 ft³/sec). Similarly, currents decreased to less than 0.4 ft/sec at a distance of 15 ft from the operating intake for typical penstock flows (2,600 ft³/sec). No near-field penstock intake velocities were collected during the 2007 and 2008 field visits.

Far-Field Penstock Intake Velocities

Figure 18 is a plot of average forebay velocity profiles for the five field visits. Each velocity profile is the average of the six forebay profiles collected at the tagline stations in front of units 2-7 on a given day. Comparison of the profiles shows that most of the variation in withdrawal zone thickness occurs above the intake centerline elevation (El. 3,470 ft). The reason for the variation is the seasonal position and strength of the thermocline and its effect on withdrawal zone expansion. The average far-field velocity profile data used for Figure 18 are included in the appendix in table V1 through V5.

The March 6, 2008 velocity profile is significantly different from the others because of the high discharge and a weak thermocline (see Figure 12). The high flow velocity profile is truncated because of the overlapping withdrawal zones associated with the 15,500 ft³/sec release from the river outlet works. Furthermore, when the withdrawal zone velocities were less than 0.2 ft/sec the data quality began to deteriorate, so the velocity data were not plotted.

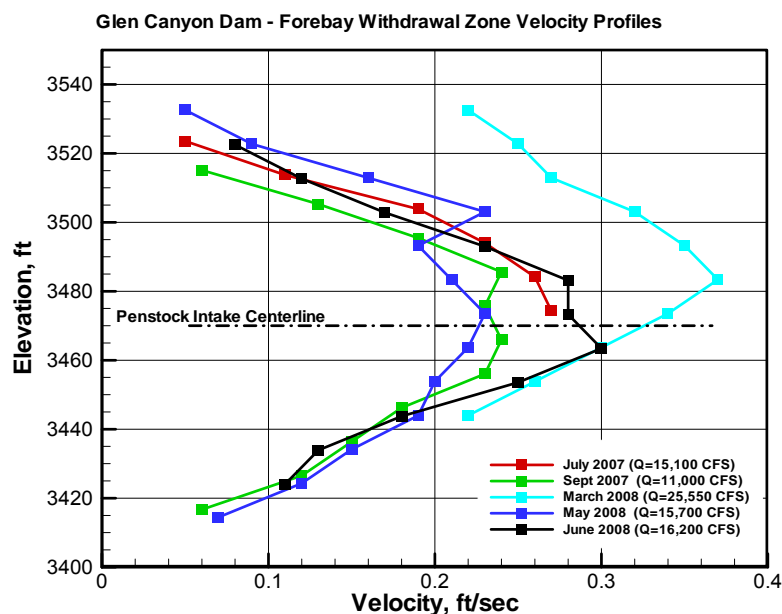


Figure 18. Comparison of average forebay withdrawal zone velocity profiles for five field visits between July 2007 and June 2008.

The lower portion of the five withdrawal zones (below the intake centerline) was very uniform because they pull water from the hypolimnion which does not have much seasonal variation in density.

Table 14 contains a summary of the forebay withdrawal characteristics for the five site visits. The average withdrawal zone velocity was determined by integrating the velocity profile over the withdrawal zone thickness. These data show that there is a small seasonal variation in the penstock intake approach velocity. The peak velocity is the maximum velocity measured in the withdrawal zone and was usually located near the intake centerline elevation, El. 3,470 ft. However, there did appear to be a trend for the peak velocity to move above the intake centerline elevation for higher flows. For example, during the high flow test, the peak velocity was measured at El. 3,485 ft. Unfortunately, there were not enough measurements over a wide range of flows to quantify this phenomenon. Elevations of the upper and lower limit of withdrawal were estimated from the ADCP velocity profiles.

Table 14. Summary of Glen Canyon Penstock Intake Withdrawal Profile Characteristics.

Date	Powerplant Flow (ft ³ /sec)	Water Surface Elevation (ft)	Upper/Lower Limit of Withdrawal, El. (ft)	Average W/D Velocity (ft/sec)	Peak W/D Velocity (ft/sec)
July 23, 2007	15,100	3609	3520/3430	0.19	0.27
Sept. 25, 2007	11,000	3602	3520/3410	0.18	0.24
March 6, 2008	25,500*	3590	3540/3355	0.30	0.37
May 29, 2008	15,700	3610	3530/3420	0.17	0.23
June 25, 2008	16,200	3629	3530/3420	0.23	0.28

*During the high flow test 15,500 ft³/sec was being released from the river outlet works

Conclusions

Five measurements of the far-field withdrawal zone velocities were collected to describe the seasonal forebay flow fields created by the penstock intakes on Glen Canyon Dam. This set of far-field velocity profiles showed there were small seasonal changes to the vertical extent of the penstock withdrawal zone and the average velocity. Changes to the flow field were confined to the upper half of the withdrawal zone i.e. above intake centerline elevation of 3,470 ft. For reservoir elevations between El. 3,590 and 3,630 ft, withdrawal zone variations are confined to the upper half because the seasonal variations in the thermocline strength and location take place above El. 3,470 ft.

In general, peak withdrawal velocities occurred near the penstock intake centerline elevation and they were less than 0.30 ft/sec. During the high flow test (March 6-8, 2008) a peak far-field velocity of 0.37 ft/sec was measured. The total powerplant release during the high flow was 25,500 ft³/sec with an additional

15,500 ft³/sec being released from the river outlet works. It is possible that the peak velocity would be higher during summertime stratification because the withdrawal zone extents would be constrained by a stronger thermocline.

The average far-field velocity generated by the two river outlet works was about 0.11 ft/sec at elevation 3,375 ft (the river outlet's withdrawal water from a centerline elevation of 3,374 ft or 96 ft below the penstock intakes). River outlet withdrawal zone velocity measurements were difficult to measure using an ADCP because the intakes are in close proximity to the canyon wall which limits the ADCPs measurement range.

ADCP data were very repeatable at the six sampling stations in the Glen Canyon Dam forebay. The uniformity of the velocity distribution across the canyon indicates that when the majority (4 or more) of the units are operational the penstock withdrawal acts as a line sink which creates a two-dimensional flow field that can be described by a single velocity profile measured near the center of the canyon at a distance of at least 250 ft uplake. The location of the security boom, about 0.25 miles uplake, would be a good site for any future velocity profile measurements.

