APPLICATION OF THE BETTER MODEL TO LAKE POWELL

Report prepared for the Upper Colorado Region
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DESCRIPTION OF LAKE POWELL

Lake Powell was formed when Glen Canyon Dam was constructed on the Colorado River about 2 miles above the town of Page, which is in north central Arizona. The dam is about 15 river miles above Lees Ferry on the Colorado River, and about 12 river miles downstream from the Arizona and Utah state line, see figure 1. The map was complied by the Grand Canyon Environmental Studies office in Flagstaff.

Glen Canyon Dam is a concrete arch-gravity dam with a structural height of 710 feet and a crest length of 1560 feet. The top of active storage is elevation 3700 ft. and originally stored over 27 million acre-ft of water at that elevation. Flood releases can occur through the spillways between elevation 3700 and 3711 ft. On July 14 1983 the maximum reservoir elevation of 3708.4 was attained during the 1983 floods on the Colorado river and the first major use of the spillways occurred. The reservoir extends about 186 miles up the Colorado River and 75 miles up the San Juan River and creates 1960 miles of winding canyon shoreline and has a surface area of 161,390 acres at elevation 3700. Capacity curves for the model and the reservoir are shown in figure 2. The volume of the reservoir is about 26 million acre-ft at full pool based on data from the 1986 sediment survey done by Reclamation (Ferrari, 1988).

Releases from the dam are made from three devices: 1.) The four river outlet hollow jet valves located near the left abutment of the dam, 2) Eight 15 foot diameter penstocks located on the upstream face of the dam which go to the turbines and 3) The two spillways located at both ends of the dam crest. The centerline elevation of the river outlets are 3374 ft. and the penstocks intakes on the upstream of the dam are 3470 ft. The spillway crest is at elevation 3700 and is controlled by radial gates which have a combined capacity of 208,000 cubic feet per second (cfs) at reservoir elevation of 3700. Maximum capacity of the four river outlets is 15000 cfs and the turbine capacity is 4000 cfs each at reservoir elevation of 3700. (U. S. Bureau of Reclamation, 1981)

Main tributaries to the reservoir are the Colorado, Green and San Juan Rivers with minor contributions from the Escalante, Dirty Devil and San Rafael Rivers and many smaller streams located around the perimeter of the reservoir. Annual flows and periods of record for these rivers are shown in Table 1.

Drainage area tributary to Lake Powell is approximately 108,000 square miles, much of this area has little or no runoff due to low precipitation occurring over the area. The differences in annual runoff from the main gages on the Colorado and Green Rivers to the headwaters of the reservoir is less than a few percent. Currently there is no way of determining the difference because no stream measurements are available near the headwaters of the reservoir.

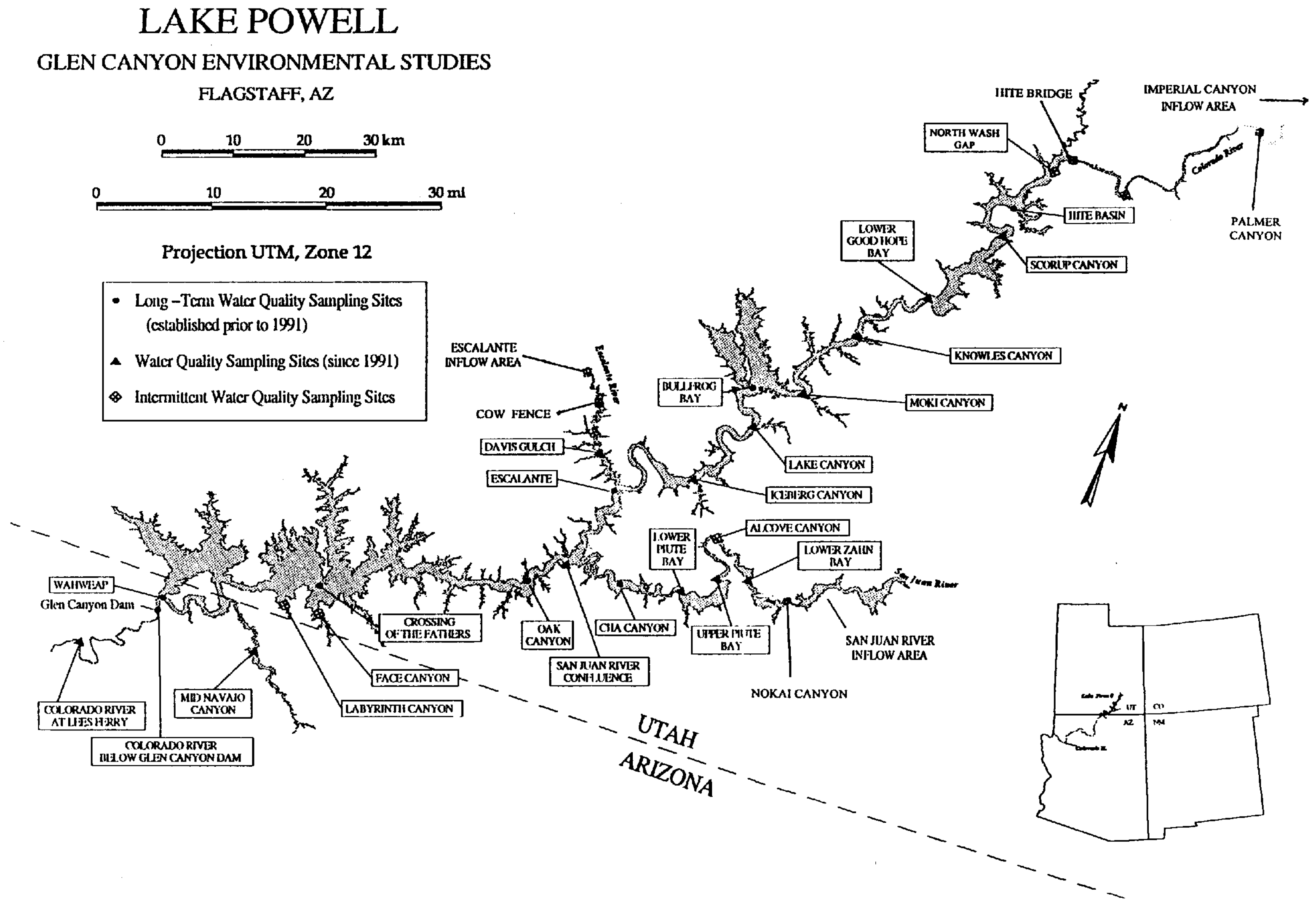


Figure 1. Map of Lake Powell

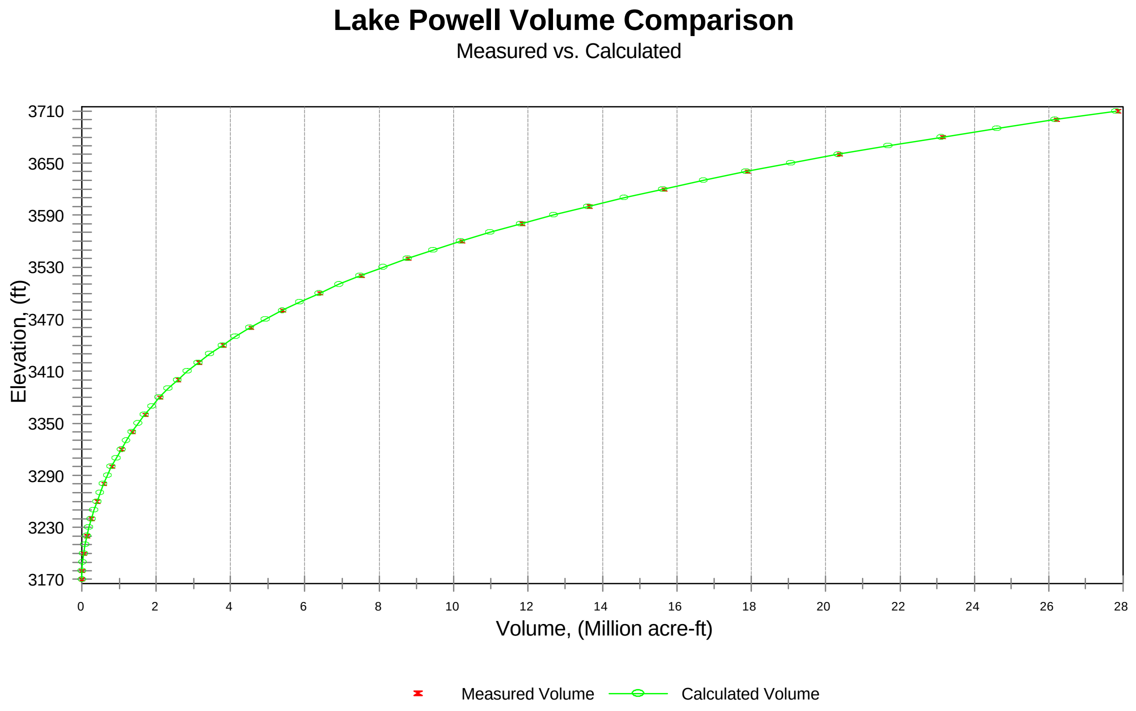


Figure 2. Comparison of model and measured volumes for Lake Powell

Table 1. Location, flow, runoff, and drainage areas for Lake Powell.

Location	Average Annual Flow (cfs)	Annual Runoff (Acre-ft)	Period of Record	Drainage Area (Square Miles)
Colorado River at Cisco Ut. 09180500	7437	5,388,000	1895-present	24100
Green River at Green River Ut. 00931500	6215	4,502,000	1904-present	40,590
San Juan near Bluff Ut. 09379500	2308	1,672,000	1914- present	23,000
San Rafael near Green River Ut. 09328500	144	104,400	1945- present	1628
Dirty Devil Above Poison Springs Ut. 09333500	99.4	72,030	1948-1993	4159
Escalante near Escalante Ut. 09337500	10.8	7800	1942-1955 1971- present	320

(U. S. Department of the Interior 1994; AZ-93-1 and UT-93-1)

MODEL DESCRIPTION

The BETTER (**B**ox **E**xchange **T**ransport **T**emperature **E**cology **R**eservoir) (Bender et. al, 1990) model developed by TVA was selected to be used on Lake Powell because it had simpler data requirements and was not subject to the small time steps needed to maintain stability. This model has been applied to many reservoirs in the Tennessee River Valley and Reclamation had used earlier versions on New Waddell and Flaming Gorge. It is somewhat easier to apply than other more rigorous hydrodynamic models.

Using a two-dimensional array of longitudinal and vertical elements, the BETTER model calculates flow exchange, heat budget, and dissolved oxygen (DO). The heat budget includes air dry-bulb and dew-point temperatures, solar radiation, wind mixing, convective cooling, and inflow density distribution. The DO components include sediment oxygen demand (SOD); biochemical oxygen demand (BOD); ammonia; surface reaeration; and algal photosynthesis, respiration, and nutrient recycling. Major physical and biological processes incorporated into the model are show in figure 3. Inflows are placed vertically in the upstream columns so the inflowing water density matches the density of the reservoir. If the inflowing water density is less than the density of the surface layers the water is distributed into the surface layers. Similarly, if the density of the inflow is more than the density of the reservoir water the inflow will flow along the bottom of the reservoir. Otherwise the inflow enters the reservoir as an interflow at an elevation which matches the densities of the inflow and the reservoir water. Heating, cooling, turbulent wind mixing, convective mixing, evaporation, aeration and evaporation processes occur at the surface. Stratification inhibits vertical mixing however convective and turbulent mixing, settling and advective outflow all promote mixing. The outflow algorithm withdraws water from the level of the outlets based on stratification, density and mixing of the adjacent water. Surface biological processes include exchange of carbon dioxide and oxygen; algal growth, decay and settling; ammonia oxidation, nitrogen uptake by algae, and decay of organic matter can occur in the model. Sediment oxygen demand and anaerobic releases from the sediment can also occur.

Modifications made to the model include: 1) The number of layers and columns were increased to 60. 2) The minimum volume element was increased for 1 acre-ft to 1000 acre-ft. 3) wind and energy exchange coefficients were modified. 4) the number of initial value profiles was increased. 5) surface wind mixing coefficients were made variable. 6) Errors in the selective withdrawal algorithm were corrected.

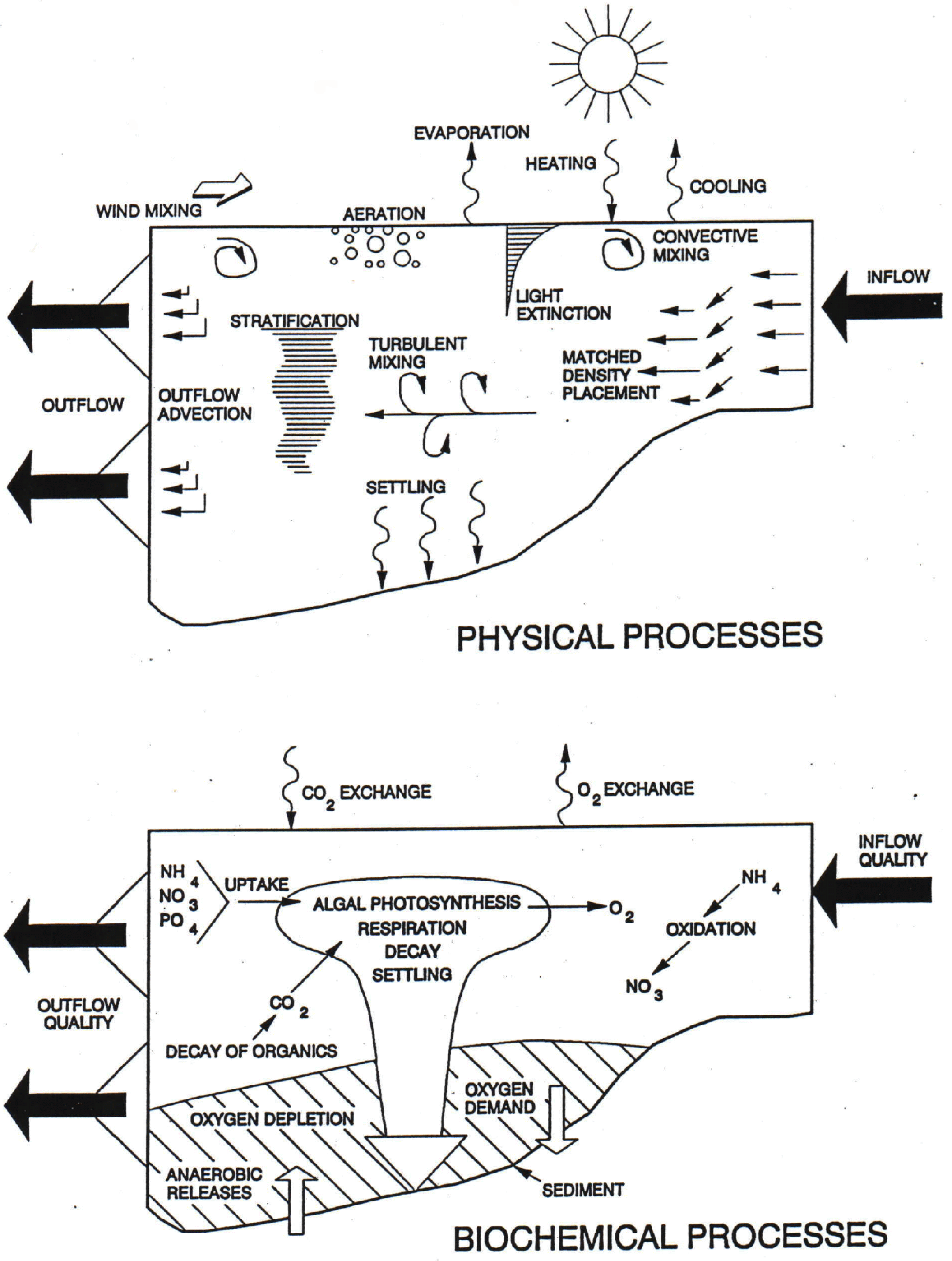


Figure 3. Overview of Major Physical and Biochemical Processes.

APPLICATION TO GLEN CANYON

The geometry for Lake Powell was developed from the original topography and the reservoir sediment survey that was completed in 1986. Each cross section on the survey was used to create tables in a spreadsheet which represented the volume, conveyance area and the surface area at ten foot layers. These sections and layers were combined into river model nodes which had similar characteristics along the length of the reservoir. The model can identify a portion of the total volume as embayment (dead storage), this was varied between 1 to 20 percent during model testing. Reservoir capacity as a function of elevation is shown in figure 2 and was used for the volume and surface area tables of the model.

Initially the model consisted of two branches, one for the Colorado River and one for the San Juan River. For the two branch scheme the first vertical column (node) starts at the dam with node 1 and goes to node 36 at the upper end of the Colorado River. The San Juan branch nodes run from 37 at the confluence to 49 at the upper end of the San Juan. Node 12 of the mainstem is where the San Juan river joins the Colorado river in the model. Figure 4a and 4b are side views of the model geometry/ reservoir profile for both the Colorado and San Juan arms. At the upper most node on each branch is a mixing node that distributes the flow vertically in the next downstream node according to the inflow algorithm and the density of the inflowing water. This two branch model scheme was used for 1992 data and worked fairly well except in November and December when the cold inflowing water did not move downstream along the reservoir bottom as fast in the model as was observed in the field.

