Expert Report of

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In the matter of

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Simulation of Millerton Lake Water Temperatures and Friant Dam Release Temperatures

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Simulation of Millerton Lake Water Temperatures and Friant Dam Release Temperatures

Introduction

This expert report describes the available data and assumptions used to build a water temperature model of Millerton Lake and match the simulated temperature profiles with those measured by Friant Water Users Authority (FWUA) and U.S. Department of the Interior, Bureau of Reclamation (Reclamation), during 2003 and 2004. The reservoir water temperature model was used to determine the expected temperature of water released from Friant Dam during 2003 and 2004 for specified river release scenarios that are assumed to represent restoration flows to support spring-run Chinook salmon. Because of the good calibration of the CE-QUAL-W2 (W2) model with measured 2003 and 2004 temperature profiles, these results are reliable and indicate the likely effects of increased river releases from Millerton Lake.

Conclusions

Because the river restoration flows are higher during the spring months of March–May when the reservoir historically fills to maximum storage levels, the simulated surface elevations for 2003 and 2004 were about 50–60 feet lower on April 30 and May 30. This caused the warm surface water and thermocline (i.e., zone of strong vertical temperature gradient) to be located about 50–60 feet lower in elevation and much closer to the canal outlets at 465 feet and 445 feet elevation. The higher release flows also caused the thermocline to be drawn lower into the reservoir than with the historical river releases. The spring inflows, with temperatures of 50–55°F in the April and May period, were placed deeper in the reservoir and caused the water near the river outlet elevation (380 feet) to be warmer than historical conditions. Each canal diversion was about 5°F warmer than historically in the spring and summer months. The higher river release during the spring and summer pulled down more water from below the Madera Canal elevation of 445 feet toward the river outlet elevation of 380 feet. The river outlet temperatures became progressively warmer than historically during the summer, with a maximum river release temperature of more than 60°F simulated for both 2003 and 2004 by the end of October. Because the lake profile temperatures were warmer, the fall cooling and mixing were delayed by a few days compared to the historical conditions.

Qualifications

Dr. Russ Brown has worked on temperature models of reservoirs and rivers for more than 25 years, beginning with his doctoral thesis from the Massachusetts Institute of Technology on reservoir temperature and water quality modeling in 1978. He worked at the Tennessee Valley Authority (TVA) Hydraulics Laboratory in Norris, Tennessee, on hourly water temperature data analysis and reservoir temperature simulation models for 6 years. He then taught hydrology and conducted research projects with graduate students at Tennessee Technological University in Cookeville, Tennessee. He developed a two-dimensional (2-D) reservoir water temperature and water quality model at TVA and used it on several TVA and U.S. Amy Corps of Engineers reservoirs. He came back to California in 1989 and has worked on a number of major water resources projects and evaluations. He developed a stream temperature model as part of the Mono Lake water rights proceedings for the State Water Resources Control Board (State Water Board) and has used the stream temperature model on several California streams, including the Merced River and the San Joaquin River. He has used the W2 model on Lake Almanor and San Luis Reservoir and has conducted many tidal hydraulic and salinity analyses in the Sacramento–San Joaquin River Delta. He has prepared a number of technical reports for the City of Stockton describing the tidal mixing and dilution of their treated wastewater effluent into the San Joaquin River. He has testified in State Water Board hearings on Mono Lake (1994), Delta Wetlands (1997), and Delta water quality standards (1994 and 1998). He has testified in Central Valley Regional Water Quality Control Board (CVRWQCB) hearings on the City of Stockton wastewater discharge permit (2002). A more complete description of his experience and publications is shown in his résumé.

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Dr. Brown’s hourly rate is $225 for this expert testimony work.

Millerton Lake Temperature Model Development

Millerton Lake Geometry and Outlets

Construction of Friant Dam began in 1937 and was completed in 1942 to form Millerton Lake. The Madera Canal, with a capacity of 1,000 cubic feet per second (cfs), began diversions in 1944. The larger Friant-Kern Canal, with a capacity of 4,000 cfs, began diversions in 1950.

The capacity of Millerton Lake is about 520 thousand acre-feet (taf) at the top of spillway gates at elevation 578 feet mean sea level (msl). The surface area is about 4,900 acres at the top of spillway gates. The storage is about 440 taf at the spillway crest elevation of 560 feet. The Kern Canal outlet is at elevation 464 feet. The minimum storage of Millerton Lake that allows some diversion into the Kern Canal is about 135 taf. The Madera Canal outlet is located at an elevation of 446 feet msl. The river outlets are located at an elevation of 380 feet, although the bottom of the river channel is about 310 feet msl. The "dead" storage below the river outlet is about 20 taf. The river outlet capacity is about 16,000 cfs, but the designated maximum flood control release is 8,000 cfs.

The Kern Canal outlet centerline (9-foot-diameter pipes) is at elevation 464 feet msl, with a 20-foot cut into the terrain upstream of the dam, suggesting that the majority of the outflow comes from slightly above the outlet. The Madera Canal outlet centerline (7.5-foot-diameter pipes) is located at elevation 446 feet, on the north bank of the dam, and the majority of the outflow must come from above the outlet. The majority of the releases from Millerton Lake are made through the two canal outlets. Only the river outlets draw water from below the canal outlet elevations. The normal minimum annual release from the river outlets to supply the hatchery (35 cfs) and irrigation along the river to Gravelly Ford is about 120 taf, with a maximum summer release flow of about 225 cfs.

Figure 1 shows the vertical distribution of reservoir area and volume for Millerton Lake behind Friant Dam. This geometry is closely approximated by two simple equations, because the volume is the "integral" of the area:

$$\text{Area (acres)} = 0.6 * (\text{Elevation} - 300) \wedge 1.6$$

$$\text{Volume (acre-feet)} = 0.6 / 2.6 * (\text{Elevation} - 300) \wedge 2.6$$

The reservoir is multi-purpose and provides both water supply storage and flood control storage. The flood control storage (space) is 170 taf during the winter rainfall season of October through March, reducing the maximum storage of Millerton to 350 taf during this period. Mammoth Pool reservoir, upstream on the San Joaquin River, can provide half of the flood control space (85 taf) if the storage space is available in Mammoth Pool, allowing the Millerton flood control maximum storage to increase by this amount to 435 taf. Large runoff events may, however, fill Mammoth Pool and require Millerton storage to be reduced to the minimum flood control storage of 350 taf. Millerton is allowed to reach maximum storage of 520 taf at the end of March. Canal diversions generally increase in April and May and are highest in June, July, and August.

Millerton Lake Operations for 2003 and 2004

Much can be learned about the operations of Millerton Lake from reviewing the historical operations of recent years. Figures 2 and 3 show the operations for 2003 and 2004, the two recent years with reservoir temperature profiles that will be used to calibrate the model (i.e., match the measured data). Both years had moderate inflows, below the median inflow of about 1,500 taf. Calendar year 2003 had an inflow of about 1,400 taf, and calendar year 2003 had an inflow of about 1,200 taf. Total canal diversions were 1,300 taf in 2003 and 965 taf in 2004, with river releases of about 120 taf in both years. There was just 1 week of spills in 2003, with a maximum release of 1,000 cfs. There were no river spills in 2004.

The initial storage in 2003 was about 300 taf, and the reservoir was filled to capacity of 520 taf on April 15. Canal diversions increased rapidly to about 3,500 cfs at the end of April to prevent spilling. In the first week of June 2003, canal diversions were more than 6,000 cfs, and the river spill was about 1,000 cfs for a few days. Canal diversions were about 4,500 in the remainder of June and July 2003 and declined to 2,500 cfs by the end of August and 1,250 cfs at the end of September. Reservoir storage was at about 200 taf at the end of September and filled slightly to 250 taf by the end of December.

Millerton storage in 2004 was 250 taf at the beginning of January and increased more slowly than in 2003, reaching a maximum storage of less than 500 taf in mid-May. Canal diversions were about 1,500 cfs in April and about 2,000 cfs in May of 2004. June and July diversions were about 3,500 cfs, and diversions declined to 1,500 cfs by the end of August and 1,000 cfs by the end of September 2004. The reservoir storage was about 200 taf at the end of August, but rose to about 325 taf by the end of December 2004.

These two years exhibit typical storage operations for years with moderate inflows. The reservoir was filled to maximum storage in April or May, and canal diversions increased in the summer months. All of the snowmelt inflow in May and June, as well as the water above 200 taf of storage, was released to the canals by the end of September. Canal flows are generally low in October–December and the reservoir is allowed to begin refilling. The months with greatest canal diversions to meet water supply demands are June–August, with about half of this maximum monthly amount required in May and September. Class I water (800 taf) is delivered in most years to water contractors (districts) without alternative sources of water. Class II water (1,400 taf) is delivered, when available in higher runoff years, to replace groundwater pumping or to recharge groundwater supplies.

Inflow Temperatures

Temperatures of inflow to Millerton Lake during the winter months of January–March produce the cool water pool (i.e., lower than 50°F) below the Kern Canal outlet at elevation 464 feet. Temperatures were recorded by the U.S. Geological Survey (USGS) below the Kerckhoff No. 1 hydroelectric plant from 1960 to 1974 and provide a good indication of the range of Millerton Lake inflow temperatures that can be expected. Variations are generally controlled by the seasonal meteorology and flow. Figure 4 shows these daily temperature records, along with the measurements made during 2004 by Reclamation. The 2004 measurements started in March. The spring and summer temperatures look similar to previous years, but the November and December 2004 data appear to be cooler and more variable than the earlier years of data (the temperature probe might have been exposed to air).

The minimum seasonal temperatures are generally 40–45°F in January and February. Inflow temperatures increase to 45–50°F by the end of March and are 50–55°F at the end of May. Inflow temperatures are a maximum of 65–70°F at the end of August and then decline to 60–65°F at the end of September, 55–60°F at the end of October, and 45–50°F at the end of December. Because the inflow temperatures fluctuate over this 5°F window, simulations of temperatures in future years should be made for the upper and lower seasonal temperature bounds. The inflow temperature during the months with high inflows (May and June) can have a substantial effect on the shape of the temperature profiles, but because the inflow temperatures are greater than 50°F, these inflows will enter the reservoir at an elevation above the 50°F cool-water storage level.

The shape of the temperature profile or thermocline (i.e., zone of vertical temperature gradient) can be modified by the inflow temperatures in May and June. The increasing canal diversions from the Kern Canal outlet at 465 feet and the Madera Canal outlet at 445 feet will have a more uniform effect on lowering the elevation of the thermocline without changing its shape. Examples of this difference between the effects of inflow and outflow on the temperature profiles will be shown for 2003 and 2004 simulations. Surface warming during the spring and summer will increase the surface temperatures and increase the thermocline gradient (i.e., temperature difference).

Friant Dam Outlet Temperatures

The river outlet temperatures are determined by the reservoir temperatures at the elevation of the river outlets, generally about 380–400 feet. The trashrack structure extends from elevation 350 feet to 465 feet, but the centerline of the penstock is at 380 feet msl. Under existing conditions, the normal release of water to the San Joaquin River for downstream water supply to Gravelly Ford is about 120 taf each year, with about 70 taf released in the May–September irrigation period. The measured river release temperatures remain about 50°F throughout the summer and fall. The summer release flow is just about equal to the reservoir volume between the river outlet elevation and the Madera Canal outlet elevation of 446 feet. Release temperatures measured by the California Department of Fish and Game (DFG) (minimum daily temperatures at North Fork Road Bridge) in 2003 are shown in Figure 5. The release temperatures were 50°F for the entire year. These release temperatures are similar to release temperatures measured by DFG in other recent years.

River release temperatures and temperatures in the Madera Canal (elevation 446 feet) and Kern Canal (elevation 464 feet) were measured by Reclamation in 2004 and are shown in Figure 6. River release temperatures were 46°F in mid-March when measurements began. River release temperatures slowly increased to 51°F at the end of November and then cooled to 49°F by the end of December. The Madera Canal temperatures were 47°F when diversions began in March 2004. The Madera temperatures increased to 60°F at the end of July and reached a peak of about 66°F in early September when diversions ceased. The Kern Canal temperatures were about 48°F when temperature measurements began in mid-March. Temperatures in the Kern Canal rose more quickly than the Madera Canal temperatures, because the outlet is about 20 feet higher. Kern Canal temperatures were 60°F in early July and reached a peak temperature of 71°F in

August. Kern temperatures cooled slightly to 68°F at the end of September and to about 65°F in mid-October when diversions ceased.

Measured Millerton Lake Temperature Profiles in 2003

Millerton Lake temperatures were measured weekly by FWUA in 2003 at three locations in the lake. The vertical profiles were collected at 3-foot intervals near the dam and at two upstream locations. The temperature profiles at these three locations were very similar. The dam profiles extend through the entire water depth and will be shown and described.

Figure 7 shows the measured temperature profiles collected for 2003, with separate panels for each quarter of the year. Data are shown every 2 weeks, although profiles were collected every week. The elevation is shown as depth below 600 feet (so the profiles could be plotted). The first panel of Figure 7 shows that on January 3, temperatures were 50°F at the bottom, and slightly warmer at 53°F in the mixed surface layer that extended about 100 feet to the thermocline at elevation 450 feet. The bottom temperatures were cooled to about 47°F by the middle of March by the cold inflows during the winter. Bottom temperatures remained cold throughout the year, warming only slightly to 49°F by the end of the year. Surface temperatures warmed to above 55°F by March 14 and continued to increase through the spring to a maximum of 75°F on June 16.

The second panel of Figure 7 shows that surface heating and thermocline were limited to the top 25–50 feet until mid-May. On May 5, temperatures below elevation 500 feet were less than 50°F. The canal diversions in combination with inflow temperatures in May caused the thermocline to descend to greater depths, and the warming above 50°F extended to elevation 450 feet on June 16.