There appeared to be a trend for the peak far-field velocity to move above the intake centerline elevation for higher flows. For example, during the high flow test, the peak velocity was measure at El 3,485 ft – about 15 ft above the intake centerline. This penstock intake withdrawal characteristic may need to be incorporated in any reservoir water quality models to accurately predict long-term trends in Lake Powell's water quality.

The independent ADV and ADCP measurements produced velocities that were comparable within the uncertainty range of the two instruments which support the use of either instrument for withdrawal zone measurements. However, it is essential to collect ADV data under calm lake conditions to minimize boat motion and to acquire the highest quality data.

The ADCP was by far the most efficient means to measure withdrawal zone characteristics in the Glen Canyon Dam forebay. It was necessary to collect several hundred profiles over a 15 to 20 minute period to average out the random variations in ADCP velocity profile measurements.

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Appendix - Average Far-Field Velocity Profiles

Table V1. Average velocity profile collected at night on July 23, 2007. The shaded data is within the penstock intake's withdrawal zone. Data below the intake centerline elevation (El. 3470) are considered suspect, so only the upper half of the withdrawal zone is shaded.

Elevation (ft)	Depth (ft)	Vmag (ft/sec)	Standard Error Vmag (ft/sec)	Vdir °	Standard Error Vdir °	Number of profiles in sample
3591.82	16.18	0.03	0.02	109.35	10.19	162
3581.97	26.03	0.04	0.02	139.29	9.91	159
3572.13	35.87	0.04	0.01	150.26	9.92	163
3562.29	45.71	0.03	0.02	172.08	9.91	164
3552.45	55.55	0.04	0.02	165.89	9.96	158
3542.60	65.40	0.04	0.02	187.00	9.80	164
3532.76	75.24	0.03	0.02	146.50	10.12	163
3522.92	85.08	0.06	0.02	182.68	9.58	162
3513.08	94.92	0.13	0.02	165.08	8.09	161
3503.23	104.77	0.21	0.02	156.27	6.46	164
3493.39	114.61	0.26	0.02	160.87	5.77	166
3483.55	124.45	0.28	0.02	166.03	5.52	167
3473.71	134.29	0.28	0.02	165.37	5.17	165
3463.86	144.14	0.29	0.02	164.24	5.18	157
3454.02	153.98	0.34	0.02	180.01	5.24	147
3444.18	163.82	0.42	0.02	195.57	5.43	133
3434.34	173.66	0.59	0.03	202.51	5.76	122
3424.49	183.51	0.94	0.04	202.70	5.66	122
3414.65	193.35	1.16	0.04	205.43	6.01	127
3404.81	203.19	1.23	0.04	207.60	6.22	124
3394.97	213.03	1.08	0.05	211.51	6.60	116
3385.12	222.88	0.86	0.03	214.71	6.93	120
3375.28	232.72	0.80	0.03	215.58	7.19	115
3365.44	242.56	0.72	0.03	217.32	7.37	109
3355.60	252.40	0.72	0.04	222.23	8.33	85

Table V2. Average velocity profile collected September 25, 2007. The shaded data is within the penstock intake's withdrawal zone.

Elevation (ft)	Depth (ft)	Vmag (ft/sec)	Standard Error Vmag (ft/sec)	Vdir °	Standard Error Vdir °	Number of profiles in sample
3584.02	18.01	0.05	0.02	159.49	9.05	134
3574.18	27.85	0.05	0.02	181.34	9.03	137
3564.34	37.70	0.06	0.02	167.75	9.03	132
3554.49	47.54	0.06	0.02	135.16	9.38	136
3544.65	57.38	0.04	0.02	157.31	9.28	135
3534.81	67.22	0.03	0.02	132.97	9.23	134
3524.97	77.07	0.04	0.02	197.53	9.00	135
3515.12	86.91	0.06	0.02	163.10	8.58	136
3505.28	96.75	0.13	0.02	159.91	7.69	139
3495.44	106.59	0.19	0.02	164.11	7.08	136
3485.60	116.44	0.24	0.02	167.64	6.33	143
3475.75	126.28	0.23	0.02	165.24	6.64	139
3465.91	136.12	0.24	0.02	162.31	6.51	138
3456.07	145.96	0.23	0.02	168.78	6.66	139
3446.23	155.81	0.18	0.02	167.05	7.12	140
3436.38	165.65	0.15	0.02	155.50	7.59	140
3426.54	175.49	0.12	0.02	165.81	7.97	133
3416.70	185.33	0.06	0.02	160.31	8.77	133
3406.86	195.18	0.04	0.02	187.17	9.02	134
3397.01	205.02	0.05	0.02	109.84	9.34	131
3387.17	214.86	0.05	0.02	132.15	9.15	132
3377.33	224.70	0.06	0.02	154.32	9.31	130
3367.49	234.55	0.04	0.02	201.44	9.46	127
3357.64	244.39	0.05	0.02	167.05	9.19	128
3347.80	254.23	0.04	0.02	205.58	9.81	122
3337.96	264.07	0.04	0.02	142.55	9.86	114
3328.12	273.92	0.05	0.02	129.92	7.47	112
3318.27	283.76	0.03	0.02	118.29	7.70	111
3308.43	293.60	0.04	0.02	92.13	9.25	98
3298.59	303.44	0.03	0.01	145.87	7.12	92
3288.75	313.29	0.04	0.02	134.60	7.29	95
3278.90	323.13	0.02	0.01	138.76	7.10	98

Table V3. Average velocity profile collected March 6, 2008. The shaded data is within the penstock intake's withdrawal zone. Velocities below El. 3444 are attributed to the river outlet releases.

