Effects of Air and Mainstem Water Temperatures, Hydraulic Isolation, and Fluctuating Flows From Glen Canyon Dam on Water Temperatures in Shoreline Environments of the Colorado River in Grand Canyon

Final Report

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Executive Summary

Backwater and other shoreline environments are preferentially used by native juvenile fish for rearing. The objective of this study was to better determine the extent to which daily variation in flow from Glen Canyon Dam effects water temperature regimes in shoreline environments. Continuously recording temperature loggers were deployed at –3.5 mile (Glen Canyon), 44.6 mile (Eminence), and 64.5 mile (Salt Mines). Loggers were deployed along chains extending from the shoreline towards the thalweg, allowing us to record the gradient in temperatures between backwaters and the mainstem, and in mainstem shoreline environments. Temperature loggers were deployed in 3 habitat types: backwaters; low angle mainstem shorelines; and talus mainstem shoreline. Loggers were deployed in mid-August and retrieved in early-November, 2004.

Maximum warming in low angle shorelines was observed in August in Glen Canyon when the difference between mainstem water temperatures and air temperatures was greatest. Across the three habitat types, the extent of warming depended on the extent of isolation from the mainstem, with backwaters showing the greatest warming, low angle shorelines showing moderate warming, and virtually no warming seen in well-mixed steep talus environments. Greater fluctuations in flow reduced the extent of warming in backwaters due to increased exchange with mainstem water. The extent of this effect was variable and depended on the timing of daily maximum and minimum flows and the topography of the backwater. With the exception of backwater temperatures at Eminence in September, shoreline temperatures were a maximum of 2-3 ^{o}C (Celsius) warmer than the mainstem and typically these larger differences only occurred in the fluctuating zone. Vertical stratification in water temperature was observed in all backwaters. Stratification patterns were dynamic and varied over a 24 Hr. period with changes in flow and air temperature. Surface waters in backwater and talus environments were a maximum of 3-7 ^{o}C and 1 ^{o}C warmer than bottom water, respectively.

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Table of Contents

1.0 Introduction

Growth of native fishes in Grand Canyon is limited by low temperature (Bulkley et al. 1982, Valdez et al. 1995, Valdez and Carothers 1998). During warmer months, water temperatures in the Colorado River in Grand Canyon increase with increasing distance from Glen Canyon Dam (GCD). Reduced flow from GCD increases water travel time which results in greater warming by the time the water reaches downstream areas used by native fish (Vernieu 2003). Backwater and mainstem shoreline environments are preferentially used by native juvenile fish for rearing (Converse et al. 1998, Maddux et al. 1987, Hoffnagle 1996). Nearshore temperatures can be higher than the mainstem during summer months because the velocity of water near shorelines is slower and provides more time for heating to occur. Reductions in daily fluctuations in flow from Glen Canyon Dam (GCD) have been shown to increase backwater temperatures (Hoffnagle 1996). Water temperatures in nearshore environments in Glen and Grand Canyons were 3-8 ^{o}C warmer than the mainstem during the 2000 Low Summer Steady Flow (LSSF) experiment (Vernieu 2003). Daily variation in flow from GCD likely reduces the extent of nearshore warming, but the magnitude of this effect has not been evaluated.

The objective of this study was to determine the extent to which daily variation in flow from Glen Canyon Dam effects water temperature regimes in nearshore environments. Backwaters represent nearshore environments that can be completely isolated from the mainstem by a sand bar. Low angle cobble or sandy shorelines, and talus shorelines, represent other types of nearshore environments that are less isolated than backwaters. Continuously recording temperature loggers were deployed at three locations in the Colorado River below Glen Canyon Dam. Series of loggers were deployed along chains extending from the shoreline towards the thalweg, allowing us to record the gradient in temperatures between backwaters and the mainstem, and between the mainstem and low angle shoreline/talus shorelines. Temperature loggers were deployed in mid-August and retrieved in early-November, 2004.

Temperature gradients during August were influenced by high solar insolation coupled with high mean daily flow and high hourly variation in discharge (10-18 thousand cubic feet per second or kcfs over a 24 Hrs.). Gradients in early-September were influenced by a similar level of insolation compared to August, but the average flow and daily variation in flow were much lower (5-10 kcfs). Gradients in October were influenced by considerably reduced solar insolation relative to August and early-September, but very similar flows to September. These contrasts potentially allow us to tease-out the effects of flow and solar insolation on shoreline temperature gradients.

We use the data to evaluate the following hypotheses:

1. The magnitude of temperature gradients should be greatest when solar insolation and air temperatures are highest. Gradients in early-September should therefore be higher compared to those in late-October, two periods with different ambient conditions but similar flow.

2. Higher daily fluctuations in flow and higher average flow will reduce the residence time of water in mainstem shoreline and backwater environments because of increased mixing and therefore reduce the magnitude of temperature gradients. Temperature gradients in early-September should therefore be higher compared to those in late-August when average flow and daily variation in flow are higher.

3. The magnitude of temperature gradients during October will be lower than in September because of both reduced air temperatures and higher release temperatures from GCD that are closer to ambient air temperatures. Note that in 2004, water temperatures from Glen Canyon Dam ranged from 11.5-12.5 °C in August and increased to 13.5-14.5 °C by October (http://www.gcmrc.gov/ what_we_do /products/discharge_temp/discharge_temp.htm).

4. Finally, we hypothesize that the extent of warming in mainstem shoreline and backwater environments will depend on river mile and habitat type. Water

temperatures increase in a downstream direction during summer months. We deployed temperature loggers at –3.5 mile (Glen Canyon), 44.6 mile (Eminence), and 64.5 mile (Salt Mines). Temperature gradients should be highest at locations at the most upstream location where the difference between water and air temperatures is greatest. At-a-site, we would expect temperature gradients to differ with the extent of mixing between nearshore environments and the mainstem. We deployed temperature loggers at steep talus shorelines, lower angle sandy or cobble shorelines, and in backwater habitats. Mixing should be highest in talus shorelines, moderate over lower angle shorelines, and lowest in backwaters. The extent of warming is therefore expected to follow the opposite pattern with the highest degree of warming expected in backwater habitats.

2.0 Methods

Water temperatures were measured using HOBO Water Temp Pro ® continuously recording temperature loggers (accuracy of ± 0.2 °C at 0°C to 50°C). Loggers were deployed at 3 locations below Glen Canyon Dam (–3.5 mile-Glen Canyon, 44.6 mile-Eminence, 64.5 mile-Salt Mines). At the 2 sites in Grand Canyon (Eminence and Salt Mines), two replicate lines of temperature loggers were deployed in steep talus shoreline, low angle sandy shoreline, and backwater habitat types. At the Glen Canyon location, replicate lines were deployed in talus and low angle cobble bar habitats only because backwater habitats are virtually absent in this reach. A temperature logger 'line' consisted of a series of up to 8 loggers that were attached to ¼" chain which was held in position over the substrate with lead weights. The loggers were positioned just above the surface of the substrate at elevations that corresponded to flows from 2.5-20 kcfs in 2.5 kcfs increments. In this analysis the elevations of loggers are referenced with respect to the flow that is required for them to be inundated. Replicate lines were placed in most habitat types. At backwater sites, one replicate (Line-1) was placed near the head of the backwater and the other (Line-2) was placed closer to the mouth. The 20 kcfs elevation logger on each line was never submerged and was used to represent the nearshore air temperature in August. When flows dropped on September 1st, loggers between 15 and 20 kcfs were removed and the 12.5 kcfs logger was used to represent air temperature.

All sites were located in FIST (Fine Integrated Sediment Transport project) reaches where stage-discharge relationships had been previously established. In the field, the 20 kcfs elevation was established based on the presence of stranded debris from the January-March 2004 experimental flows. Loggers were deployed the following August at the daily maximum flow (ca. 18 kcfs) when it was very easy to identify the 20 kcfs stage line. Elevations for each logger at 2.5 kcfs increments were determined by calculating the required stage difference relative to 20 kcfs. A laser-level and survey rod was used to measure the required elevation differences determined from the stage-discharge relationships. Loggers were deployed and retrieved at the Glen Canyon, Eminence, and Salt mines sites on: August 6th – November 1st, 2004; August 11th – November 16th, 2004; and August 14th – November 20th, 2004, respectively. Instantaneous water and air temperature were recorded every 15 minutes.

Temperature loggers were also deployed vertically from floats for 16-24 Hr. periods to evaluate the extent of temperature differences in the water column. A lead weight was attached to a Styrofoam buoy and temperature loggers were suspended from the buoy 5 and 25 cm below the water surface. The buoy was then positioned so that the 3 vertical lines of loggers were suspended immediately above the 2.5, 5, and 7.5 kcfs loggers attached to the line anchored to the substrate. Vertical profile data were collected on September 7th – 10th, 2004 in Glen Canyon, August 11th-12th, and Sep 15th-16th, 2004 at Eminence, and August 14th - 15th, and September 17th, 2004 at Salt mines.

Upon retrieval, the data time series from each logger was downloaded onto a PC and combined into a single file for each location. The time series for each logger was edited to delete measurements taken before the loggers were positioned on the substrate or in the water column, and after they were removed. We used a 3-week subset of the entire dataset to represent temperatures in August (22nd-28th), September (5th-11th), and October (24th-30th). These dates were selected to provide similar air temperature and solar insolation conditions between August and September when flows were very different (10-18 kcfs vs. 5-10 kcfs, respectively) and maximum contrast in air temperature and solar insolation between September and October when flows were very similar. A large flood from the Little Colorado River influenced water temperatures during the week of September 5th-11th at the Salt Mines location. As the objective of the study was to evaluate the effects of discharge from Glen Canyon Dam on nearshore temperatures, we used the first week following the recession of the flood to represent temperatures at this location (September 17th-24th).

Considerable editing was required to remove temperature measurements taken when loggers in the fluctuating zone (in the elevation between daily minimum and daily maximum daily flows) were exposed due to daily fluctuations in flow. First, an automated algorithm was used to make a rough classification of whether a logger was submerged or exposed. This algorithm was based on the spatial temperature gradient between two adjacent loggers on the same line with the same time stamp, and the air temperature. If the spatial temperature gradient was greater then an acceptable threshold then the logger at the higher elevation and all loggers located above it on the same line were considered to be exposed. The threshold for an acceptable temperature gradient was determined based on air temperature and varied by location. This algorithm picked-up the basic pattern of exposure and inundation, but failed where spatial differences were subtle or when air and water temperatures were too similar.

Once the automated algorithm was run, the data was manually edited using a more complicated set of rules. For the Glen Canyon data set, the flow predicted by the USGS Unsteady Flow Model (Wiele and Griffin 1997) showed a very close match to the pattern of logger exposure and inundation based on an examination of the temperature data. Note that there is some error in both the predicted flow at a particular river mile and the elevation of the loggers on each line. As a result, it is not possible to use the predicted flow for each 15-minute sampling interval to determine a logger's inundation status. At the Glen Canyon site, the data were examined to determine the predicted flows when loggers were unambiguously submerged. These flows were then used to classify logger data for other times during the week when temperature-based classifications were harder to determine. The Eminence data set did not show a close relationship between flow predicted by the Unsteady Flow Model and the pattern of exposure and inundation seen in the temperature data. This likely occurred because the timing of changes in discharge at this site was not well predicted by the Unsteady flow model. Thus, at the Eminence location, data-editing rules were developed that used both spatial and temporal temperature gradients, but did not depend on flow predictions. Predictions of flow at the Salt Mines location showed a reasonable correspondence with the expected pattern of inundation and exposure determined from the temperature data. In this case, the predicted flow was taken into account along with the spatial and temporal temperature gradient rules during the editing process.

Water temperature data were summarized at four functional zones: Mainstem; Low_Permanent; High_Permanent; and Fluctuating. The latter 3 zones represent the water temperatures in nearshore environments while the Mainstem zone represents the temperature in the thalwag. The average water temperature at the lowest elevation (typically 2-2.5 kcfs) for the steep talus shorelines was used to represent the mainstem thalwag temperature for each time interval. The lowest and highest elevation loggers on each line that were permanently wetted are referred to as Low_Permanent, and High_Permanent, respectively. The elevation for the Low_Permanent statistic was generally fixed across months except in cases where a logger at 2 kcfs was added in September. Korman et al. (2005) have shown that most young-of-year (YoY) rainbow trout do not follow the waters edge as it rises and falls over a 24 Hr. period but instead reside near the elevation that is permanently wetted. If YoY and juvenile native fish follow this same behaviour, then water temperatures for the High_Permanent elevation represent the nearshore temperatures that most fish are exposed to. This elevation will vary with the flow regime, and was 10 kcfs in August and 5 kcfs in September and October 2004. The alternate hypothesis is that YoY and juvenile native fish follow the waters edge as it rises and falls. To quantify water temperature regimes for this fluctuating zone, we computed a statistic that represented the temperature at the waters edge. This statistic was computed using a composite set of water temperatures for the loggers between the minimum and maximum daily flow. Table 1 provides a summary of the elevations used to represent the Low_Permanent, High_Permanent, and Fluctuating zones.

3.0 Results

Classifying each 15-minute temperature value recorded by a logger as inundated or exposed, for 3 one-week intervals, given the large number of temperature loggers that were deployed, was a time-consuming and difficult process. Figures 1-3 show time series data for 3-day periods in Glen Canyon in August and October, and at Salt Mines in August 2004. The inundation/exposure status of a logger was easy to determine when there were large discontinuities in water temperature over short time intervals (Fig. 1 and 3). When air temperatures dropped in the fall (Fig. 2), temporal discontinuities in temperature were smaller, and spatial discontinuities (differences among loggers on the same line at one time interval) and discharges were used for the classification.

Shoreline gradients in water temperature depended on ambient air temperatures and the extent of isolation of the nearshore environment from the mainstem. A detailed summary of 3-days of water temperature data for all loggers on each line at the Glen Canyon site is provided in Figures 4-6 and the entire week of data at the Low_Permanent, High_Permanent, and Fluctuating zones is presented in Figures 7-9. Average mainstem water temperature, air temperature statistics, and average water temperatures during the daytime, nighttime, and the entire day for each week are provided in Tables 2-5. The time series plots show:

- Substantial shoreline warming at higher elevations for brief periods in the fluctuating zone in August (Fig.'s 4 and 7) and September (Fig.'s 5 and 8) in backwater and low angle shoreline habitats;

- Very modest shoreline warming in the permanently wetted zone in August and September in backwater and low angle shorelines for brief periods; and

- Very little shoreline warming in steep talus habitats that are well mixed with the mainstem.

The tabular summaries, which average temperatures for the entire daytime, nighttime, and 24 Hr. periods for the three week-long periods that were evaluated, show much less warming because the effects of short-duration high temperatures events are diluted by generally lower temperatures for the majority of the 12-24 Hr. periods. During the day, the permanently wetted zone is approximately 0.6 ^{o}C warmer than the mainstem in low angle shorelines. In the fluctuating zone there was about 3 ^{o}C of warming in low angle shorelines (Table 3). As expected there was very little difference in temperatures at night because the gradient between air and water temperatures was much lower (Table 4). As a result, nearshore warming, computed over a 24 Hr. period, was generally only a few 10^{ths} of a degree in the High Permanent zone, and reached a maximum of 1.5 ^{o}C in the fluctuating zone in August in low angle habitats only (Table 5).