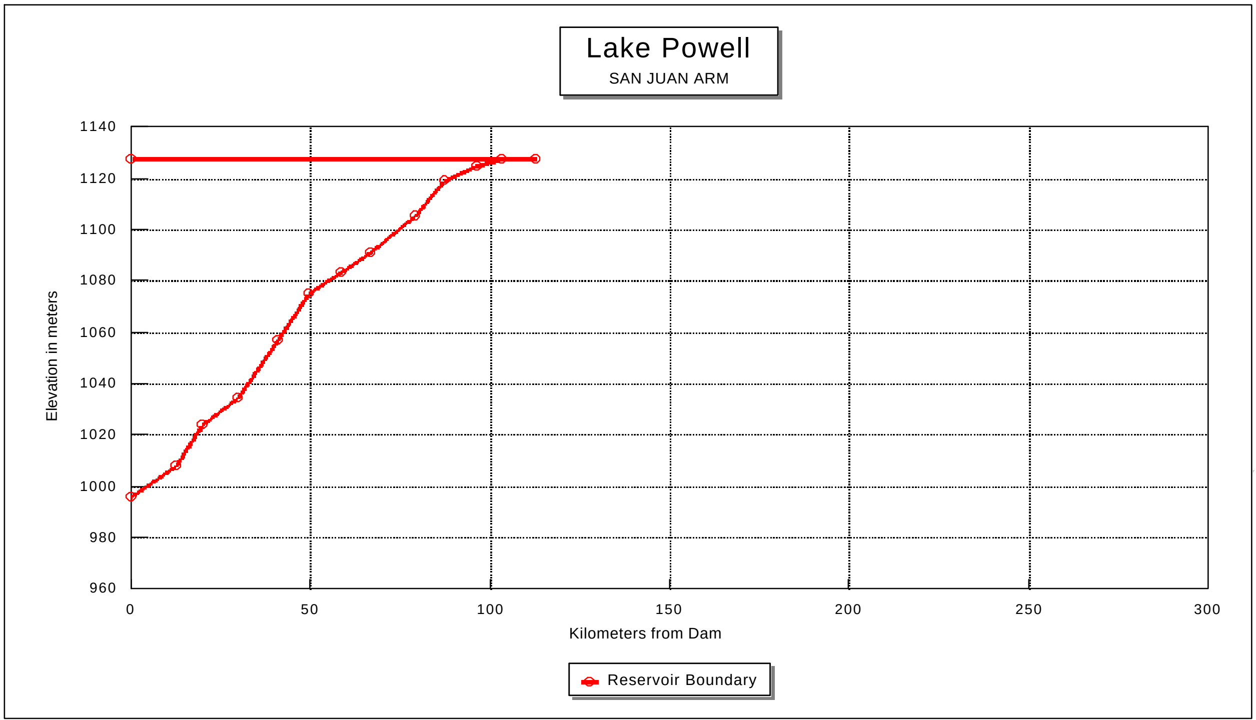


Figure 4b. San Juan River model geometry and profile.

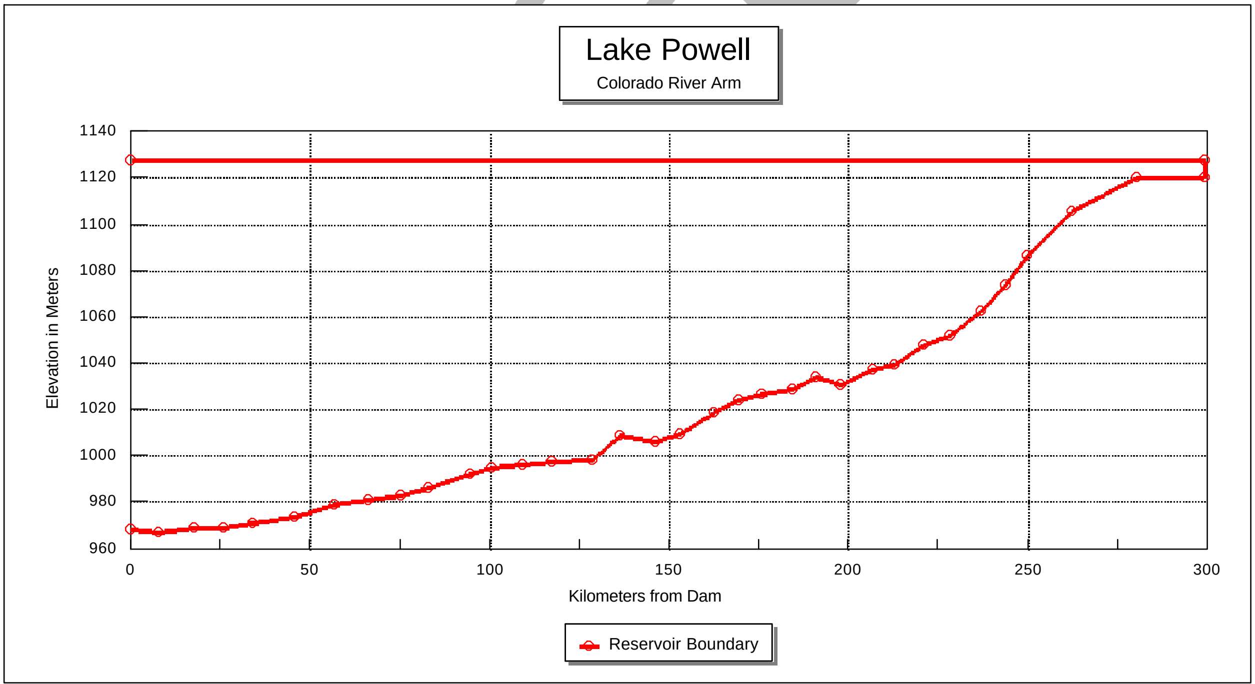


Figure 4a. Colorado River model geometry and profile.

Also the inflowing electrical conductivity data during the fall of the year were lower than measured values in the upstream end of the reservoir. This may be due to flows from the Dirty Devil River, Escalante River or other un-gaged flows not being represented by the water quality at the Green River and Cisco gages. Also the initial profiles at the dam did not represent the conditions in the upper reaches of the reservoir. To better represent the reservoir in the model, it was decided that more bays should be treated as dynamic branches and that more than one initial profile should be used. Also to capture the initial conditions caused by cold water plunging and following the bottom of the reservoir toward the dam it was decided to start the model near the beginning of March when these effects were reflected in the measured profiles.

Later, the five branch layout was developed to address the issues above and to combine the model nodes at the upstream end of the reservoir. Figure 5 is a box diagram of the five branch layout. Dynamic branches were developed for Wahweap, Crossing of the Fathers, and Bullfrog basin. The upper 4 nodes on the Colorado River were combined into 2 nodes because riverine conditions exist most of the times in those reaches of the reservoir. Nodes 1-34, 35-36, 37-38,39-51, 52-53 are for the main-stem Colorado, Wahweap bay, Crossing of the Fathers, San Juan, and Bullfrog, respectively. Layers for both the two branch and five branch schemes have 42 layers for the Colorado River and 38 layers for San Juan River.

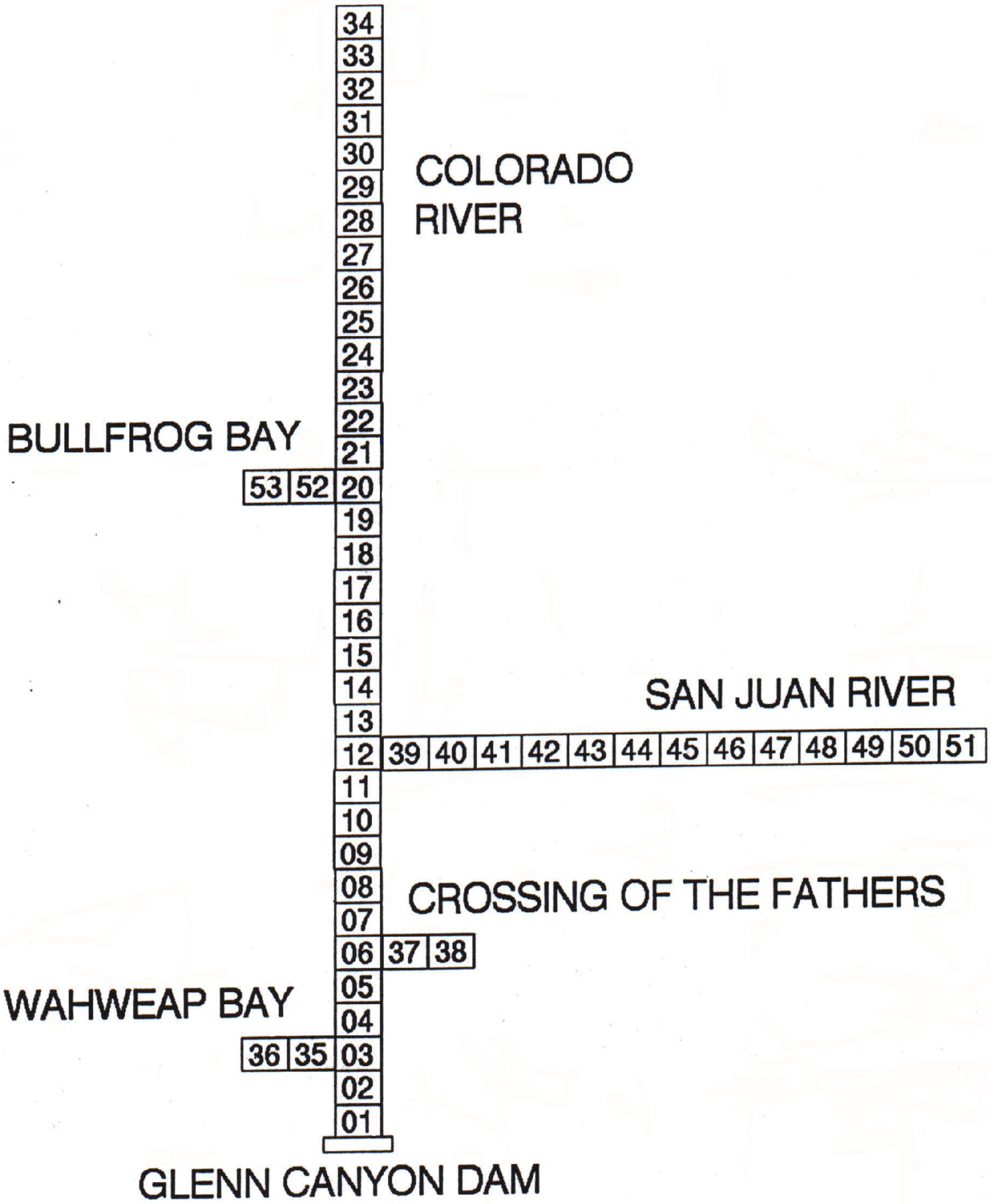


Figure 5. Box diagram of five branch model nodes

Model data - Hydrologic data assembled for the model were obtained from USGS, State and EPA databases. The Colorado River at the upper end of the reservoir is a flow weighted average of the flows at the following stations: 1) Colorado at Cisco, 2)Green River at Green River, and 3) the San Rafael River near Green River. The USGS gage at Bluff Utah was used for the data on the San Juan river. The data during 1992 and 1993 are during a low flow period and in 1992 the reservoir was at it's lowest level since completely filling in 1983. Therefore, the impacts or changes of water quality in the reservoir would be larger than for full pool conditions or at higher reservoir elevations.

Daily water quality data for temperature and electrical conductivity were compiled for 1992 and 1993. Some holes in the data were filled in by linear interpolation or regression in both years. Water quality data for the other variables; bio-chemical oxygen demand (BOD), dissolved oxygen, turbidity, pH, detritus, dissolved organic matter, alkalinity, algae, ammonia, nitrate, phosphate, total inorganic carbon, and electrical conductivity were obtained from all available records for both years but the data are very sparse, not sufficient to allow modeling of these variables. Data for 1992 are more complete than for 1993 so it was chosen as the first year to be used to calibrate the model. Many of the water quality parameters only have four to six instantaneous values in any one year. Estimates of these water quality parameters were averaged by month or quarter from several years of data. Most of the data indicate that dissolved oxygen is at or near saturation and the dissolved oxygen in the water was computed from water temperature and the station barometric pressure. (Bowie, et al. 1985)

No climatological data are available for the area around Page Arizona. The weather station at Page is an FAA data station that is only used by aviation and is not recorded. However the National Center for Atmospheric Research (NCAR) at Boulder has obtained daily information to compile dry bulb and dew point temperature. Data for windspeed at the Page Station was obtained from the Western Regional Climatological Center (WRCC) in Reno Nevada. NCAR has archived windspeed data only since 1994, so the wind speed data for Page was obtained from WRCC. Neither WRCC or NCAR data have any solar radiation data. Solar radiation data was obtained from the Utah State Climatologist at Logan, UT. Which maintains a collection station at Hanksville, Utah. Solar radiation data were compiled on a daily basis from these records and data from St George, Utah. (Jensen, 1997)

Input data 1992 - The inflows on both the Colorado and San Juan rivers are low from the first of the year until about March when the flow increases sharply. The peak flow is reached near the end of May, day 150, then the floods recede to near constant flows of about 5000 ft^3/s and 1000 ft^3/s, respectively for the Colorado and San Juan rivers. Minor increases in the flow are observed during the spring and summer due to storm events during the year, see figure 6.

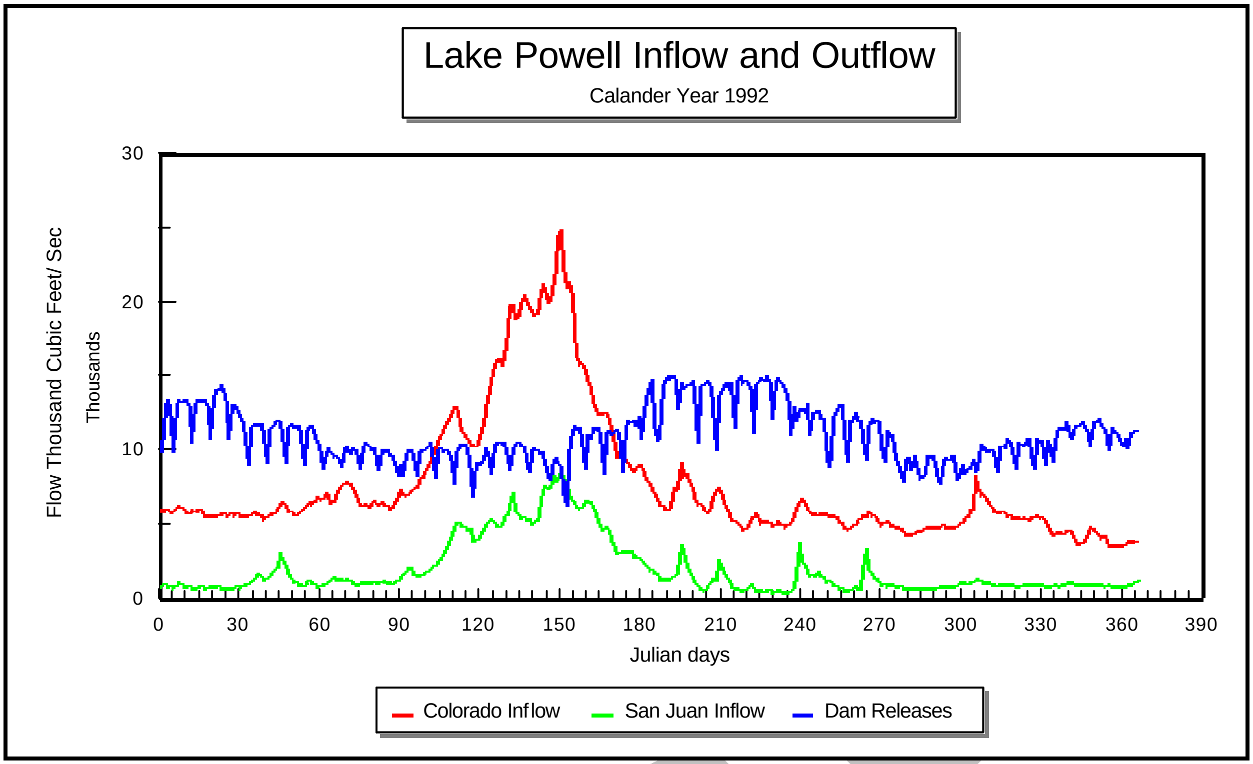


Figure 6. Powell inflow and downstream releases for 1992.

Water quality data for these inflows are shown on figure 7 for temperature and figure 8 for Electrical conductivity (EC). Water temperature for the Colorado River is near zero degrees Celsius for January and most of February, rises slowly and almost linearly to a maximum of 26 degrees near the middle of August and drops during Autumn to zero during the last half of December. San Juan temperatures follow a similar pattern except the temperatures in the San Juan are warmer during the earlier part of the year, vary from 4 °C to 0 °C until the middle of February, rise more slowly than the temperatures in the Colorado to about 26 °C, and then cool slower than the Colorado during the Autumn.