Elevation (ft)	Depth (ft)	Vmag (ft/sec)	Standard Error Vmag (ft/sec)	Vdir °	Standard Error Vdir °	Number of profiles in sample
3571.95	17.81	0.08	0.01	41.42	5.56	402
3562.11	27.65	0.11	0.01	80.58	5.14	410
3552.27	37.50	0.13	0.01	95.71	4.77	414
3542.43	47.34	0.16	0.01	116.54	4.26	420
3532.58	57.18	0.22	0.01	123.16	3.77	430
3522.74	67.02	0.25	0.01	125.55	3.48	437
3512.90	76.87	0.27	0.01	131.02	3.22	444
3503.06	86.71	0.32	0.01	124.73	2.89	455
3493.21	96.55	0.35	0.01	126.06	2.61	459
3483.37	106.39	0.37	0.01	124.33	2.54	469
3473.53	116.24	0.34	0.01	125.15	2.77	461
3463.69	126.08	0.30	0.01	120.97	3.29	438
3453.84	135.92	0.26	0.01	116.90	3.63	430
3444.00	145.76	0.22	0.01	125.44	3.95	410
3434.16	155.61	0.22	0.01	120.90	4.30	382
3424.32	165.45	0.22	0.01	123.34	4.33	357
3414.47	175.29	0.20	0.01	123.97	4.69	328
3404.63	185.13	0.19	0.01	125.83	5.06	291
3394.79	194.97	0.19	0.02	129.42	6.22	223
3384.95	204.82	0.13	0.02	143.59	7.28	194
3375.10	214.66	0.11	0.02	137.25	7.96	212
3365.26	224.50	0.13	0.03	113.69	10.40	106
3355.42	234.34	0.14	0.04	124.70	15.34	73
3345.58	244.19	0.15	0.06	184.53	21.93	59

Table V4. Average velocity profile collected May 29, 2008. The shaded data is within the penstock intake's withdrawal zone.

Elevation (ft)	Depth (ft)	Vmag (ft/sec)	Standard Error Vmag (ft/sec)	Vdir °	Standard Error Vdir °	Number of profiles in sample
3591.65	17.93	0.16	0.01	112.73	6.19	306
3581.80	27.78	0.14	0.01	141.05	5.10	330
3571.96	37.62	0.06	0.01	99.31	6.00	305
3562.12	47.46	0.05	0.01	102.09	5.70	335
3552.28	57.30	0.03	0.01	134.83	5.87	333
3542.43	67.15	0.04	0.01	213.39	5.76	323
3532.59	76.99	0.05	0.01	171.12	5.62	322
3522.75	86.83	0.09	0.01	140.37	5.33	328
3512.91	96.67	0.16	0.01	161.44	4.43	343
3503.06	106.52	0.23	0.01	172.57	3.84	348
3493.22	116.36	0.19	0.01	177.77	4.18	340
3483.38	126.20	0.21	0.01	174.83	4.04	341
3473.54	136.04	0.23	0.01	168.63	3.91	343
3463.69	145.89	0.22	0.01	166.81	3.91	348
3453.85	155.73	0.20	0.01	167.99	4.15	341
3444.01	165.57	0.19	0.01	167.63	4.25	337
3434.17	175.41	0.15	0.01	168.81	4.64	339
3424.32	185.26	0.12	0.01	160.94	4.97	332
3414.48	195.10	0.07	0.01	160.47	5.37	329
3404.64	204.94	0.05	0.01	203.00	5.63	329
3394.80	214.78	0.05	0.01	203.37	5.70	324
3384.95	224.63	0.04	0.01	204.72	5.72	326
3375.11	234.47	0.04	0.01	240.68	5.80	325
3365.27	244.31	0.04	0.01	206.34	5.81	317
3355.43	254.15	0.04	0.01	178.92	6.05	299
3345.58	264.00	0.06	0.02	230.58	7.69	253
3335.74	273.84	0.05	0.01	257.58	6.19	307
3325.90	283.68	0.05	0.01	285.67	6.51	287
3316.06	293.52	0.04	0.01	261.26	6.52	266
3306.22	303.36	0.05	0.01	259.06	7.17	234
3296.37	313.21	0.05	0.02	251.40	7.69	211
3286.53	323.05	0.06	0.02	232.42	7.45	215
3276.69	332.89	0.07	0.02	225.52	8.54	175

Table V5. Average velocity profile collected June 25, 2008. The shaded data is within the penstock intake's withdrawal zone.

Elevation (ft)	Depth (ft)	Vmag (ft/sec)	Standard Error Vmag (ft/sec)	Vdir °	Standard Error Vdir °	Number of profiles in sample
3611.09	18.04	0.16	0.02	269.22	7.06	260
3601.25	27.89	0.19	0.02	165.03	6.14	225
3591.40	37.73	0.06	0.01	134.44	6.27	259
3581.56	47.57	0.03	0.01	156.37	6.38	269
3571.72	57.41	0.04	0.01	128.91	6.20	273
3561.88	67.26	0.02	0.01	134.62	6.56	265
3552.03	77.10	0.03	0.01	192.78	6.50	264
3542.19	86.94	0.04	0.01	194.91	6.56	264
3532.35	96.78	0.03	0.01	153.10	6.31	266
3522.51	106.63	0.08	0.01	142.95	5.91	271
3512.66	116.47	0.12	0.01	148.44	5.49	269
3502.82	126.31	0.17	0.01	144.69	5.17	271
3492.98	136.15	0.23	0.01	148.00	4.53	277
3483.14	146.00	0.28	0.01	148.63	4.14	283
3473.29	155.84	0.28	0.01	151.09	4.16	282
3463.45	165.68	0.30	0.01	145.46	3.96	292
3453.61	175.52	0.25	0.01	149.36	4.42	279
3443.77	185.37	0.18	0.01	143.27	5.00	278
3433.92	195.21	0.13	0.01	127.63	5.71	263
3424.08	205.05	0.11	0.01	131.56	6.00	269
3414.24	214.90	0.09	0.01	124.92	6.35	266
3404.40	224.74	0.09	0.01	111.54	6.33	261
3394.55	234.58	0.09	0.01	169.86	6.56	265
3384.71	244.42	0.10	0.01	111.31	6.58	259
3374.87	254.27	0.13	0.01	115.06	6.66	256
3365.03	264.11	0.14	0.02	162.57	6.56	261
3355.18	273.95	0.21	0.01	94.72	6.14	275
3345.34	283.79	0.26	0.02	182.40	6.04	278
3335.50	293.64	0.25	0.02	69.52	7.10	276
3325.66	303.48	0.27	0.02	191.60	7.03	287
3315.81	313.32	0.32	0.03	183.35	7.49	253
3305.97	323.16	0.22	0.02	69.51	6.94	267
3296.13	333.01	0.20	0.02	186.56	6.94	255

Appendix - Water Quality Profile Data

Table WQ1. Glen Canyon Dam forebay water quality data collected by the USGS-GCMRC on July 19, 2007.