Data for Eminence is presented in Figures 10-15 and Tables 6-9. We generally saw less nearshore warming at Eminence compared to Glen Canyon because mainstem water temperatures at Eminence were at least 1 ^{o}C warmer due to longitudinal warming and maximum air temperatures were 18 ^{o}C lower (Table 6 vs. Table 2). During the day, backwater temperatures in August were about 1 ^{o}C warmer than the mainstem, but were over 3 ^{o}C warmer in September (Table 7). Higher flows in August resulted in considerable exchange of water between the mainstem and the backwater. In September, the backwater was more isolated from the mainstem and therefore experienced greater warming. This dynamic is seen in the time series data for the backwater in August (Fig. 10) and September (Fig. 11). In August, water temperatures rise as the day warms until the afternoon and then drop sharply (e.g. 10,000 cfs logger) as the discharge rises. Air temperature also drops at this time, so it is difficult to determine whether the reduction in backwater temperature in late afternoon is due to reduced solar insolation or increased exchange of water with the mainstem. However, in September, a similar drop in afternoon air temperatures was observed, yet the water temperature in the backwater continued to rise (e.g. 5,000 cfs logger). This dynamic is also seen in the summary temperature plots (Fig.'s 13 and 14) in the High_Permanent zone. Backwater temperatures in August at night (Table 8) were very similar to the mainstem temperature because of the inundation of mainstem water (Table 5), but were about 2 ^{o}C warmer than the mainstem in September because the backwater remained isolated at 10 kcfs. Over a 24 Hr. period, backwater temperatures in September were 2-3 ^{o}C warmer than the mainstem, as opposed to < 1 ^{o}C warmer in August. Backwater temperatures in October were generally about 1 ^{o}C less than the mainstem (Fig. 15) owing to reduce air temperatures.

Data for Salt Mines is presented in Figures 16-21 and Tables 10-13. There was very little nearshore warming at this location except for very brief periods in the fluctuating zone in the backwater and the low angle shoreline samples in August and September. The backwater at Salt Mines did not warm much relative to the mainstem, even in September when flows were lower. We suspect that the difference in mainstem-backwater temperatures at Salt Mines compared to Eminence was caused both by the timing of daily maximum flows and differences in air temperatures between early- (Eminence summary period) and mid-September (Salt Mines summary period). At Salt Mines, daily maximum flows coincided with periods of maximum air temperatures. In August, the backwater was inundated with cooler mainstem water during the day. At night, when it was more isolated, air temperatures were much lower resulting in less warming. This flow dynamic was less important in September because the flow range was only 5-10 kcfs, allowing the backwater to be isolated from the mainstem even at the maximum daily flow. We saw substantial warming on one day in the September time series when air temperatures were high (Fig.'s 17 and 20), however most of the other days of the sample week were cooler, resulting in minimal warming. Over a 24 Hr. period, water temperatures at Salt Mines were about 14.5 ^{o}C in August, 15-15.5 ^{o}C in September, and 13-13.5 ^{o}C in October, compared to mainstem temperatures of 14.3, 15.0, and 15.5 ^{o}C, respectively.

Backwaters had very dynamic patterns of vertical stratification. At the Eminence backwater in August, surface waters warmed just after air temperature peaked and as discharge declined (Fig. 22). By late afternoon the surface water was ca. 1.5 ^{o}C warmer than the bottom. In the morning, when there was a rapid increase in air temperatures due to direct solar insolation, the water at the bottom of the backwater appeared warmer than surface water. This reverse vertical stratification, in the order of 0.5 ^{o}C, was even seen in well-mixed talus environments. It is possible that direct solar insolation heated the substrate that in turn heated water near the bottom more than water at the surface. Normal thermal stratification (i.e., warmer water on top) was the more common pattern. The extent of stratification increased when flows were reduced in September. Surface water at the Eminence backwater was as much as 7 ^{o}C warmer than the bottom water in the late afternoon in September at the end of the minimum daily flow period. As discharge rose, cooler mainstem water entered the backwater and surface temperatures declined even though air temperatures were increasing. There was less vertical stratification in the backwater at Salt Mines because it was less isolated from the mainstem (Fig. 23). Surface waters were less than one-half a degree warmer than water on the bottom in August. However, we did not sample through the late afternoon when discharge was dropping but air temperatures were still high. It is possible that there was just as much stratification at the Salt Mines backwater but that it did not occur over our 12:00 pm – 15:00 sample window. More stratification was observed in September with surface temperatures reaching a maximum of 22 ^{o}C compared to a maximum bottom temperature of 19 ^{o}C. Surface temperatures in talus environments were a maximum of one degree warmer than bottom temperatures, and this difference only occurred when air temperatures peaked.

4.0 Conclusions

Assessment of shoreline temperature gradients during periods of fluctuating flows was difficult because temperature loggers were continually exposed and inundated over the 24 Hr. daily cycle in flow created by operation of Glen Canyon Dam. We did not have sufficient resources to stay at our study sites for extended periods to determine when exposure and inundation occurred. As a result, we had to estimate the times when this happened based on predictions of flow, and spatial and temporal gradients in logger temperatures. There is a circularity in this approach, as the rules used to classify a logger as exposed or inundated are based mostly on temperature gradients, which is the variable of most interest in a study of shoreline temperature gradients. Fortunately, ambiguities in classification would likely only have a minor effect on the results presented here. There was no error in classification for loggers that were permanently submerged. Temperatures in the permanently inundated zone would be considered more important than in the fluctuating zone under the assumption that there is limited use of the fluctuating zone by YoY and native juvenile fish (Korman et al. 2005). However, as the use of the fluctuating zone by native fish may be important, the relative importance of temperatures in permanent vs. fluctuating zones is uncertain. To avoid the potential errors introduced into estimates of water temperature in the fluctuating zone, future studies of shoreline temperature gradients should deploy a continuously recording stage sensor at a permanently submerged logger on each line.

The extent of shoreline warming was consistent with some of the initial predictions that were posed:

1. Maximum nearshore warming in low angle shorelines was observed in August in Glen Canyon when the difference between mainstem water temperatures and air temperatures was greatest;

2. The extent of nearshore warming depended on the extent of isolation from the mainstem, with backwaters showing the greatest warming, low angle shorelines

showing moderate warming, and virtually no warming seen in well-mixed steep talus environments; and

3. Greater fluctuations in flow reduce the extent of warming in backwaters due to increased exchange with mainstem water. However, as seen by differences between the Salt Mines and Eminence backwaters, the extent of this effect is variable and depends on the timing of maximum and minimum flows and the topography of the backwater. Our dataset was of limited use for this assessment because there were large differences in air temperatures over the two different weeks used in the Eminence-Salt Mines comparison for September.

With the exception of backwater temperatures at Eminence in September, nearshore temperatures were a maximum of 2-3 ^{o}C warmer than the mainstem over the study period. Typically, these larger differences occurred in the fluctuating zone.

Vertical stratification in water temperature was observed in both backwaters and talus shorelines but was much greater in backwaters. Stratification patterns were dynamic and varied over a 24 Hr. period with changes in discharge and air temperature. Surface waters in backwater and talus environments were a maximum of 3-7 ^{o}C and 1 ^{o}C warmer than bottom water, respectively. Remote-sensed measurements of water temperature, which only measure conditions at the water surface, will under- or over-estimate temperatures near the bottom depending on the time of day of the over flight in relation to flow and air temperature patterns.

Mainstem water temperatures are continuously measured as part of GCMRC baseline monitoring activities. This monitoring network could be inexpensively supplemented with a series of continuously recording stage and temperature loggers (ca. cost of $400/unit) that would measure water temperatures in both backwater and low angle shoreline habitats. Loggers should be placed near the highest elevation of the permanently wetted stage. This placement would require adjustments with changes in the daily minimum flow, which generally occurs on monthly or longer time scales. Due to logistic limitations, there will inevitably be periods when these loggers would become exposed, but this could be unambiguously determined using the data from the stage sensors. These data would be helpful in future evaluations of the effects of steady and fluctuating flows on shoreline warming.

5.0 References

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Tables

Table 1. Elevations (cfs) associated with temperature loggers located at the lowest elevation that was sampled that was always permanently inundated (Low Permanent), the highest elevation that was sampled that was permanently inundated (High Permanent), and the highest elevation that was sampled in the zone of daily fluctuations (Fluctuating). The daily range of discharge was ca. 10,000-18,000 cfs in August and 5,000-10,000 cfs in September and October, 2004.

Location	Month	Line #	Low Permanent	High Permanent	Fluctuating
Glen	Aug.	1-3	2,500	10,000	15,000
		4	2,500	10,000	12,500
	Sep.	1-4	2,000	2,500	7,500
	Oct.	1-4	2,000	2,500	7,500
Eminence	Aug.	1-5	2,500	10,000	17,500
	Sep.	1-2	2,500	5,000	7,500
		3	2,500	2,500	7,500
		4-5	2,500	2,500	10,000
	Oct.	1	2,000	5,000	7,500
		2		No Data	
		3-4	2,500	2,500	10,000
		5	2,000	2,500	10,000
Salt Mines	Aug.	1-5	2,500	10,000	17,500
	Sep.	1	No Data		
		2	2,500	5,000	10,000
		3	2,500	2,500	10,000
		4-5	2,500	7,500	10,000
	Oct.	1	No Data		
		2	2,500	7,500	No Data
		3	2,500	2,500	10,000
		4	2,500	7,500	10,000
		5	2,500	5,000	10,000

Table 2. Mainstem water and air temperature statistics for a one-week period for each month at the Glen Canyon site.

Month	Mainstem	Air (Avg.)	Air (Min.)	Air (Max.)
Aug.	12.5	28.3	12.2	58.4
Sep.	13.5	23.4	10.2	59.4
Oct.	13.3	12.8	4.1	41.3

Table 3. Average daytime water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Glen Canyon site by habitat type for a one-week period in each month. The Low-Permanent and High-Permanent elevations are the lowest elevation logger (2-2.5 kcfs), and the highest elevation that was permanently inundated for the sample periods, respectively (see Table 1). The elevation associated with the Fluctuating zone changes over a 24 Hr. cycle with changes in discharge (see Table 1 for the ranges for each month).

		Day (10:00am to 10:00pm)		
Month	Logger Line	Low Permanent	High Permanent	Fluctuating
Aug.	Low Angle Shoreline line-1	12.9	13.6	16.3
	Low Angle Shoreline line-2	12.9	13.5	15.7
	Talus line-3	12.8	12.9	13.5
	Talus line-4	12.8	13.0	13.1
Sep.	Low Angle Shoreline line-1	14.0	14.0	15.7
	Low Angle Shoreline line-2	14.0	14.0	15.2
	Talus line-3	13.9	13.9	14.3
	Talus line-4	13.8	13.9	14.3
Oct.	Low Angle Shoreline line-1	13.5	13.5	13.4
	Low Angle Shoreline line-2	13.5	13.5	13.5
	Talus line-3	13.5	13.5	13.6
	Talus line-4	13.4	13.5	13.7

Table 4. Average nighttime water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Glen Canyon site by habitat type for a one-week period in each month. See caption for Table 3 for details.

		Night (10:00pm to 10:00am)		
Month	**Logger Line**	**Low Permanent**	**High Permanent**	**Fluctuating**
Aug.	Low Angle Shoreline line-1	12.1	12.3	12.6
	Low Angle Shoreline line-2	12.1	12.2	12.4
	Talus line-3	12.1	12.2	12.3
	Talus line-4	12.2	12.2	12.3
Sep.	Low Angle Shoreline line-1	13.1	13.1	13.1
	Low Angle Shoreline line-2	13.1	13.2	13.2
	Talus line-3	13.2	13.2	13.3
	Talus line-4	13.2	13.2	13.3
Oct.	Low Angle Shoreline line-1	13.2	13.1	12.7
	Low Angle Shoreline line-2	13.1	13.1	12.8
	Talus line-3	13.3	13.0	13.1
	Talus line-4	13.2	13.3	13.2

Table 5. Average daily water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Glen Canyon site by habitat type for a one-week period in each month. See caption for Table 3 for details.

		Daily (24 Hrs.)		
Month	**Logger Line**	**Low Permanent**	**High Permanent**	**Fluctuating**
Aug.	Low Angle Shoreline line-1	12.5	12.9	14.3
	Low Angle Shoreline line-2	12.5	12.8	14.0
	Talus line-3	12.5	12.6	12.9
	Talus line-4	12.5	12.6	12.7
Sep.	Low Angle Shoreline line-1	13.6	13.5	14.4
	Low Angle Shoreline line-2	13.6	13.6	14.2
	Talus line-3	13.6	13.6	13.8
	Talus line-4	13.5	13.6	13.8
Oct.	Low Angle Shoreline line-1	13.3	13.3	13.2
	Low Angle Shoreline line-2	13.3	13.3	13.3
	Talus line-3	13.4	13.3	13.3
	Talus line-4	13.3	13.4	13.5

Table 6. Mainstem water and air temperature statistics for a one-week period in each month at the Eminence site.

Month	Mainstem	Air (Avg.)	Air (Min.)	Air (Max.)
Aug.	13.6	24.3	14.3	42.2
Sep.	14.7	22.3	8.2	42.0
Oct.	13.3	9.6	3.0	17.6

Table 7. Average daytime water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Eminence site by habitat type for a one-week period in each month. See caption for Table 3 for details.

		Day (10:00am to 10:00pm)		
Month	Logger Line	Low Permanent	High Permanent	Fluctuating
Aug.	Backwater line-1	14.0	14.8	14.7
	Backwater line-2	13.9	15.0	15.1
	Low Angle Shoreline line-3	13.6	14.2	14.4
	Talus line-4	13.7	13.6	13.7
	Talus line-5	13.6	13.7	13.8
Sep.	Backwater line-1	16.4	17.1	16.7
	Backwater line-2	16.5	18.0	18.1
	Low Angle Shoreline line-3	14.8	14.8	15.1
	Talus line-4	14.9	14.9	14.9
	Talus line-5	14.7	14.7	14.9
Oct.	Backwater line-1	12.0	12.3	12.8
	Low Angle Shoreline line-3	13.3	13.3	13.0
	Talus line-4	13.4	13.4	13.0
	Talus line-5	13.2	13.2	13.3

Table 8. Average nighttime water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Eminence site by habitat type for a one-week period in each month. See caption for Table 3 for details.

		Night (10:00pm to 10:00am)		
Month	Logger Line	Low Permanent	High Permanent	Fluctuating
Aug.	Backwater line-1	13.6	13.8	13.9
	Backwater line-2	13.7	13.9	14.4
	Low Angle Shoreline line-3	13.4	13.7	14.2
	Talus line-4	13.5	13.4	13.6
	Talus line-5	13.4	13.4	13.7
Sep.	Backwater line-1	16.3	16.8	15.8
	Backwater line-2	16.4	17.1	17.4
	Low Angle Shoreline line-3	14.6	14.6	15.1
	Talus line-4	14.7	14.7	14.7
	Talus line-5	14.6	14.6	14.9
Oct	Backwater line-1	12.0	12.3	13.3
	Low Angle Shoreline line-3	13.3	13.3	13.3
	Talus line-4	13.4	13.4	13.0
	Talus line-5	13.2	13.2	13.3

Table 9. Average daily water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Eminence site by habitat type for a one-week period in each month. See caption for Table 3 for details.

		Daily (24 Hrs.)		
Month	**Logger Line**	**Low Permanent**	**High Permanent**	**Fluctuating**
Aug.	Backwater line-1	13.8	14.3	14.3
	Backwater line-2	13.8	14.4	14.5
	Low Angle Shoreline line-3	13.5	14.0	14.1
	Talus line-4	13.6	13.5	13.5
	Talus line-5	13.5	13.6	13.6
Sep.	Backwater line-1	16.4	16.9	16.7
	Backwater line-2	16.5	17.5	17.6
	Low Angle Shoreline line-3	14.7	14.7	14.9
	Talus line-4	14.8	14.8	14.8
	Talus line-5	14.7	14.7	14.7
Oct.	Backwater line-1	12.0	12.3	12.5
	Low Angle Shoreline line-3	13.3	13.3	13.2
	Talus line-4	13.4	13.4	13.2
	Talus line-5	13.2	13.2	13.2

Table 10. Mainstem water and air temperature statistics for a one-week period in each month at the Salt Mines site.