The EC of the San Juan River is generally less than that of the Colorado until the end of June. Then the Colorado River salinity increases quicker than the San Juan and stays high through out the year, while the EC in the San Juan decreases from the end of the irrigation season until the end of the year, see figure 8.

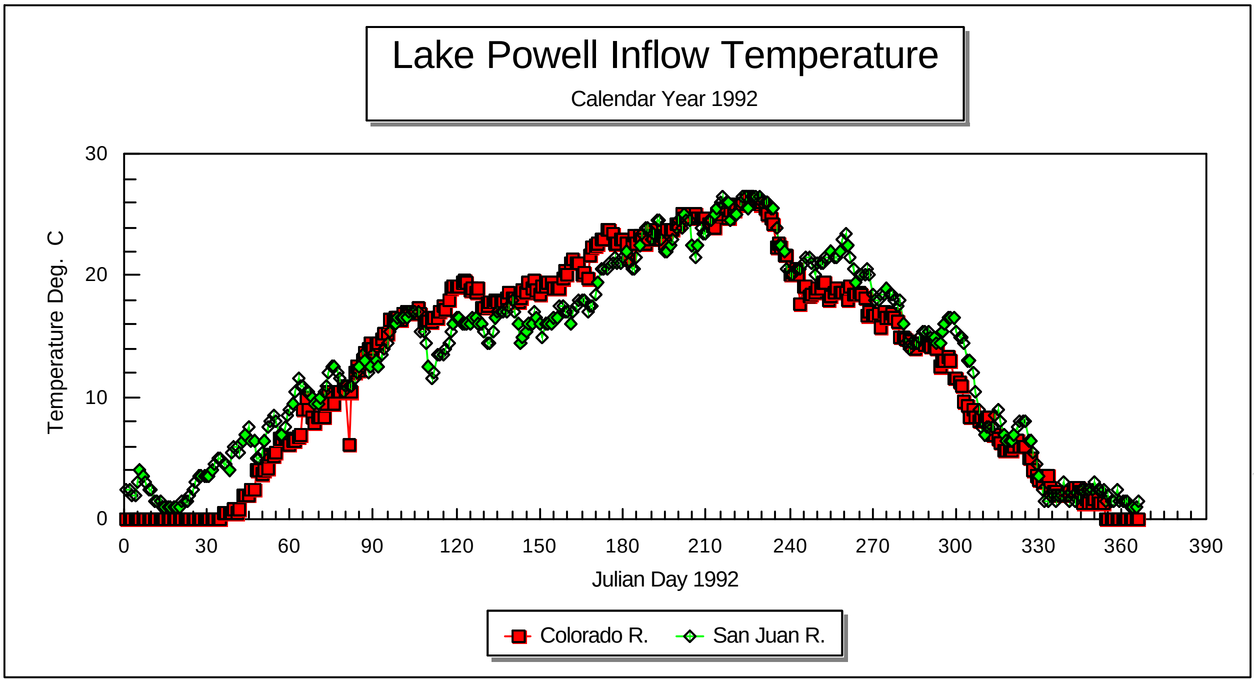


Figure 7. Inflowing water temperatures for 1992.

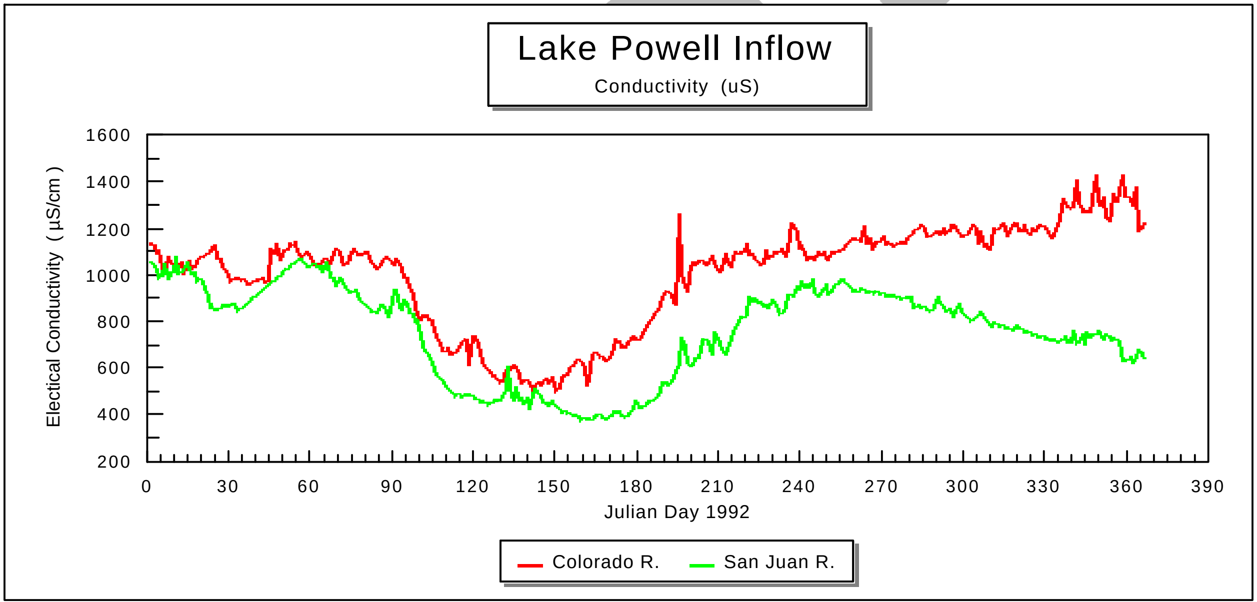


Figure 8. 1992 inflow electrical conductivity.

Meteorological data were assembled as discussed above and were compiled into the daily inflow file. Air temperatures varied from 0 °C to nearly 30 °C in August and returned to below freezing temperatures in November and December. During the summer there is a greater spread between dry bulb temperature and the dew point temperature due to the low moisture content of the air. The trend of the dry bulb temperatures follow the solar radiation curve through the year except during August and September. Direct heating of the atmosphere is generally the reason for this trend.

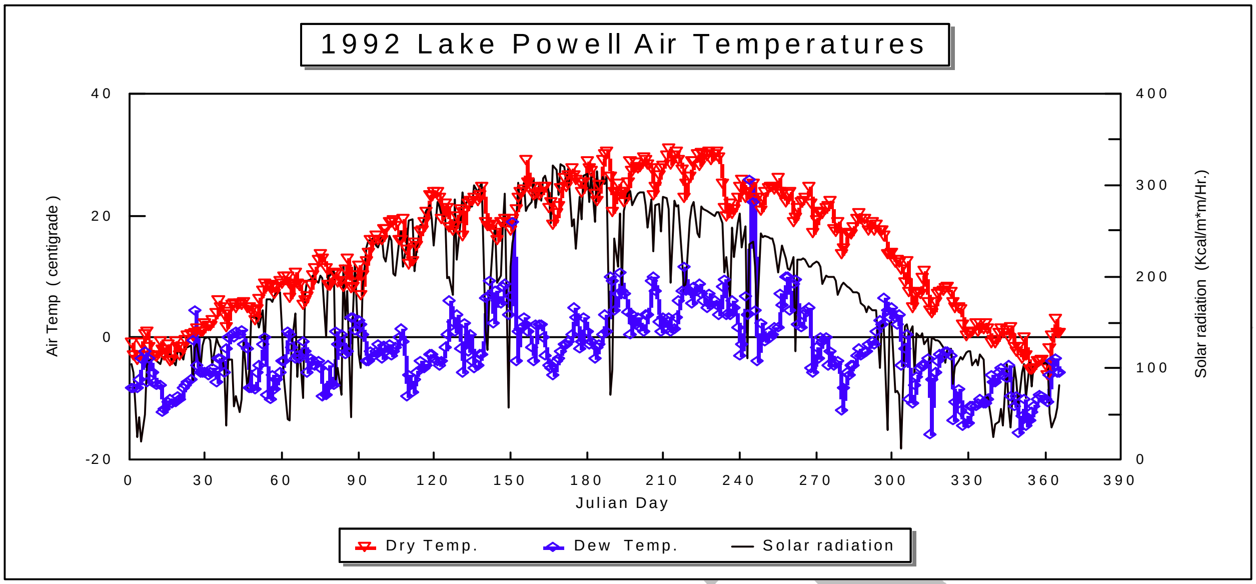


Figure 9. Dry bulb, dew point temperatures and Solar radiation 1992.

Wind speed data are shown on figure 10. Seldom during the year is the wind quiet for a day and storm events are indicated by the peaks in the chart. Usually the wind is above 1 m/s and often is moving above 3 m/s during most of the day. The daily wind speed values are the only wind data set we could obtain and was provided by the Western Climatological Data Center in Reno, Nevada.

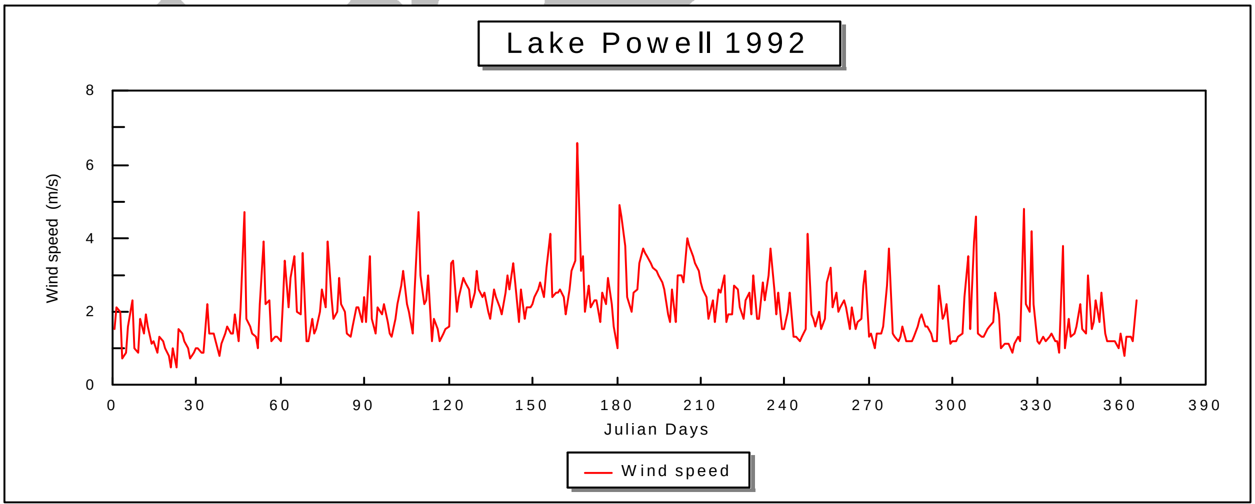


Figure 10. Lake Powell wind speed for 1992

Input data 1993 - Flows into the reservoir in 1993 were much higher in the Colorado River than in 1992, see figure 11. The peak flow in 1992 was about 25000 ft³/s and the flow during 1993 was over 75000 ft³/s and had a secondary peak near the end of June. The total inflow in 1993 was 13,258,200 ac-ft and in 1992 the inflow totaled 7,035,900 ac-ft. This indicates a theoretical reservoir residence time of two to four years. The reservoir increased from a capacity of 13,329,000 ac-ft to 18,403,000 ac-ft in 1993. The San Juan River did not have a very large peak run-off in the spring of 1993. However, the flow in the San Juan was elevated from the base flow from mid March to mid June. Releases from the dam were steady throughout the year with only small downturns during the weekends when power generation was lower than during the week.

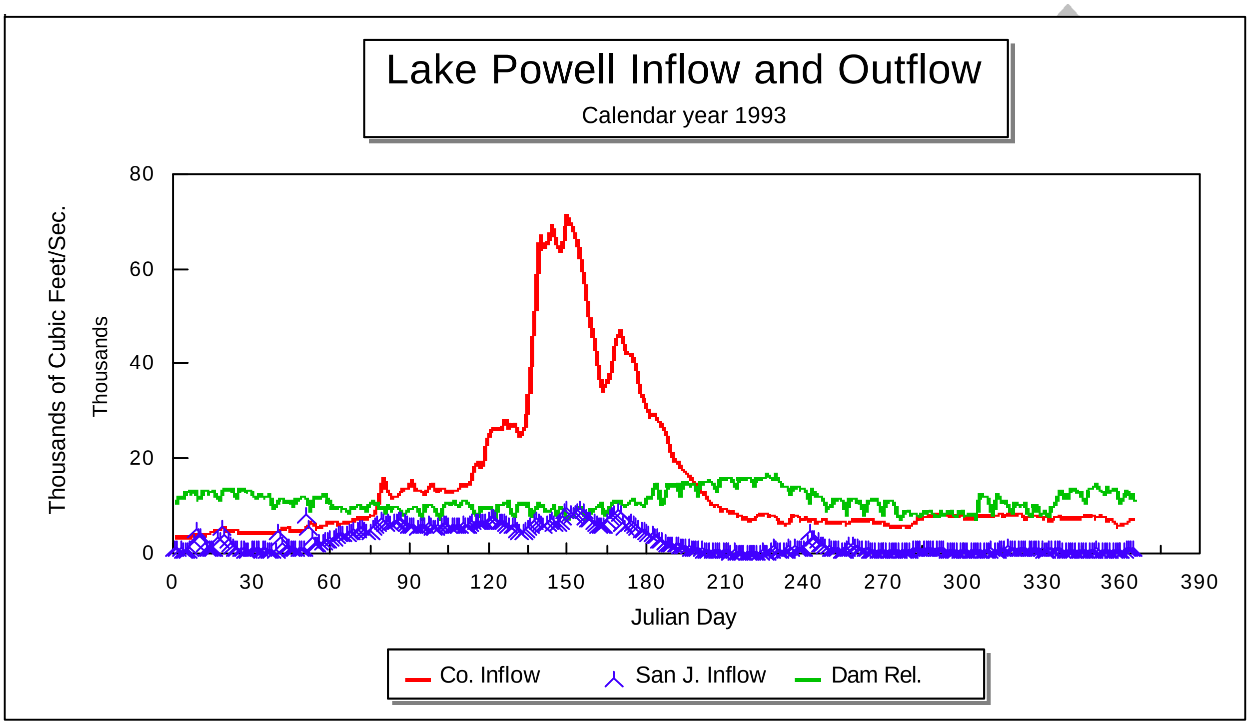


Figure 11. Lake Powell inflows and dam releases during 1993.

Inflowing water temperatures followed the same patterns as 1992 with near zero temperatures in the Colorado River in the winter and raising to a maximum temperature of about 27 °C in mid-June as shown in figure 12. The high spring inflows did not cause the temperatures to be much lower than 1992. But the amount of warm water going into the reservoir was much more than in 1992 which may have increased the depth of the warm layer on the surface.

Electrical conductivity in the San Juan during 1993 was very similar to the trace for 1992 which started near 1050 µS/cm, dropped to about 850 at the end of January, raised to about 1000 at the end of February, to a minimum of 400 in June, and raised to 800 to 900 during the remainder of the year as shown in Figure 13. Conductivity for the Colorado river started near 1200 µS/cm the first half of January, increased to about 1300, followed a seesaw path to a minimum of about 400 in June, increased during July to about 1000 by August and remained near that value during the remainder of the year. These traces showed the impact of the larger flows in 1993 with more dilute water going into the reservoir during the last half of the year.