Elevation, ft	Depth, ft	Temperature, °F	Dissolved Oxygen, mg/l	Specific Conductance, µS/cm	pH
3607.87	0.33	83.08	7.90	788.00	8.29
3604.92	3.28	82.99	7.93	787.00	8.29
3602.29	5.91	82.60	8.03	787.00	8.29
3600.00	8.20	81.32	8.19	786.00	8.30
3595.08	13.12	81.07	8.21	786.00	8.30
3590.16	18.04	80.44	9.00	781.00	8.30
3587.20	21.00	79.16	10.15	770.00	8.31
3584.58	23.62	78.03	11.47	760.00	8.31
3581.63	26.57	73.85	13.67	737.00	8.31
3579.00	29.20	71.85	13.32	736.00	8.30
3576.38	31.82	71.02	13.00	735.00	8.29
3571.13	37.07	69.62	12.15	747.00	8.28
3566.21	41.99	68.14	11.11	753.00	8.25
3564.56	43.64	68.00	10.73	752.00	8.24
3559.32	48.88	66.70	9.50	749.00	8.20
3554.07	54.13	65.52	8.72	759.00	8.18
3549.14	59.06	64.40	8.24	765.00	8.16
3544.22	63.98	63.34	7.95	766.00	8.12
3540.29	67.91	61.72	7.51	764.00	8.04
3536.02	72.18	60.06	7.39	765.00	7.99
3531.10	77.10	58.66	7.10	763.00	7.91
3526.84	81.36	57.88	7.00	763.00	7.87
3522.24	85.96	57.34	6.99	762.00	7.86
3518.30	89.90	56.59	6.96	760.00	7.84
3514.04	94.16	55.24	6.82	759.00	7.80
3510.10	98.10	54.66	6.77	758.00	7.78
3504.85	103.35	53.35	6.73	758.00	7.74
3500.26	107.94	52.11	6.68	759.00	7.70
3496.00	112.20	51.58	6.69	758.00	7.69
3491.40	116.80	50.94	6.59	760.00	7.66
3487.79	120.41	50.50	6.48	763.00	7.63
3483.20	125.00	49.78	6.41	766.00	7.61
3476.97	131.23	48.56	6.55	771.00	7.58
3474.34	133.86	47.89	6.59	777.00	7.57
3466.80	141.40	46.96	6.62	794.00	7.55
3459.25	148.95	46.72	6.51	804.00	7.53
3442.52	165.68	45.73	5.99	862.00	7.48
3425.46	182.74	45.27	6.10	883.00	7.48
3408.07	200.13	44.82	6.65	890.00	7.52

3386.09	222.11	44.47	7.09	890.00	7.55
3361.48	246.72	44.17	7.53	889.00	7.58
3347.05	261.15	43.84	7.85	887.00	7.62
3324.74	283.46	43.57	7.92	886.00	7.62
3298.16	310.04	43.32	8.00	886.00	7.63
3269.29	338.91	43.18	8.05	886.00	7.63
3250.59	357.61	43.12	8.14	886.00	7.64
3224.67	383.53	43.07	7.96	886.00	7.62
3207.61	400.59	43.03	7.95	886.00	7.62
3204.98	403.22	43.03	7.96	886.00	7.63
3194.16	414.04	43.03	7.94	886.00	7.63

Table WQ2. Glen Canyon Dam forebay water quality data collected on September 26, 2007.

Elevation, ft	Depth, ft	Temperature, °F	Dissolved Oxygen, mg/l	Specific Conductance, µS/cm	pH
3601.90	0.00	73.22	6.73	748.20	8.36
3598.62	3.28	73.22	6.73	748.20	8.36
3595.34	6.56	72.77	6.73	745.70	8.35
3592.06	9.84	72.66	6.79	745.50	8.34
3588.78	13.12	72.63	6.81	745.40	8.33
3585.50	16.40	72.59	6.39	745.00	8.33
3582.21	19.69	72.57	6.32	745.00	8.33
3578.93	22.97	72.55	6.31	744.70	8.33
3575.65	26.25	72.54	6.25	744.40	8.32
3572.37	29.53	72.54	6.47	744.00	8.32
3569.09	32.81	72.54	6.30	742.00	8.32
3565.81	36.09	72.52	6.22	743.90	8.32
3562.53	39.37	72.52	6.26	743.50	8.33
3559.25	42.65	72.52	6.17	743.10	8.33
3555.97	45.93	72.52	6.26	743.30	8.31
3552.69	49.21	72.50	6.25	744.40	8.33
3549.41	52.49	72.43	6.22	742.30	8.33
3546.13	55.77	72.30	6.16	741.70	8.30
3542.84	59.06	69.49	5.63	726.70	7.99
3539.56	62.34	68.40	5.20	730.40	7.96
3536.28	65.62	67.75	5.17	735.70	7.97
3533.00	68.90	67.21	5.07	736.70	7.97
3529.72	72.18	66.49	4.89	739.90	7.98
3526.44	75.46	65.80	4.67	739.70	7.97
3523.16	78.74	65.01	4.37	740.70	7.92
3519.88	82.02	64.51	4.14	742.30	7.90
3516.60	85.30	63.97	4.12	742.50	7.90
3513.32	88.58	63.55	4.18	742.80	7.92
3510.04	91.86	62.87	4.25	742.70	7.95
3506.76	95.14	62.08	4.22	743.60	7.96
3503.47	98.43	60.93	4.11	743.40	7.93

3500.19	101.71	59.31	4.20	740.60	7.94
3496.91	104.99	58.28	4.36	740.40	7.93
3493.63	108.27	56.61	4.43	741.10	7.92
3490.35	111.55	55.18	4.51	740.90	7.90
3487.07	114.83	54.57	4.55	742.30	7.89
3483.79	118.11	53.83	4.62	740.30	7.89
3480.51	121.39	52.97	4.72	735.90	7.89
3477.23	124.67	51.98	4.87	736.60	7.87
3473.95	127.95	51.28	4.93	734.40	7.86
3470.67	131.23	50.14	5.07	733.20	7.87
3467.39	134.51	49.93	5.16	734.60	7.87
3464.10	137.80	49.55	5.20	735.40	7.89
3460.82	141.08	49.06	5.30	737.20	7.87
3457.54	144.36	48.22	5.42	745.60	7.87
3454.26	147.64	47.52	5.55	756.20	7.88
3450.98	150.92	47.50	5.59	757.50	7.87
3447.70	154.20	47.23	5.64	762.50	7.88
3444.42	157.48	47.03	5.67	768.00	7.88
3441.14	160.76	46.80	5.71	771.40	7.88
3437.86	164.04	46.44	5.70	791.60	7.88

Table WQ3. Glen Canyon Dam forebay water quality data collected by the USGS-GCMRC on March 8, 2008.