Month	Mainstem	Air (Avg.)	Air (Min.)	Air (Max.)
Aug.	14.3	29.4	18.3	47.2
Sep.	15.0	19.0	11.7	43.0
Oct.	13.5	12.8	6.8	24.4

Table 11. Average daytime water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Salt Mines site by habitat type for a one-week period in each month. See caption for Table 3 for details.

		Day (10:00am to 10:00pm)		
Month	Logger Line	Low Permanent	High Permanent	Fluctuating
Aug.	Backwater line-1	14.3	14.5	15.0
	Backwater line-2	14.2	14.4	14.7
	Low Angle Shoreline line-3	14.3	14.3	14.5
	Talus line-4	14.4	14.5	14.7
	Talus line-5	14.3	14.5	14.7
Sep.	Backwater line-1			
	Backwater line-2	15.9	15.9	16.1
	Low Angle Shoreline line-3	15.2	15.2	15.0
	Talus line-4	15.3	15.3	15.4
	Talus line-5	15.2	15.3	15.5
Oct.	Backwater line-1			
	Backwater line-2	13.5	13.1	12.7
	Low Angle Shoreline line-3	13.4	13.4	13.5
	Talus line-4	13.8	13.5	13.6
	Talus line-5	13.5	13.4	13.6

Table 12. Average nighttime water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Salt Mines site by habitat type for a one-week period in each month. See caption for Table 3 for details.

		Night (10:00pm to 10:00am)		
Month	**Logger Line**	**Low Permanent**	**High Permanent**	**Fluctuating**
Aug.	Backwater line-1	14.1	14.5	14.6
	Backwater line-2	14.3	14.5	14.6
	Low Angle Shoreline line-3	14.1	14.3	14.4
	Talus line-4	14.2	14.3	14.4
	Talus line-5	14.2	14.3	14.4
Sep.	Backwater line-1			
	Backwater line-2	15.2	15.2	14.8
	Low Angle Shoreline line-3	15.1	15.1	14.9
	Talus line-4	15.1	15.0	15.0
	Talus line-5	15.1	15.0	15.0
Oct.	Backwater line-1			
	Backwater line-2	13.6	13.3	12.9
	Low Angle Shoreline line-3	13.2	13.2	13.0
	Talus line-4	13.8	12.9	12.9
	Talus line-5	13.2	13.0	12.9

Table 13. Average daily water temperatures in the Low-Permanent, High-Permanent, and Fluctuating zones at the Salt Mines site by habitat type for a one-week period in each month. See caption for Table 3 for details.

		Daily (24 Hrs.)		
Month	**Logger Line**	**Low Permanent**	**High Permanent**	**Fluctuating**
Aug.	Backwater line-1	14.2	14.5	14.7
	Backwater line-2	14.3	14.5	14.6
	Low Angle Shoreline line-3	14.2	14.3	14.4
	Talus line-4	14.3	14.4	14.5
	Talus line-5	14.3	14.4	14.5
Sep.	Backwater line-1			
	Backwater line-2	15.6	15.6	15.6
	Low Angle Shoreline line-3	15.1	15.1	15.1
	Talus line-4	15.2	15.2	15.2
	Talus line-5	15.1	15.2	15.2
Oct.	Backwater line-1			
	Backwater line-2	13.5	13.2	13.0
	Low Angle Shoreline line-3	13.3	13.3	13.3
	Talus line-4	13.8	13.2	13.2
	Talus line-5	13.3	13.2	13.3

Figures

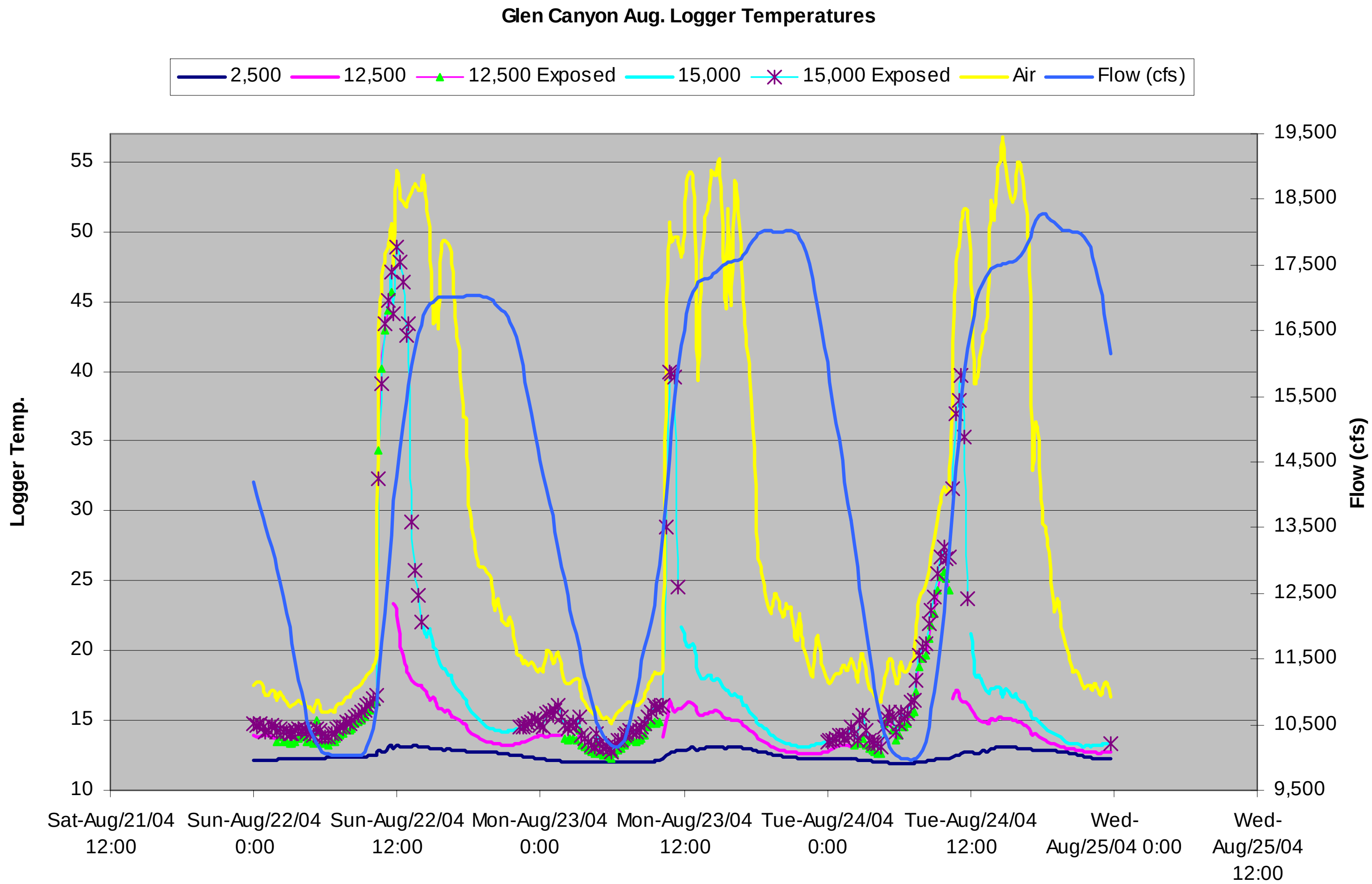

Figure 1. Water and air temperatures and routed flow at a low angle site in Glen Canyon (Line-1) during August. Symbols denote periods when loggers were exposed.

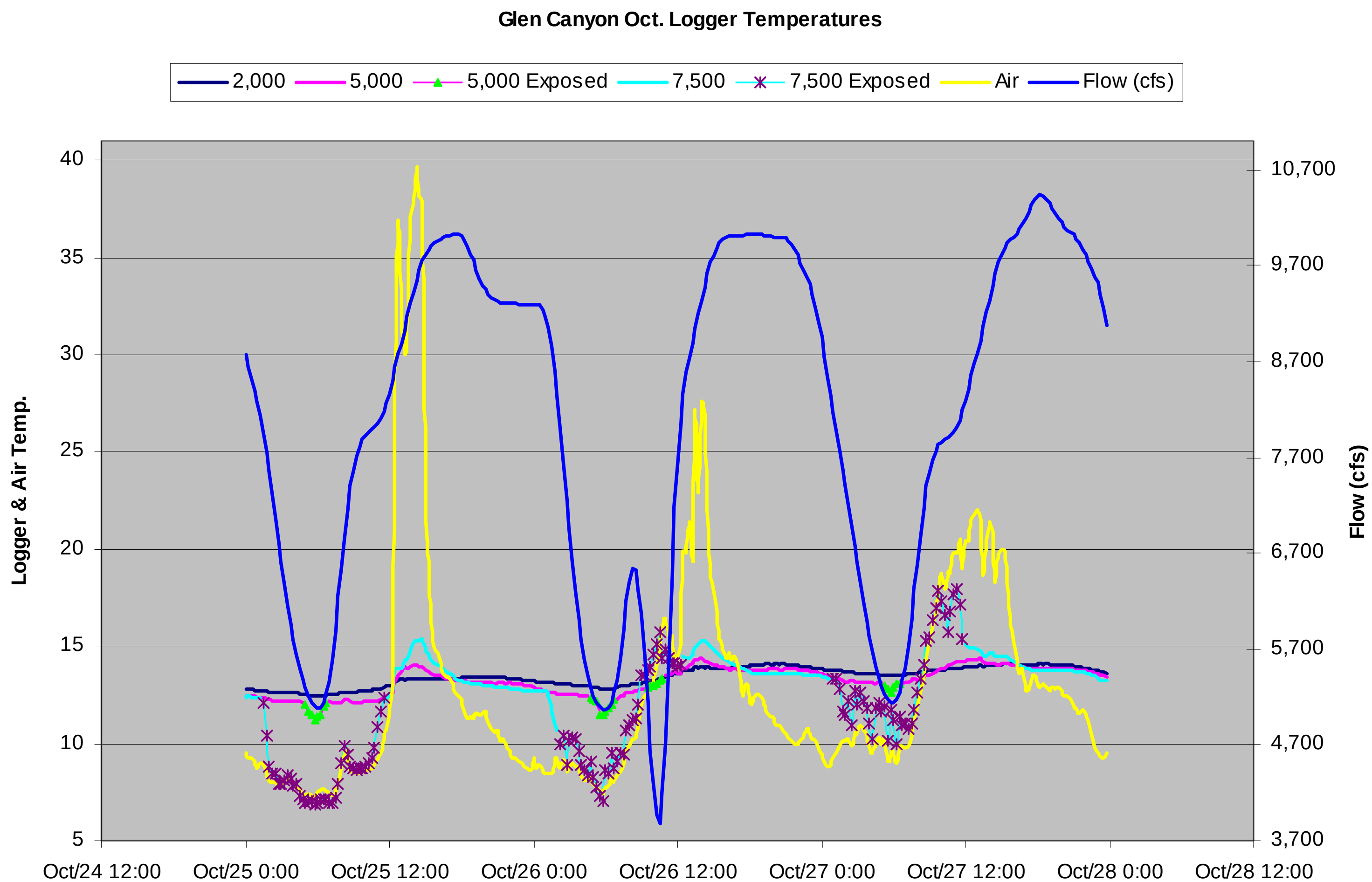

Figure 2. Water and air temperatures and routed flow at a low angle shoreline in Glen Canyon (Line-1) during October. Symbols denote periods when loggers were exposed.

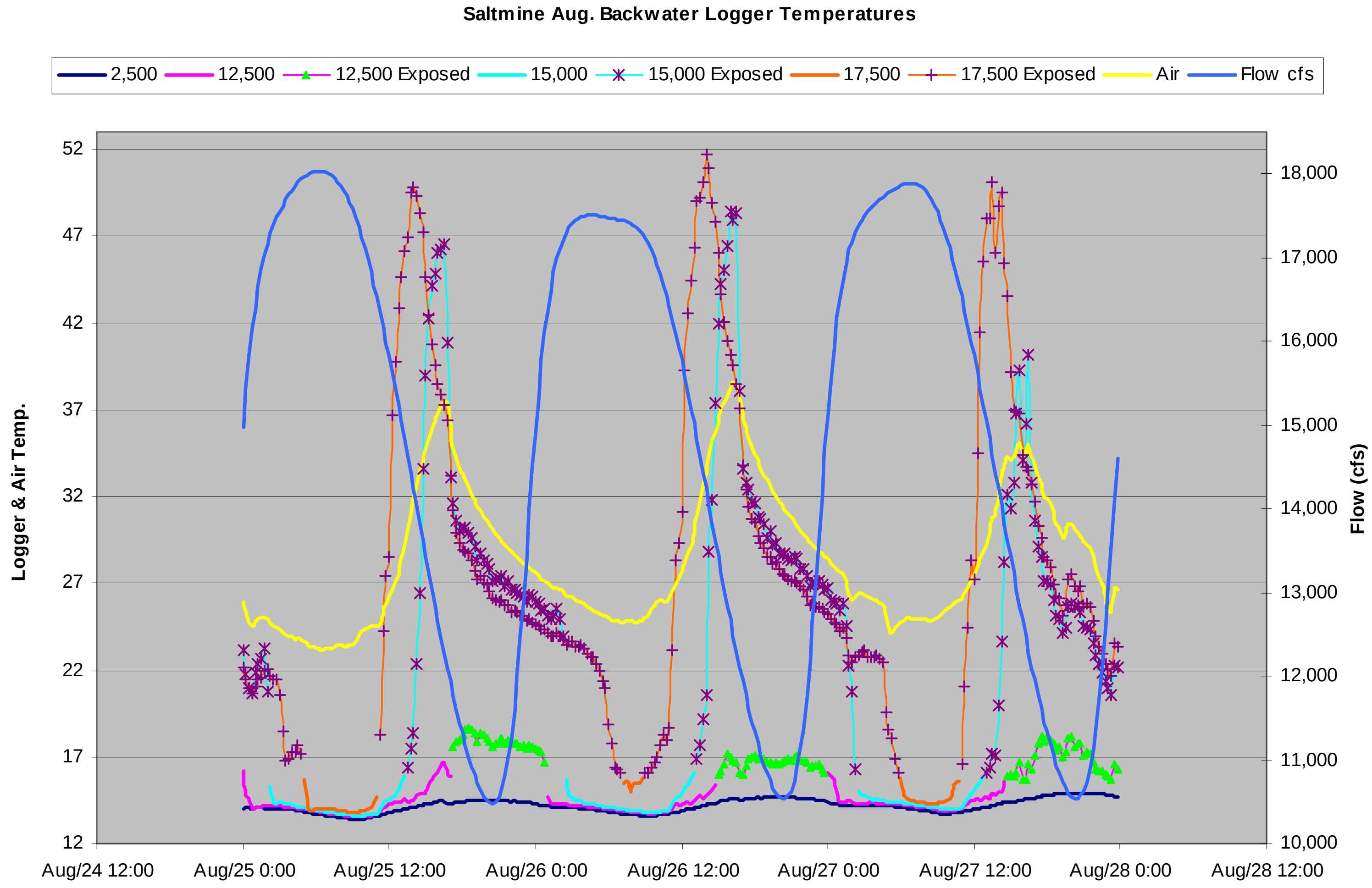

Figure 3. Water and air temperatures and routed flow at the backwater at the Salt Mines location (Line-1) during August. Symbols denote periods when loggers were exposed.