The third panel of Figure 7 shows that on July 1, the surface mixed layer of 20 feet had a temperature of about 77°F, and a strong temperature gradient extended about 10 feet to about 59°F at elevation 490 feet. The temperatures then indicated a second thermocline with a reduced temperature gradient extending about 60 feet to 57°F at elevation 475 feet, with a stronger temperature gradient over 25 feet to 50°F at elevation 450 feet. These two thermoclines then merge into a single temperature gradient through the summer as the canal diversions from 445 feet and 465 feet pull more warm water down from the surface. By September 15, the temperatures at elevation 400 feet had increased to 50°F, and the temperatures at elevation 450 feet were about 65°F. Surface temperatures of 80°F were measured on several of the summer profile dates.

The fourth panel of Figure 7 shows that the surface temperatures remained above 70°F until November 15, and the surface mixed layer at a temperature of 55°F extended to a depth of 75 feet (to elevation 425 feet) on the last measurement date of December 15. These measured temperature profiles in Millerton Lake during 2003 provide a detailed picture of typical reservoir temperature patterns, including bottom cooling in the winter, surface warming and stratification (i.e., heated layers) in the spring, deepening of the thermocline in the summer, and surface cooling and mixing in the fall. These measured profiles provide a very good record for judging the success of the model calibration process.

Measured Millerton Lake Temperature Profiles in 2004

Millerton Lake temperature profiles were also collected during 2004. The frequency was reduced, but a good record of surface stratification and canal diversion effects was measured. The measured temperature profiles for 2004 are shown in Figure 8, with separate panels for each quarter of the year.

The first panel of Figure 8 shows that on January 9, temperatures were 49°F at the bottom and slightly warmer at 52°F in the mixed surface layer that extended about 90 feet to the thermocline at elevation 430 feet. The bottom temperatures were cooled to about 45°F by the end of February because of the cold inflows during January and February. Bottom temperatures remained cold throughout the year, warming only slightly to 46°F by the end of the year. Surface temperatures warmed to above 65°F by April 30, and were almost 75°F on June 4, 2004.

The second panel of Figure 8 indicates that surface heating and the thermocline were limited to the top 25–50 feet until the end of April. On April 30, temperatures below elevation 500 feet were less than 50°F. The canal diversions, in combination with inflow temperatures in May, caused the thermocline to descend to greater depths, and warming to more than 50°F extended to elevation 475 feet on June 4.

The third panel of Figure 8 shows that on July 2, the surface mixed layer of 20 feet had a temperature of about 76°F, and a strong temperature gradient to 62°F extended about 10 feet to elevation 500 feet. The measured temperatures then indicated a slightly reduced temperature gradient extending about 50 feet to 50°F at elevation 450 feet. The “double” thermocline that was observed in 2003 was not measured in 2004. The thermocline elevation slowly descended through the summer as the reservoir level declined and the canal diversions from 445 feet and 465 feet pulled more warm water down from the surface. Nevertheless, by August 6, temperatures were still 50°F at elevation 450 feet, between the Kern diversions at 465 feet and the Madera Canal diversions at 445 feet. Temperatures at the river outlet elevation of 380 feet were about 47°F through the summer. Because the release temperatures were 50°F, some of the release water was coming from elevation 400 feet or higher (as a result of withdrawal zone or trashrack structure effects).

The fourth panel of Figure 8 shows that by October 1, when the reservoir elevation was less than 500 feet, the surface temperatures were still about 70°F, and the surface mixed layer was about 40 feet deep. By November 15 the reservoir surface cooled to about 60°F, and by December 14 the surface temperatures had cooled to less than 55°F. Temperatures below elevation 400 feet remained at less than 50°F.

These measured temperature profiles of Millerton Lake in 2004, along with the release temperatures in the river outlet and the two canals, provide a second year of typical reservoir temperature patterns, including bottom cooling in the winter, surface warming and stratification (i.e., heated layers) in the spring, deepening of the thermocline in the summer, and surface cooling and mixing in the fall. These measured profiles from 2004 provide a second good record for judging the success of the model calibration process.

Calibration of the Millerton Lake Temperature Model for 2003

The W2 temperature model was calibrated to match both years of data with the same set of coefficient values. Appendix A describes the W2 model and the normal calibration procedures used to adjust the model coefficient values. Measured hourly meteorology from the Fresno CIMIS station was used for each year. Because Millerton Lake inflow temperatures were measured only beginning in March 2004, the inflow temperatures for all of 2003 and the winter of 2004 were estimated. The average inflow temperatures for each date measured for 1960–1974 were used as the starting estimate, and some periods were adjusted to match the bottom temperatures in the winter and the temperature profiles in the spring.

An unusual feature of Millerton Lake is the three separate outlet elevations—the river outlet at elevation 380 feet, the Madera Canal outlet at elevation 445 feet, and the Kern Canal outlet at elevation 465 feet. The W2 model blends the diversions (i.e., withdrawals) from the dam to give a single downstream mixed temperature. The Madera and Kern Canal were moved upstream to the second and third model segment so that the outflow temperatures from each separate outlet would be preserved in the model output.

Figure 9 shows the 2003 calibrated profiles obtained with the W2 model, after about 10 adjustment (calibration) simulations. Most of the calibration adjustments were made to the inflow temperatures. Some adjustments of the outlets and withdrawal zone limits were also tried. The wind speed was adjusted to 75% to better match the measured surface temperatures, which are sensitive to the evaporative cooling that increases with wind. The January 9 temperatures were used as the initial conditions for January 1. The measured temperature profiles from the end of each month are shown in Figure 9. The “old” simulation (dotted brown line) used the daily average of the inflow temperatures from 1960 to 1974. The calibrated model values (black solid line) used slightly reduced (2.5°F) inflow temperatures in April and May to adjust the inflow placement during these high inflow months. The measured temperatures are shown as small box symbols.

The simulated surface warming and mixing in the winter was slightly different from the measured profiles at the end of January and February. This is a difficult period to simulate accurately because the surface stratification and mixing depth are very dynamic and dependent on the local meteorological conditions that may not be reflected in the Fresno data. The temperatures below elevation 500 feet are well matched, with a bottom temperature of about 47°F. The simulated surface temperatures of 60–65°F and the thermocline depth were reasonably matched with the data at the end of March and April, although the simulated temperatures between 500 feet and 550 feet were 2–3°F cooler than the data.

Simulated temperatures at the end of May and June illustrate the sensitivity of the thermocline temperatures between elevation 400 feet and 500 feet to the inflow temperatures, and the resulting placement of the inflows into the reservoir profile during April and May. The observed profiles show a “double” thermocline at the end of June, with a very strong surface gradient. Temperatures were 60°F at elevation 550 feet, 75°F at elevation 560 feet and almost 80°F at the surface elevation of 575 feet. The second gradient was located between elevations 450 feet, where the temperature was 50°F, and 500 feet, where the temperature was about 57°F. The simulated temperatures were warmer than the data between elevation 400 feet and 475 feet, and cooler than the data between elevation 475 feet and 550 feet. The simulated 50°F temperature elevation of 410 feet was 40 feet below the measured 50°F temperature elevation of 450 feet. This mismatch developed during the month of June, and apparently is caused by the placement of the inflows in May and June. Without measured inflow temperatures, it is more difficult to adjust the inflow temperatures to match the measured profiles.

Surface temperatures were more than 80°F at the end of July and 77°F at the end of August. The double thermocline was almost merged into a single temperature gradient by the end of August. The 50°F elevation was lowered to about 440 feet at the end of July and 420 feet at the end of August. The simulated 50°F elevation also was reduced by a similar amount, but remained 40 feet too deep. The bottom temperatures were about 48°F by the end of August, but the simulated bottom temperatures warmed too fast, reaching 49°F at the end of August.

Surface temperatures were cooled slightly to 75°F at the end of September and were less than 70°F at the end of October, with a deepening surface mixed layer of about 40 feet, that was caused by the surface cooling and convective mixing (i.e., cool surface water is dense and tends to sink to the matched temperature in the profile). The measured 50°F temperature elevation was 400 feet, but the simulated 50°F elevation was 360 feet (still 40 feet too deep) at the end of October.

Surface cooling and deepening of the mixed surface layer continued into November and December. The measured bottom temperature was 48°F, but the simulated bottom temperature was 51°F on December 19. The warmer simulated temperature profile below elevation 450 feet that developed in June persisted and influenced the simulated bottom temperatures for the remainder of the year.

However, the general effects of the canal outlet diversions and river releases on the elevation of the thermocline during the summer were accurately simulated.

Figure 10 shows the simulated temperatures at several depths in Millerton Lake and the temperatures of the river release (380 feet elevation), the Madera Canal (445 feet elevation), and the Kern Canal (465 feet elevation). The simulated river temperatures match the measured minimum daily temperatures at the North Fork Road Bridge throughout the year. Although the simulated temperatures at elevation 380 feet were warmer than 50°F beginning in August, and were 2–3°F warmer than measured in November, the simulated river temperatures remained less than 1°F warmer than measured. The simulated withdrawal zone must extend below the elevation of the outlet. Temperature measurements were not made in the canals during 2003.

Calibration of the Millerton Lake Temperature Model for 2004

Inflow temperatures were available for 2004 beginning in mid-March. The calibration of the simulated 2004 temperature profiles in Millerton Lake generally involved some adjustment in the inflow temperatures to reproduce the inflow placement in May. The wind speed was reduced to 75% of the measured Fresno data to increase the surface temperatures. The outflow zone was limited to above the canal outlet elevation, because the canal outlets are at the bottom of the reservoir embankment at their respective outlet elevations.

Figure 11 shows the simulated temperature profiles in Millerton Lake for 2004. The initial temperature conditions on January 9 were 52°F from the surface at elevation 520 feet to the bottom of the surface mixed layer at elevation 440 feet. The 50°F temperature was at elevation 400 feet, and the bottom temperature was 49°F below elevation 350 feet. There were apparently relatively cool inflow temperatures in January and February because on February 27 the bottom temperature was 46°F and the 50°F temperature was at elevation 500 feet. On April 14 the surface temperatures were 64°F and the 50°F temperature was at elevation 500 feet. The simulated temperature profile matched the measured data very well, with a cooler surface temperature of 61°F.

On April 30, the simulated double thermocline between elevation 450 feet and 500 feet was about 3°F too warm. Because canal diversions were relatively small in April, this appears to be the result of slightly too much inflow of about 50°F in April. The measured 50°F elevation was still at 500 feet, but the simulated 50°F elevation was at 475. Simulated bottom temperatures below 425 feet elevation matched the measured data well. On June 4, the surface temperatures were approaching 75°F, and the simulated temperatures in the double thermocline were 1–2°F warmer than measured temperatures between elevation 425 feet and 500 feet.

On June 21, the surface temperatures were above 75°F and the gradual drawdown of the thermocline by the canal diversions at elevation 465 and

445 feet dominated the measured and simulated profiles. The simulated profile was warmer than the measured temperatures between the 425 feet and 475 feet elevations. By July 14, the measured thermocline, with almost 80°F from the surface at 525 feet to the 500 feet elevation and 50°F at elevation 450 feet, was closely matched by the simulated temperatures. Simulated bottom temperature remained at 47°F below elevation 350 feet.

On August 6, the surface temperature was about 80°F and the 50°F temperature was at elevation 425 feet, a drop of about 25 feet during the 45 days since the June 21 profile. On October 1, the surface temperature was reduced to about 70°F, and the 50°F temperature was at elevation 400 feet, indicating a drop of another 25 feet since August 6. Simulated bottom temperature was about 48°F. Both of these temperature profiles were matched by the simulated temperature profiles to within 1°F.

On November 16, surface cooling reduced the temperature to 60°F, and the mixed layer extended 60 feet to 450 feet elevation. The 50°F temperature was simulated at 375 feet elevation with a bottom temperature of 48°F below elevation 375 feet. On December 14, surface temperatures had cooled to 54°F, with a mixed layer depth of 80 feet to elevation 460 feet. The measured 50°F temperature was at elevation 400 feet, although the simulated bottom temperatures were warmer and the simulated 50°F temperature was at elevation 375 feet. Bottom temperatures below the river outlet (i.e., below elevation 375 feet) were very constant throughout the year, increasing only 2°F.

Figure 12 shows the daily measurements of temperatures from various depths in Millerton Lake, collected by Reclamation with a string of floating sensors. Data from deeper sensors began in mid-March, with temperatures of 49°F at depths of 60 feet, 75 feet, and 90 feet. Data from the surface sensors began in mid-July, with temperatures of about 80°F. The simulated surface temperatures match well through the summer and fall, with a major cooling event in mid-September when the surface temperatures dropped from 75°F to 70°F in just a few days. The measured 30 feet temperatures were much closer to the surface temperatures than the simulated values and do not agree with the profile measurements. The deeper temperature measurements were also much warmer than the corresponding simulated values. The deeper sensors indicated a cooling of temperatures between July and October; this cooling resulted from the surface elevation declining over this period. Overall, these floating sensors should have given a very good picture of the temperature patterns within the reservoir, but they appear to be recording temperatures from depths that are not as deep as intended. Perhaps the line was tangled or angled, so that the sensors were not measuring as deep as expected.

The bottom of Figure 12 shows the simulated outlet temperatures for 2004 compared with the measurements made in the river and the two canals, beginning in mid-March. The measured river outlet temperatures slowly warmed from about 47°F in mid-March to 51°F at the end of November. These measurements were well matched by the simulated outflow temperatures. The Madera and Kern Canal temperatures began at 48°F in mid-March and increased during the spring and summer as surface warming increased reservoir temperatures and the canal and river outflows lowered the thermocline elevation. The Madera Canal temperatures (outlet at 445 feet elevation) increased to 60°F at the end of July and 65°F at the end of August. The Kern Canal temperatures increased to 60°F in early July and reached 70°F in early August. The Kern Canal temperatures remained about 70°F through September and then decreased to 65°F in late October when the canal diversions ceased. The model simulations of these outlet temperatures were generally very close (within 1°F) to the measured temperatures.