Elevation, ft	Depth, ft	Temperature, °F	Dissolved Oxygen, mg/l	Specific Conductance, μ S/cm	pH
3589.47	0.33	48.31	9.38	744.00	7.87
3586.52	3.28	48.34	9.38	745.00	7.92
3583.24	6.56	47.97	9.41	745.00	7.93
3574.38	15.42	47.88	9.38	745.00	7.93
3560.60	29.20	47.70	9.37	743.00	7.94
3547.15	42.65	47.59	9.35	745.00	7.94
3534.03	55.77	47.46	9.27	744.00	7.94
3522.54	67.26	47.28	9.12	745.00	7.92
3507.45	82.35	47.12	8.91	749.00	7.90
3498.26	91.54	46.96	8.64	751.00	7.88
3494.00	95.80	46.83	8.49	757.00	7.86
3490.06	99.74	46.67	8.19	762.00	7.82
3484.49	105.31	46.62	8.06	766.00	7.81
3481.20	108.60	46.54	7.92	769.00	7.79
3478.25	111.55	46.51	7.86	769.00	7.79
3474.31	115.49	46.40	7.63	777.00	7.76
3473.00	116.80	46.15	6.94	798.00	7.69
3471.03	118.77	46.08	6.90	802.00	7.68
3469.72	120.08	46.00	6.73	810.00	7.67
3468.08	121.72	45.77	6.21	831.00	7.61
3466.44	123.36	45.73	6.16	833.00	7.61
3463.16	126.64	45.61	5.93	844.00	7.59

3458.24	131.56	45.50	5.79	852.00	7.57
3453.97	135.83	45.27	5.65	860.00	7.56
3449.71	140.09	45.16	5.57	864.00	7.56
3444.46	145.34	45.01	5.53	869.00	7.55
3435.60	154.20	44.78	5.54	875.00	7.55
3427.07	162.73	44.74	5.54	875.00	7.55
3413.95	175.85	44.62	5.62	877.00	7.56
3400.82	188.98	44.53	5.72	882.00	7.57
3388.03	201.77	44.42	5.78	883.00	7.57
3383.44	206.36	44.35	5.80	886.00	7.58
3379.50	210.30	44.35	5.80	885.00	7.58
3374.58	215.22	44.28	5.77	887.00	7.57
3370.97	218.83	44.24	5.73	887.00	7.57
3366.70	223.10	44.22	5.70	887.00	7.57
3362.77	227.03	44.22	5.69	887.00	7.57
3354.89	234.91	44.20	5.67	888.00	7.57
3341.11	248.69	44.15	5.59	888.00	7.56
3327.66	262.14	44.11	5.49	889.00	7.55
3314.87	274.93	44.11	5.47	890.00	7.55
3301.74	288.06	44.10	5.42	889.00	7.55
3288.95	300.85	44.10	5.40	889.00	7.55
3276.15	313.65	44.08	5.27	890.00	7.54
3264.01	325.79	44.04	5.11	890.00	7.52
3250.89	338.91	44.02	4.93	890.00	7.51
3238.42	351.38	44.01	4.93	892.00	7.50
3227.27	362.53	44.02	4.91	892.00	7.50
3217.75	372.05	44.01	4.91	892.00	7.50
3208.57	381.23	43.99	4.90	892.00	7.49
3200.36	389.44	44.01	4.91	892.00	7.49
3192.49	397.31	44.01	4.91	893.00	7.49
3189.21	400.59	44.01	4.88	893.00	7.49

Table WQ4. Glen Canyon Dam forebay water quality data collected on May 29, 2008.

Elevation, ft	Depth, ft	Temperature, °F	Dissolved Oxygen, mg/l	Specific Conductance, μ S/cm	pH
3609.50	0.00	65.48	8.74	742.50	8.40
3606.22	3.28	65.32	8.24	743.80	8.40
3602.94	6.56	64.85	8.75	741.70	8.41
3599.66	9.84	64.62	8.68	741.60	8.41
3596.38	13.12	64.20	8.80	740.30	8.42
3593.10	16.40	62.58	8.89	738.50	8.44
3589.81	19.69	62.22	8.92	734.30	8.45
3586.53	22.97	62.15	8.99	734.20	8.45
3583.25	26.25	61.93	9.01	739.20	8.45
3579.97	29.53	61.75	9.05	738.90	8.44
3576.69	32.81	61.65	9.13	738.40	8.44