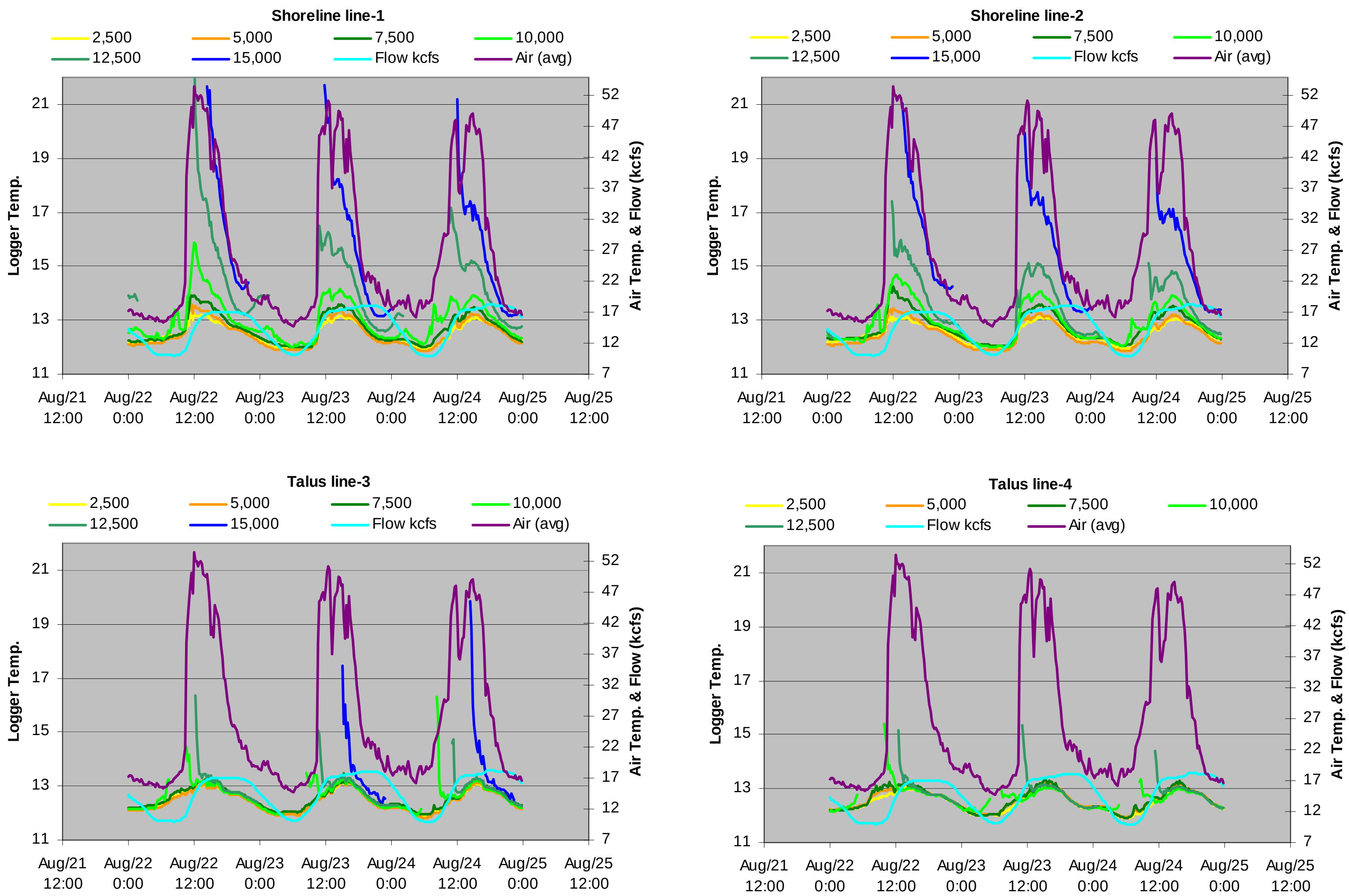

Figure 4. Water and air temperatures and routed flow by habitat type in Glen Canyon for 3 days in August.

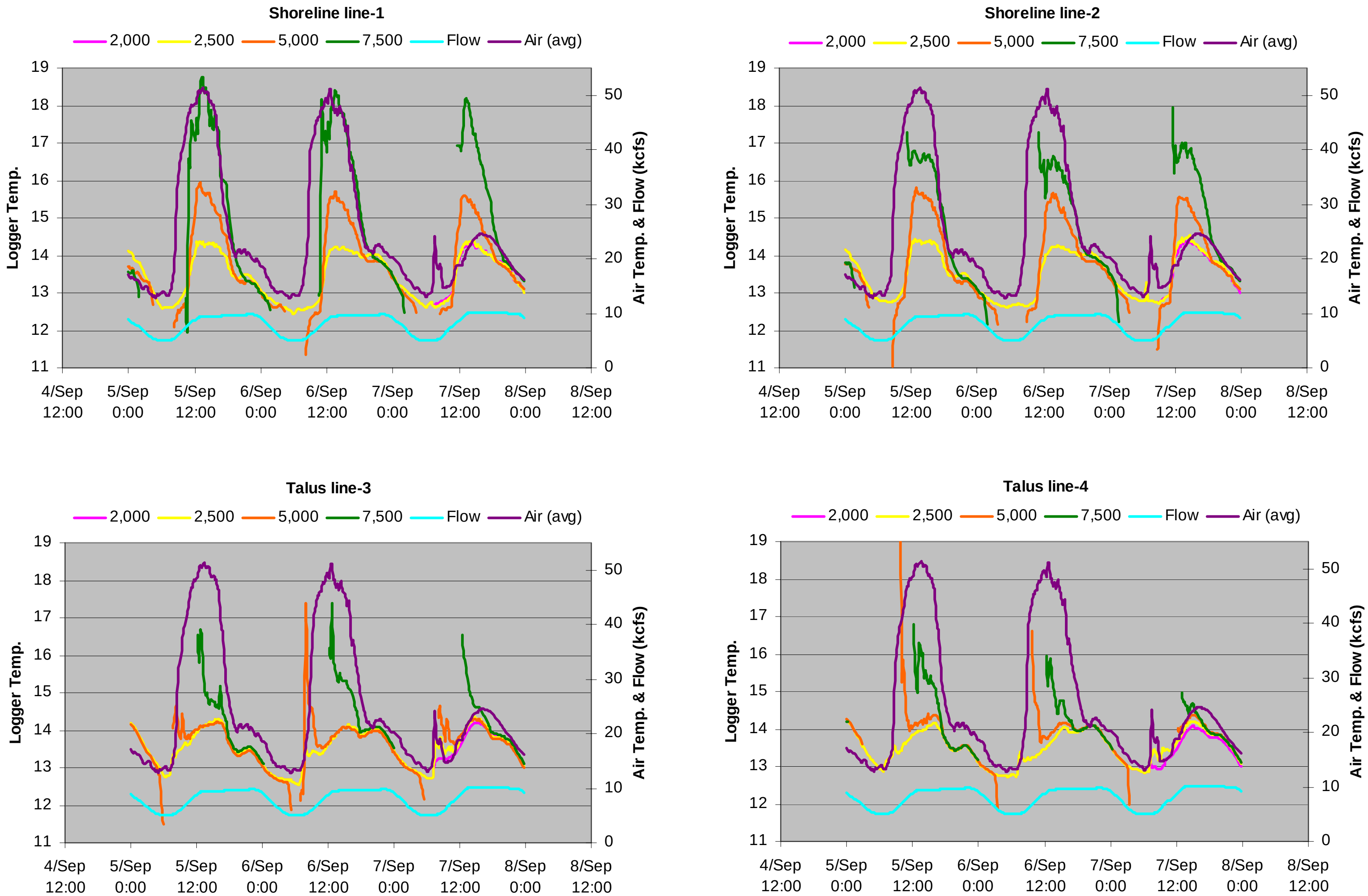

Figure 5. Water and air temperatures and routed flow by habitat type in Glen Canyon for 3 days in September.

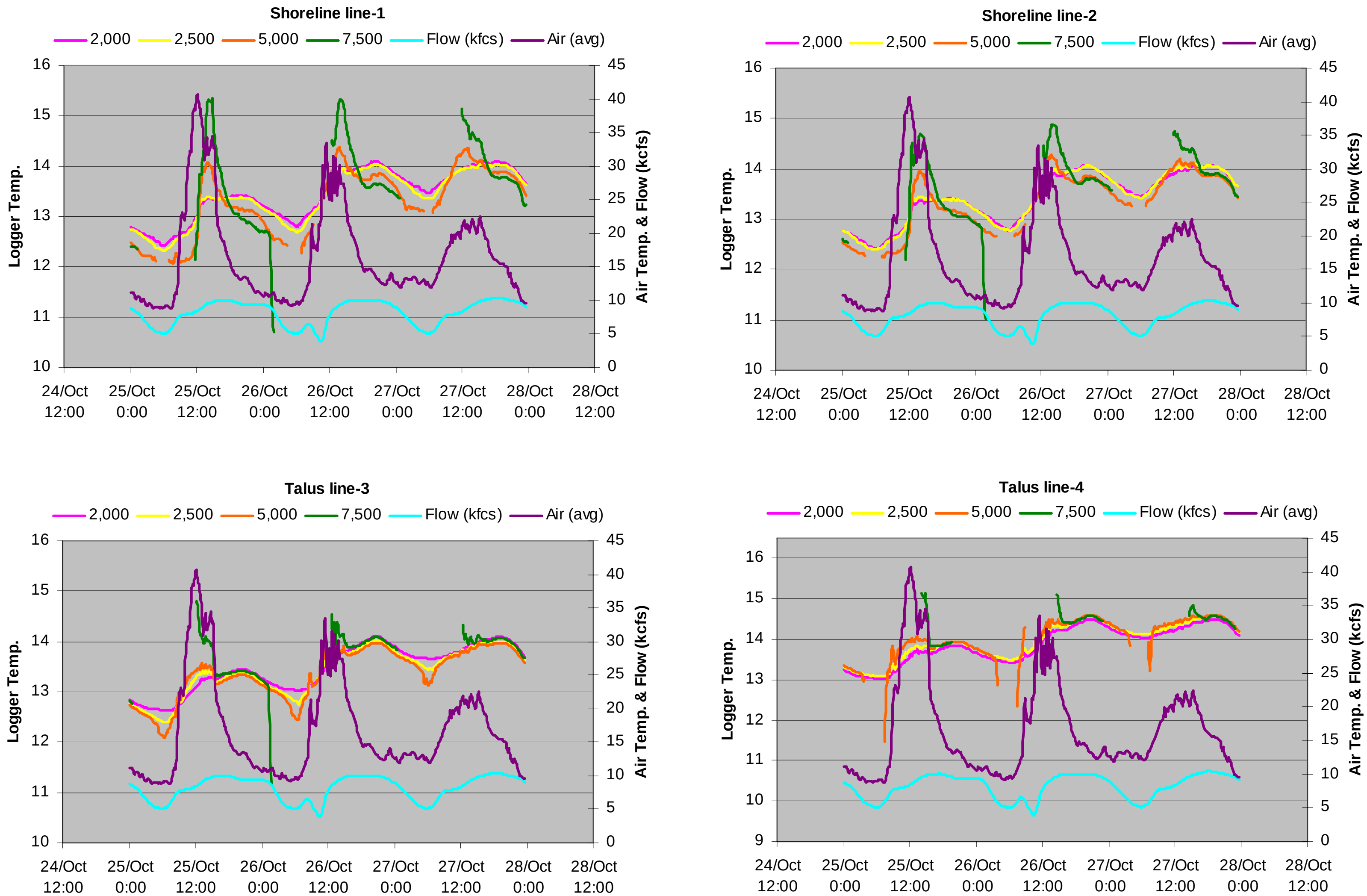

Figure 6. Water and air temperatures and routed flow by habitat type in Glen Canyon for 3 days in October.

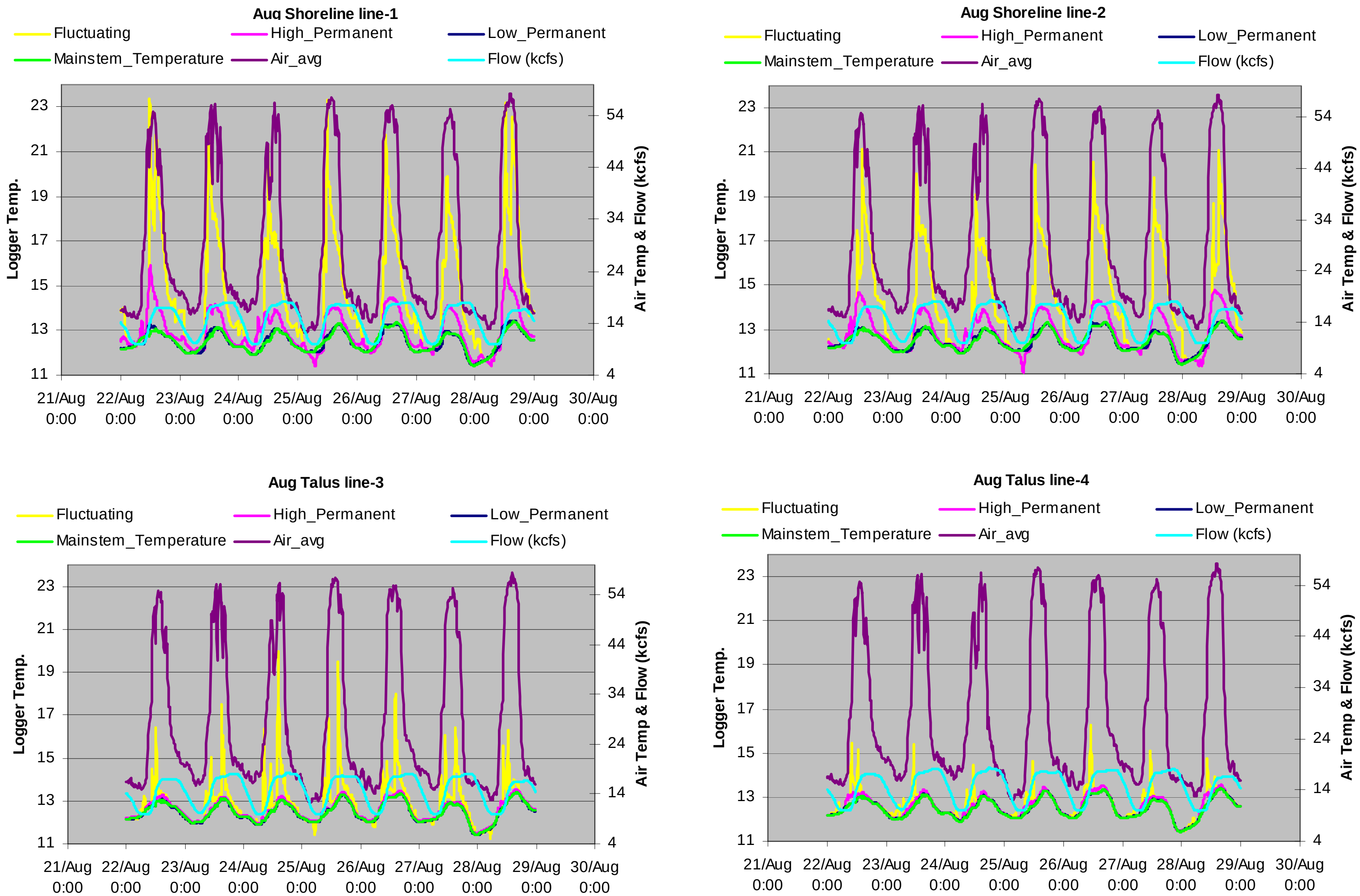

Figure 7. Water and air temperatures and routed flow in Glen Canyon for 7 days in August. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