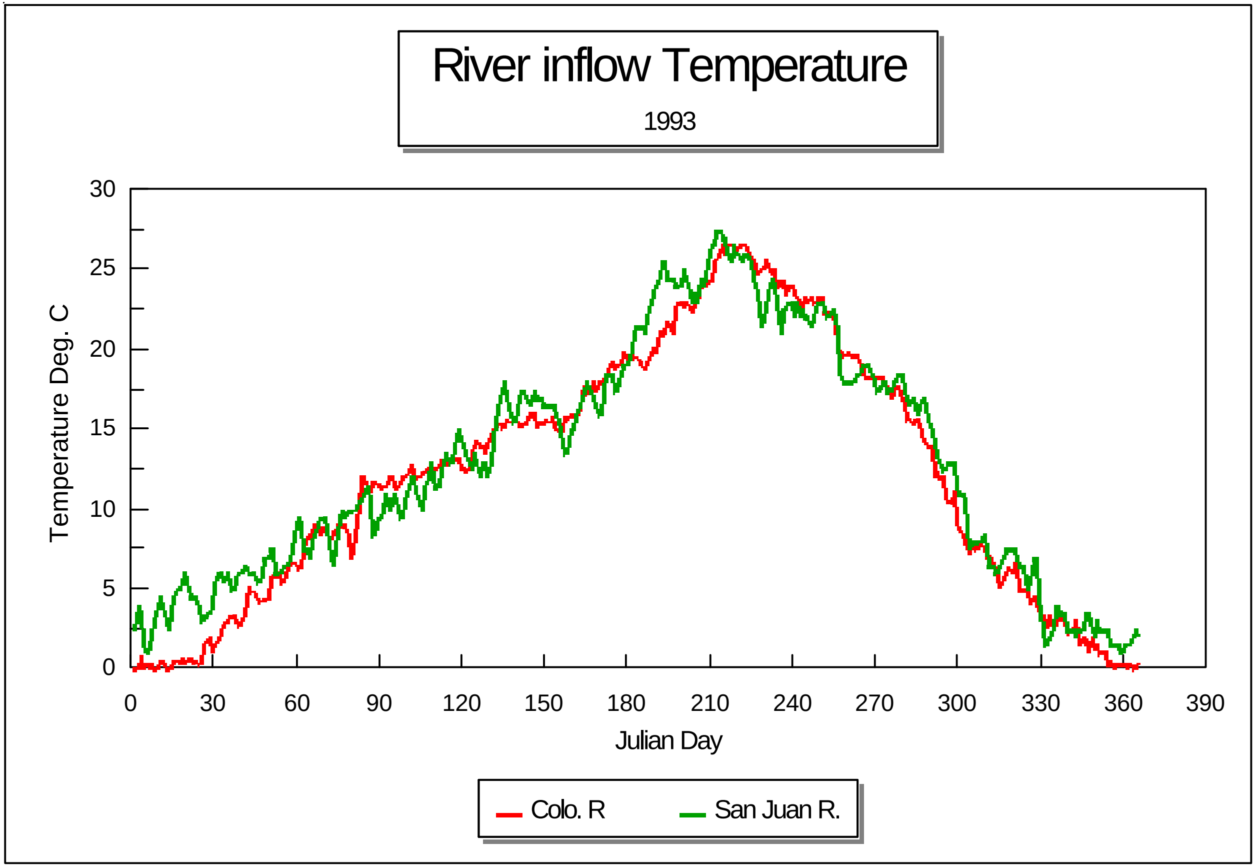


Figure 12. Inflowing water temperature for 1993.

Figure 14 shows the meteorological data from 1993. It shows that the air temperatures were somewhat warmer and drier than during 1992. Solar data are lower in 1993 than the corresponding data in 1992. Therefore there may have been less heat to increase the temperature of the epilimnion in the reservoir than in 1992. Surface temperatures appear to be similar to those in 1992 but the heated layer appears to be not as deep as in 1992.

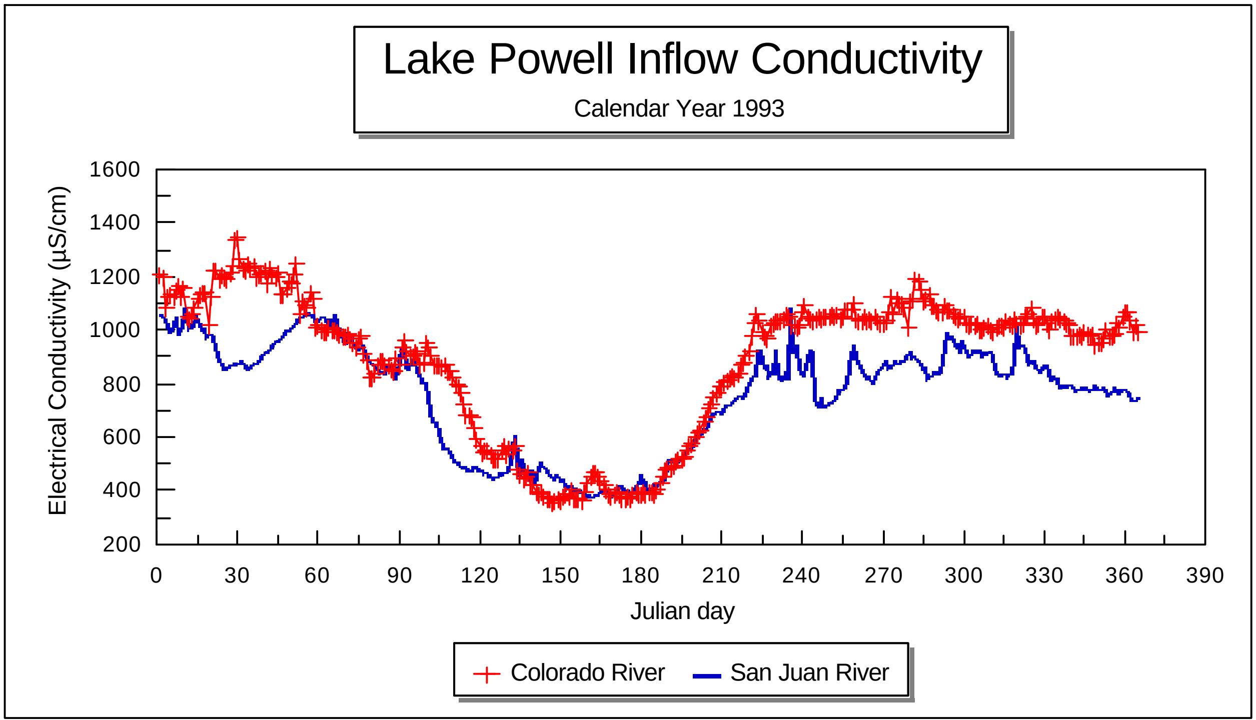


Figure 13. Inflowing electrical conductivity for 1993.

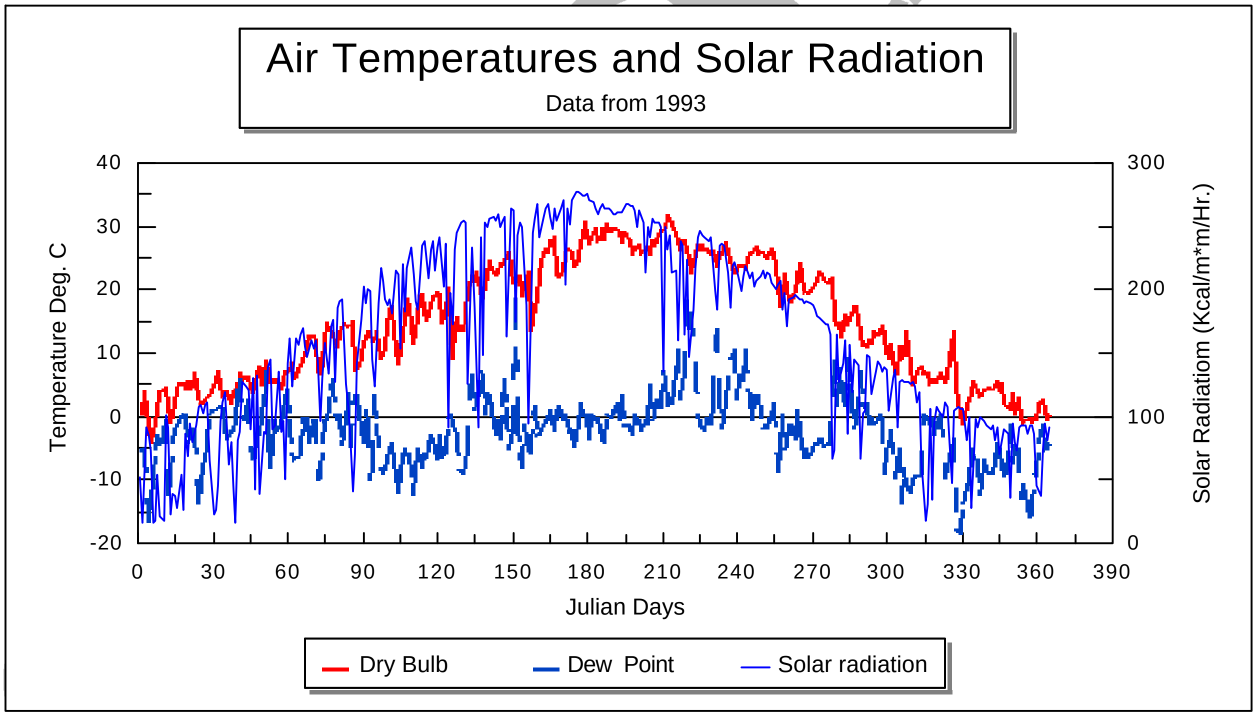


Figure 14. Meteorological data at Lake Powell 1993.

Daily average wind data for 1993 are shown in Figure 15 and the speed stays above 1 m/s most of the time. Many times from mid February until September the speed is at or above 2 m/s and often increases above the 4 m/s as storms occur during the year.

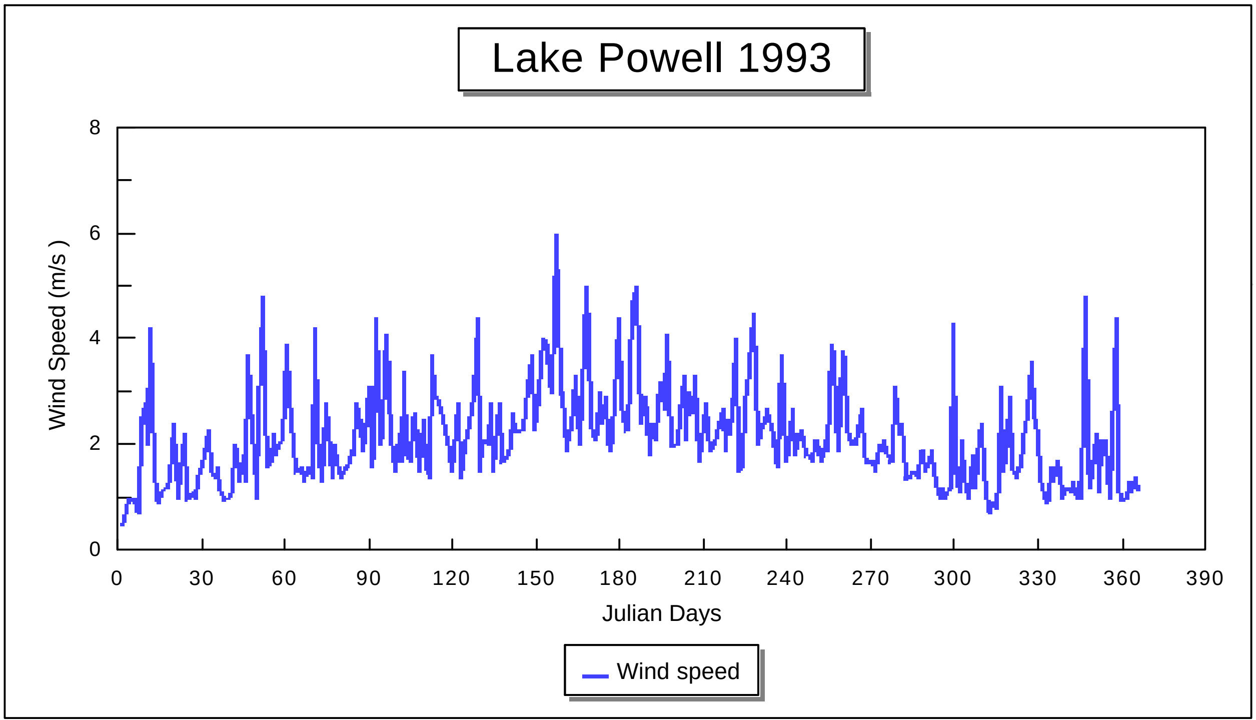


Figure 15. Daily average wind speed for 1993.

MODEL CALIBRATION

The input data files for both years were used to calibrate the model, first to calibrate for 1992 then to obtain a verification/calibration for 1993. Many runs were required to obtain a calibration for 1992, but as data for 1993 were processed and it became evident that the two branch model scheme was not accounting for the embayments on Lake Powell. We then reconfigured the geometry and input files for the five branch model scheme shown in figure 5. After doing this the model was again re-calibrated using both years to compare to the observed data sets. Only quarterly data exists for the sampling stations above the dam, monthly data exists for the sampling station (LPCR0024) at Wahweap Bay and it was primarily used to obtain a calibration. This station was used because it had a more complete data set and the selective withdrawals would be most sensitive to this profile. Initially, the model was started at the first of the year from measured temperature and electrical conductivity profiles. However, starting the model at the beginning of March allowed the model to include the effects of cold water and higher conductivity in the bottom of the reservoir, from cold inflows during December, January and February. Also a profile that matched the upper part of the reservoir was used as initial conditions for the upper reaches of the reservoir. The following sections will discuss the results of the last set of calibrations for both 1992 and 1993.

Calibration plots for 1992- Plots for 1992 began at the end of January and are shown on Figure 16 which is a graphic that has all the days that correspond to field sampling days during 1992. The first plot at day 32 is near the first of February and shows that the model data were about 1 °C cooler than the measured data below 250 feet of depth. The temperatures above that depth are nearly identical to the measured data. Plots at the first of May, day 122, and first of June, day 154, are very close to the measured data throughout the whole profile. The plots near the first of August, September, October, days 206, 246, 275 all are within about 1.5 degrees C at the surface, and below 200 feet of depth the difference is less than 1 degree C. The differences between measured and computed values are about 2 degrees C for depths between 50 to 125 feet. The last plot for 1992 is near the first of November and shows about a 1 °C lower temperature observed than the model results indicate in the top 100 feet. Otherwise the plot shows very little difference between measured and computed profiles.

Calibration plots for 1993 - Starting reservoir elevation for 1993 calibration was at about 3633 feet. The results of comparing field data with computed values from the model are shown in figure 17. Only five days during 1993 are available from the field data and they occur near the first of March, June, August, September, and November; days 61, 153, 214, 244, and 306. In March and June less than 1 degree C difference occurs between the measured and computed profiles. However, in August and September larger differences occur. The profiles are similar to about 75 feet of depth, diverge to about 3.5 degrees C difference at about 125 feet of depth and converge at about 180 feet of depth and remaining within 1 degree C to the bottom. The measured profiles are typically warmer than the computed profiles below 125 feet of depth. The1993 comparisons between measured and modeled profiles are not as close as 1992 profiles. However, combinations of the coefficients affecting wind mixing, turbulent mixing, solar radiation, light penetration, diffusion and percent of wind energy expended to mix the surface layer did not achieve a better fit of the measured data.

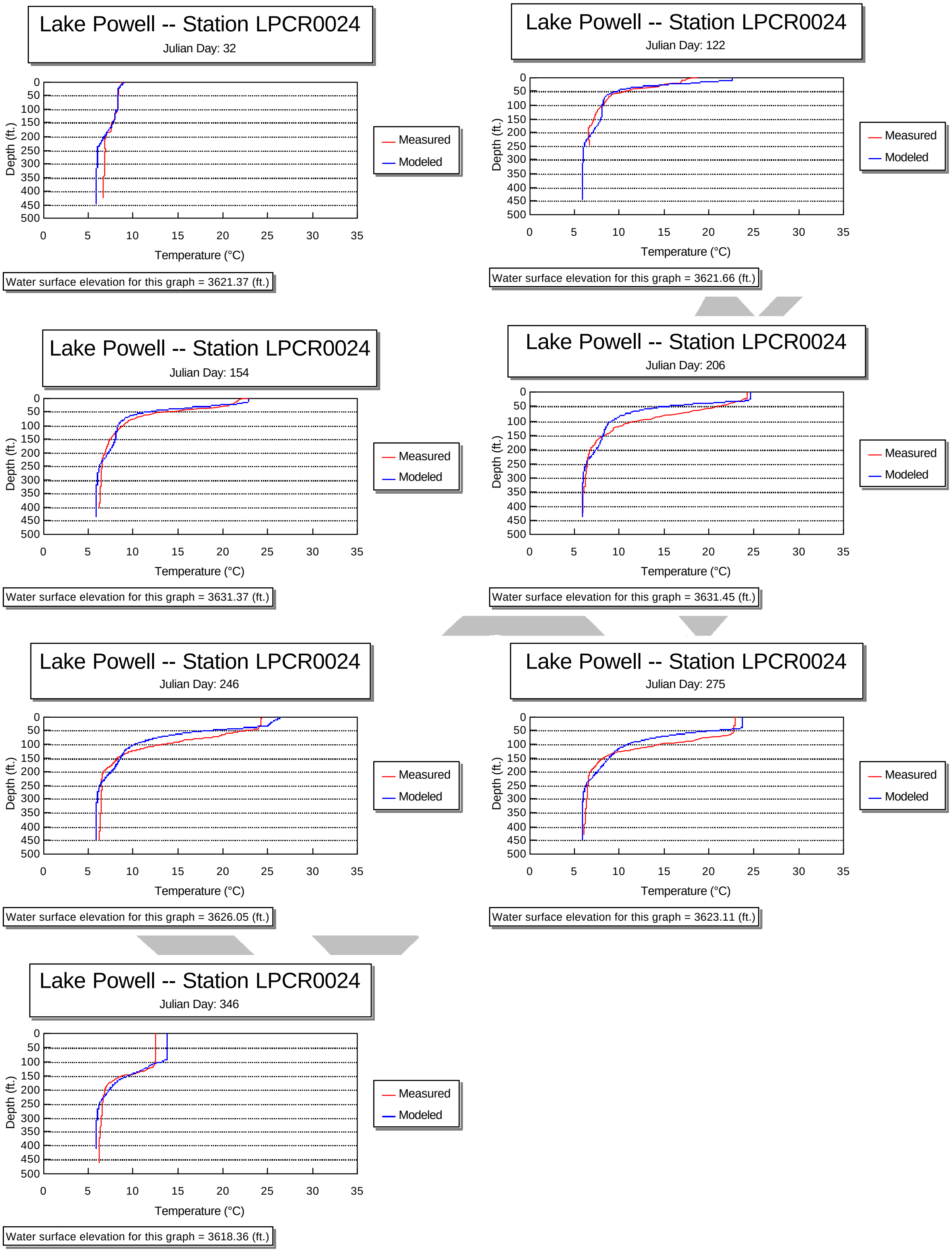


Figure 16. Comparison of measured and computed values, calibration 1992.