3573.41	36.09	60.75	9.23	734.90	8.42
3570.13	39.37	59.81	9.35	736.00	8.40
3566.85	42.65	58.68	9.41	735.10	8.35
3563.57	45.93	57.52	9.36	735.40	8.32
3560.29	49.21	57.07	9.32	734.30	8.30
3557.01	52.49	56.37	9.31	733.80	8.27
3553.73	55.77	55.56	9.07	733.30	8.25
3550.44	59.06	54.88	8.96	733.10	8.22
3547.16	62.34	54.55	8.94	734.30	8.20
3543.88	65.62	54.41	8.93	734.40	8.19
3540.60	68.90	54.00	8.86	732.80	8.12
3537.32	72.18	53.44	8.71	730.50	8.14
3534.04	75.46	52.84	8.68	730.40	8.11
3530.76	78.74	52.68	8.46	729.30	8.11
3527.48	82.02	52.39	8.39	728.80	8.09
3524.20	85.30	52.20	8.28	729.70	8.08
3520.92	88.58	52.05	8.20	729.00	8.08
3517.64	91.86	51.40	8.18	727.10	8.05
3514.36	95.14	50.83	8.14	725.40	8.04
3511.07	98.43	50.67	8.01	726.00	8.02
3507.79	101.71	50.32	8.02	726.30	8.01
3504.51	104.99	49.91	7.98	723.20	8.00
3501.23	108.27	48.92	7.82	725.20	7.95
3497.95	111.55	48.61	7.78	727.40	7.94
3494.67	114.83	48.33	7.71	728.90	7.93
3491.39	118.11	48.04	7.70	733.60	7.94
3488.11	121.39	47.52	7.61	734.40	7.90
3484.83	124.67	47.16	7.51	740.20	7.88
3481.55	127.95	47.14	7.47	739.80	7.88
3478.27	131.23	46.89	7.40	752.60	7.86
3474.99	134.51	46.56	7.22	754.20	7.85
3471.70	137.80	46.36	7.16	764.70	7.84
3468.42	141.08	46.24	7.07	773.70	7.82
3465.14	144.36	46.15	6.96	782.10	7.81
3461.86	147.64	46.08	6.90	788.10	7.80
3458.58	150.92	45.90	6.84	807.00	7.78
3455.30	154.20	45.64	6.68	818.20	7.77
3452.02	157.48	45.55	6.56	822.20	7.77
3448.74	160.76	45.43	6.47	828.80	7.76
3445.46	164.04	45.37	6.41	831.00	7.75
3442.18	167.32	45.32	6.34	834.80	7.75
3438.90	170.60	45.18	6.29	840.20	7.75
3435.62	173.88	45.16	6.25	842.00	7.74
3432.33	177.17	45.12	6.24	842.70	7.74
3429.05	180.45	45.07	6.25	844.70	7.74
3425.77	183.73	45.01	6.26	846.80	7.75
3422.49	187.01	44.98	6.30	848.00	7.75
3419.21	190.29	44.94	6.31	849.10	7.76
3415.93	193.57	44.91	6.64	851.00	7.76
3412.65	196.85	44.89	6.37	850.80	7.77

3406.09	203.41	44.80	6.39	853.80	7.77
3399.53	209.97	44.78	6.39	855.00	7.76
3392.96	216.54	44.73	6.42	857.70	7.77
3386.40	223.10	44.69	6.45	858.50	7.78
3379.84	229.66	44.65	6.44	860.70	7.78
3373.28	236.22	44.62	6.48	861.20	7.78
3366.72	242.78	44.60	6.48	863.20	7.78
3360.16	249.34	44.58	6.54	864.60	7.79
3353.59	255.91	44.56	6.57	864.80	7.79
3347.03	262.47	44.55	6.59	865.90	7.79
3340.47	269.03	44.55	6.65	867.40	7.80
3333.91	275.59	44.53	6.67	868.10	7.81
3327.35	282.15	44.49	6.73	868.90	7.81
3320.79	288.71	44.46	6.80	870.40	7.82
3314.22	295.28	44.44	6.86	870.80	7.83
3307.66	301.84	44.40	6.98	871.30	7.74
3301.10	308.40	44.37	7.08	871.90	7.70
3294.54	314.96	44.33	7.13	872.00	7.69
3287.98	321.52	44.29	7.19	872.20	7.68
3281.42	328.08	44.29	7.20	872.20	7.65
3274.85	334.65	44.26	7.22	872.40	7.68
3268.29	341.21	44.22	7.26	872.90	7.60
3261.73	347.77	44.19	7.28	872.30	7.60
3255.17	354.33	44.17	7.29	873.20	7.68

Table WQ5. Glen Canyon Dam forebay water quality data collected on June 26, 2008.

Elevation, ft	Depth, ft	Temperature, °F	Dissolved Oxygen, mg/l	Specific Conductance, μ S/cm	pH
3629.60	0.00	76.69	6.88	743.00	8.46
3626.32	3.28	76.08	6.81	742.00	8.46
3623.04	6.56	75.92	6.79	743.00	8.45
3619.76	9.84	75.85	6.80	742.30	8.45
3616.48	13.12	75.69	6.83	742.00	8.44
3613.20	16.40	75.36	6.95	742.00	8.44
3609.91	19.69	74.77	6.96	740.00	8.45
3606.63	22.97	70.39	7.60	732.00	8.49
3603.35	26.25	69.60	7.78	734.70	8.49
3600.07	29.53	69.21	7.92	732.50	8.49
3596.79	32.81	68.22	8.02	730.70	8.49
3593.51	36.09	67.68	7.88	736.50	8.49
3590.23	39.37	66.15	7.97	732.60	8.50
3586.95	42.65	63.77	8.24	697.60	8.53
3583.67	45.93	62.44	8.45	694.20	8.53
3580.39	49.21	61.66	8.51	691.00	8.52
3577.11	52.49	60.98	8.49	688.00	8.50
3573.83	55.77	60.55	8.24	689.00	8.47

3570.54	59.06	60.24	8.34	690.00	8.49
3567.26	62.34	59.83	8.38	691.00	8.47
3563.98	65.62	59.77	8.37	691.00	8.47
3560.70	68.90	59.58	8.36	691.00	8.46
3557.42	72.18	59.31	8.40	696.00	8.47
3554.14	75.46	59.05	8.40	702.00	8.46
3550.86	78.74	58.48	8.44	699.00	8.45
3547.58	82.02	58.08	8.27	701.00	8.44
3544.30	85.30	57.74	8.30	708.00	8.42
3541.02	88.58	57.49	8.26	710.00	8.40
3537.74	91.86	57.38	8.16	709.00	8.40
3534.46	95.14	57.15	8.14	709.00	8.40
3531.17	98.43	57.00	7.99	707.00	8.39
3527.89	101.71	56.77	8.00	707.00	8.37
3524.61	104.99	56.44	7.91	699.00	8.37
3521.33	108.27	56.19	7.88	699.00	8.37
3518.05	111.55	56.03	7.77	698.00	8.35
3514.77	114.83	55.72	7.75	699.00	8.33
3511.49	118.11	55.40	7.66	703.00	8.31
3508.21	121.39	55.11	7.60	704.00	8.28
3504.93	124.67	54.90	7.58	702.00	8.28
3501.65	127.95	54.59	7.56	703.00	8.25
3498.37	131.23	53.80	7.47	710.00	8.20
3495.09	134.51	53.42	7.38	709.00	8.18
3491.80	137.80	53.04	7.32	713.00	8.14
3488.52	141.08	52.74	7.28	725.00	8.11
3485.24	144.36	52.12	7.16	719.00	8.08
3481.96	147.64	51.24	7.15	725.00	8.04
3478.68	150.92	51.13	7.05	737.00	8.03
3475.40	154.20	50.02	6.98	744.00	7.99
3472.12	157.48	49.69	6.91	734.00	7.99
3468.84	160.76	49.19	6.86	722.00	7.98
3465.56	164.04	48.54	6.85	725.00	7.96
3462.28	167.32	48.16	6.83	726.00	7.96
3459.00	170.60	47.73	6.80	742.00	7.95
3455.72	173.88	47.53	6.77	738.00	7.95
3452.43	177.17	47.32	6.77	739.00	7.94
3449.15	180.45	47.01	6.72	751.00	7.93
3445.87	183.73	46.69	6.70	756.00	7.93
3442.59	187.01	46.63	6.67	761.00	7.92
3439.31	190.29	46.31	6.57	780.00	7.91
3436.03	193.57	46.17	6.45	789.70	7.90
3432.75	196.85	46.04	6.35	798.00	7.89
3426.19	203.41	45.95	6.19	803.00	7.88
3419.63	209.97	45.75	6.18	811.00	7.88
3413.06	216.54	45.48	6.14	827.00	7.87
3406.50	223.10	45.43	6.09	826.00	7.87
3399.94	229.66	45.41	6.06	833.00	7.88
3393.38	236.22	45.30	6.08	841.00	7.89
3386.82	242.78	45.23	6.08	841.10	7.88