Overall, the simulated 2004 temperatures in Millerton Lake for the historical river releases and canal diversions and reservoir surface elevations were quite close to the measured temperature profiles, available on a monthly interval. The 2003 and 2004 temperature profile data provides a solid basis for testing of the ability of the W2 temperature model to reproduce the basic temperature patterns in Millerton Lake, including winter inflow placement and cooling, surface heating and stratification, the drawdown of the thermocline by the canal outflows during the summer, and the surface cooling and convective mixing of the surface layer in the fall. The W2 model was able to reproduce the measured temperature patterns for 2003 and 2004 conditions and, therefore, provides a reliable tool for evaluating the potential temperature effects from changes in Millerton Lake operations to provide additional river releases.

Uncertainties in the W2 Temperature Model of Millerton Lake

The simulations of Millerton Lake temperatures with the W2 model indicate that there were some minor discrepancies in the calculations used in the model to simulate 2003 and 2004 historical temperatures. A relatively minor discrepancy was the match with surface temperatures. The hourly measured surface temperatures in 2004 provide an excellent record of surface temperature fluctuations. Some of the variations in wind speed and air temperatures at Millerton Lake may not be captured in the Fresno data that were used for these simulations. The most sensitive model parameter for adjusting the surface temperatures is the wind-sheltering coefficient, which reduces the wind speed value. The Millerton Lake calibration reduced the wind speed to 75% of the measured Fresno values. Figure 12 indicates that a very close match with surface temperatures was obtained once this calibration adjustment was made.

A second source of minor uncertainty was the inflow temperatures. The placement of the inflow in the reservoir is dependent on the matched density (i.e., equal temperature). However, the W2 model assumes inflow mixing will increase just the temperature of the inflow as it moves down the reservoir segments. A relatively cool inflow temperature (of 41–42°F) was used from January to mid-March 2004 to place the water at the bottom of the reservoir and reduce the bottom temperatures to the measured 46°F below elevation 400 feet. The effective inflow temperatures were warmed by several degrees Fahrenheit by the model, and placement tended to be higher than the matched profile temperature. This effect was the likely cause of the moderate discrepancy in the simulated and measured profiles (double thermocline) in May and June 2003. The adjusted inflow temperatures provided a good match with the measured bottom temperatures in March of 2003 and 2004, and provided a fair match with the temperature profiles in April and May of 2003 and 2004.

A third minor discrepancy was that the simulated warming of the bottom temperatures remained slightly greater than measured. The measured 2003 data suggest that the bottom temperatures warmed by only 1°F (47°F to 48°F) during the entire year, while the simulated temperatures warmed by 4°F (47°F to 51°F). The measured 2004 data indicate that the bottom temperatures warmed about 2°F (46°F to 48°F), while the W2 model bottom temperatures warmed from 45°F to 49°F. The W2 model includes a bottom heat transfer term that is dependent on a heat exchange coefficient and the estimated average “soil” temperature. This warming term in the W2 model should be reduced to better match the measured warming of the Millerton Lake bottom temperatures.

A fourth small discrepancy between the W2 model and the observed temperatures involves the simulated withdrawal zone for each outlet. The W2 model uses an equation to distribute the outflow over a range of layers. For example, the river outlet at elevation 380 feet is simulated to draw water from a relatively wide range of elevations during the summer. In particular, the model apparently takes some water from below the outlet elevation. This contributes to the simulated warming of water located below the river outlet. In contrast, the measured temperature profiles in 2003 indicate less warming below the elevation of the river outlet. However, the measured temperatures below elevation 400 feet were very well matched by the simulated temperatures in 2004. The river outlet temperatures were well matched in both years, so the discrepancy in the calculated withdrawal zone is relatively small.

The uncertainties that have been identified in the surface temperatures, inflow placement, bottom warming, and withdrawal zone distributions produced relatively minor discrepancies that did not influence the general temperature profile patterns in Millerton Lake. The calibration of the W2 model simulations with the measured temperature profiles, measured outlet temperatures, and measured surface temperatures provides a reliable tool for evaluating the effects of river restoration outflows on Millerton Lake temperatures and river outflow temperatures.

Simulation of Millerton Lake Temperatures with Increased River Releases for Restoration

Because of the good calibration results, the W2 model of Millerton Lake temperatures can be used with confidence to simulate the temperature effects from increased river releases and reduced reservoir storage conditions (lower surface elevations). The potential river flows, identified by Chuck Hanson for the FWUA to support restoration of spring-run Chinook salmon along the San

Joaquin River below Friant Dam, were used to evaluate the effects on Millerton Lake water temperatures.

Figure 13 shows the restoration flows, for a “normal–dry” year type (i.e., 20% to 50% cumulative natural inflow, 950 taf to 1,500 taf runoff). The daily minimum release flow is about 500 cfs (490 cfs) year-round, with a steady increase in flows during February, March, and April to a maximum of about 3,000 cfs at the end of April. Recommended flows decrease to the base flow of 500 cfs by mid-May. These suggested river release flows require a total volume of about 675 taf, an increase of 550 taf from the current releases of 125 taf for downstream water supply. The base flow of 500 cfs requires about 30 taf of water each month, and the ramping flows in February–May require an additional 315 taf.

For 2003 the initial reservoir storage was assumed to be 250 taf, about 50 taf less than the historical storage, based on monthly operational modeling by Daniel Steiner, based on the USAN model. The larger river flows in February–May, during the period when the reservoir historically fills to capacity in most years, reduce the reservoir storage substantially. In 2003, the simulated restoration flows reduce the reservoir storage to a maximum of 350 taf at the end of February, and storage is reduced to a minimum of 200 taf at the end of May. This reduction in storage will greatly reduce the available cool-water storage (i.e., water with a temperature of less than 50°F). The historical canal diversions of 1,300 taf were reduced to just 700 taf (55%) in 2003 to allow the increased river releases of 675 taf.

Figure 14 shows the similar changes in reservoir operations for 2004. The initial storage was about 250 taf (same as historical), but the maximum storage was just 300 taf at the end of March, and was reduced to 225 taf at the end of May. This is nearly 275 taf less than the historical maximum storage of almost 500 taf in mid-May. The reduced storage will likely reduce the available cool-water storage in 2004. The historical canal diversions of 965 taf were reduced to 430 taf (45%) to allow the river releases to increase from 120 taf to 675 taf in 2004.

Simulated Millerton Lake Temperature Profiles with Increased River Releases for 2003

Figure 15 shows simulated temperature profiles for these potential spring-run Chinook salmon river restoration outflows from Millerton Lake in 2003. The changes from the historical simulated temperatures are emphasized, because these modeled incremental temperature changes are assumed to be caused by the changed operations that are necessary to release more water to the river. The differences between the simulated historical conditions and the measured temperature data indicate the calibration of the model.

The January temperatures were similar to the historical simulation, although the initial elevation was lower and the river releases were about 500 cfs rather than 100 cfs. On March 28, because of the high river releases in February and March, the reservoir surface elevation was 40 feet lower and the thermocline was located 40 feet below the historical conditions. Bottom temperatures below 350 feet elevation were the same, but temperatures at 400 feet (river outlet is at elevation 380 feet) were about 1°F warmer than the historical simulation. On April 25, the reservoir surface was 60 feet lower than historically because of the very high releases in April. Simulated bottom temperatures were 1°F warmer and temperatures at 400 feet were 2°F warmer than the historical simulation.

On May 30 the reservoir elevation was 60 feet lower than historical conditions and the surface thermocline was very strong, with 75°F at the surface elevation of 500 feet, and 55°F just 10 feet deep. The temperatures between 475 feet and 375 feet were about 2–3°F warmer than historical conditions, so the outlet temperatures were higher. On June 27 the reservoir was 40 feet lower than historically, and the temperatures between elevation 500 feet and 350 feet were about 2°F warmer than the historical simulation (the historical data were 1–3°F cooler than simulated on this date).

On July 25 the reservoir elevation was 40 feet lower than historically, and bottom temperatures were 50°F, about 2°F warmer than historical simulations. The temperatures at 475 feet were 5°F warmer, and the temperatures below 450 feet were about 2°F warmer than historical simulations. On August 29 the simulated reservoir elevation was about the same as historically because of reduced canal diversions necessary to compensate for the increased river releases. Temperatures near the surface (top 50 feet) were similar to the historical temperatures, but temperatures below elevation 460 feet were 2–4°F warmer than the historical simulation.

On September 26, temperatures in the top 50 feet were similar to historical temperatures, but temperatures at 400 feet were 6°F warmer and temperatures at 350 feet were 2°F warmer than the historical simulation. A similar pattern was simulated on October 24, with temperatures of 62°F at 400 feet (just above the river outlet), about 8°F warmer than the historical simulation.

On November 18 and December 19, the simulated surface temperatures remained 2–3°F warmer than the historical simulation because the deeper temperatures were warmer and required more days of cooling to reduce the temperature of the mixed layer. Bottom temperatures remained 2°F warmer than historically throughout the cooling period, so there was still a 6°F gradient between the surface mixed layer and the bottom on December 19.

Figure 16 shows the simulated surface elevation for the spring-run Chinook salmon restoration river outflows for 2003. The minimum elevation in May was 500 feet, just 35 feet above the Kern Canal outlet. The simulated outlet temperatures are shown at the bottom of Figure 16. The Kern Canal temperatures began at 55°F in May, about 5°F warmer than historically and continued warmer until September, when the maximum temperature of 70°F was simulated. The Madera Canal temperatures were warmer than historical temperatures and remained about 5°F cooler than the Kern Canal. The maximum temperature of 65°F was reached at the end of August, 1 month earlier than historically. Both canal diversions ceased at the end of September in the river restoration simulation, in order to maintain the higher than historical outflows of 500 cfs.

The simulated river release temperature was about 50°F in April and May during the high river release flows, about 1°F warmer than historically. The river release temperatures then increased much more than historically in the summer months, reaching 54°F at the end of August, 57°F at the end of September, 60°F at the end of October, and a maximum of 61°F in mid-November (9°F warmer than historical temperatures). The additional river releases in the months of June through October were about 80 taf. Because the river releases reduce the elevation of the reservoir, warmer surface water was located closer to the river outlet elevation at the beginning of the summer. The additional summer river releases of 80 taf, in addition to the normal summer releases of 70 taf, required all the water between elevation 380 feet (20 taf storage) and elevation 475 feet (150 taf storage). Although there is not a large temperature difference between these two elevations in the historical May 30 profile, the effects of the greater drawdown of water to the river outlet increases the outlet temperatures by almost 10°F at the end of October.

Simulated Millerton Lake Temperature Profiles with Increased River Releases for 2004

Figure 17 shows simulated temperature profiles for the potential spring-run Chinook salmon river restoration outflow from Millerton Lake in 2004. The changes from the simulated historical temperatures are emphasized, because these modeled incremental temperature changes are assumed to be caused by the operational changes that were necessary to release more water to the river. The differences between the simulated historical conditions and the measured temperature data indicate the calibration of the model.

The January and February temperatures were similar to the historical conditions, although the river releases were about 500 cfs rather than 100 cfs. On April 30, because of the high river releases in February–April, the reservoir surface elevation was 60 feet lower and the thermocline was located 60 feet below the historical conditions. Simulated temperatures at 450 feet were 54°F, 5°F warmer than the historical simulation; temperatures at 400 feet were 52°F, about 5°F warmer than the historical simulation; and temperatures at 350 feet were 49°F, 3°F warmer than the historical simulation. Because the river outlet is at elevation 380 feet, this warming was not likely caused directly by the higher river releases. It is likely that the inflow temperatures of less than 50°F in April were placed much deeper in the reservoir than under historical conditions and warmed these bottom layers of the reservoir.

On June 4 the reservoir elevation was 50 feet lower than historically, with 73°F at the surface elevation of 500 feet, and 55°F at elevation 450 feet. The temperatures below elevation 450 feet were 3–7°F warmer than the historical simulations, so the outlet temperatures would likely be correspondingly higher.

On July 2 the reservoir elevation was 30 feet lower than historical conditions, and bottom temperatures were 50°F, about 3°F warmer than the historical simulation. The temperatures at 475 feet were 7°F warmer, and the temperatures below 450 feet elevation were 4–7°F warmer than the historical simulation. On August 6 the simulated reservoir elevation was about the same as historically because of reduced canal diversions necessary to compensate for the increased river releases. Temperatures near the surface were 80°F and the top 50 feet (to elevation 450 feet) were similar to the historical simulation, but temperatures below elevation 450 feet were 5–7°F warmer than the historical simulation. Simulated bottom temperatures were 51°F.

On October 1 the simulated reservoir elevation was 10 feet higher than historically, and temperatures in the top 40 feet (to elevation 450 feet) were similar to the historical simulated temperatures. Simulated temperatures at 400 feet elevation were 60°F, about 10°F warmer than the historical simulation. On November 16, the simulated surface temperatures remained 2°F warmer than the historical simulation because the deeper temperatures were warmer and required more days of cooling to reduce the temperature of the surface mixed layer. Bottom temperatures were 53°F, about 4°F warmer than the historical simulation.

Figure 18 shows the simulated surface elevation for the spring-run Chinook salmon restoration river outflows for 2004. The minimum elevation in August was 500 feet, just 35 feet above the Kern Canal outlet. The simulated outlet temperatures are shown at the bottom of Figure 18. The Kern Canal temperatures began at 50°F in May, about 3°F warmer than historically. The Kern Canal temperatures warmed rapidly in April because the thermocline and reservoir surface elevation were lowered 25 feet as a result of the high river releases. The Kern Canal temperatures were warmer than historical temperatures until the beginning of August, when the maximum temperature of about 70°F was simulated. The simulated Kern Canal temperatures were slightly cooler in August and September because the reservoir surface elevation was higher. The Madera Canal temperatures were warmer than historically and remained about 5°F cooler than the Kern Canal. The maximum temperature of 67°F was reached at the beginning of September, the same as historical simulation, when the Madera Canal diversions ceased. The Kern Canal diversions cease at the end of September in the river restoration simulation in order to maintain the higher-than-historical outflows of 500 cfs.