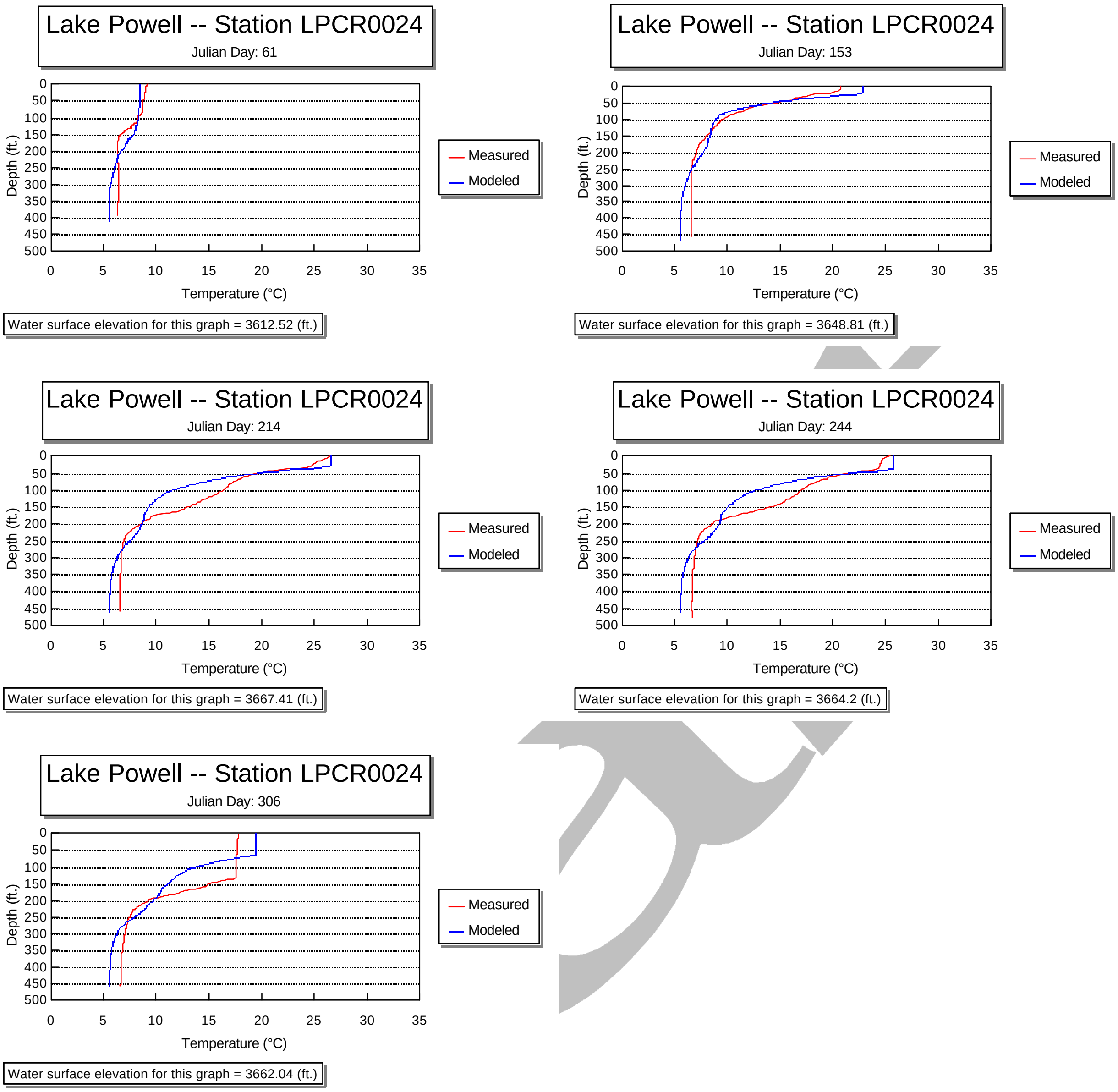
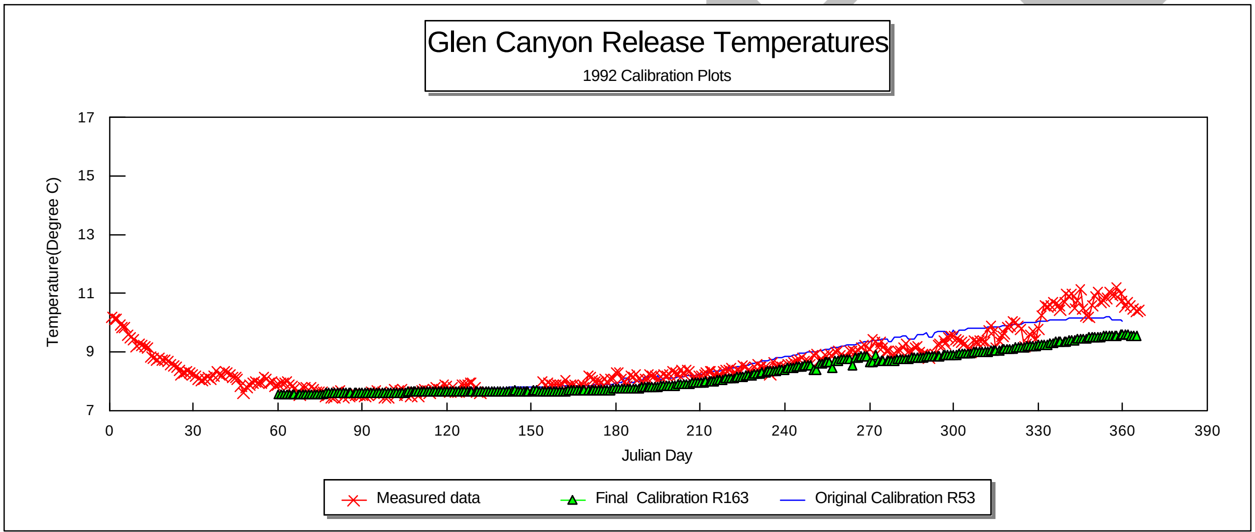


Figure 17. Comparison of measured and computed values calibration 1993.

Events that may explain these differences are increased heating on the surface, increased mixing in the metalimnion, wind mixing events not captured by daily average meteorological data, and inaccurate recording of the depths because of wind driven drift while sampling. Surface water and air temperatures did not vary much from 1992 to 1993. Solar heating decreased in 1993. Neither of these increased surface heating. Some increased vertical mixing could be attributed to higher wind speeds in 1993. If heat was mixed from the surface into the mid-depths the surface temperature of the lake would have cooled; it did not cool in 1993. Average daily meteorological data were used in the model and the model could not resolve mixing events that occur within a day. Also, if the temperature probe was at a shallower depth than reported in the field data by as little as 10 feet, the model results could be within 1.5 degrees of the field data. With the model and measured data comparing well for the first 75 feet, and comparing well below 180 feet, indicates the basic heat transfer and mixing are correct.

The calibration process involved selecting the model coefficients and parameters that matched both the measured profiles and the release temperatures. Many different combinations were tried and the combination used for figure16 and 17 was the best to match both the profiles and release temperatures. Consequently, the model calibration and verification phase was considered completed and specific model runs were made to evaluate how the release temperatures and the in-reservoir conditions changed with different withdrawals, from different elevations, and at different times of the year while maintaining the same total discharge.



Comparison of release data - Releases associated with the model calibration for 1992 and 1993 are shown on figure 18. The first plot is for 1992 and indicates that the original calibration fit the historic release temperatures better than the final calibration. But the need to achieve the best fit for release temperatures and the reservoir measured profiles for both years, using the same model coefficients, was quite difficult and some compromises were made to achieve the goal of fitting the two years of data.

Final calibration plot for 1992 data is less than 1 °C. from the measured values until December. Data in 1993 also are within 1 ° C except November and December. Generally, the temperatures from the model are less than the measured values and will be conservative. This needs to be explained, if the model under predicts the release temperature and actual releases are slightly warmer, then less warm water from the surface layers will be required to achieve warmer releases.

MODEL SIMULATIONS

The objective of the simulation runs was to select runs which warmed the releases downstream and did not cool the surface temperatures of the reservoir too much. Cooling the water surface could have an adverse effect on the biological growth and the shad fishery. Decreasing the summer surface temperatures may cause the shad to die the following winter. Shad are the food base for many of the fish in Lake Powell.

The data for 1993 was chosen for these simulations because it was wetter, had above mean inflows and had the largest reservoir volume increase since 1983, when the reservoir first filled. Also, the increase in reservoir elevation was the largest since filling in 1983. All of the above conditions makes it more difficult to recover from loss of warm water from the surface of the reservoir.

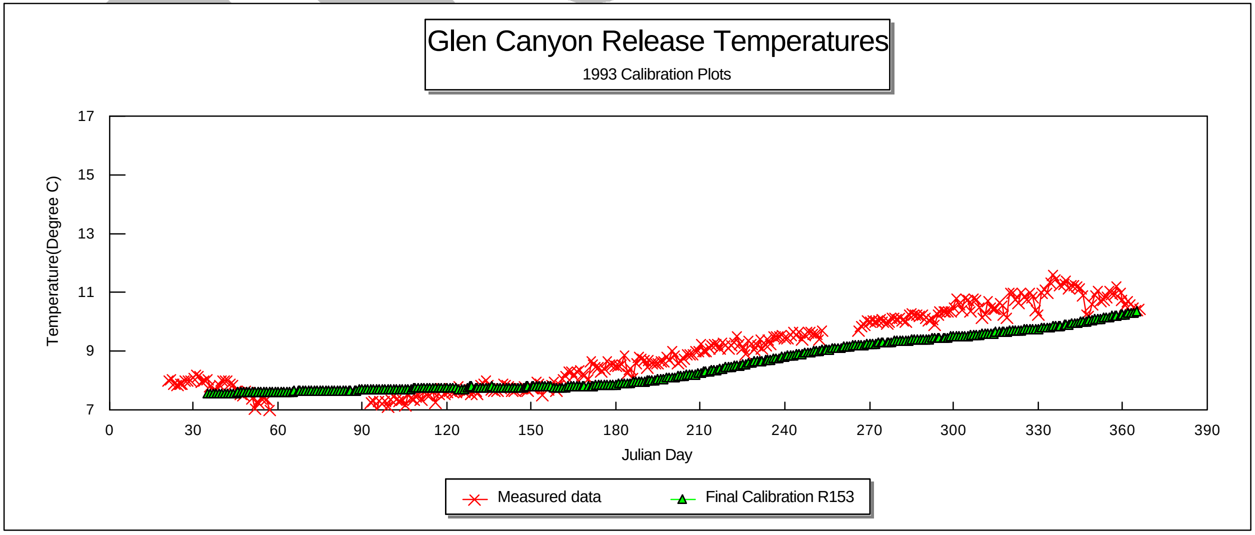


Figure 18 Dam release temperatures for 1992 and 1993 calibration.

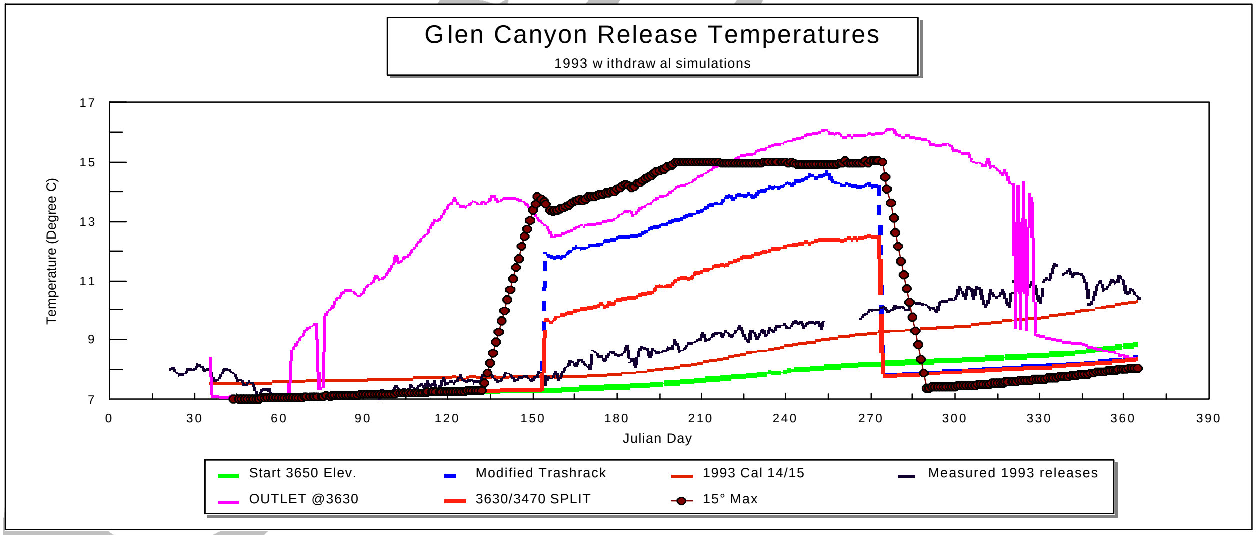


Figure 19. Modeled and measured discharge temperatures for 1993

A starting elevation was computed from 1993 data so that the 1993 inflows would reach a maximum reservoir elevation of about 3700 feet during the year. A starting elevation of 3650 feet resulted from the calculation. A run using 3650 feet as a starting elevation and 1993 flows is shown on figure 19 and was used as a baseline for most of the future simulations. It was designated as ‘Starting 3650 Elev.’ and is the wide grey line below the measured data. The centerline of the outlet was at elevation 3470 for this simulation. Comparison of this run with the 1993 calibration run indicates the effect of changing the starting elevation. Releases were cooler than the calibration run by less than 1 °C in March to almost 2 ° C by the end of the year. Cooler releases result because the outlet is deeper than with a starting elevation of about 3633 ft. used in the calibration simulation.

Many model runs were made with the centerline of the outlet submerged 30, 40, or 50 feet below the water surface to determine, if warm water could be obtained from the reservoir without cooling the water surface drastically. Figure 19 shows the results from simulations using outlets placed at elevation 3630 and from the penstocks at elevation 3470. Data supplied by the Upper Colorado region indicated that the reservoir surface would be above elevation 3670 more than 50 percent of the time in future years. The hydraulics laboratory studies indicate 40 feet of submergence is required to limit vortex formation on the reservoir surface (Vermeyen, 1999). If 40 feet of submergence is maintained, elevation 3630 is the highest elevation that will be usable 50 percent of the time. An outlet at elevation 3630 ft. was simulated to determine the warmest releases that could be obtained and it is highest thin trace on figure 19. The run is designated as ’outlet @3630' and has maximum temperature of about 16 °C. The temperature varied from about 13 to 16+ degrees from May to November in this simulation.

The maximum temperature run (‘outlet @ 3630') and the baseline run established the warmest and coolest water expected from selective withdrawal outlets at elevation 3630 which would maintain minimum submergence during the year. In a meeting held in Denver between Upper Colorado and Denver staff it was discussed that the warm water would only be needed during the period from June to the end of September to facilitate spawning and growth of the young endangered fish. Accordingly, simulations were run with flow coming from the penstocks at 3470 until June then withdrawal was shifted to elevation 3630 ft. until the end of September, when withdrawal was shifted down to the penstocks at elevation 3470. One of these simulations was designated as ‘Modified trashrack’ release temperatures and is indicated by the wide black dashed line on figure 19. Release temperatures followed the baseline to June, then it jumped sharply to about 12 degrees, increased almost linearly with time until the end of September(day 273) to about 14 degrees, then dropped to about 0.5 degrees below the baseline or about 2 degrees below the 1993 calibration run. A significant amount of heat was removed from the reservoir by the higher outlets operating from June to October in this case. Another of these simulations had a 50/50 flow split between outlets at 3630 and

3470, the penstock elevation, is designated as ‘3630/3470 SPLIT’. Release temperatures are very similar to the ‘Modified trashrack’ except the near linear temperature rise from June to October varied from about 9.5 to 12 degrees then followed the Modified trashrack run to the end of the year. It is the line just below the wide dashed line for the Modified trashrack simulation.