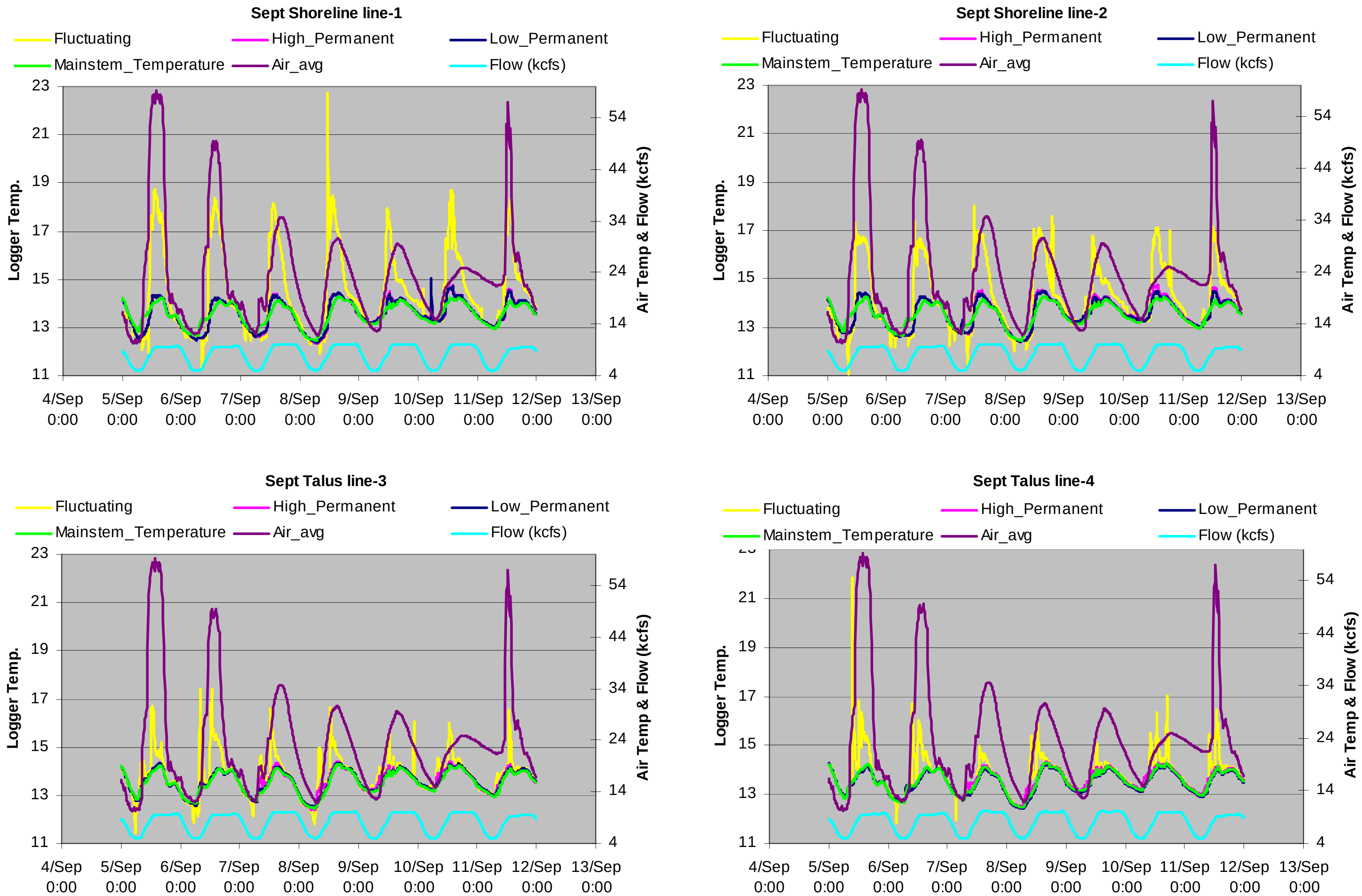

Figure 8. Water and air temperatures and routed flow in Glen Canyon for 7 days in September. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

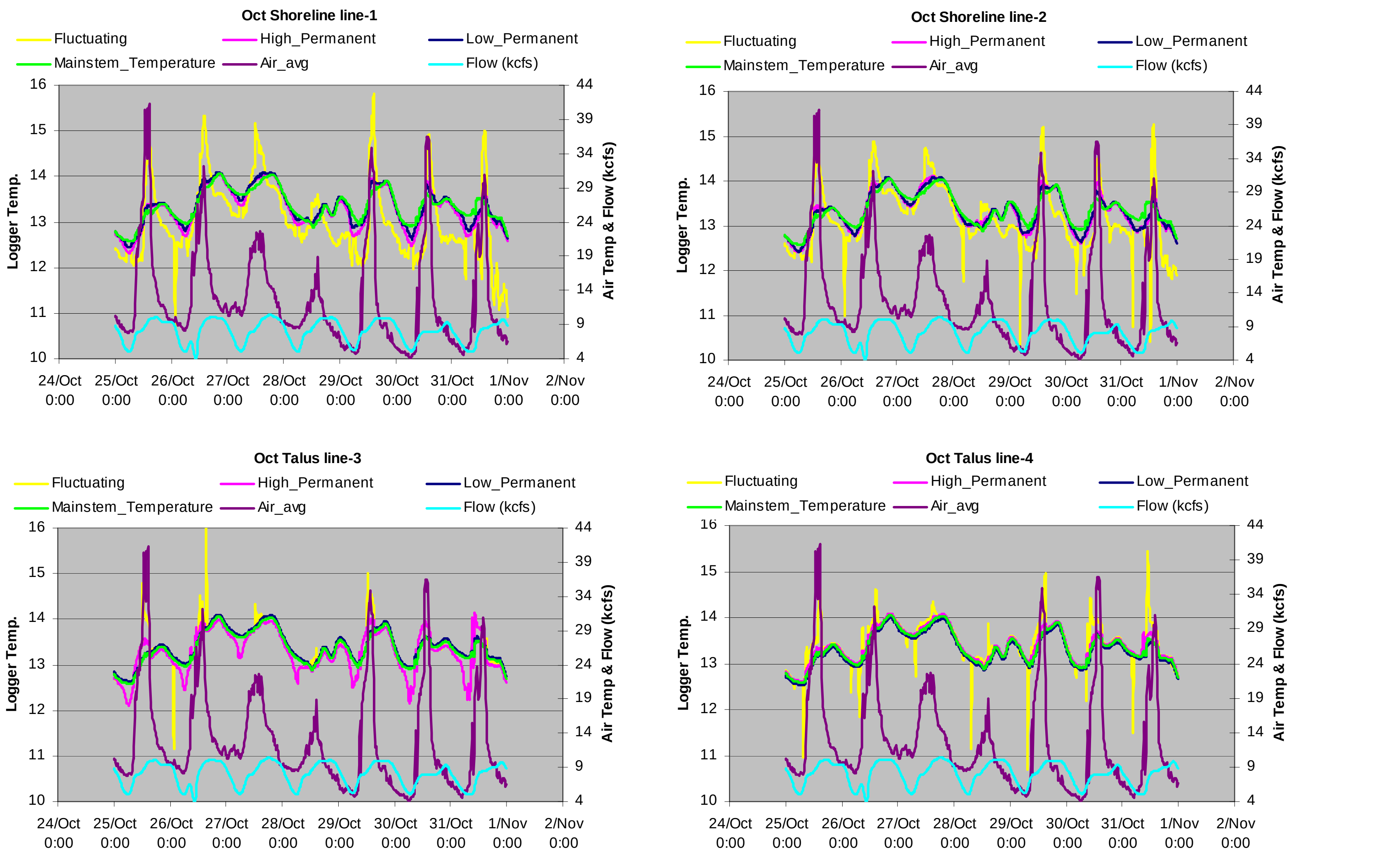

Figure 9. Water and air temperatures and routed flow in Glen Canyon for 7 days in October. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

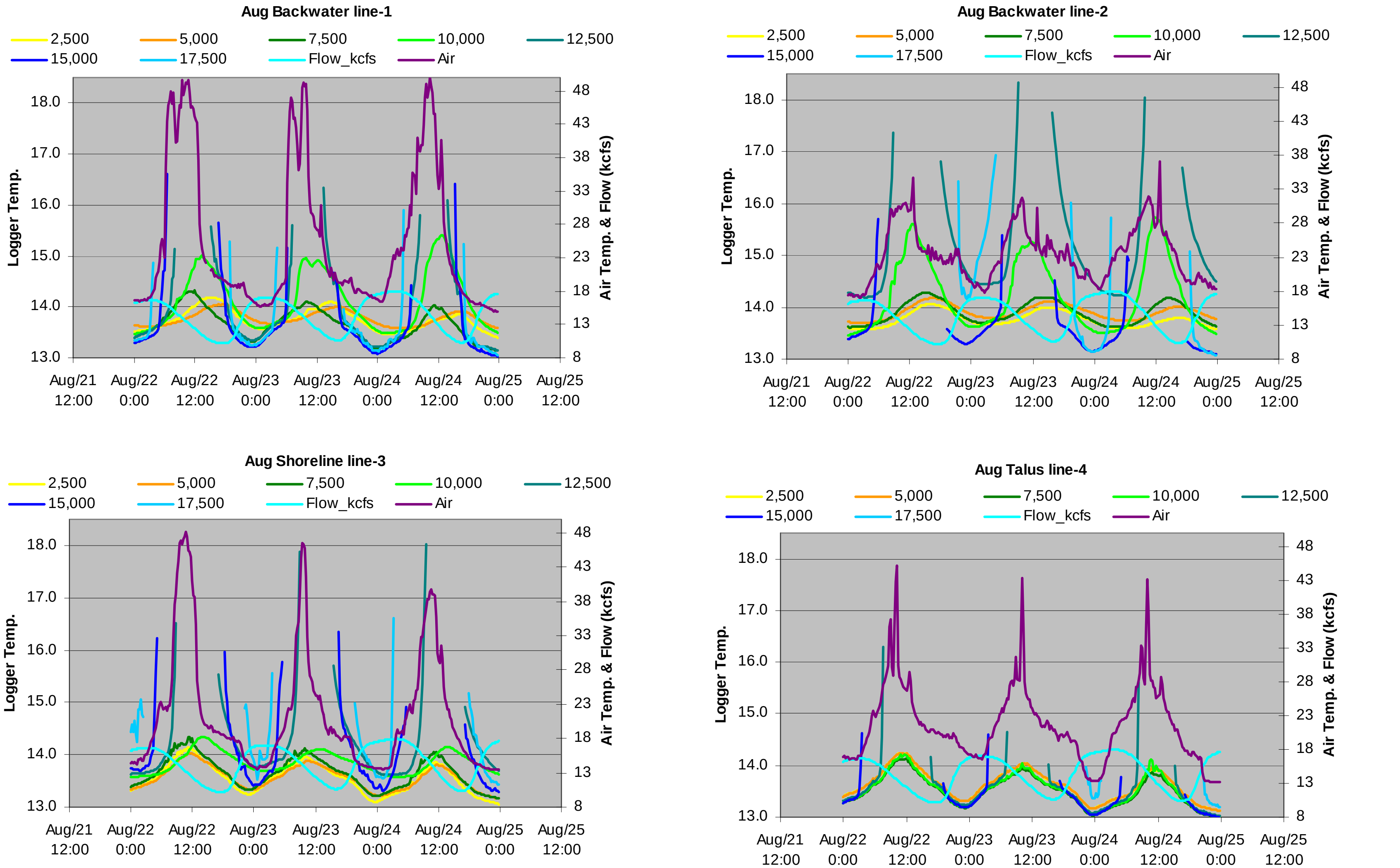

Figure 10. Water and air temperatures and routed flow by habitat type at Eminence for 3 days in August.

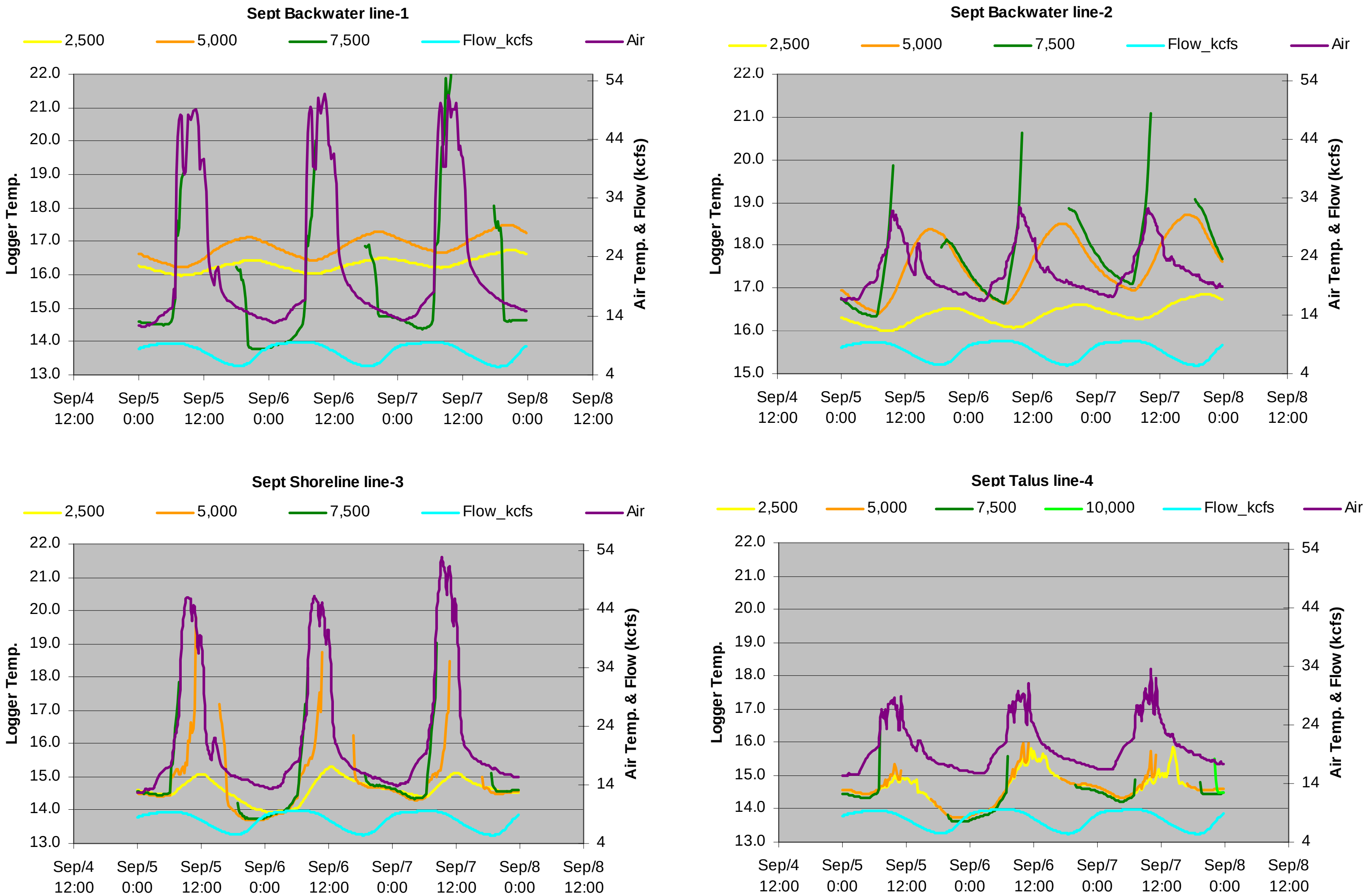

Figure 11. Water and air temperatures and routed flow by habitat type at Eminence for 3 days in September.