The simulated river release temperature was about 52°F at the end of April, about 6°F warmer than the historical simulation, because of the higher river releases and placement of inflow temperatures into the bottom layers of the reservoir. The river outlet temperature then increased during the summer, reaching 55°F at the end of August, and then increased more rapidly, reaching a maximum of 61°F at the end of October (11°F warmer than the historical simulation). The river outlet temperature then decreased in November and December as surface cooling and mixing reached the river outlet at 380 feet elevation.

Simulated Millerton Lake Temperature Profiles with Minimum Canal Diversions and Increased River Releases for 2003

The previous simulations of the increased San Joaquin River restoration flows assumed that no Madera Canal or Kern Canal diversions would be made prior to May 1 or after August 31. However, there are required deliveries to some crops and orchards that must be maintained. The result of some canal diversions in January to April, and increased releases for river restoration flows, will be reduced reservoir storage and much less filling of Millerton Lake in the spring months. The temperatures in Millerton Lake and the release temperatures will likely be slightly higher than simulated for the river restoration releases alone.

Figure 19 shows the simulated surface elevations compared with the historical elevations for 2003. The initial storage of 217 taf (500 feet) is based on monthly modeling by Daniel Steiner that included the river restoration releases but maintained a fraction of the historical monthly diversions, while holding Millerton storage above the 135 taf minimum required for Kern Canal diversions. The historical canal diversions in January–April of 2003 were about 150 taf, and the simulated canal diversions in these months were about 50 taf. Nevertheless, the reservoir storage was at the minimum 135 taf at the beginning of May (elevation 470 feet) with just barely enough water to allow Kern Canal diversions. The simulated elevations increased during the high runoff of May and June, reaching a maximum simulated elevation of about 530 feet on July 1.

The bottom of Figure 19 shows the simulated outlet temperatures for 2003. The Kern Canal temperatures increased from 50°F in March to higher than 60°F in late April and early May, because the canal outlet was in the surface layer as the reservoir elevation declined to below 500 feet. The Kern Canal temperatures were about 5°F warmer than historically until September, when the maximum temperature of 70°F was simulated. The simulated temperatures in September were similar to historical temperatures because the simulated elevations were about the same as historically in this period. The Madera Canal temperatures were also warmer than historically and remained about 5°F cooler than the Kern Canal. The maximum temperature of 67°F (2°F warmer than historical temperatures) was reached in the middle of October.

The simulated river release temperatures were about 50°F in April and May during the high river release flows. The river release temperatures then increased much more than historically in the summer months, reaching 54°F at the end of August, 57°F at the end of September, and 60°F at the end of October and remained 60°F until mid-November (8°F warmer than historical temperatures). Because the increased river releases and the minimum canal diversions reduced the elevation of the reservoir, warmer surface water was located closer to the river outlet elevation at the beginning of the summer. Although the reservoir elevation remained lower for this simulation than the previous 2003 river restoration flows without any canal diversions in January–April, this simulation of river release temperatures remained 1°F cooler in November.

Figure 20 shows the simulated temperature profiles for the 2003 conditions with high river restoration flows and minimum canal diversions in the January–April period. The lower reservoir elevations apparently produced less inflow mixing, and slightly cooler inflow temperatures were simulated to fill the bottom of the reservoir, below elevation 400 feet. These slightly cooler bottom temperatures persisted to the end of the year, and the river release temperatures were about 1°F cooler than the previous simulation of increased river releases without minimum canal diversion (See Figure 15). Nevertheless, the river releases were much warmer than the historical conditions. The river release temperatures during the spring-run Chinook salmon spawning period of October and November were 56–60°F, and were 6–8°F warmer than the historical release temperature simulations in these months. Both simulations of river restoration flows resulted in similar warming of the river release temperatures to a maximum of about 60°F in November 2003.

Simulated Millerton Lake Temperature Profiles with Minimum Canal Diversions and Increased River Releases for 2004

Figure 21 shows the simulated surface elevations compared with the historical elevations for 2004. The initial storage of 192 taf (490 feet) is based on monthly modeling by Daniel Steiner that included the river restoration releases but maintained a fraction of the historical monthly diversions, while holding Millerton storage above the 135 taf minimum required for Kern Canal diversions. The historical canal diversions in January–April of 2004 were about 180 taf, and the simulated canal diversions in these months were about 60 taf. Nevertheless, the reservoir elevation remained at about 500 feet through March and declined to a minimum of about 480 feet at the beginning of May. The simulated elevations remained between 480 feet and 500 feet through October and then increased to 525 feet by the end of the year. Simulated elevations were similar to historical elevations in September and October, at a minimum of 480 feet.

The bottom of Figure 21 shows the simulated outlet temperatures. The Kern Canal temperatures increased from 50°F in March to higher than 60°F in May and June because the canal outlet was in the surface layer as the reservoir elevation declined to below 500 feet. The Kern Canal temperatures were warmer than historically until September, when the maximum temperature of 74°F was simulated. The simulated temperatures in September were similar to historical temperatures because the simulated elevations were about the same as historically. The Madera Canal temperatures were warmer than historical temperatures and remained about 5°F cooler than the Kern Canal. The maximum temperature of 69°F (2°F warmer than historical temperatures) was reached at the beginning of September.

The simulated river release temperatures increased from 46°F to 52°F in April and remained at about 53°F in May. The river release temperatures then increased at about the same rate as historically in the summer months, reaching

57°F at the end of August, and 59°F at the end of September, but then increased rapidly at the end of September and reached a maximum of 64°F in mid-October. The release temperatures then declined with surface cooling and mixing, decreasing to 61°F at the end of October, and 55°F at the end of November. Because the river releases and the minimum canal diversions reduced the elevation of the reservoir, warmer surface water was located closer to the river outlet elevation at the beginning of the summer. The simulated reservoir elevations remained 15–25 feet lower for this simulation than the previous simulation of river restoration flows without any canal diversions in January–April, and this simulation resulted in a maximum release temperature of 64°F, 3°F warmer than the previous simulation and 13°F warmer than the historical maximum of 51°F at the end of November.

Figure 22 shows the simulated temperature profiles for the 2004 conditions with high river restoration flows and minimum canal diversions in the January–April period. The simulated temperatures below elevation 450 feet were generally 1–2°F warmer than the previous simulation of increased river releases without minimum canal diversions (See Figure 17) and were much warmer than the historical temperature simulation. Both simulations of river restoration flows resulted in similar warming of the river release temperatures, to higher than 60°F in October 2004.

Summary of Changes in Millerton Lake Temperature Profiles with Increased Releases for River Restoration

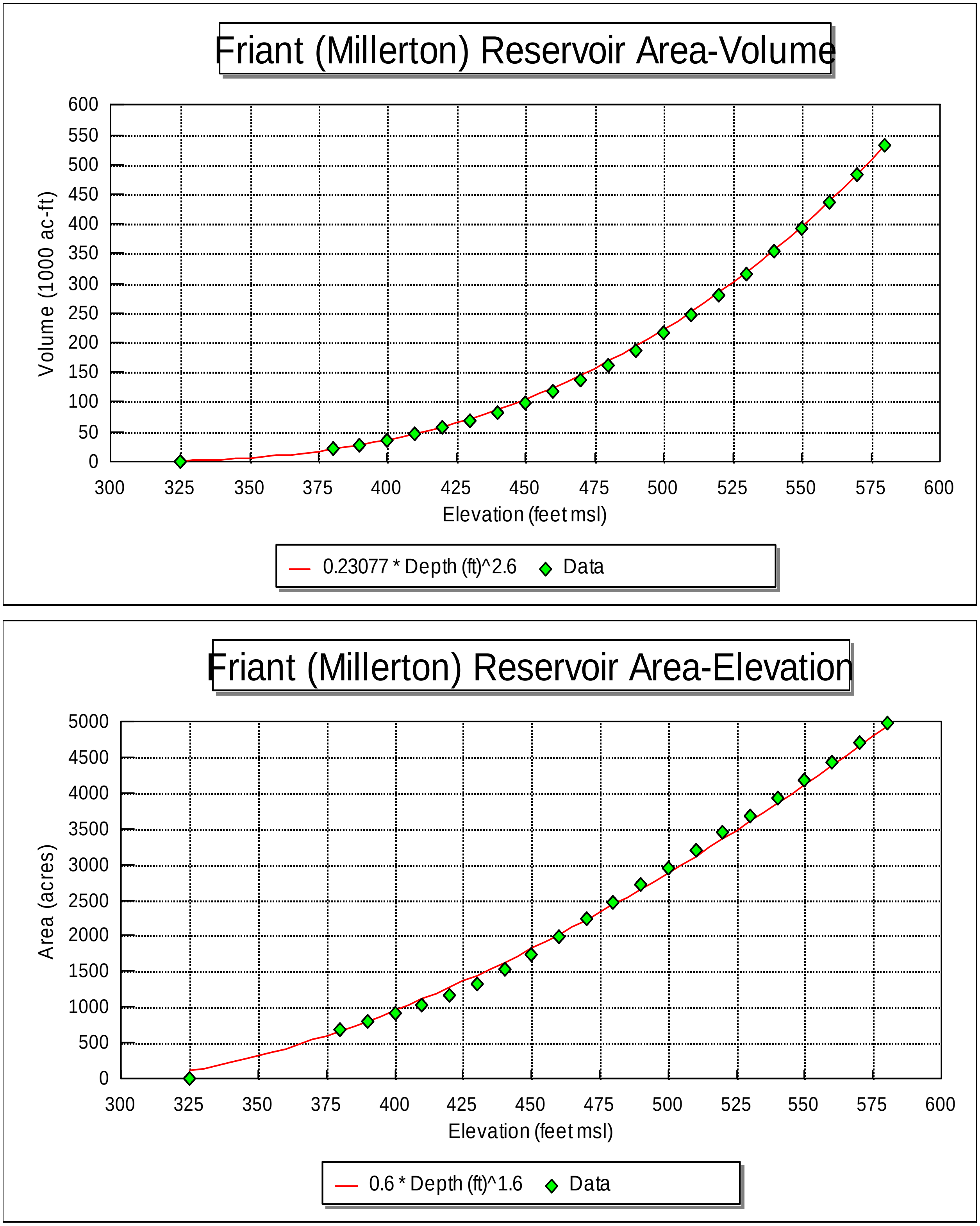
Because the river restoration flows are higher during the spring months of March–May when the reservoir fills to maximum storage levels, the simulated surface elevations for 2003 and 2004 were about 50–60 feet lower on April 30 and May 30. This caused the warm surface water and thermocline to be located about 50–60 feet lower in elevation and much closer to the canal outlets at 465 feet and 445 feet elevation. The higher release flows also caused the thermocline to be drawn lower into the reservoir than with the historical river releases. The spring inflows, with temperatures of 50–55°F in the April and May period, were placed deeper in the reservoir and caused the water near the river outlet elevation (380 feet) to be warmer than historical conditions. Each canal diversion was about 5°F warmer than historically in the spring and summer months. The higher river release during the spring and summer pulled down more water from below the Madera Canal elevation of 445 feet toward the river outlet elevation of 380 feet. The river outlet temperatures became progressively warmer than historically during the summer, with a maximum river release temperature of more than 60°F simulated for both 2003 and 2004 by the end of October. Because the lake profile temperatures were warmer, the fall cooling and mixing was delayed by a few days compared to the historical conditions. Because of the good calibration of the W2 model with measured 2003 and 2004 temperature profiles, these results are reliable and indicate the likely effects of increased river releases from Millerton Lake.

Dated August 22, 2005 ____________________________________

Russell T. Brown

Reference

Cole, T., and S. Wells. 2003. *CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model*. Version 3.2. Draft report. Instruction report EL-03-1. Prepared for U.S. Army Corps of Engineers, Washington, DC. Available: <http://www.cee.pdx.edu/w2>.



Note: Surface area and volume as a function of elevation (feet). Bottom of reservoir is at about 300 feet. Volume is the mathematical integral of area.