The final simulation discussed in this report is designated as ‘15 ° Max’ on figure 19 and maintained the release temperature at 15 ° C, if the surface temperature was warm enough to achieve 15 ° C. Before Julian day 132 and after day 294 all discharge was from the penstock elevation, 3740 feet. The discharge on day 132 was 100 percent from the penstocks and on day 152 all the discharge was from elevation 3630 feet. The discharge was shifted from the lower penstocks to the upper elevation 5 percent per day between these two days. All discharge remained from the upper outlet until day 225. Then discharge was split between the upper and lower outlets to limit the discharge temperature to a maximum of about 15 °C. until day 272, when discharge was shifted from the upper outlet to the lower outlet at a rate of about 5 percent per day until all the discharge was from the penstock elevation. Table 2 contains the total discharge and the discharges for elevations 3470 and 3630 during this period and some temperatures associated with the discharges. Discharge remained at the penstock elevation until the end of 1993.

Release temperature shown as the dotted symbol on figure 19 follows the baseline until mid-May, rises sharply to about 13 degrees, and stays between 13 and 15 degrees until October, then moves downward linearly in time to about 7.5 degrees in mid-October and rises slightly until the end of the year. After mid-October the temperature is about 1° lower than the baseline run temperature. This difference is attributable to the heat lost from the withdrawals from the upper layers earlier in the summer on the 15 ° Max simulation. Temperature profile changes within the reservoir are a result of the heat removal and will be discussed later.

Table 2. Selected 1993 flows, temperatures by Julian day for 15° Max run.

Julian Day	Release T Deg C	Total flow cfs	Lower flow cfs	Lower T Deg C	Upper flow cfs	Upper T Deg C
132		10869	10869		0	
135		8791	7472		1319	
145		8349	2922		5427	
152		9824	0		9824	
155		9942	0		9942	
165		10061	0		10061	
175		11045	0		11045	
185		10538	0		10538	
195		15192	0		15192	
202	15.01	15409	0	7.62	15409	15.01
205	15.00	14544	232	7.64	14312	15.12
210	15.00	16306	801	7.69	15504	15.38
215	15.00	16133	1378	7.73	14755	15.68
225	15.00	16852	2126	7.83	14726	16.04
235	15.00	14341	2221	7.92	12120	16.30
245	15.00	12116	2239	8.06	9877	16.57
255	15.00	8401	1708	8.13	6693	16.75
265	15.00	11890	2226	8.20	9663	16.57
275	14.61	8069	2017	8.26	6052	16.73
285	10.33	9209	6906	8.30	2302	16.42
290	8.32	7675	7675	8.32	0	16.26

CHANGES IN RESERVOIR PROFILES

Removal of water from the warmer layers in the summertime causes some changes to the reservoir and these changes can best be demonstrated by comparing profiles for the baseline and the 15 ° Max run. Differences between the profiles are shown in Figure 20 for the end of August 1993, Julian day 244. Wahweap Bay temperatures for the 15 ° Max run are nearly the same above 110 feet, cools to about 1° C cooler than the baseline at 240 feet, and matches the baseline from 325 feet to the bottom. Bullfrog temperatures are nearly identical to about 110 feet, then the 15 ° Max temperatures are about 2 °C cooler than the baseline, and converge to the baseline temperature of 5 °C at about 300 feet. Hite temperature profiles are very similar to 110 feet of depth, then the 15 ° C Max temperature cools more than the baseline and at the bottom it is about 3.5 ° C cooler. These temperature patterns suggest that an inter-flow is entering the dam at the headwater and is flowing the length of the reservoir at mid-depth and is being withdrawn by the outlets. San Juan Arm temperatures are represented by the profile in Cha Canyon which has a very similar trace for both temperature profiles to about 65 feet of depth. Then temperature profiles cross each other at about 75 feet of depth. The 15 ° C Max trace is about 1 °C cooler than the baseline at 90 feet of depth and remain very similar below 150 feet.

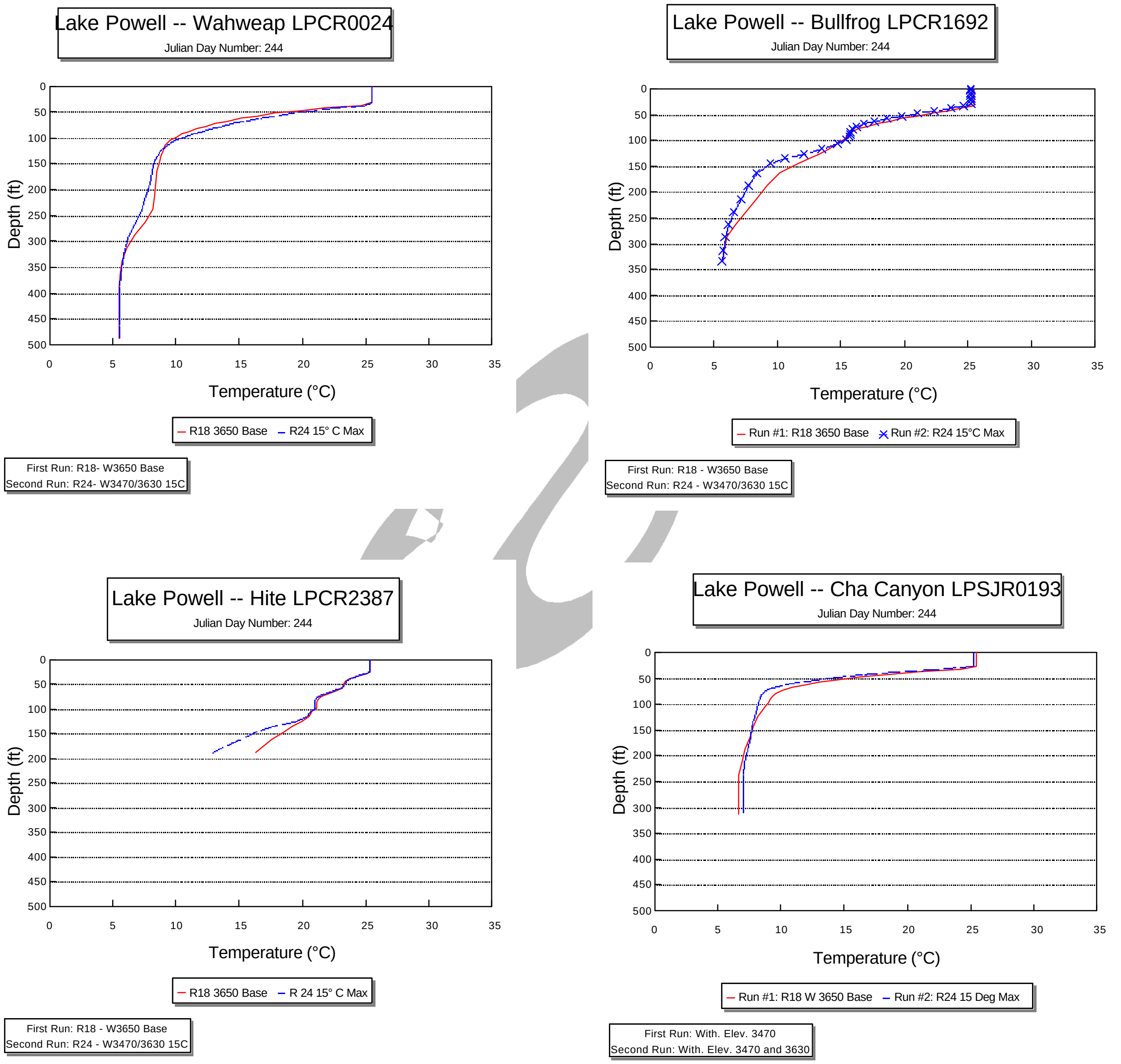


Figure 20. Baseline temperatures compared to 15 ° C Max releases for about 140 days after June, profiles are near the end of August.

Figure 21 shows the temperature profiles for the first of December, after the reservoir has cooled considerably on the surface and about 90 feet of depth is at about 15 °C. Cooling has also penetrated the deeper depths in the reservoir. At Wahweap the 15 °C Max trace starts to cool more than the baseline run and is about 1 °C cooler at 200 feet and then the profiles converge to 5.5 °C at about 300 feet. Below 300 feet of depth both temperatures stay constant at about 5.5 °C. Temperatures at Bullfrog are a few tenths of a degree cooler for the 15 ° C Max trace to about 100 feet of depth. Then it cools rapidly with increased depth to a maximum difference of 3 ° C at 200 feet, and converges near 300 feet of depth at about 6 °C temperature. This change was caused

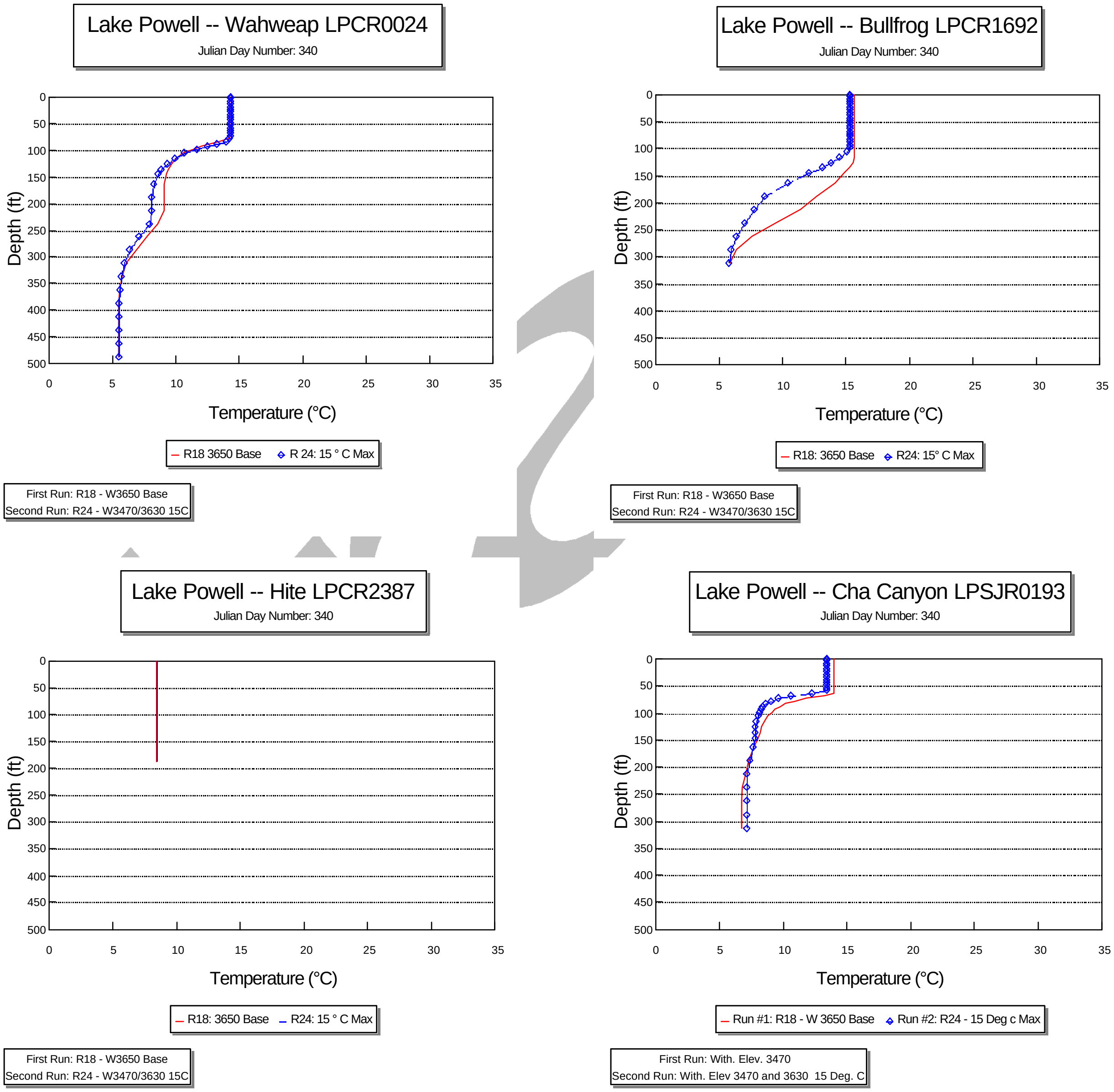


Figure 21. Baseline temperatures compared to 15 ° Max releases for about 140 days after June, profiles near the first of December.

by the cold water flowing along the bottom of the reservoir to replace the slightly warmer water being withdrawn from the penstocks at elevation 3470. A constant 9 degree temperature existed at Hite for both traces in December as the upper end of the reservoir was completely mixed to about 200 feet.

The wintertime reservoir changes caused by releasing warm water (the 15 ° Max run) in summertime were evaluated by replicating the inflows, meteorological data, and the outflow for 1993 and placing them at the end of the existing files. This allowed the model to be run for about 440 days from the beginning of 1993 to evaluate the changes that might occur in the reservoir by skimming warm water off at elevation 3630 during the prior summer. The resulting reservoir profiles are shown in figure 22 .

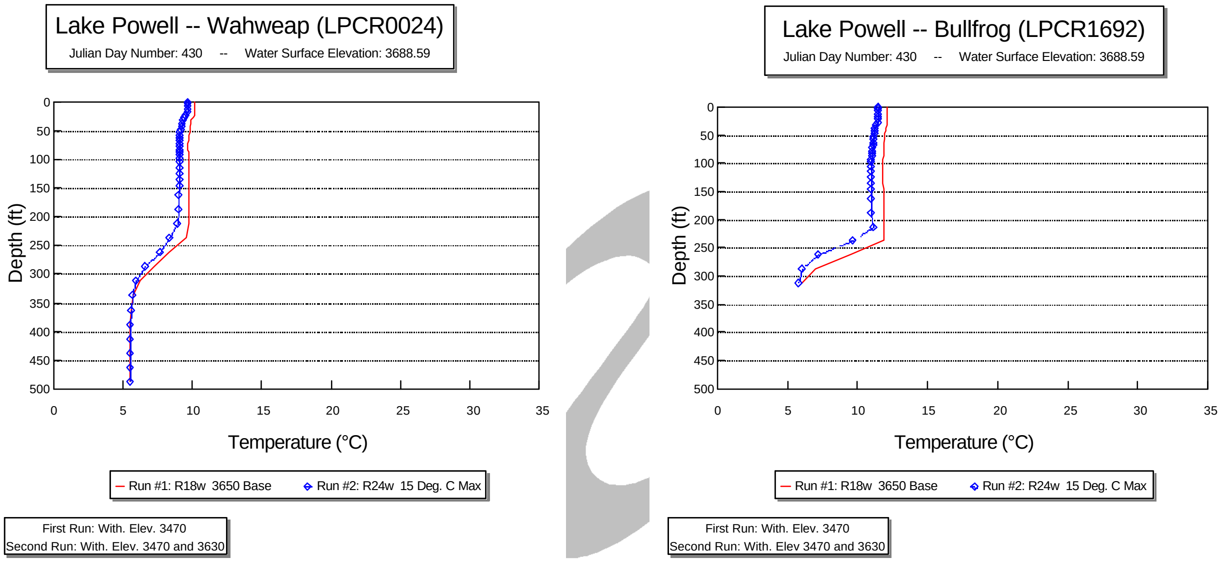


Figure 22. Early March temperature profiles comparing extended baseline and 15 °C Max traces to evaluate wintertime reservoir temperatures changes.

Both Wahweap and Bullfrog profiles are about 1 ° C cooler for the 15 ° C Max profile from the surface to the depth of nearly 300 feet. The depth of the reservoir at Bullfrog is about 300 feet at the end of the simulation. A one degree cooling is fairly minimal in the middle of the winter. Wahweap temperature of about 10 ° C exists for this plot in the top 200 feet of the reservoir. Similarly, a 11° C temperature exists in the top 200 feet of depth at Bullfrog.

MISCELLANEOUS DATA FROM THE MODEL

Several parameters in addition to temperature are included in the model but were not calibrated. These parameters have reasonable good inflow data, but may be influenced by other factors that do not have complete inflow data.

Total Dissolved Solids / Conductivity - Electrical conductivity (EC) data were obtained from the USGS data files on the Green and Colorado Rivers. The data were combined by flow weighing to get the combined inflow values at the headwater of the reservoir. These data are fairly complete having daily values with few exceptions. Missing data were filled in by interpolation from adjacent values or by regression, if necessary. No calibration factors are available in the model so the flow patterns in the reservoir dominate how EC will be distributed in the reservoir and the withdrawal scheme will dictate how EC will be removed from the dam. Field data are only available quarterly at Wahweap near the dam, at Bullfrog about mile 80, and at Hite near mile 180. The data are sparse and the plotting software interpolates to plot the field data. Modeled data has 37 data values distributed along the same length of river so the plots from the model has more data values or more detail in the plots. Figure 23 shows the field and model EC data for day 215 (about the first of August) 1993. The contours of EC for the whole reservoir are displayed. The plots are fairly similar except for slightly higher EC near the dam in the field data and along the bottom of the reservoir. Also the field EC at the mid-depth and in the lower part of the reservoir is slightly higher than the modeled results.