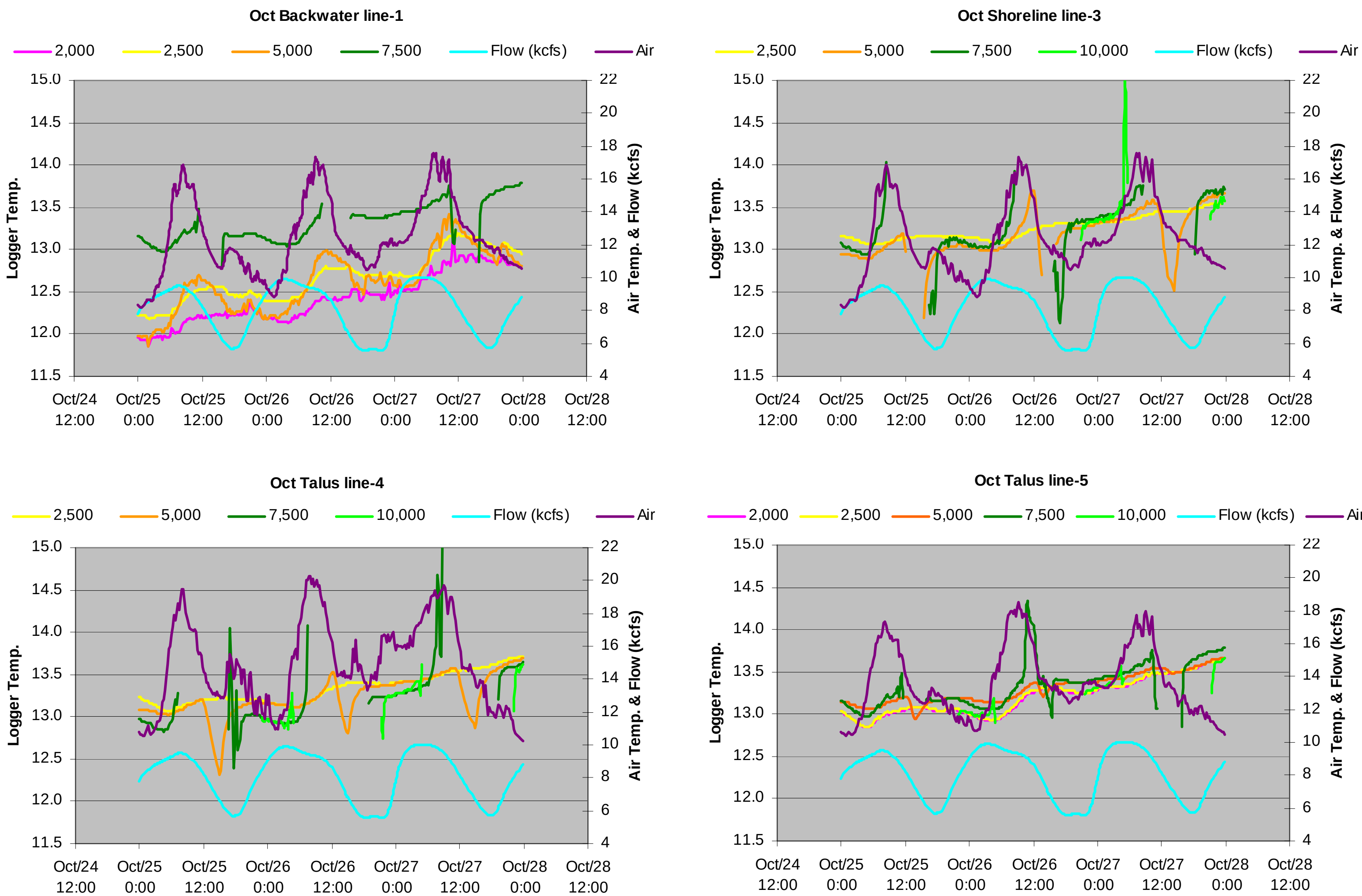

Figure 12. Water and air temperatures and routed flow by habitat type at Eminence for 3 days in October.

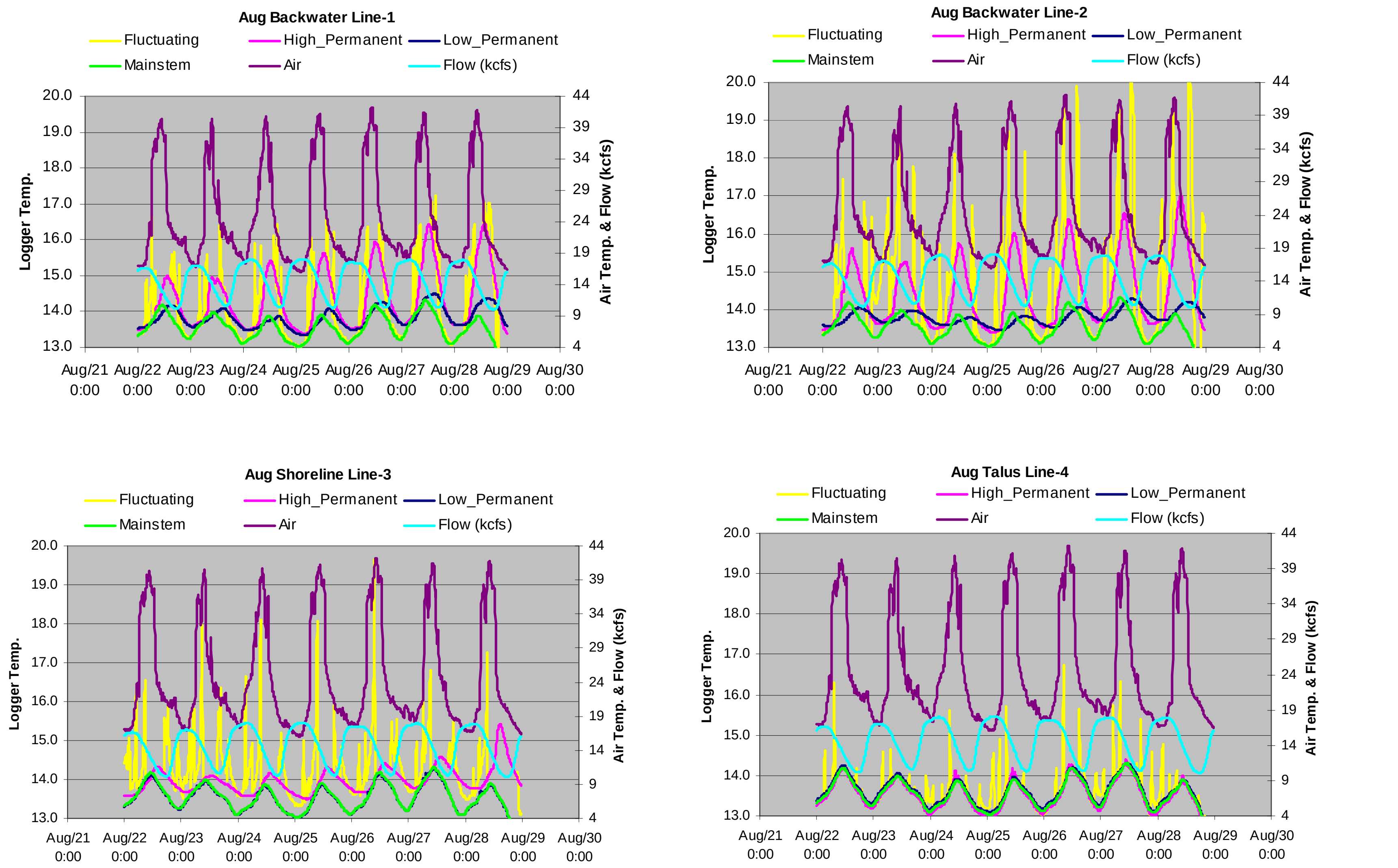

Figure 13. Water and air temperatures and routed flow at Eminence for 7 days in August. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

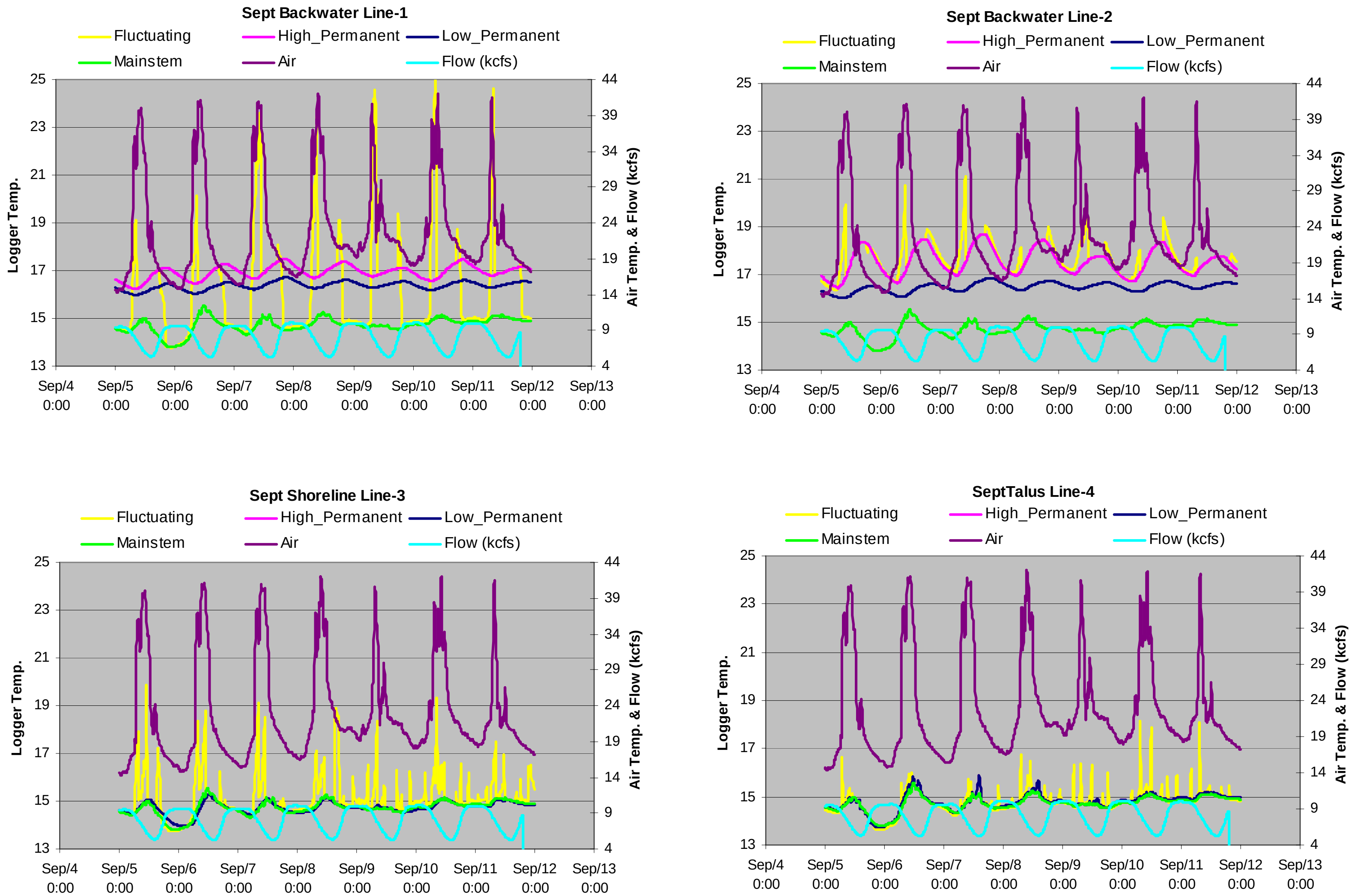

Figure 14. Water and air temperatures and routed flow at Eminence for 7 days in September. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

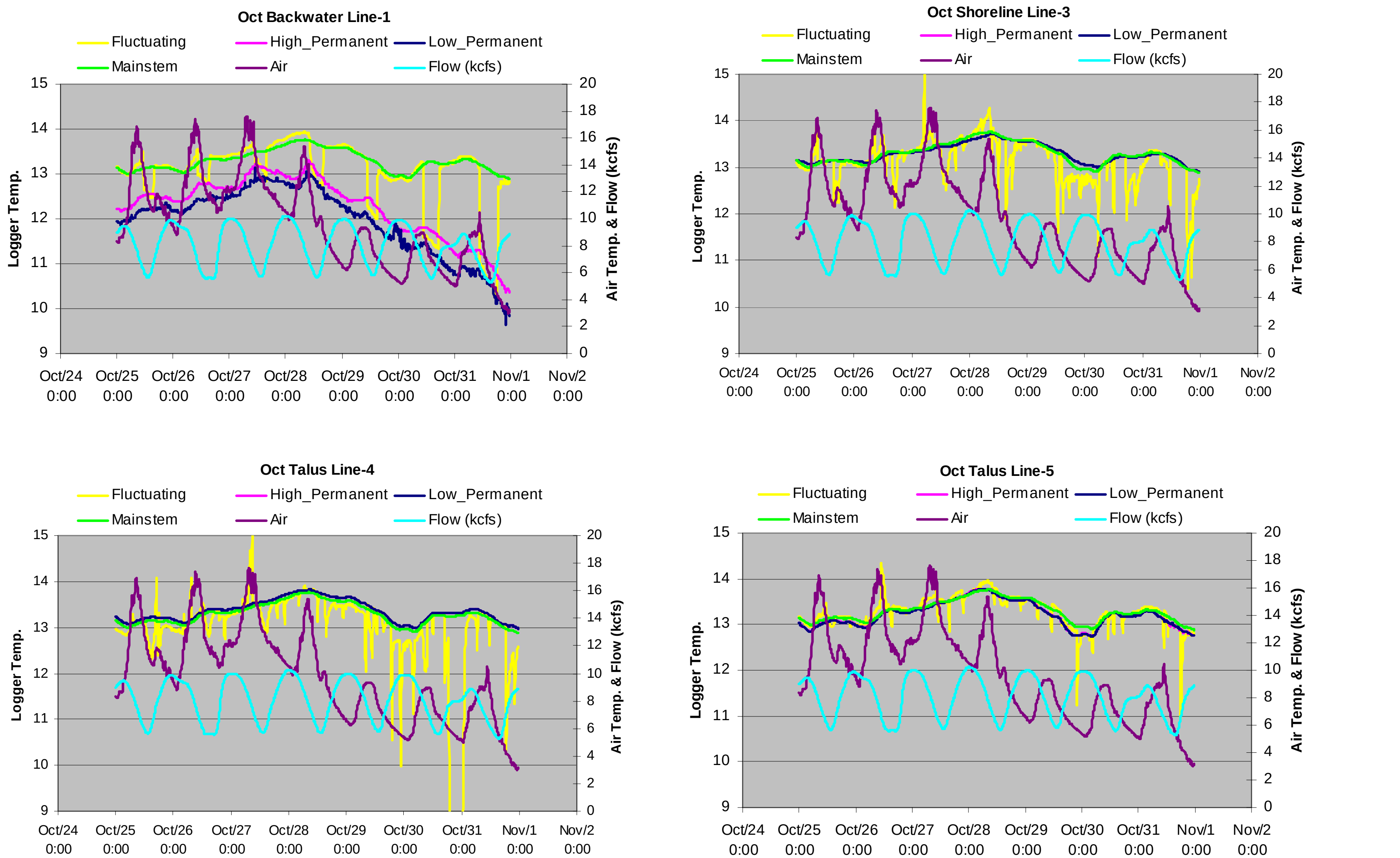

Figure 15. Water and air temperatures and routed flow at Eminence for 7 days in October. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