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Figure 1

Millerton Lake Geometry

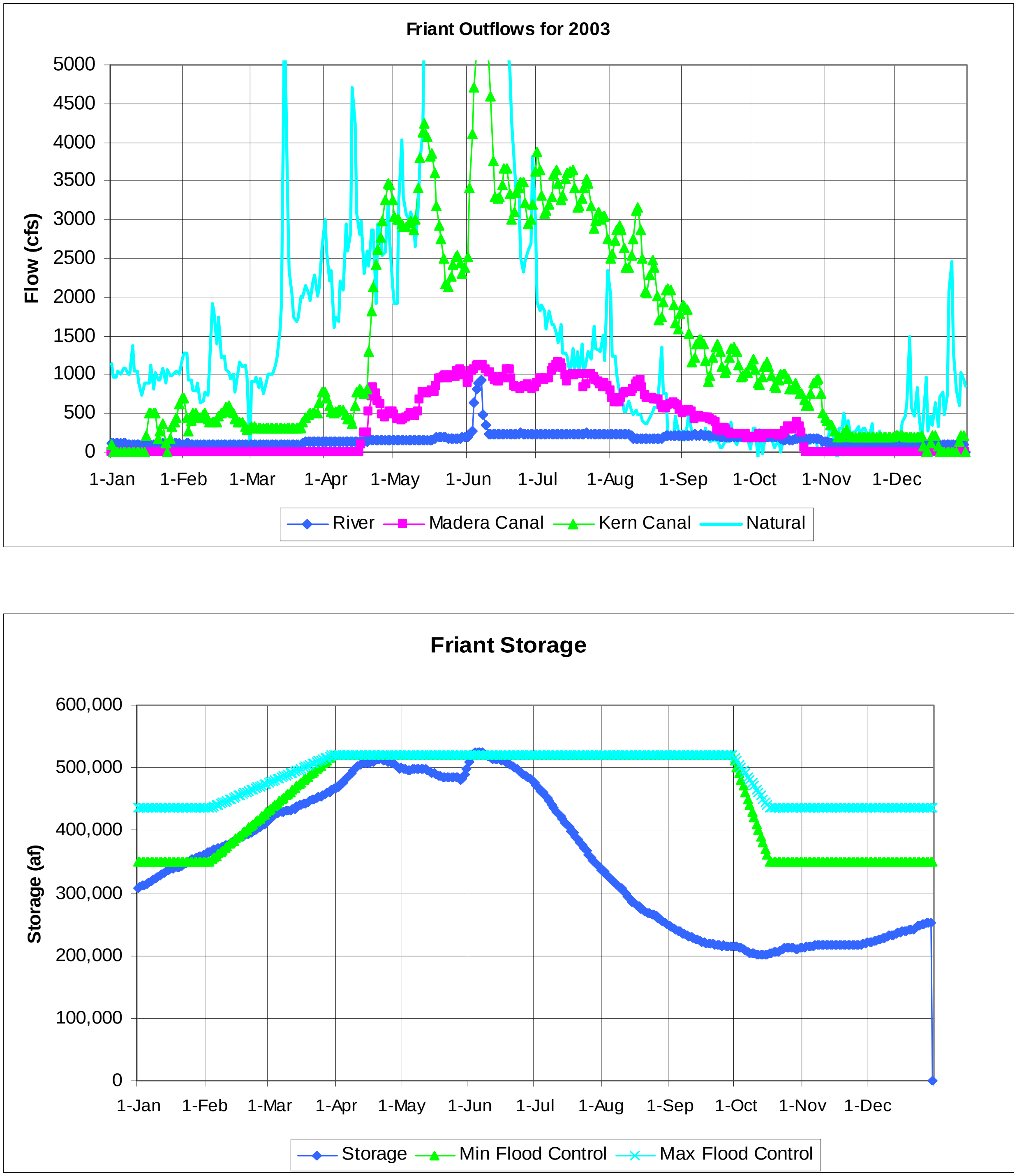

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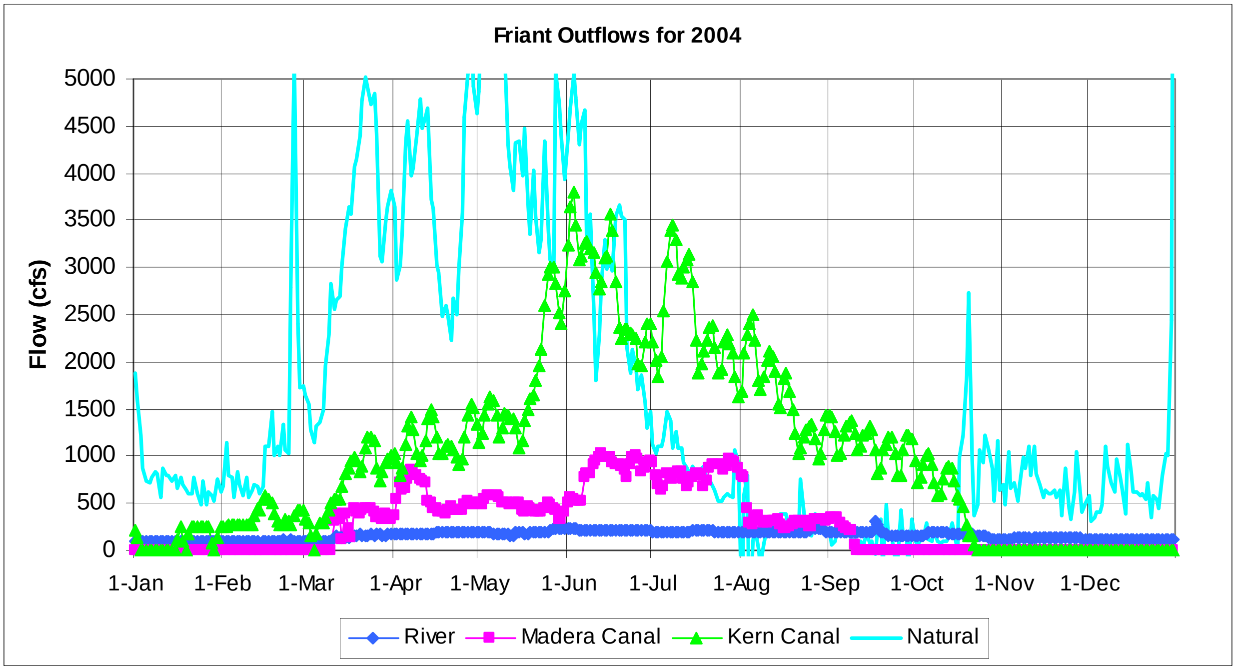
Figure 2

Historical Operations of Millerton Lake for 2003



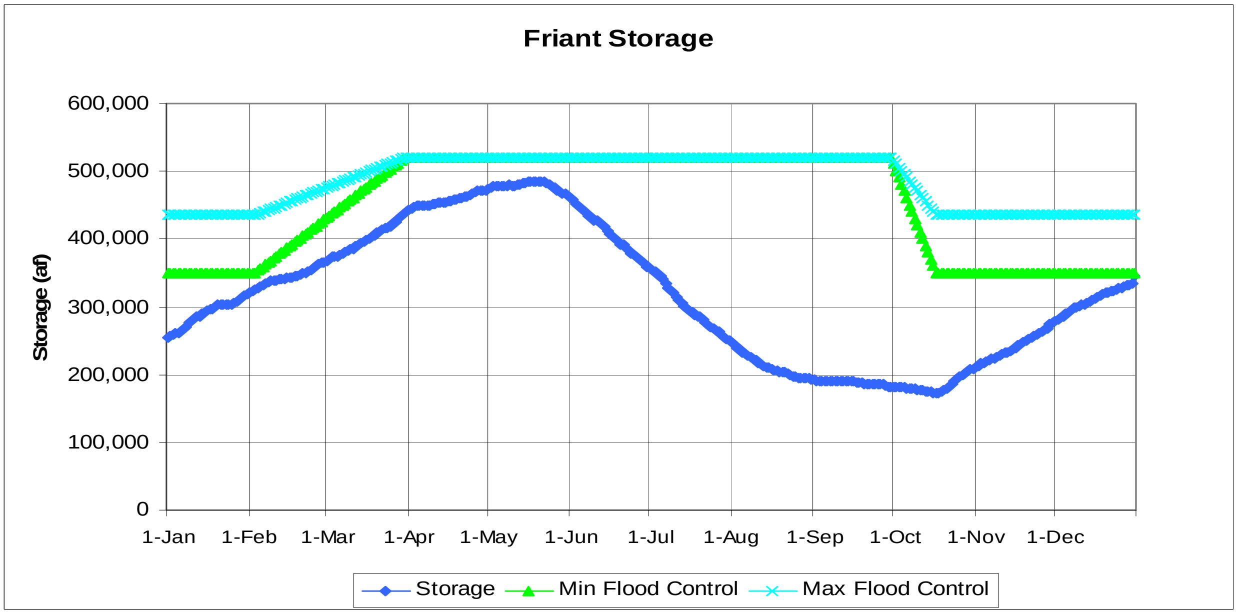


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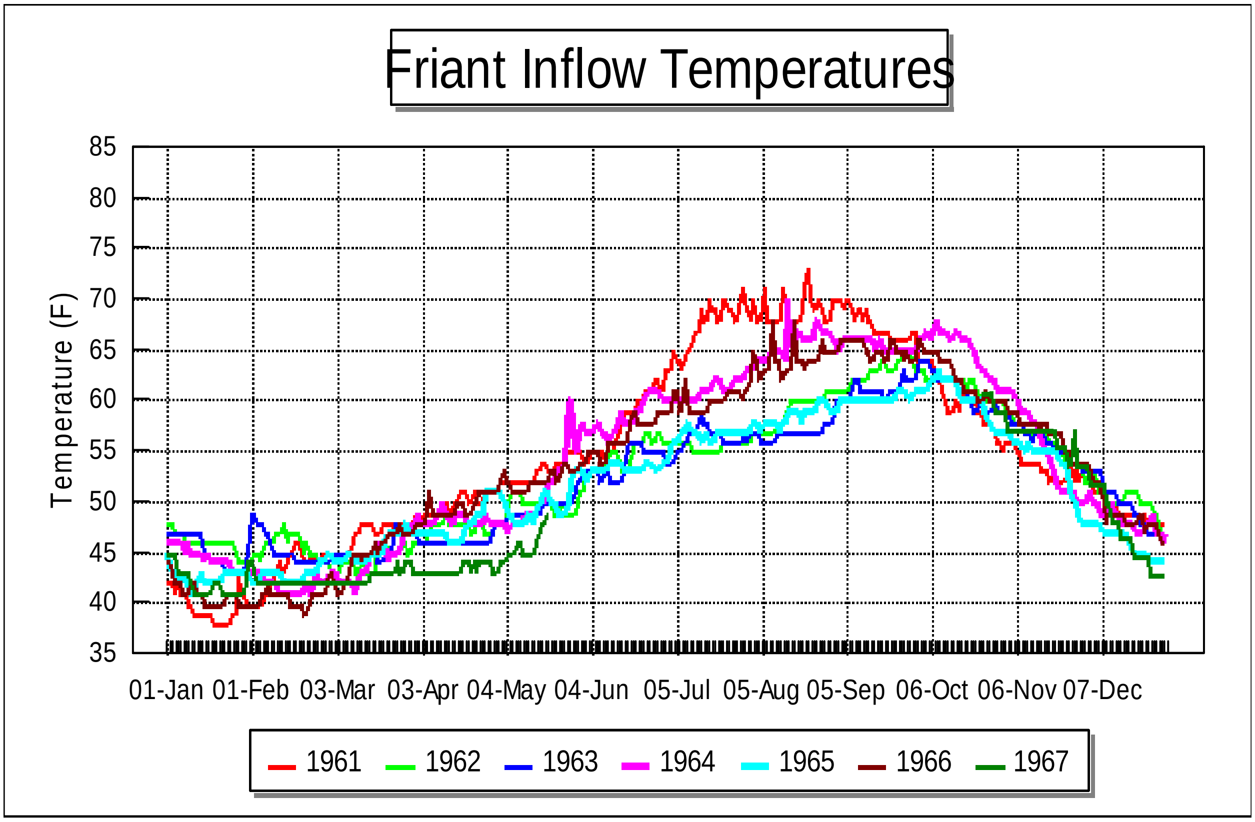
Figure 3