3380.26	249.34	45.16	6.08	843.00	7.88
3373.69	255.91	45.12	6.08	844.00	7.88
3367.13	262.47	45.07	6.10	849.00	7.89
3360.57	269.03	45.05	6.06	849.00	7.89
3354.01	275.59	44.96	6.05	854.00	7.89
3347.45	282.15	44.87	6.11	856.00	7.89
3340.89	288.71	44.80	6.09	858.00	7.89
3334.32	295.28	44.80	6.09	859.00	7.90
3327.76	301.84	44.74	6.14	863.00	7.90
3321.20	308.40	44.69	6.16	865.00	7.91
3314.64	314.96	44.65	6.24	867.00	7.92
3308.08	321.52	44.62	6.26	867.00	7.92
3301.52	328.08	44.62	6.32	869.00	7.93
3298.24	331.36	44.47	6.47	870.00	7.95

Appendix - List of ADCP Configuration Commands

RD Instruments WinRiver Configuration File

Version=10.06.00
[Offsets]
ADCP Transducer Depth [m]=0.3048
Magnetic Variation [deg]=11.75
Heading Offset [deg]=0
One Cycle K=0
One Cycle Offset=0
Two Cycle K=0
Two Cycle Offset=0
[Processing]
Speed of Sound Correction=0
Salinity [ppt]=0
Fixed Speed Of Sound [m/s]=1500
Mark Below Botom Bad=YES
Screen Depth=NO
Backscatter Type=0
Intensity Scale [dB/cts]=0.43
Absorption [dB/m]=0.139
Projection Angle [deg]=0
[GPS]
GPS Time Delay [s]=0
[Recording]
Filename Prefix=LMXR
Output Directory=C:\ADCP\SNWS\
GPS Recording=YES
DS Recording=NO
Maximum File Size [MB]=0
Comment #1=glen canyon dam forebay PROFILES 3M CELLS with Extended Range
Comment #2=September 25, 2007 Night Profiles,
Next Transect Number=0
Add Date Time=NO

ADCP Commands

WF176	WD111100000
WM1	EX11111
BM5	EZ1111111
WV80	ED3
WN50	CF11111
WS300	BX1600
WP1	TP000050
BP1	
WB1	

Results of PlanADCP model on ADCP Performance

```
;Instrument      = Workhorse Monitor
;Frequency       = 307200
;Water Profile   = YES
;Bottom Track    = YES
;High Res. Modes = NO
;High Rate Pinging = NO
;Shallow Bottom Mode= NO
;Wave Gauge      = NO
;Lowered ADCP    = NO
;Beam angle      = 20
;Temperature     = 15.00
;Deployment hours = 2400.00
;Battery packs   = 0
;Automatic TP    = YES
;BT range [m]    = 160.00
;Memory size [MB] = 256
;Saved Screen    = 2
;
;Consequences generated by PlanADCP version 2.04:
;First cell range = 5.35 m
;Last cell range  = 152.35 m
;Max range        = 382.14 m
;Standard deviation = 0.42 cm/s (for the average of 400 ensembles)
;Ensemble size    = 1241 bytes
;Storage required  = 2.84 MB (2978400 bytes)
;Power usage      = 3111.35 Wh
;
; WARNINGS AND CAUTIONS:
; Advanced settings have been changed.
; Expert settings have been changed.
```