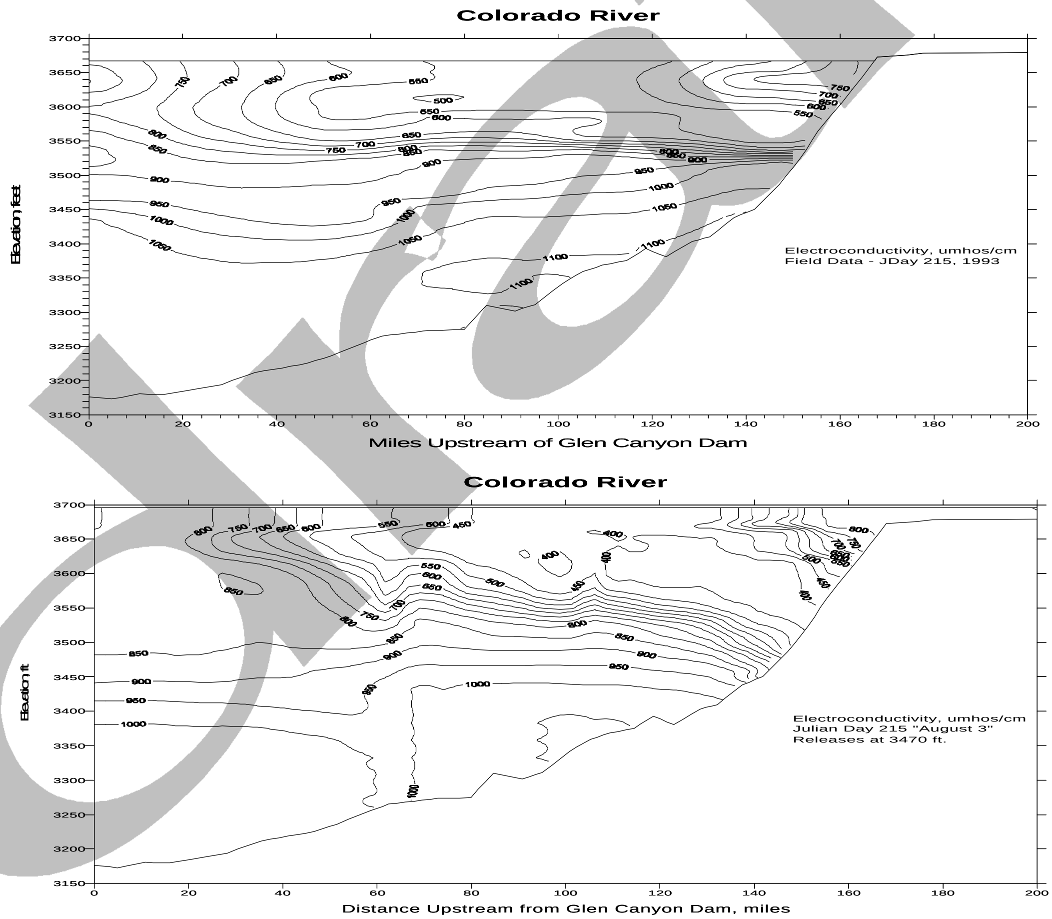


Figure 23. Field (upper) and Modeled (lower) Electrical Conductivity contours near August 3 1993.

The modeled plot has a section of lower EC at about mile 60, this is caused by lower EC water flowing into the reservoir from the San Juan River. This lower EC water may also be why the model has lower EC in the lower part of the reservoir. However, cold, high EC water is found in the lower parts of the reservoir from high EC flow during November and December. The model does not move the high EC water toward the dam as quickly as the field data indicate. Generally, the shape of the plots and values are similar at the dam, at the surface and in the inflow region.

Dissolved Oxygen - Data for the inflow were computed as described earlier in this report. Average daily values were computed from the water temperature and barometric pressures for saturated conditions. Oxygen in water is influenced by wind mixing, water transfer (advection and diffusion), temperature, nutrients, algae, BOD, light energy and organic matter. Data for most of these values do not exist or have less than 6 values throughout the year. Certainly not enough to provide a good data set for modeling any of them. Available data were used and kept constant until more data were available to provide input to the model. A rough calibration for dissolved oxygen (DO) was done so that it compared generally with the field data plots of the model and field data which are shown on Figure 24 for 1993 near the beginning of August. Both plots have surface DO at about 8 mg/l, decreases to 6 or 7 mg/l at about 120 feet of depth, then approaches 5 mg/l or less at the bottom of the reservoir. The field data show two cells of 5 mg/l DO, one located at 75 feet of depth at mile 120 and the other at mile 70 at 3470 feet elevation. These were not reproduced in the model; the one at mile 120 is likely due to an algae die-off or from inflowing oxygen demanding material that was not in the model inflow data file. The other deeper DO depression was very near the San Juan River Arm and it may have been due to an influx of algae and oxygen demanding material in that arm. However the plots are in agreement and the same trends exist in both of them considering the small number data and average calibration values used in this simulation.

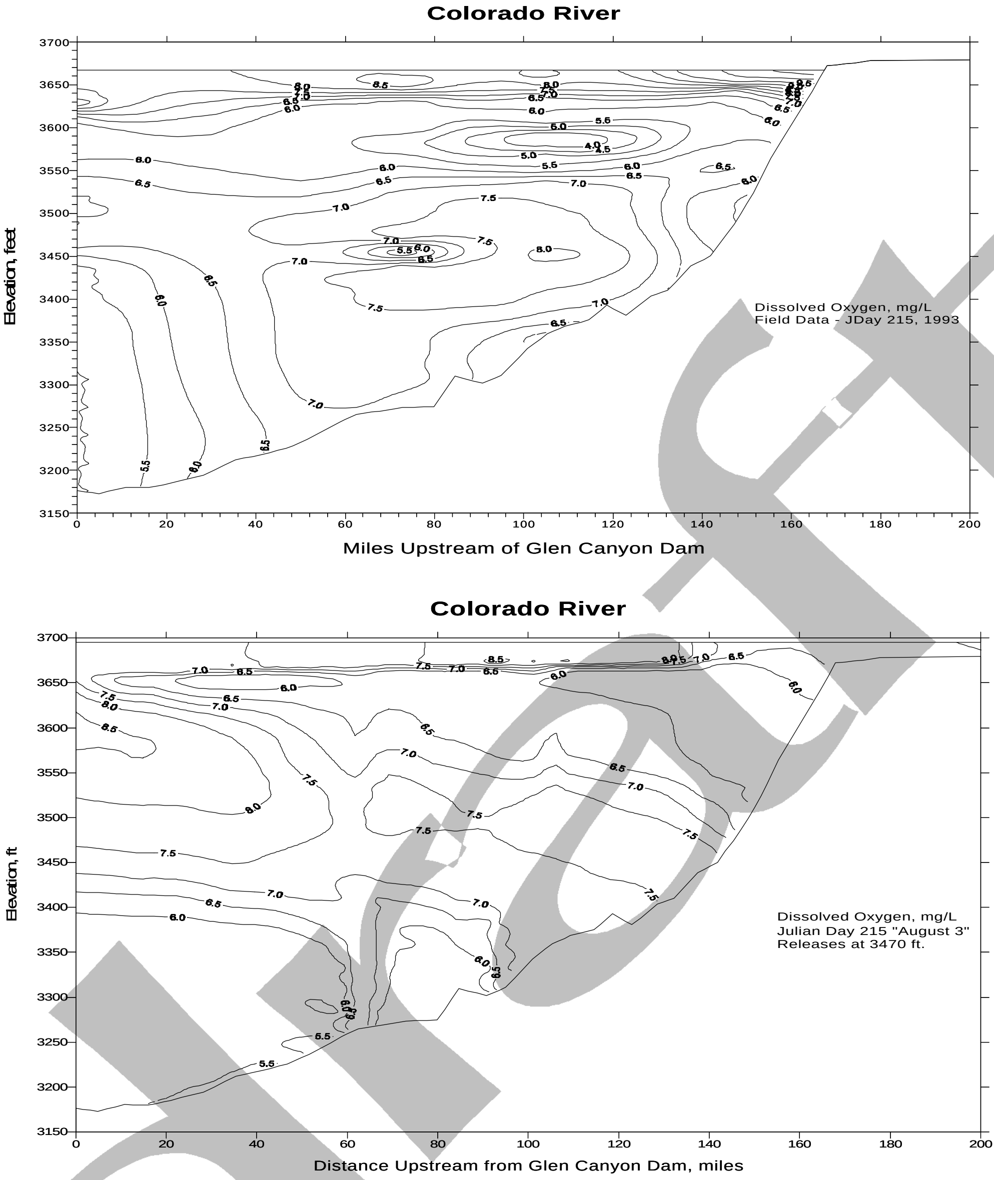


Figure 24. - Dissolved oxygen contours comparing field (upper) and modeled (lower) data for 3 August 1993.

CONCLUSIONS

1. The BETTER model was calibrated for 1992 and verified using 1993 data; adjustments to calibration factors were made based on the verification phase to obtain a compromise set that would fit both years reasonably well.

2. Different elevations for selective withdrawal placement were studied and their effect

on release temperatures were evaluated.

a) Surface withdrawal using the spillway is viable if the reservoir is at or above full pool, 3700 feet elevation. However, reservoir is at full pool less than 5 percent of the time.

b)The selective withdrawal outlet needs 40 feet of submergence to minimize vortices and their associated problems. Outlet elevations at 3660, 3650, 3640 and 3630 were evaluated. Elevation 3630 was chosen for model simulations. If modeling results worked at elevation 3630 then less flow would be needed at any higher elevations, such as 3640 or 3650 to achieve the same warm release temperature. The impact on the reservoir would be more severe from an outlet at 3630 than the higher elevations because a smaller volume of water would be needed from a higher elevation than at 3630 as the temperature is slightly warmer closer to the surface.

c) Warm surface water is available from mid-May to the end of September that can be used to warm the releases. Fall reservoir temperatures decrease at Wahweap Bay and in the San Juan Arm less than 1° C, Bullfrog basin temperatures decrease about 2° C, and Hite temperature profiles do not change, if the dam releases are maintained above 15 ° C for 140 days beginning in June.

d) Winter time impacts in the reservoir are less than 1 °C at Wahweap and Bullfrog and smaller elsewhere if the 15 °C releases are maintained during the summer.

3. Reservoir surface temperatures are not decreased by upper level withdrawals. Reservoir cooling of the reservoir is limited to depths less than 150 feet.

4. Surface withdrawal outlets in connection with the existing penstocks will remove more algae and warm water from the surface of the reservoir than using the existing penstocks alone.

5. Model results for the 15 °C Max simulation had about 140 days of 15 °C releases from the dam. Actual releases may need to be only 30 - 60 days instead of the 140 days modeled. Actual impact to the reservoir will be less than indicated by these studies if periods less than 140 days are used to release the required warm water.

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Appendix A

Sensitivity comparison of dam releases
between baseline and 15° Max simulation

Release sensitivity for baseline (all flows released through the penstocks at elevation 3470) and the 15° Max (flow adjusted between elevation 3630 and 3470 to achieve 15 degree Centigrade release temperature) runs were evaluated for some parameters that are modeled but have not been calibrated. The model requires input data on the complete set of all parameters in the model, some of these parameters have little or no measured data available, let alone, enough daily data for the model or to calibrate them. The model was calibrated primarily for temperature. Daily data for temperature, EC, pH and dissolved oxygen were explained in the main report. Data for turbidity, detritus, dissolved organics, alkalinity, algae, and nutrients are limited in both numbers of data and spatial distribution. Some were constructed by regression from other data or from the few existing instantaneous values obtained by the USGS and averaged from the available data.

The above parameters do not have enough data in time or distance to properly characterize the changes in these parameters. Comparing the sensitivity of the releases to changes in operations will indicate the response to the changes. The direction of the response will be correct but the magnitude is not quantitative. Use these sensitivity results with caution, they are <u>rough estimates</u> at best.

The following seven figures compare the baseline and 15° Max releases from the dam and are to be used with caution, because they are not calibrated and are based on very few data values, sometimes with 4 to 6 data values during the year.

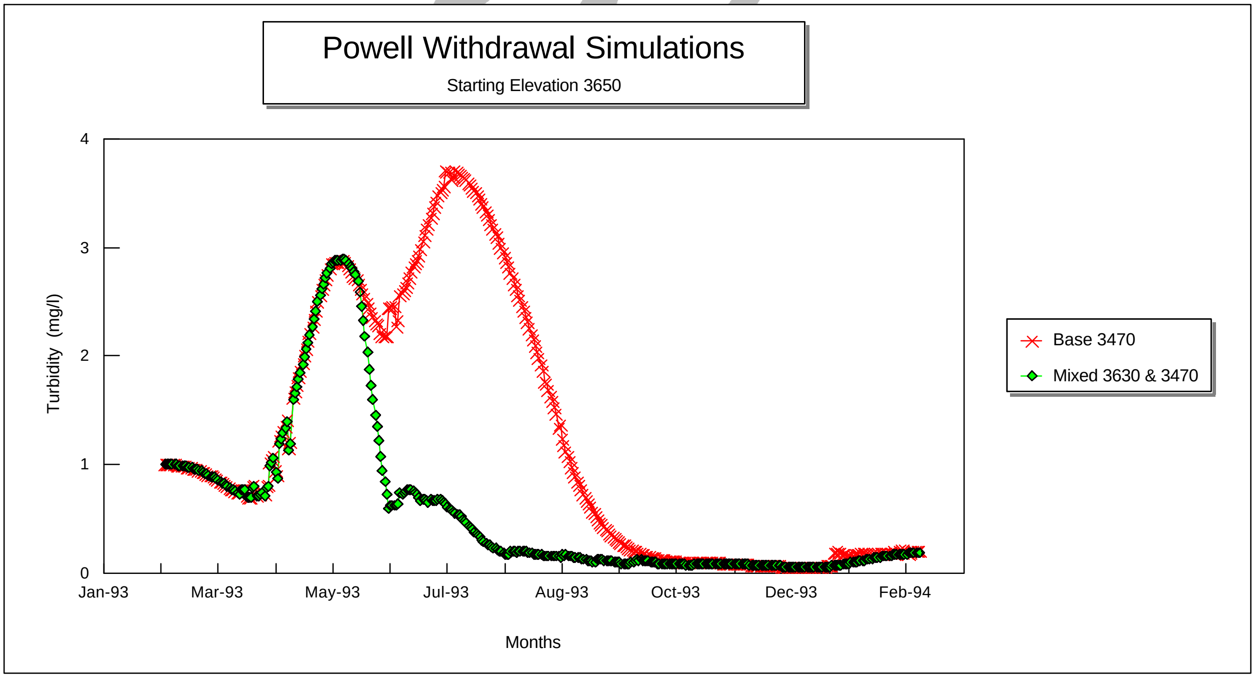

Figure 1. Modeled sensitivity of turbidity releases for 15° Max and baseline.

Figure 1 has a peak in turbidity that corresponds to the spring floods and another higher peak during the period from June to early July. This increase for the baseline would be expected due to the inter-flows at depth which carry contributions from the spring floods and the increased turbidity from dead algae as it settles in the reservoir. Both detritus, Figure 2, and algae, Figure 4 show higher values in late springtime then decrease rapidly in the fall to baseline values. However, when releases are coming from both the surface and at the penstocks the turbidity decreased rapidly as water was drawn from the clear surface layers.

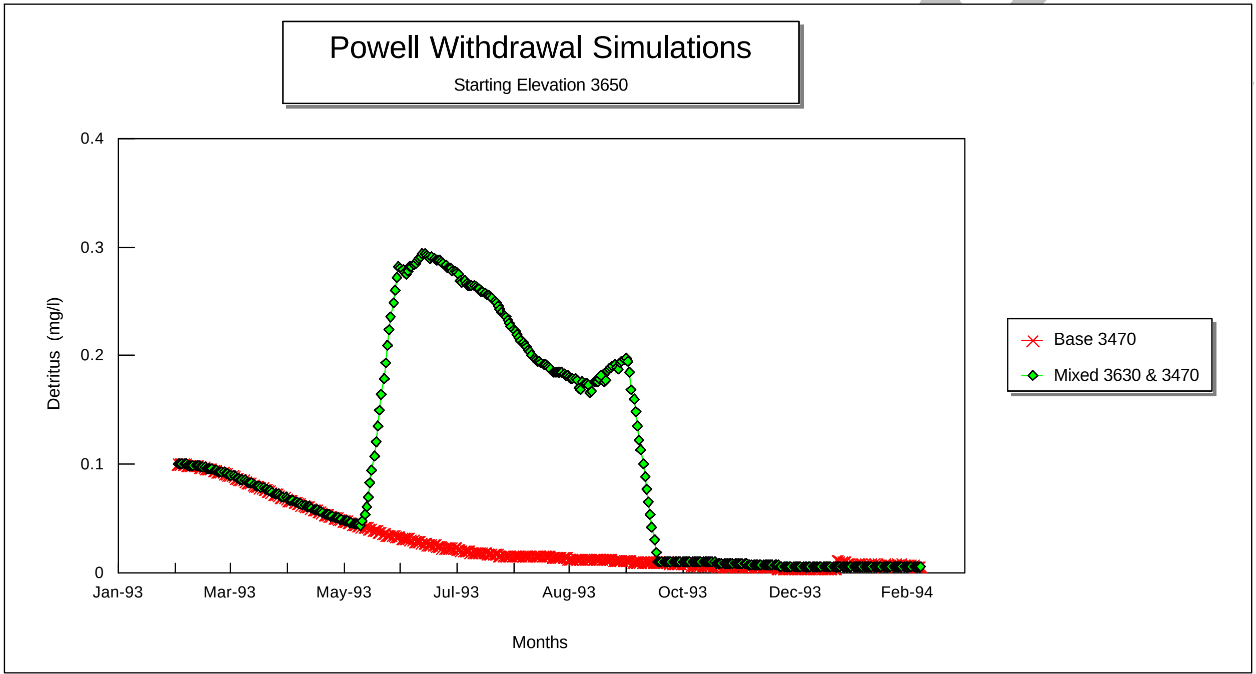

Figure 2. Sensitivity of detritus releases for 15° Max and baseline.