Historical Operations of Millerton Lake for 2004



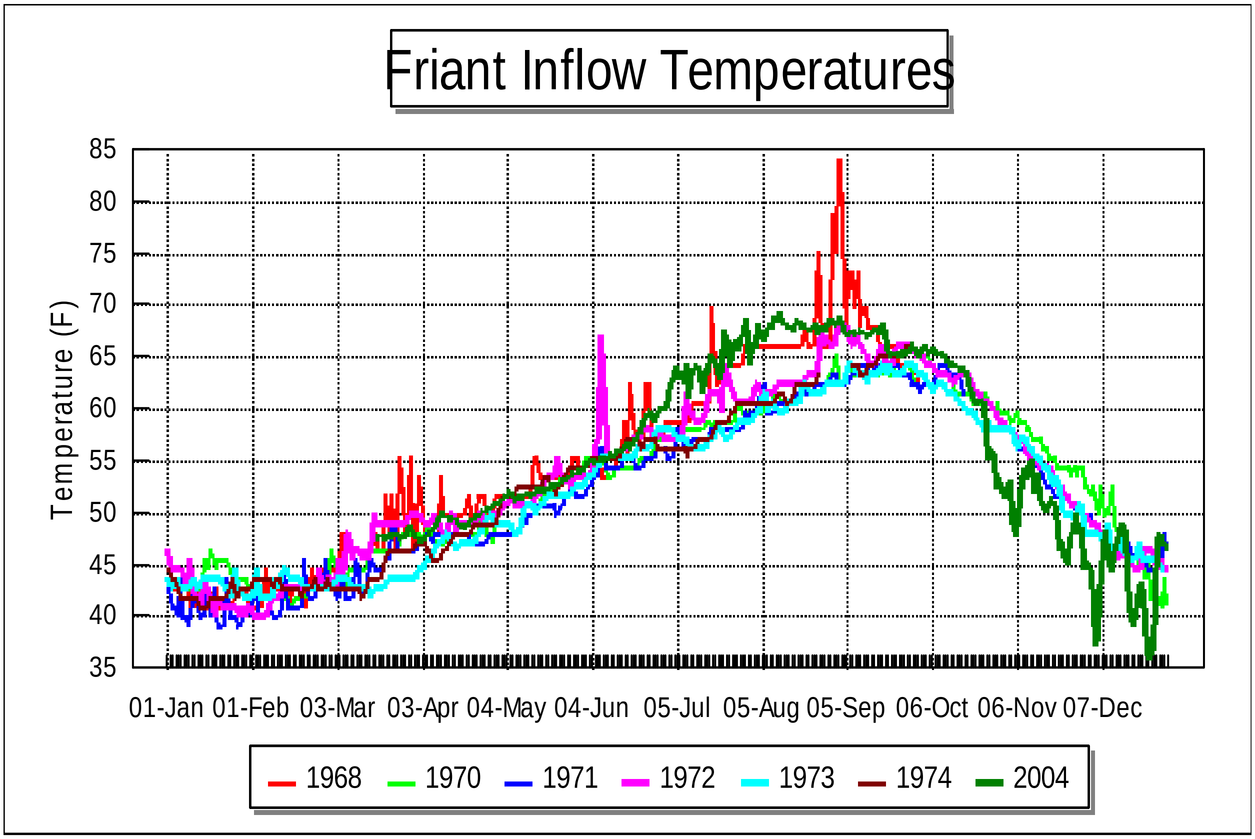


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Figure 4

Measured Inflow Temperatures for Millerton Lake, from 1961 to 1974, and 2004

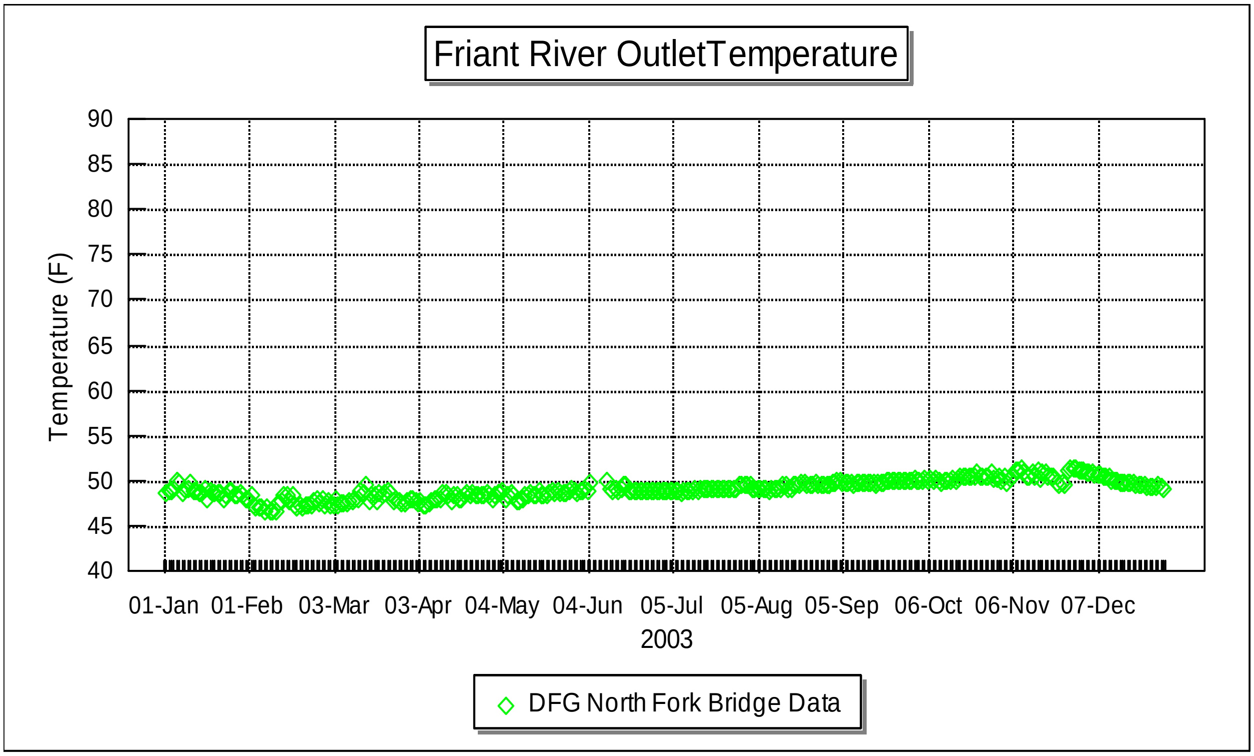

Figure 5. Measured Friant Dam Release Temperatures for 2003
(DFG minimum temperatures at North Fork Bridge.)

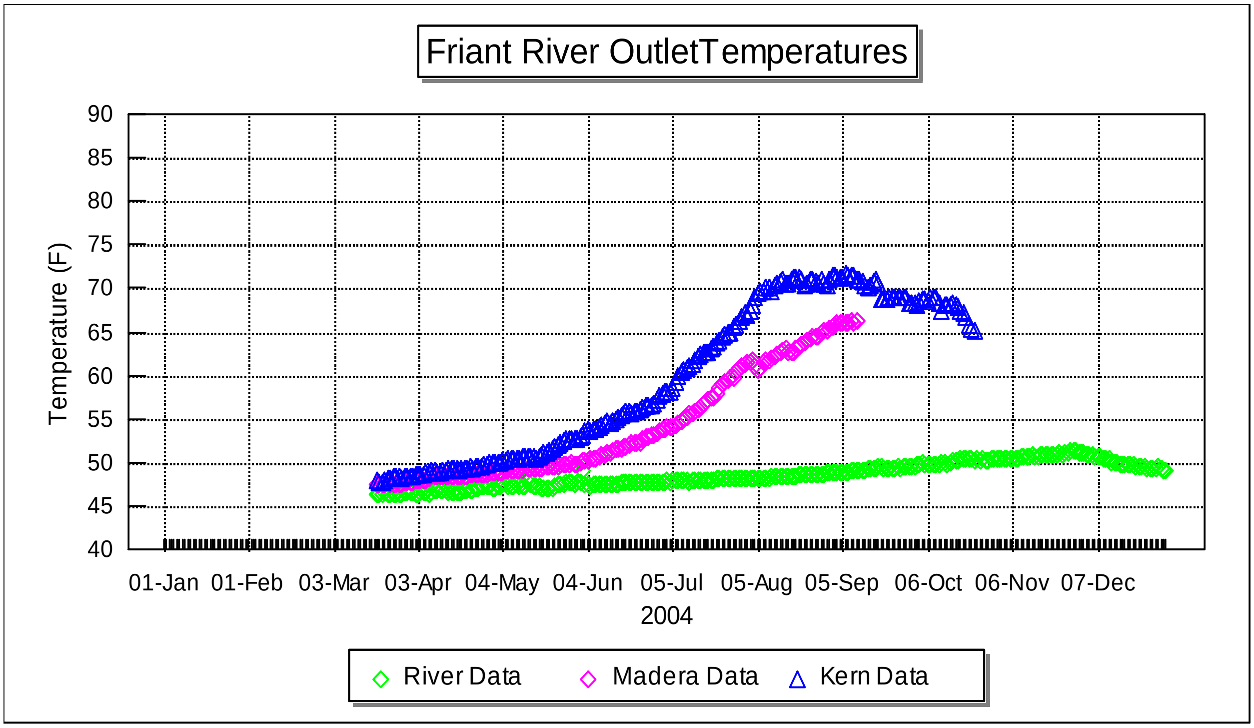

Figure 6. Measured Friant Dam Release Temperatures for 2004

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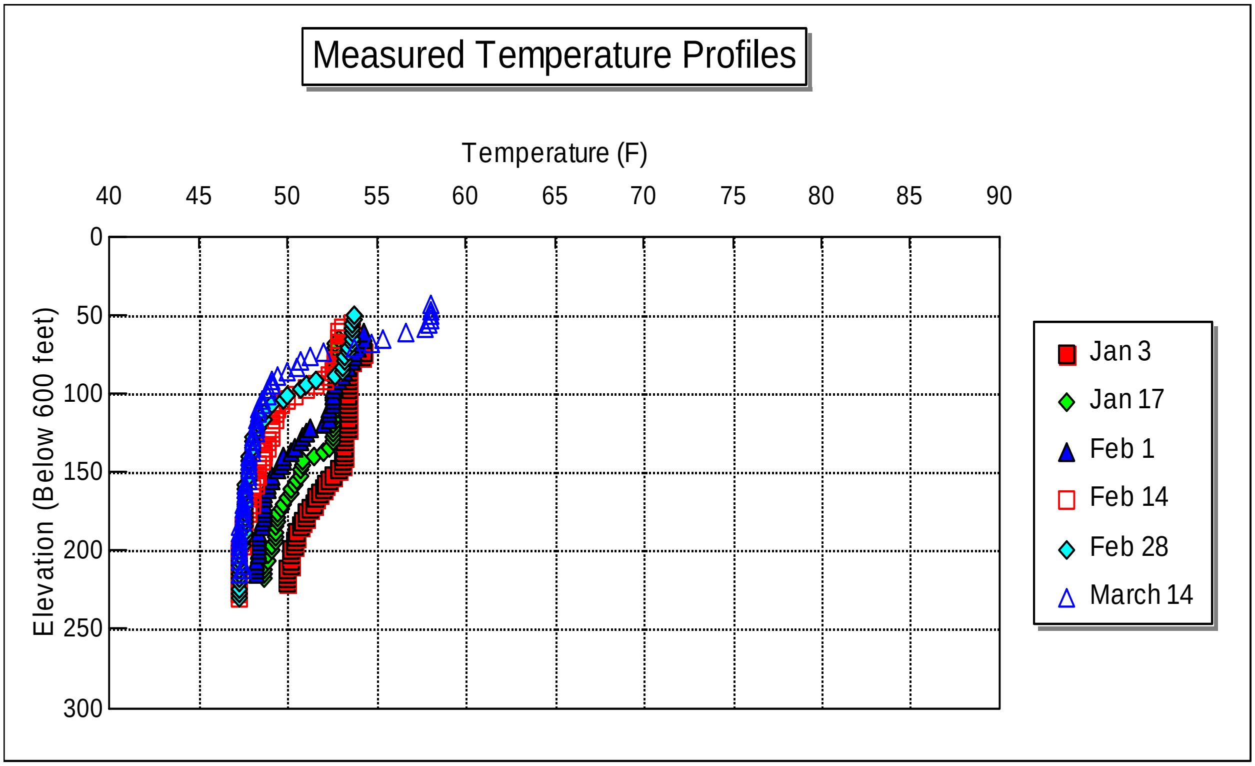
Figures 5 and 6

Measured Friant Dam Release Temperatures for 2003 and 2004



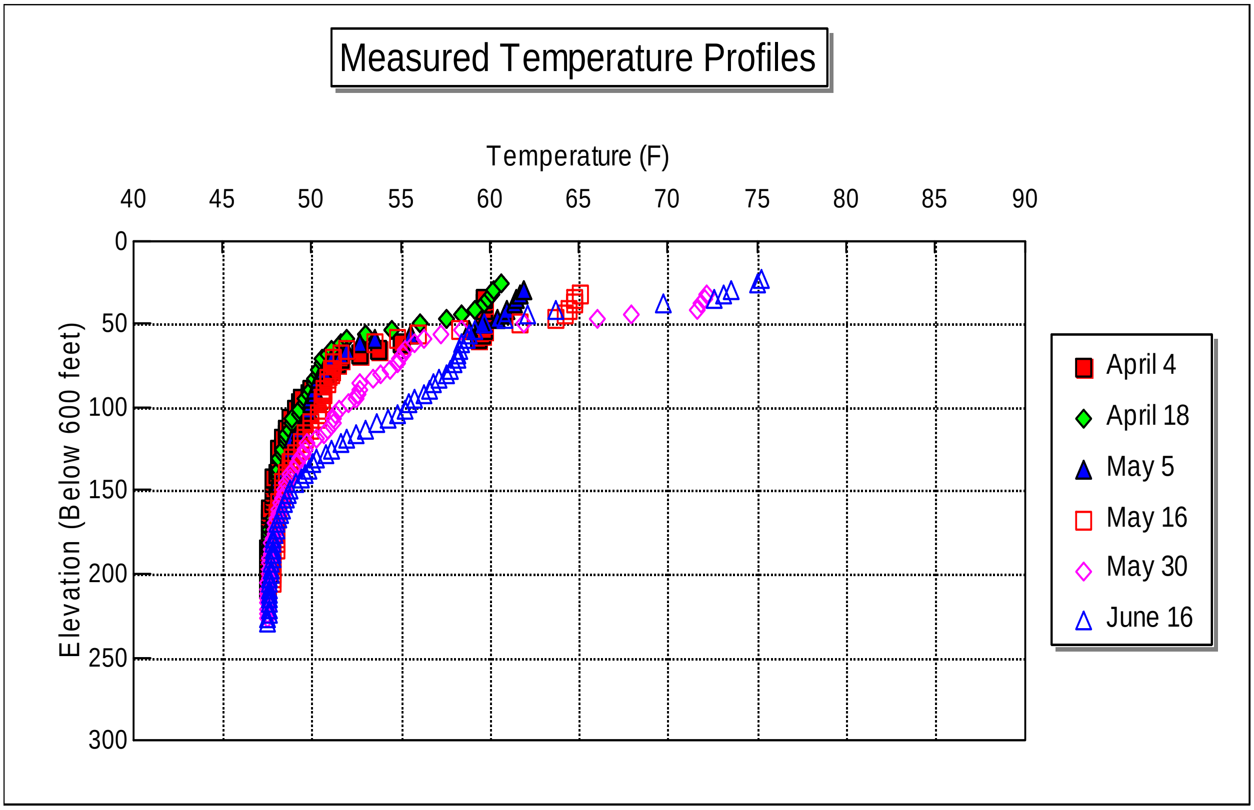
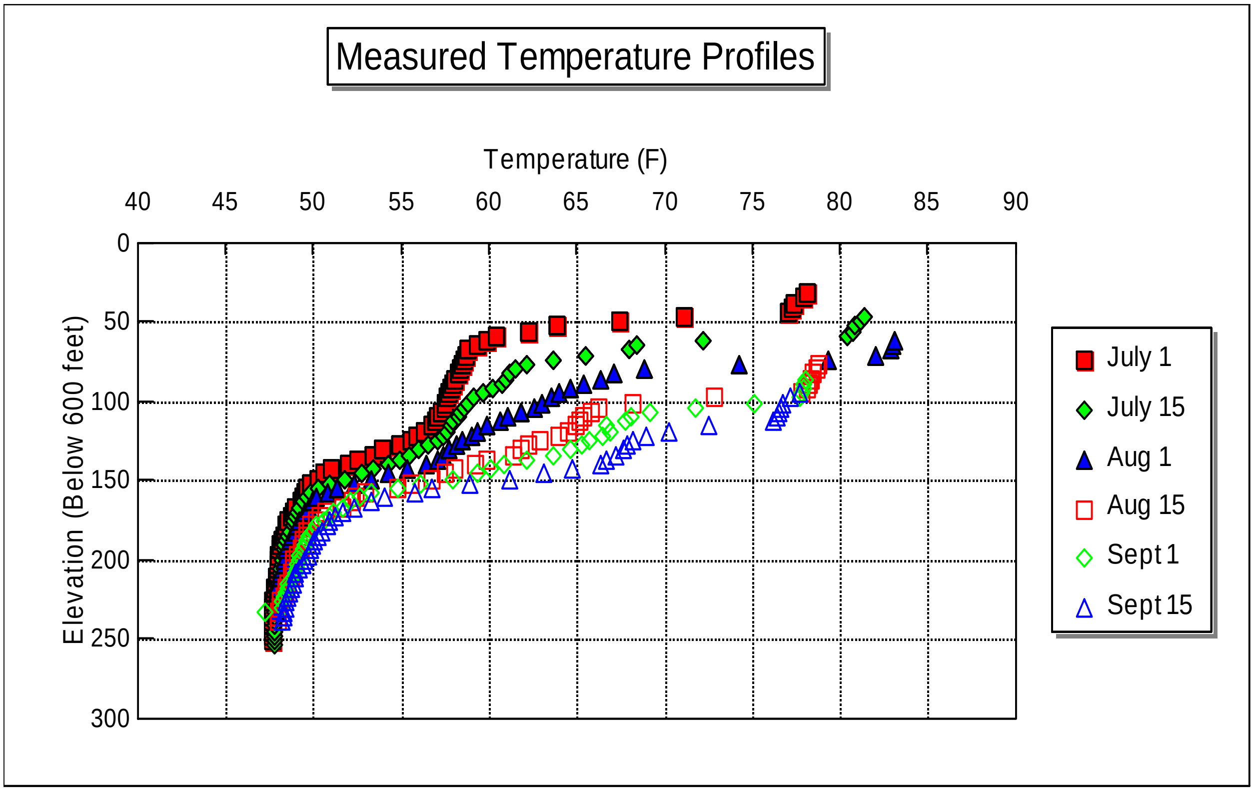