Appendix – Drawings

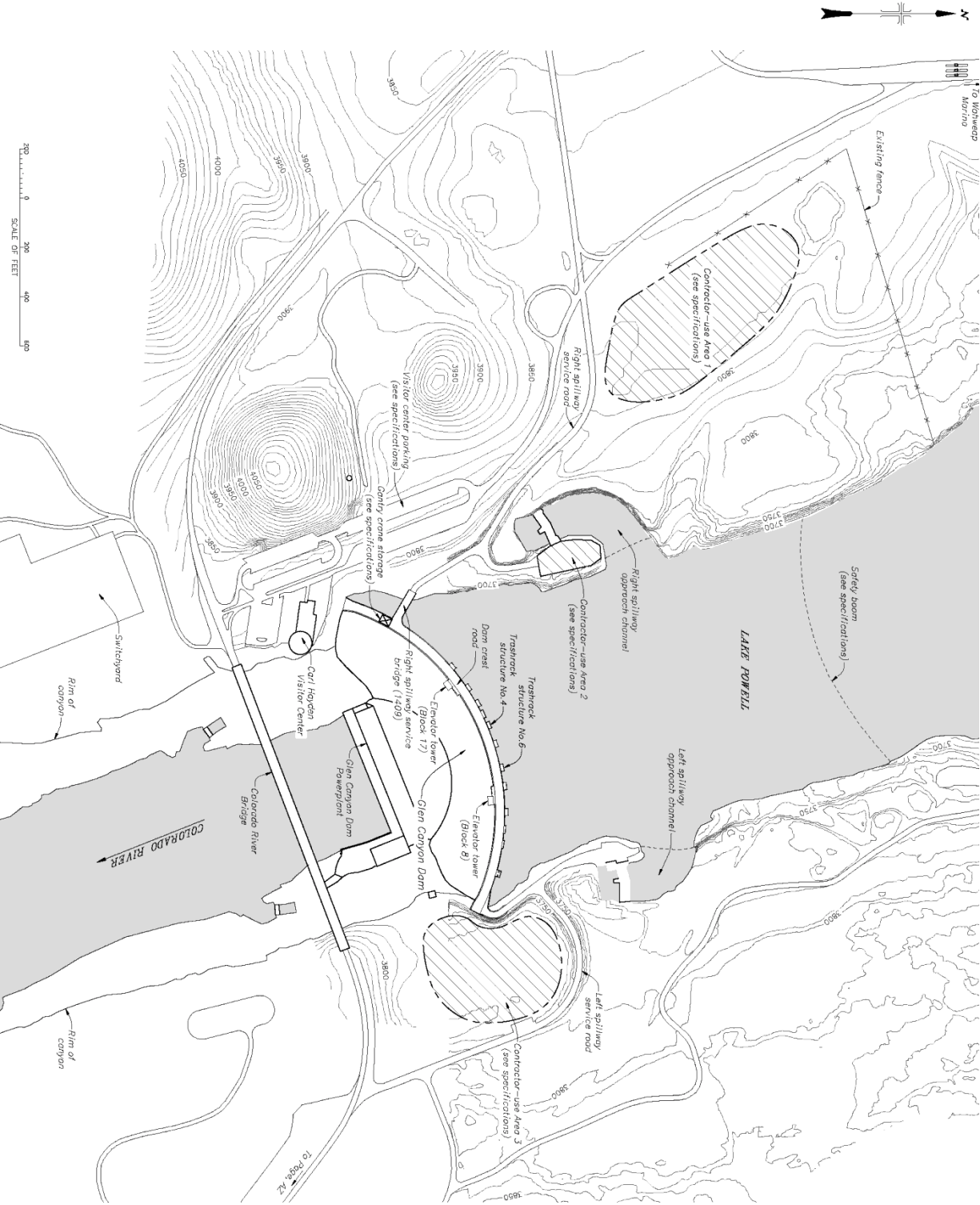


Figure D 1. General plan view of Glen Canyon Dam

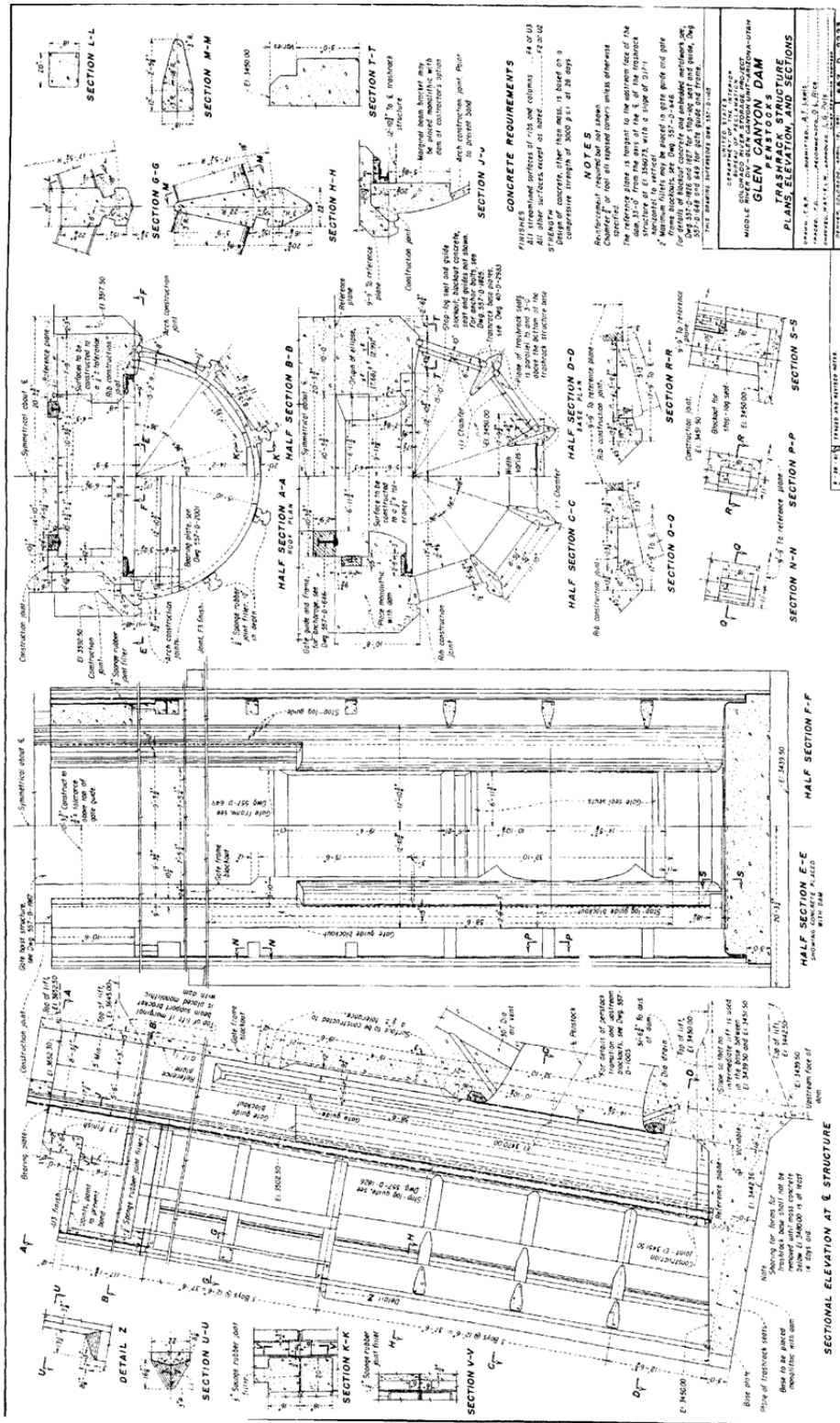


Figure D 3. Detail drawing of the penstock intake and trash rack structure.