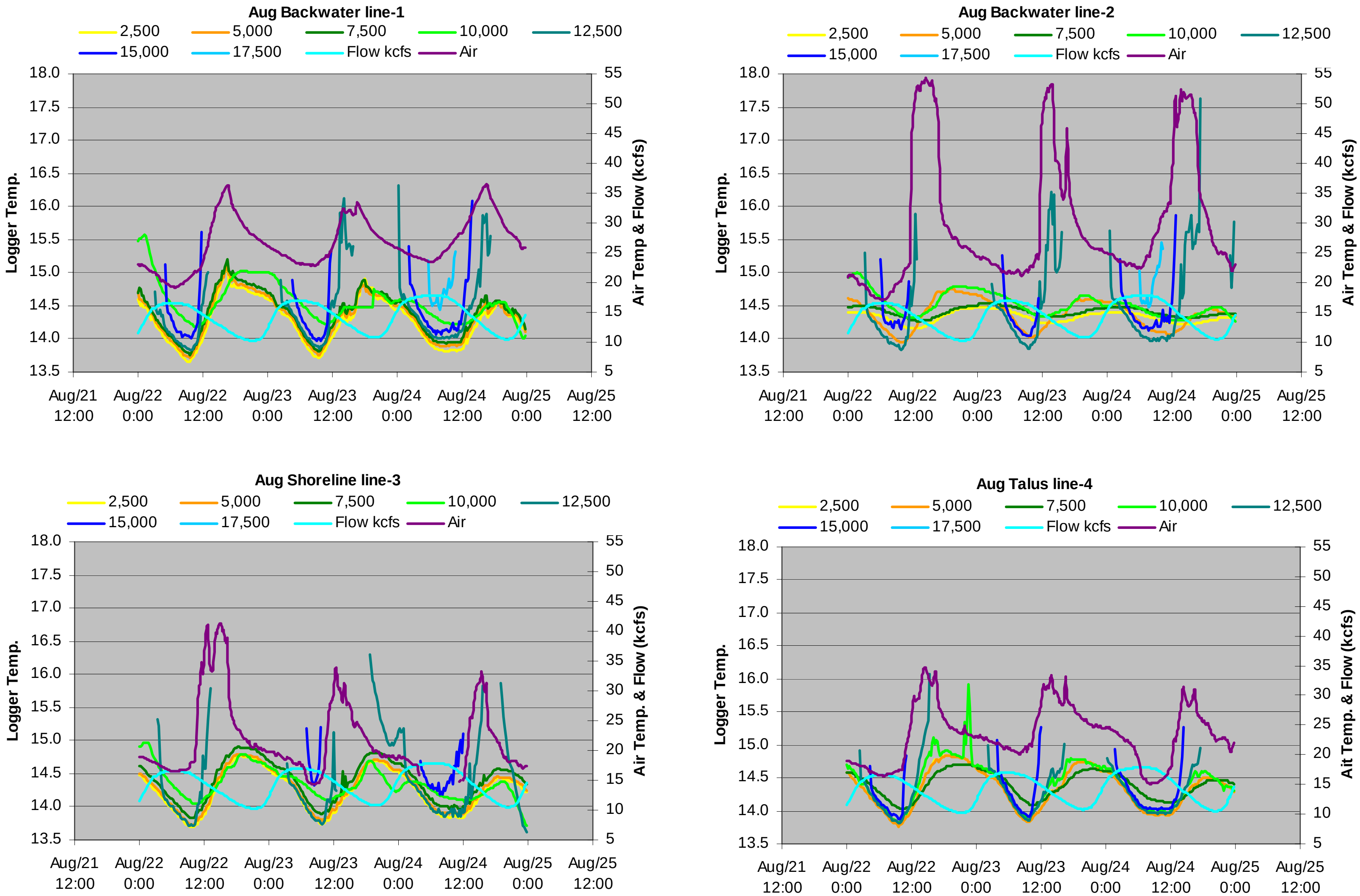

Figure 16. Water and air temperatures and routed flow by habitat type at Salt Mines for 3 days in August.

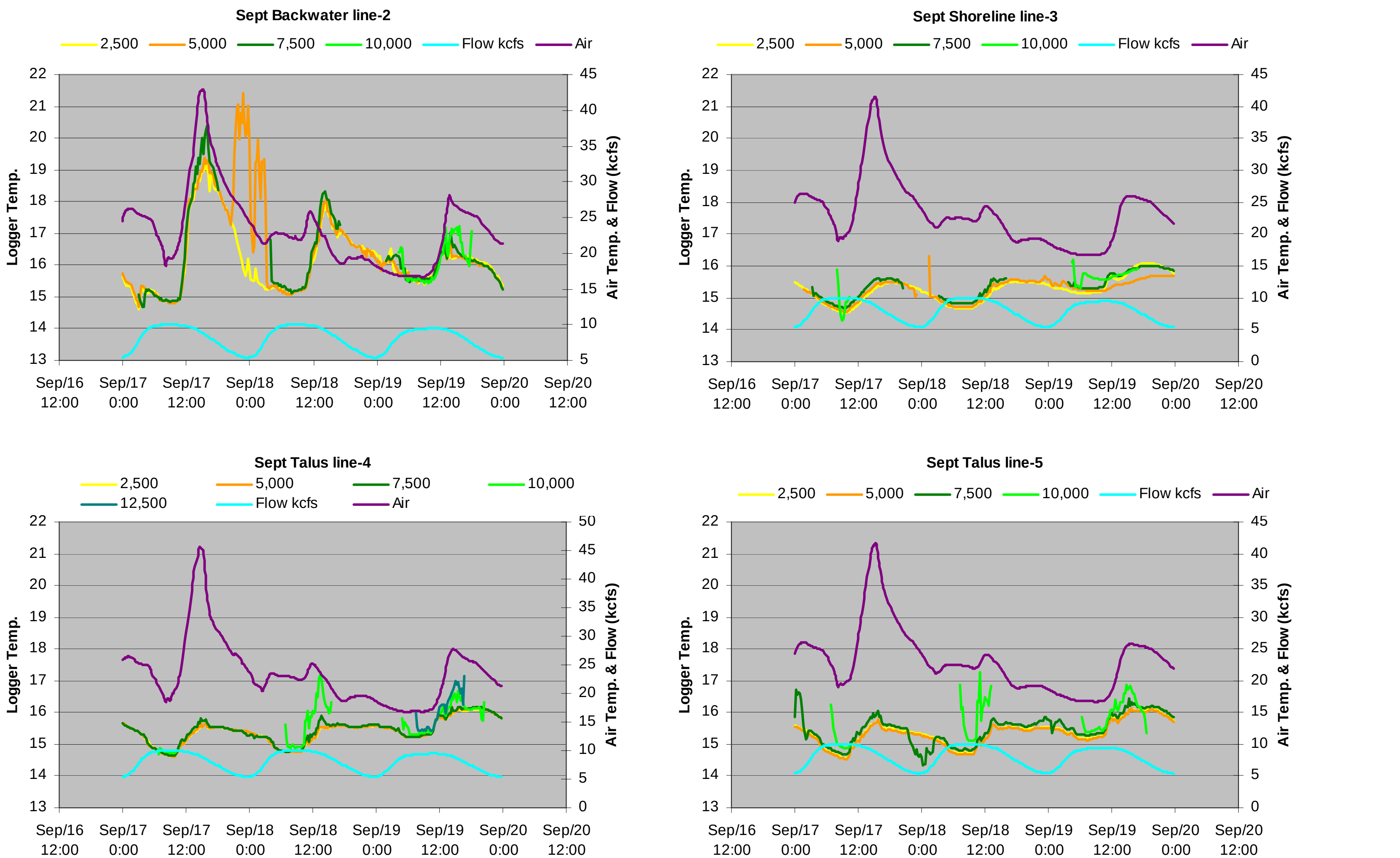

Figure 17. Water and air temperatures and routed flow by habitat type at Salt Mines for 3 days in September.

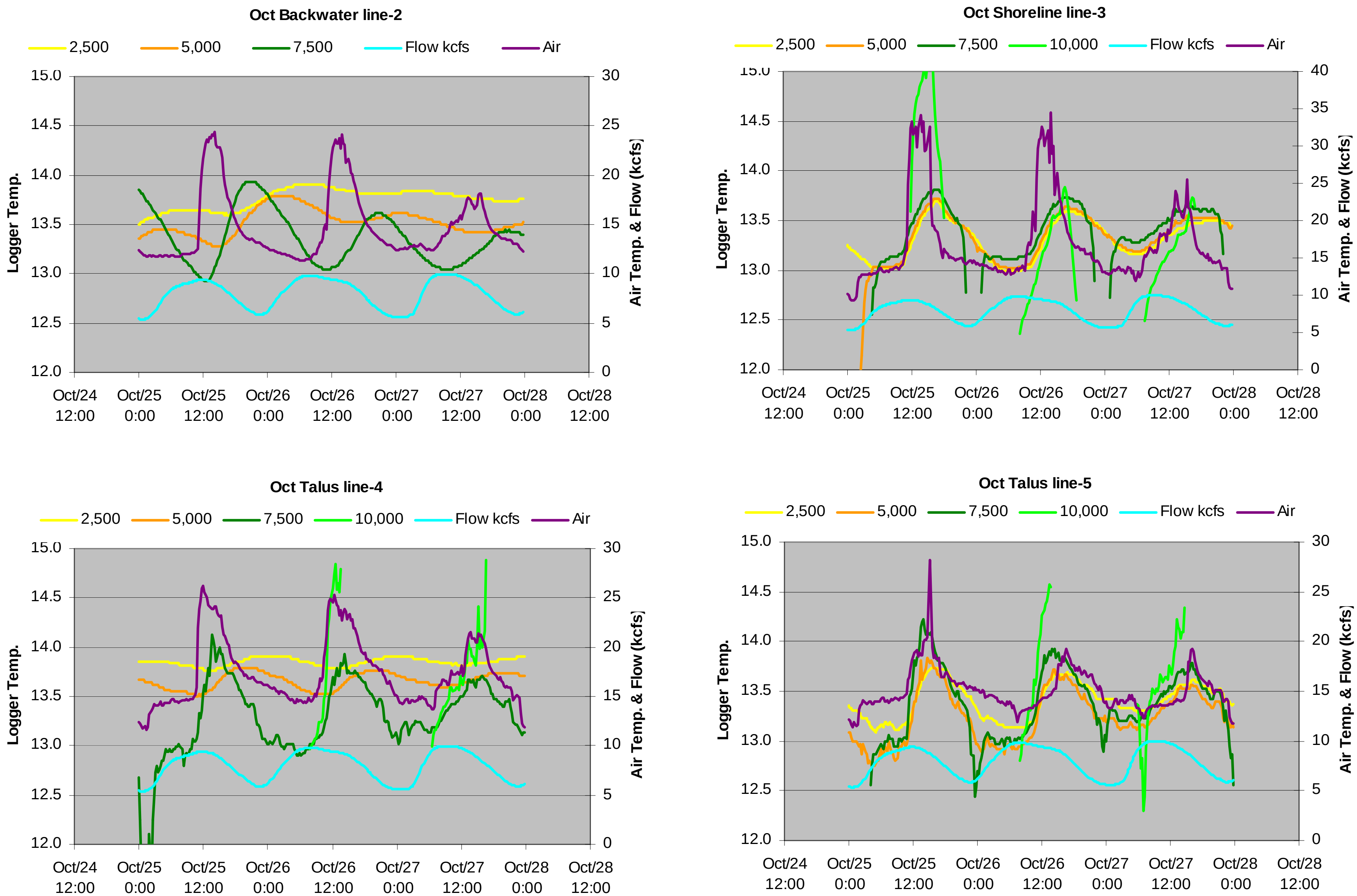

Figure 18. Water and air temperatures and routed flow by habitat type at Salt Mines for 3 days in October.

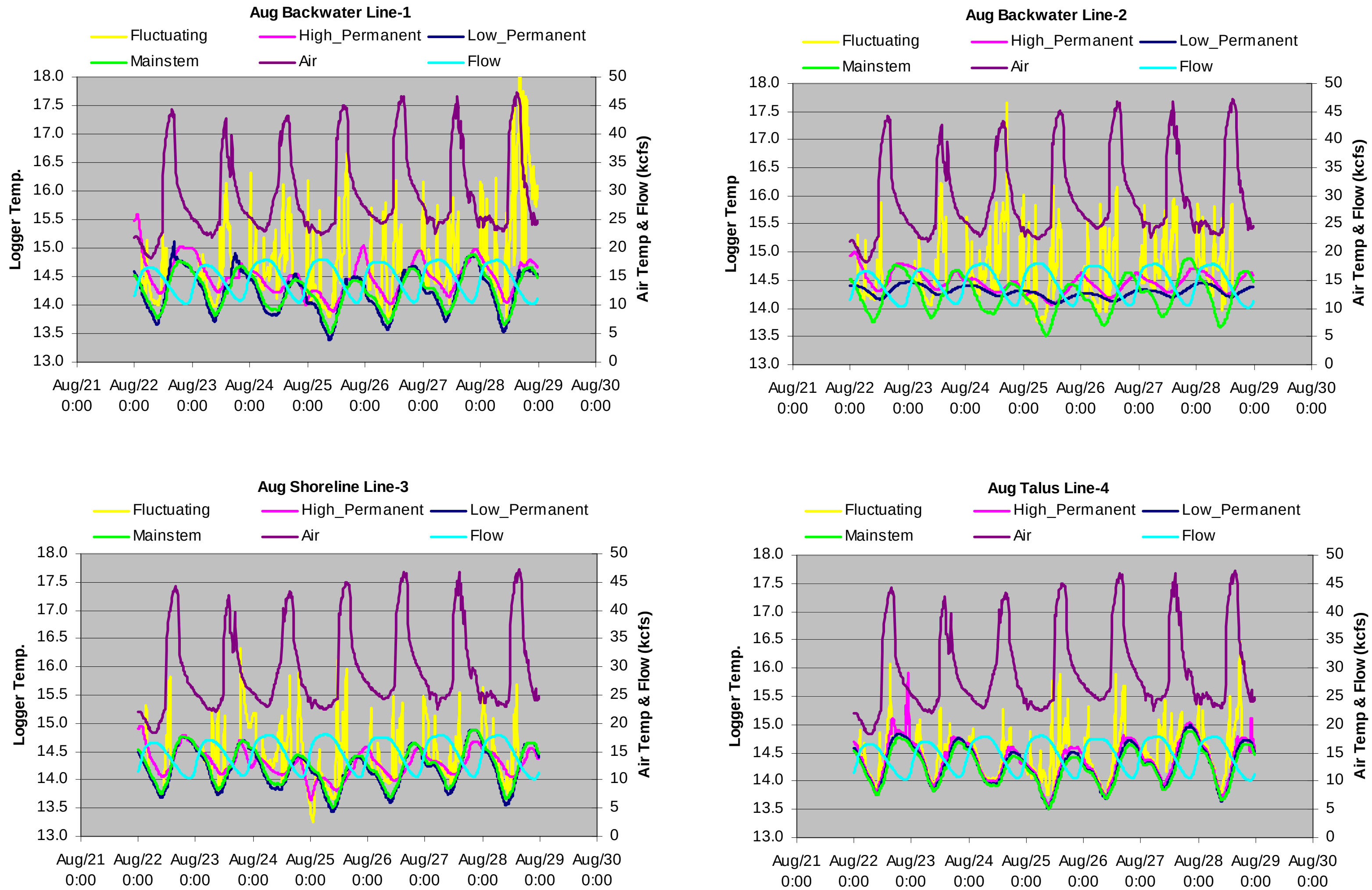

Figure 19. Water and air temperatures and routed flow at Salt Mines for 7 days in August. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