Figure 7 (Page 1 of 2)

Measured Millerton Lake Temperature Profiles for 2003



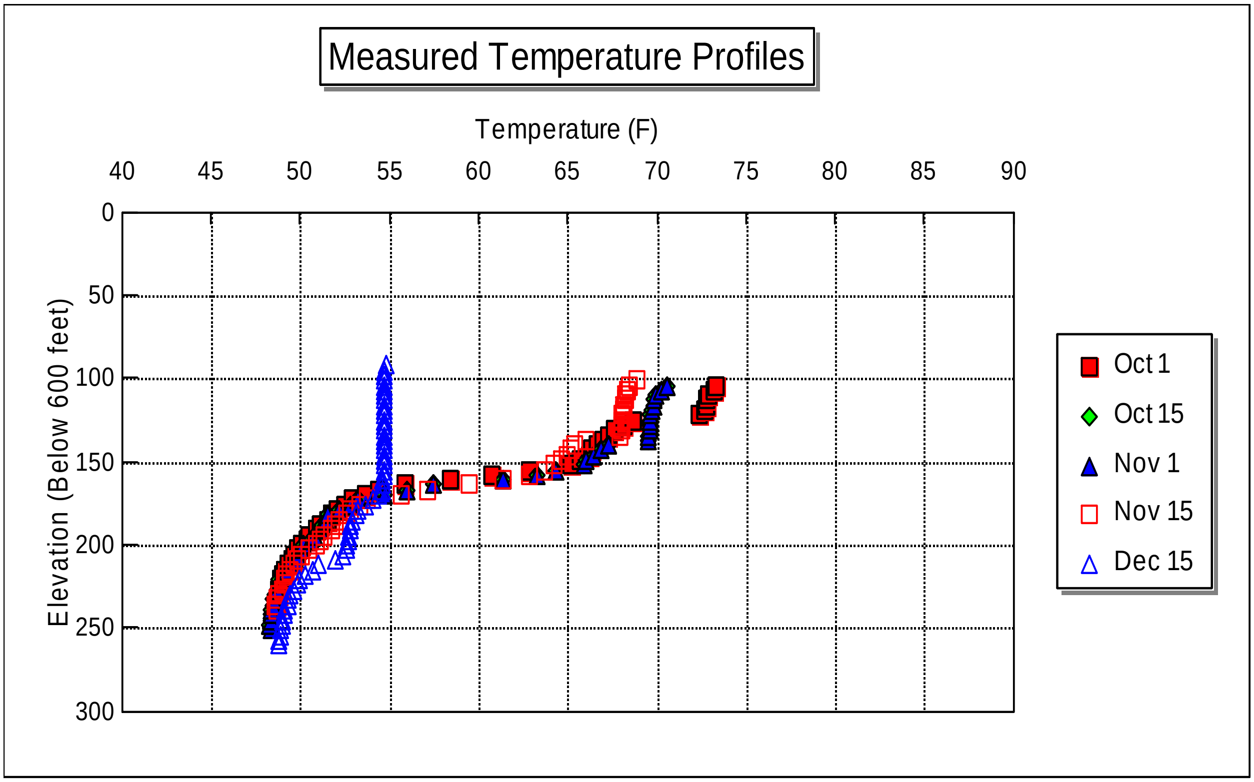


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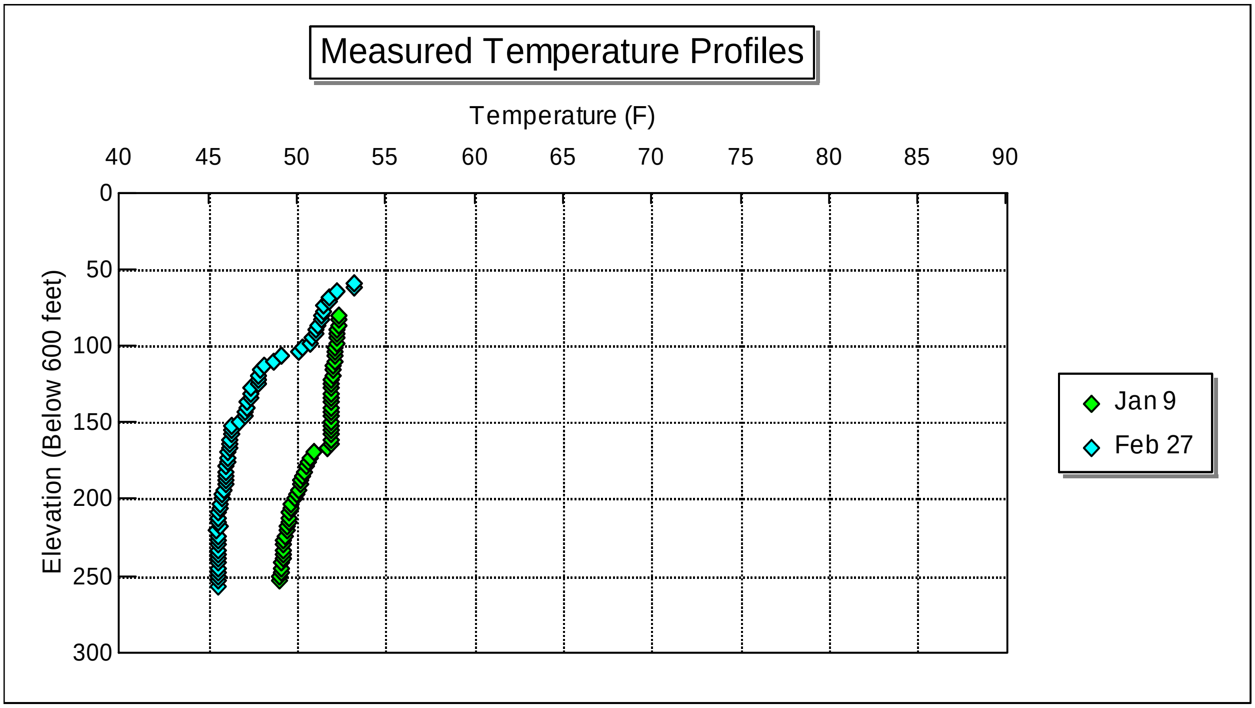
Figure 7 (Page 2 of 2)

Measured Millerton Lake Temperature Profiles for 2003



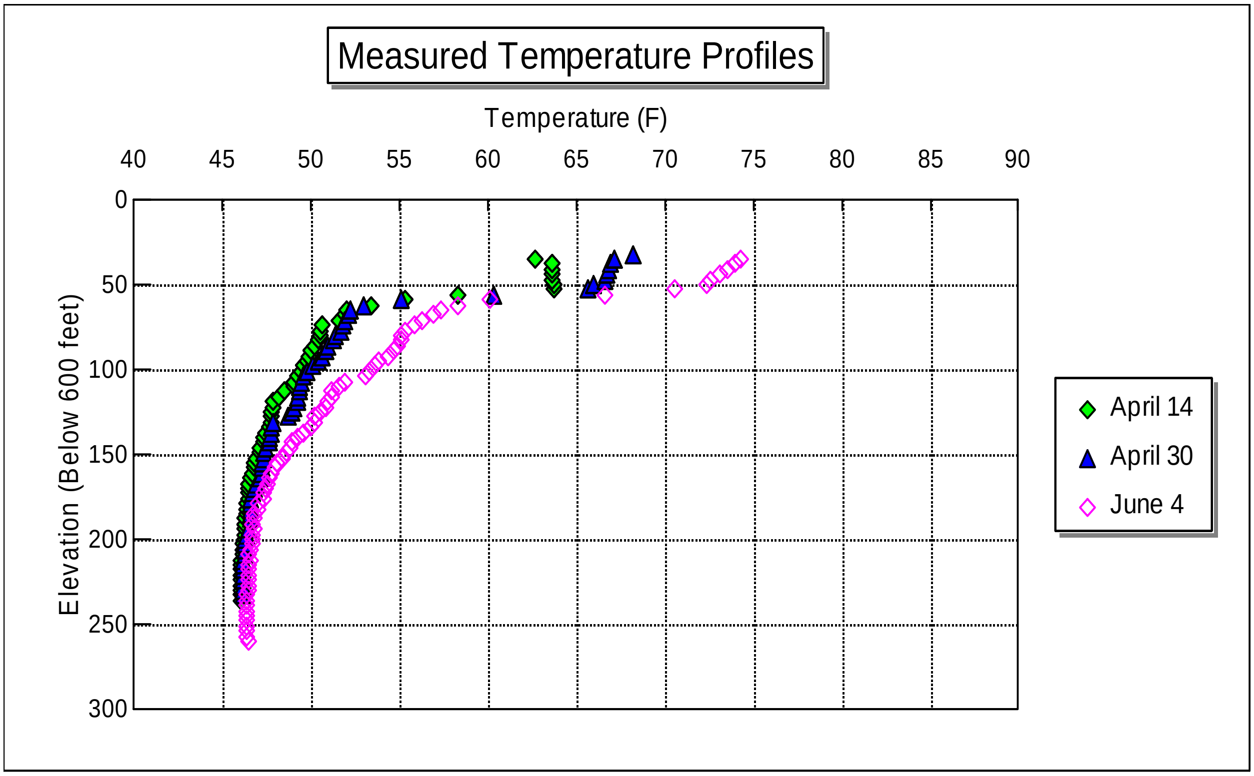


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Figure 8 (Page 1 of 2)