Detritus in Figure 2 increases sharply as compared to the base case, because withdrawals from the surface layers includes algae and other parameters that are in the surface layers. The graph shows an increase that is about three times as large as the base case but it is only a few tenths of a mg/l and the maximum is low. During the fall of the year when flow is again from the penstocks, detritus values are low because there is little organic matter deep in the reservoir.

Dissolved organics in Figure 3 for the base case and the 15° Max run show little change as they are close to zero, less than 0.1 mg/l, and it is well distributed vertically, consequently there was no change between the runs.

Algae grow at or near the surface of the reservoir in the euphotic zone where light, temperature and nutrients are available. However, the magnitude is low as compared to most reservoirs. Even the 15° max results have less than .15 mg/l of algal

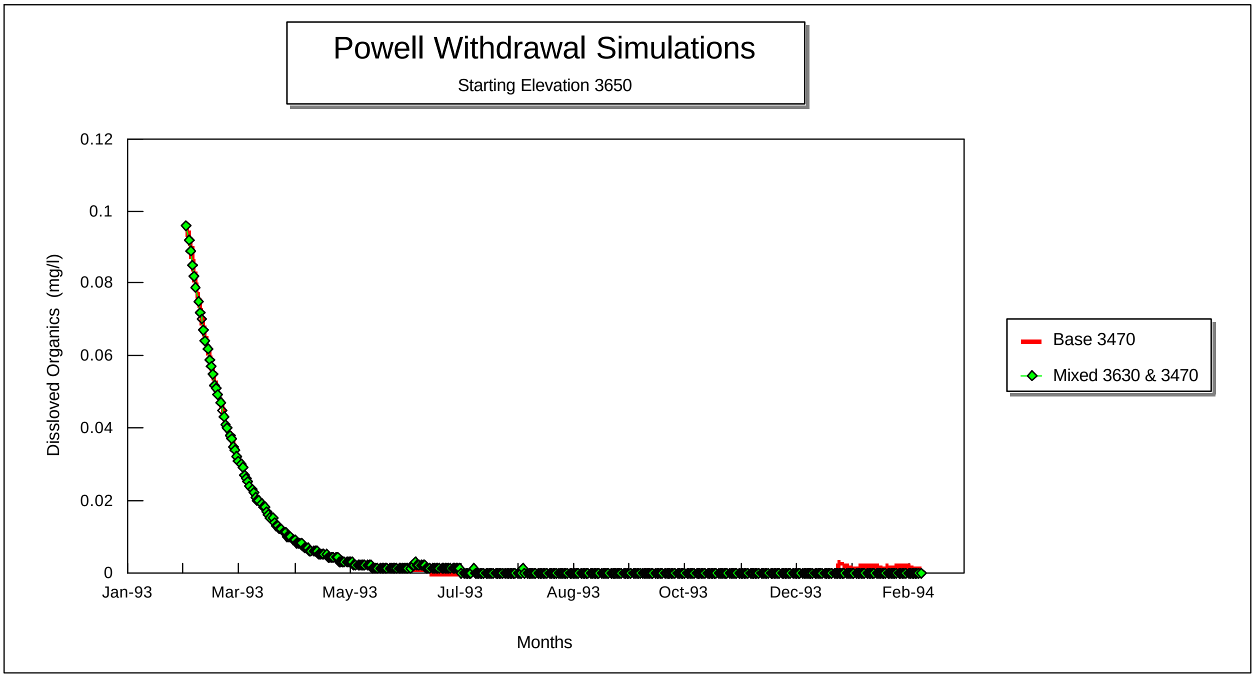

Figure 3. Sensitivity of dissolved organics releases for 15° Max and baseline.

concentration. Algal response increases sharply in the middle of May, deceases quickly as most of the nutrients are used and cycles at a low concentration until the withdrawal is shifted to the penstocks, see Figure 4. Again the base case is extremely low as the withdrawal is far below the surface where the algae grow. Slight increases in ammonia for the surface and low level outlet are observed in Figure 5. The ammonia increases, due to increased algal production and greater oxygen demand as the algae die and decay as they settle in the water column.

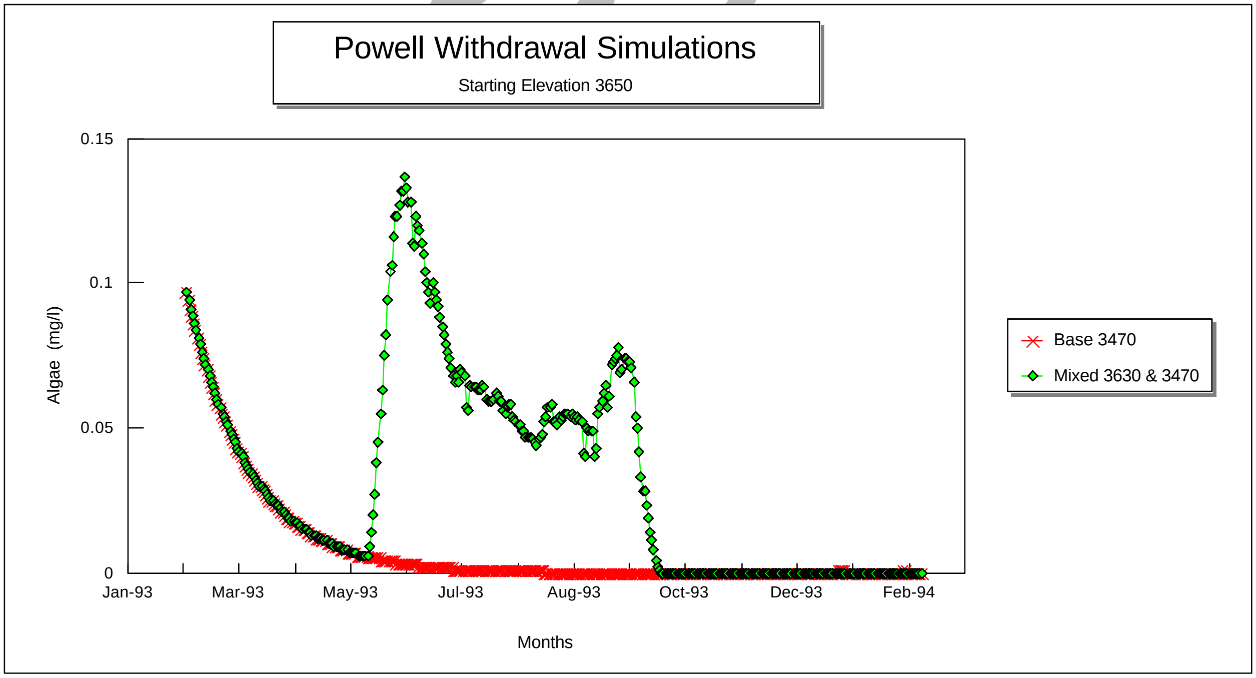

Figure 4. Sensitivity of algae releases for 15 ° Max and baseline.

Higher oxygen in May could be from withdrawals higher in the water column and algae growth in the springtime. Some algae may be removed from the reservoir by near surface withdrawals; as algae start growing rapidly the oxygen concentration is increased. Later, as the algae begin to die and decay the demand for oxygen

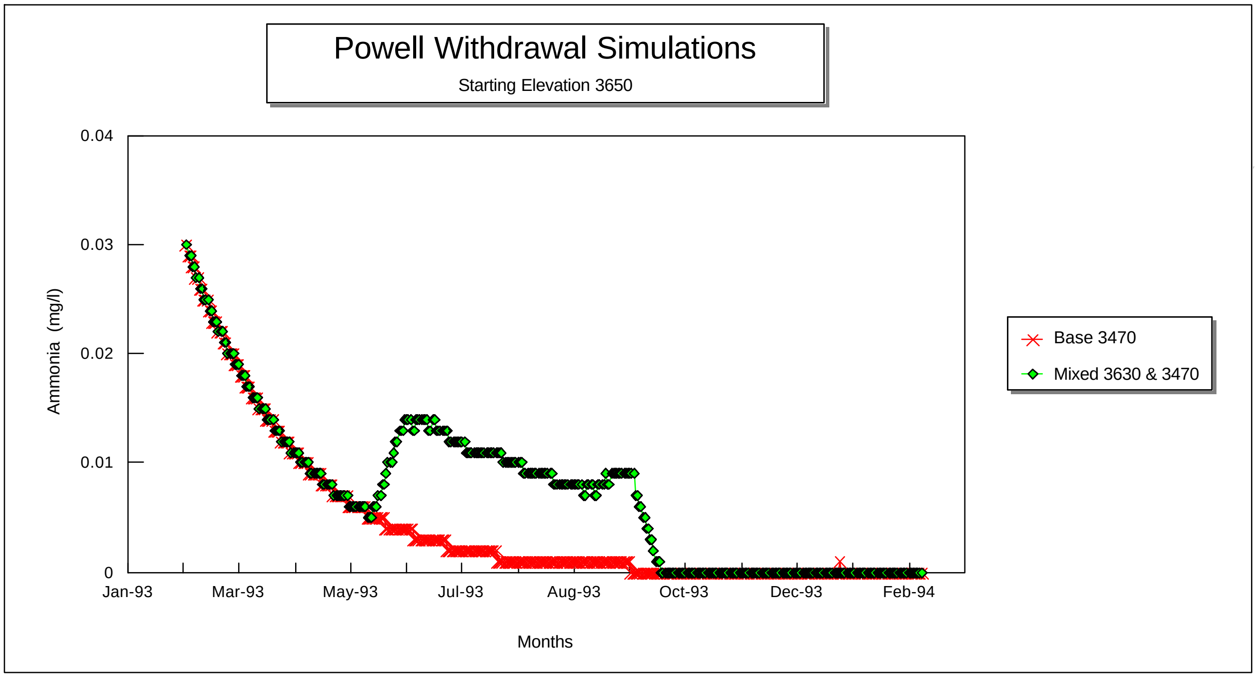

Figure 5. Sensitivity of ammonia releases for 15° Max and baseline.

increases and dissolved oxygen decreases, see Figure 6. Oxygen demand increases for the 15 ° Max run as compared to the baseline simulation because decaying algae and oxidation of the ammonia to inorganic forms of nitrogen. As algal production and ammonia decrease near the fall of the year, demand for oxygen decreases and oxygen concentrations increase.

Figure 7 shows the change in alkalinity between the two runs. Because the Colorado River is high in the carbonate ion the alkalinity, Figure 7, shows little change and decreases in a similar fashion the changes in EC. Higher EC occurs in the lower part of the reservoir and slightly lower EC values occur in the upper layers of the reservoir. The plot shows a slight decrease in alkalinity as lower EC water is released by the surface withdrawals of the 15° Max run.

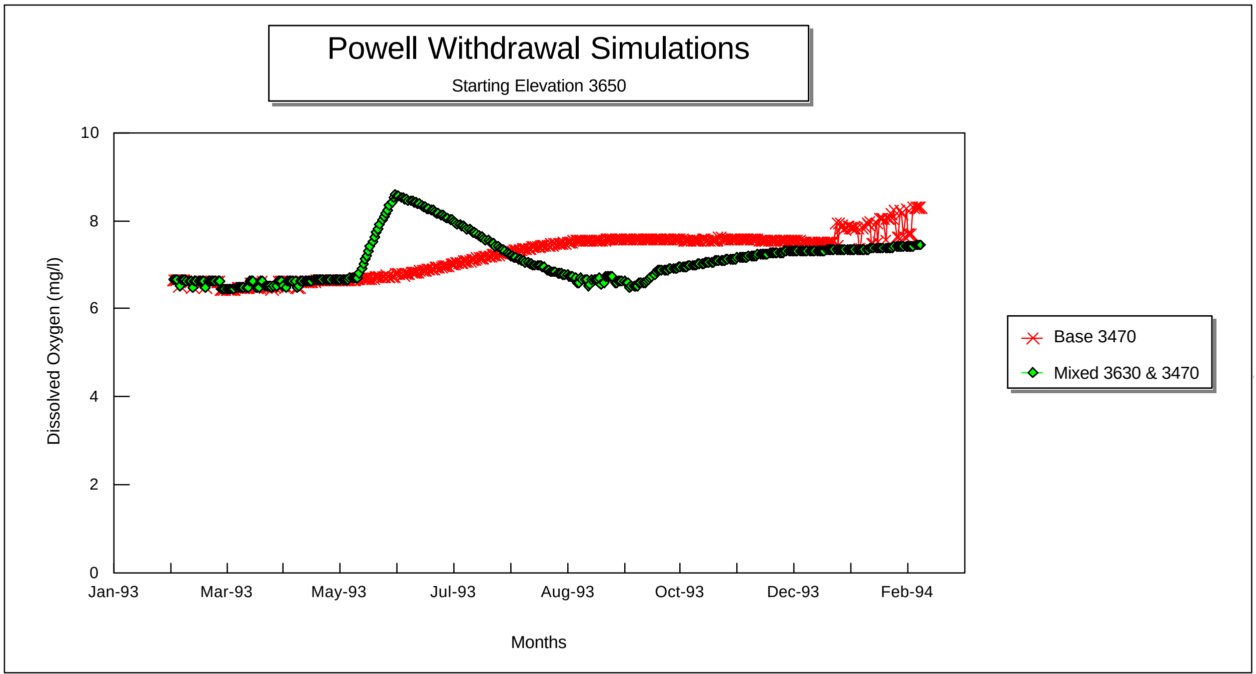

Figure 6. Sensitivity of dissolved oxygen releases for 15° Max and baseline.

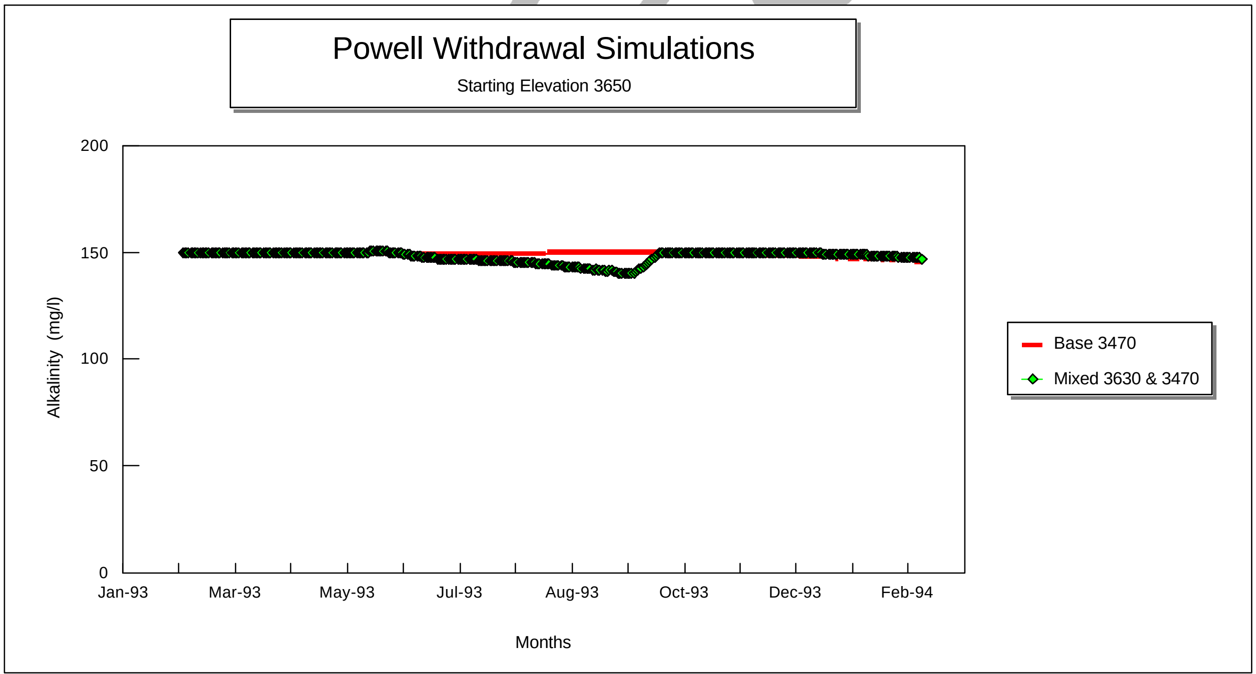

Figure 7. Sensitivity of alkalinity releases for 15° Max and baseline.