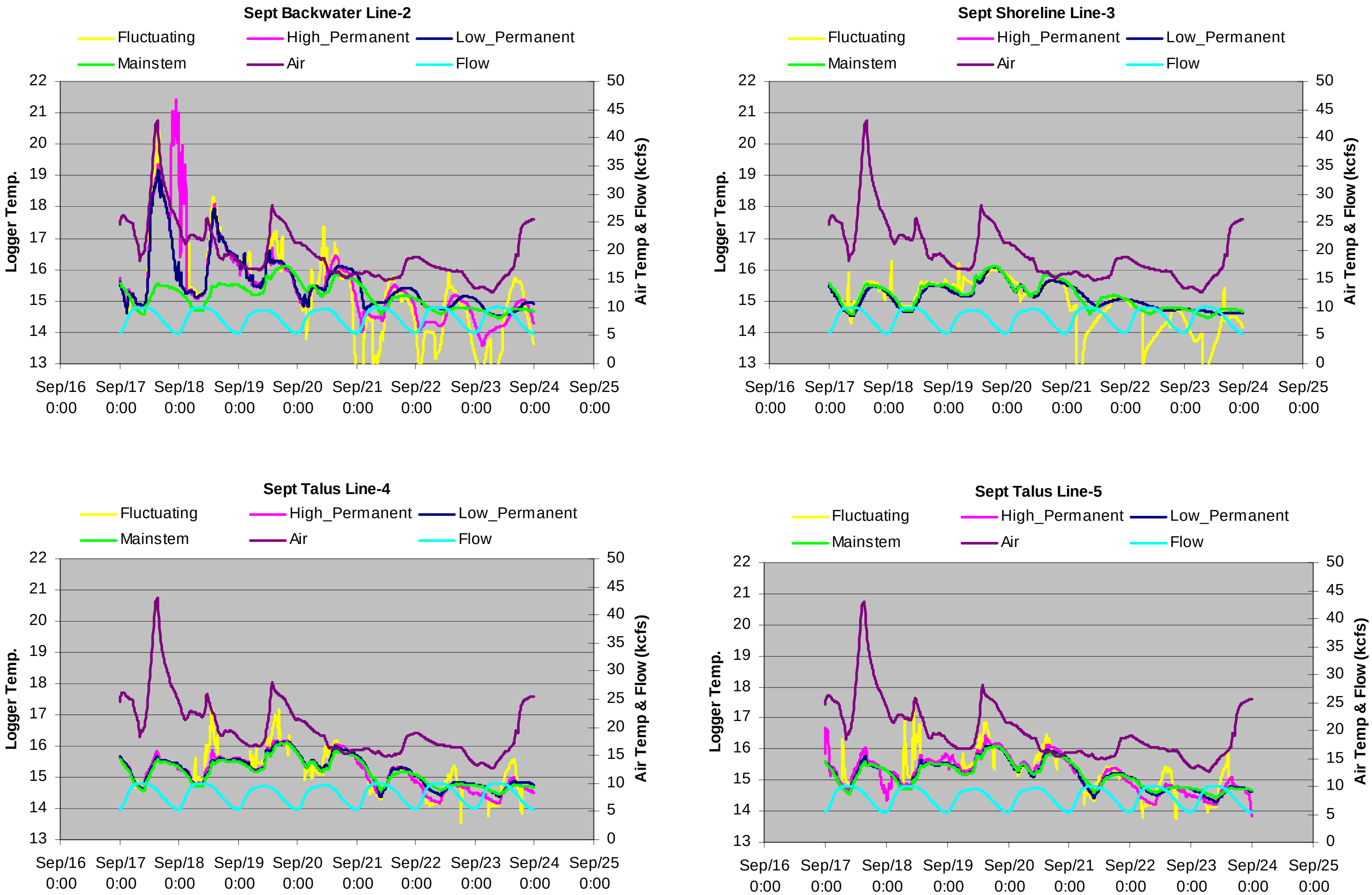

Figure 20. Water and air temperatures and routed flow at Salt Mines for 7 days in September. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

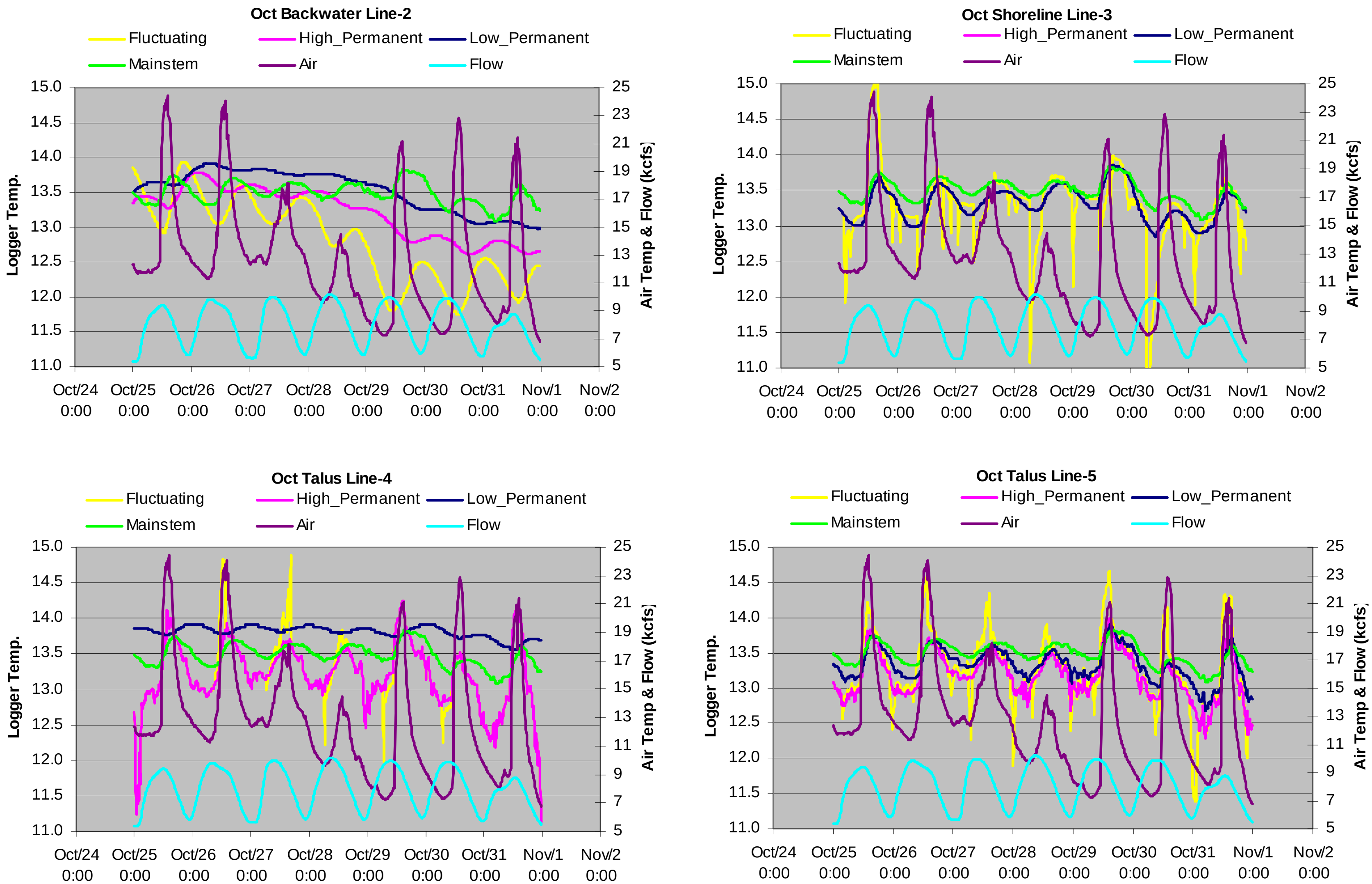

Figure 21. Water and air temperatures and routed flow at Salt Mines for 7 days in October. See Table 1 for the elevations that represent the Low_Permanent, High_Permanent, and Fluctuating zones.

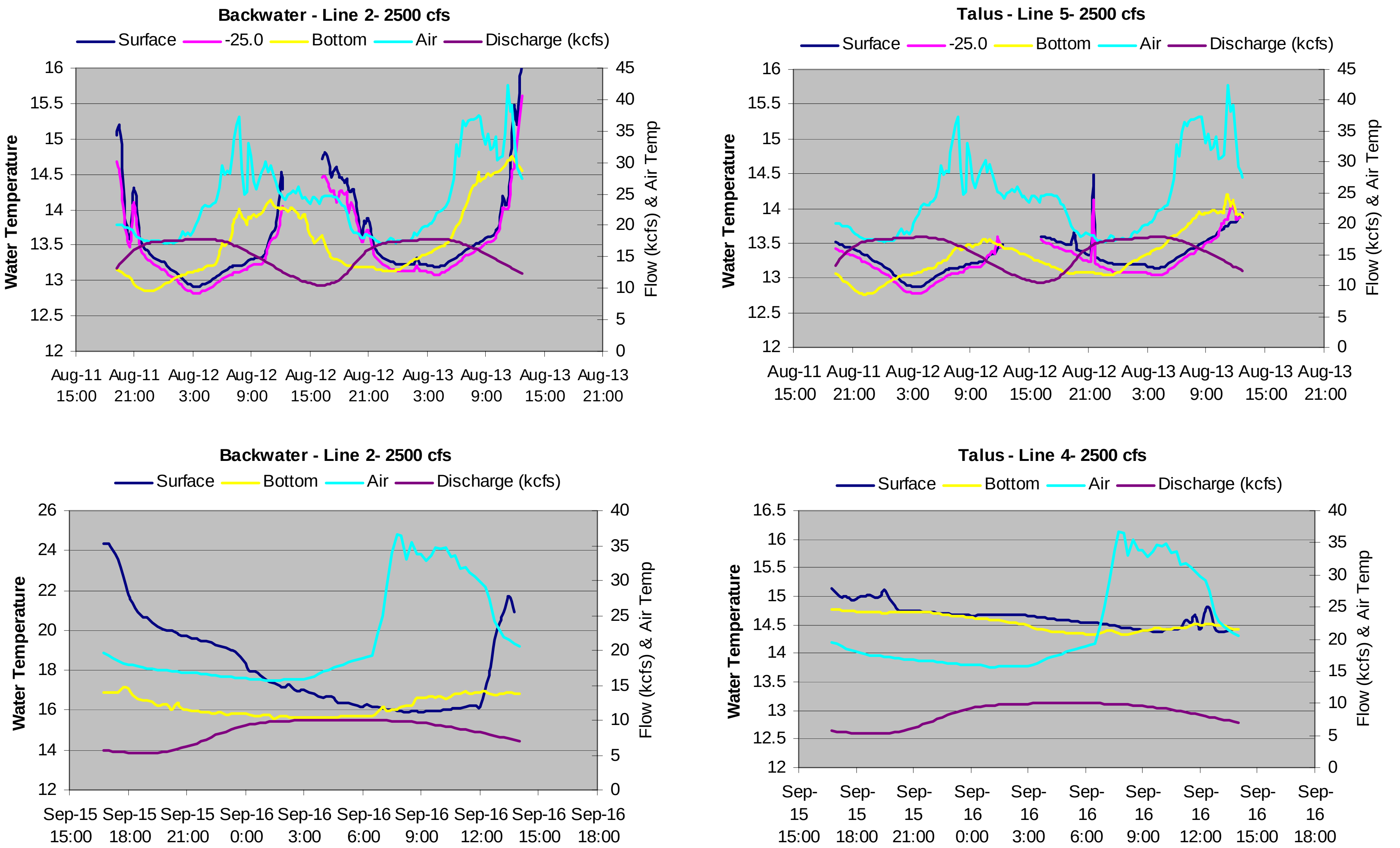

Figure 22. Vertical stratification in water temperature in August and September in backwater and talus shoreline environments at Eminence.

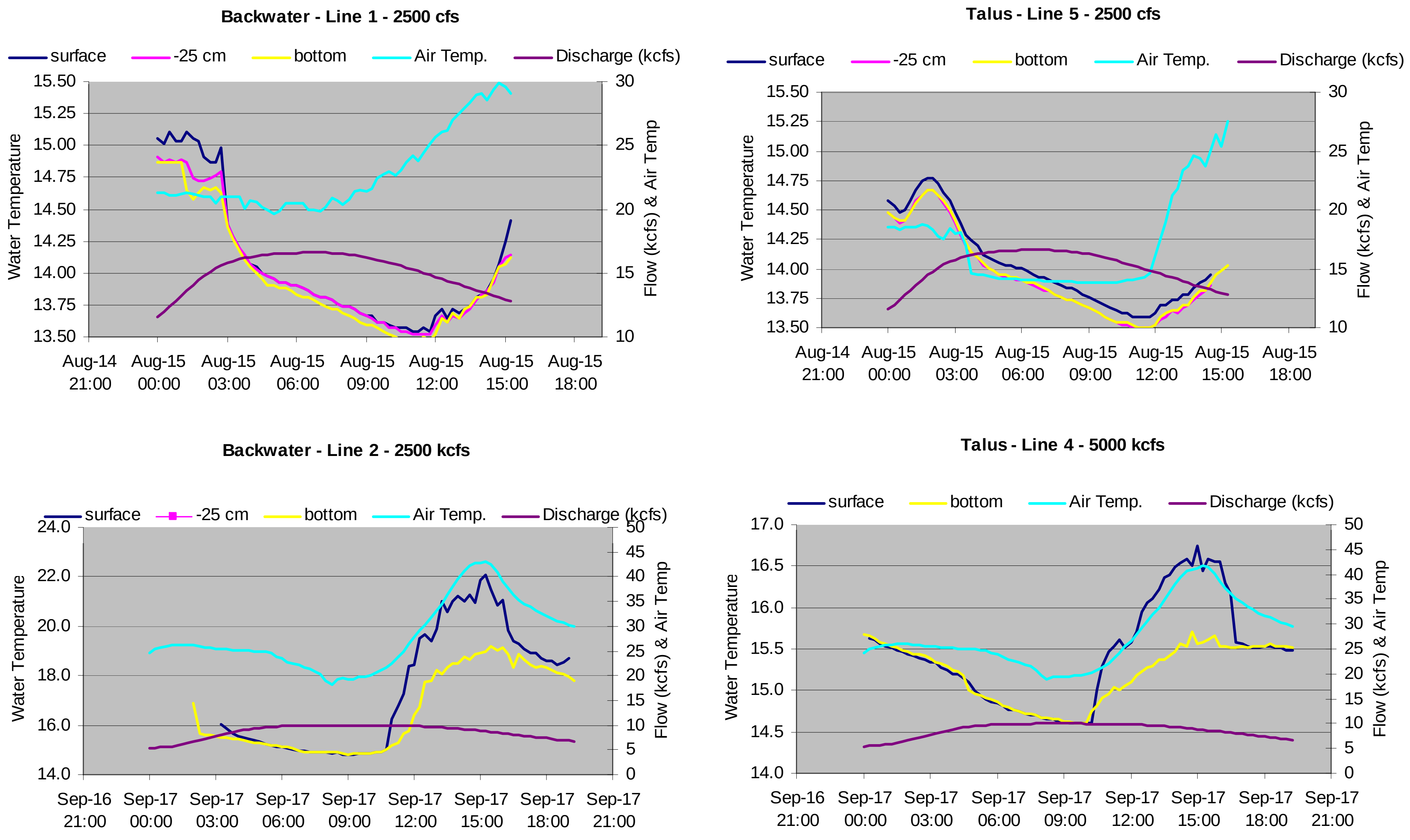

Figure 23. Vertical stratification in water temperature in August and September in backwater and talus shoreline environments at Salt Mines.