Measured Millerton Lake Temperature Profiles for 2004

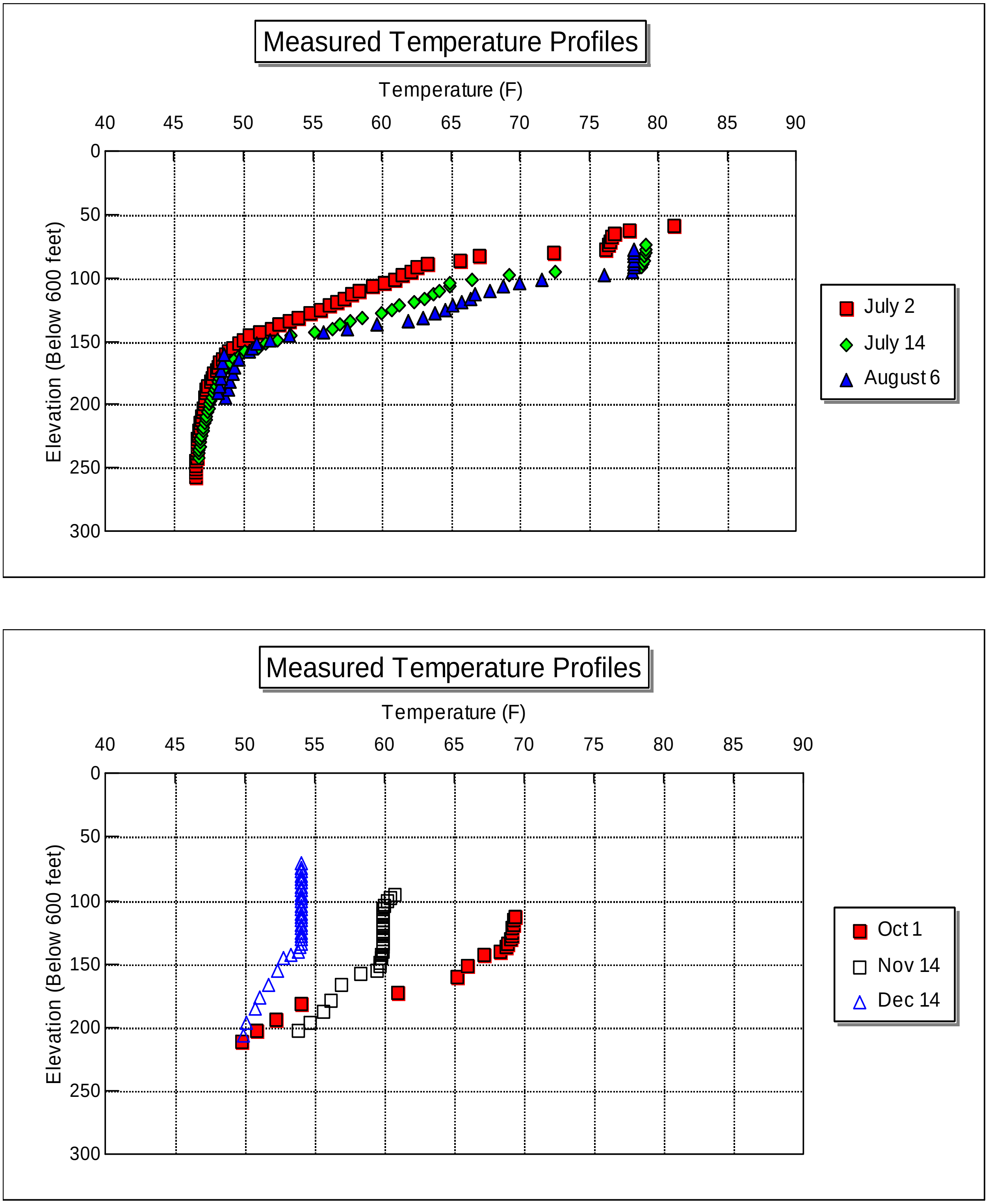

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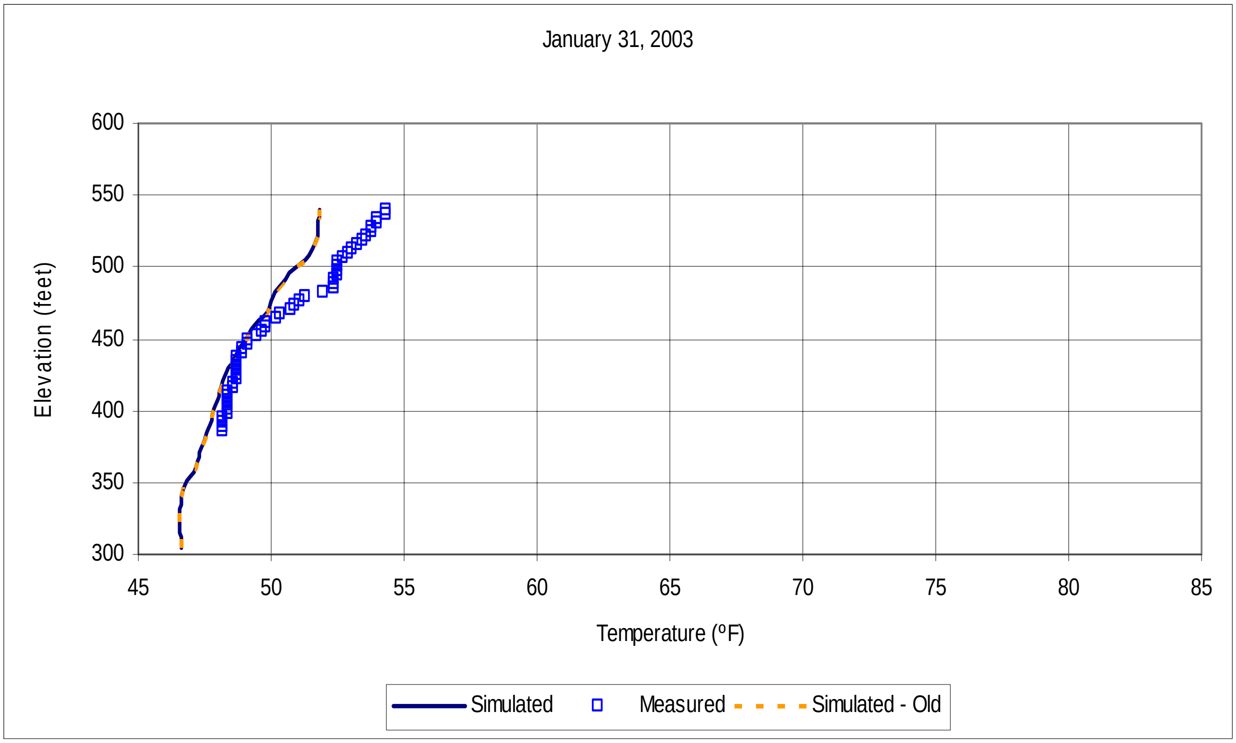
Figure 8 (Page 2 of 2)

Measured Millerton Lake Temperature Profiles for 2004



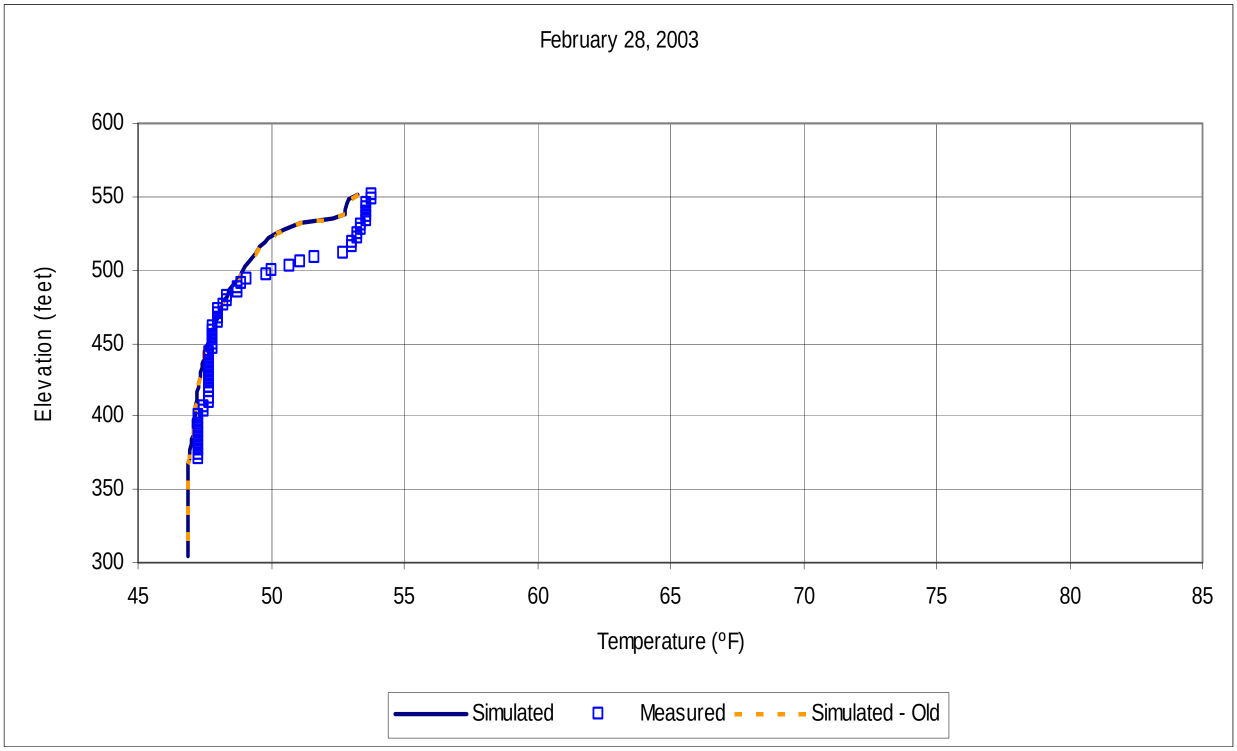
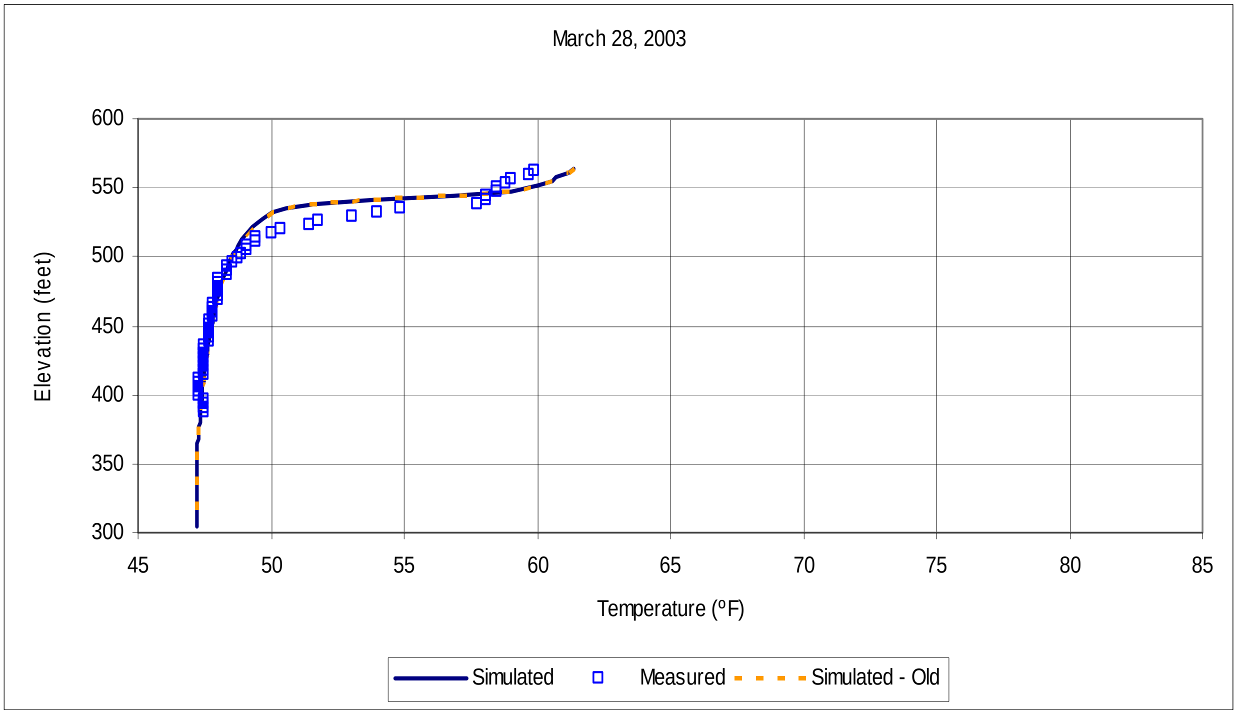


Figure 9 (Page 1 of 6)

Calibration of W2 Temperature Model to Match Measured 2003 Temperature Profiles in Millerton Lake



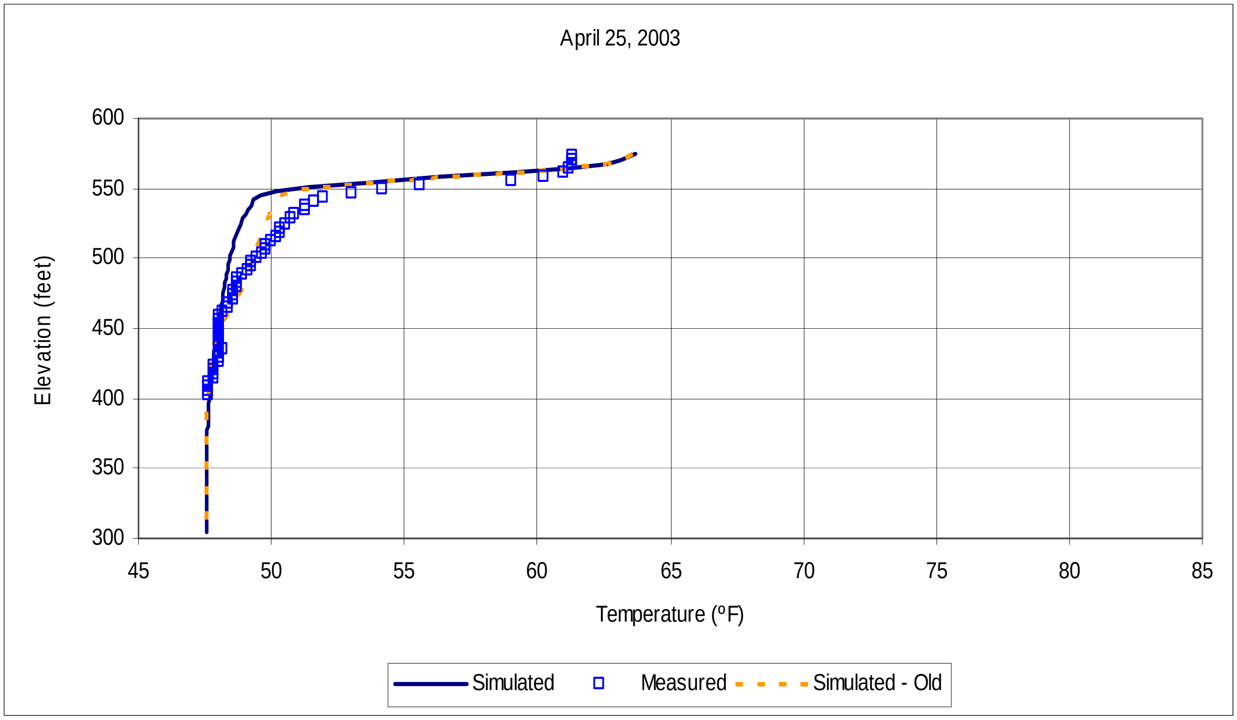
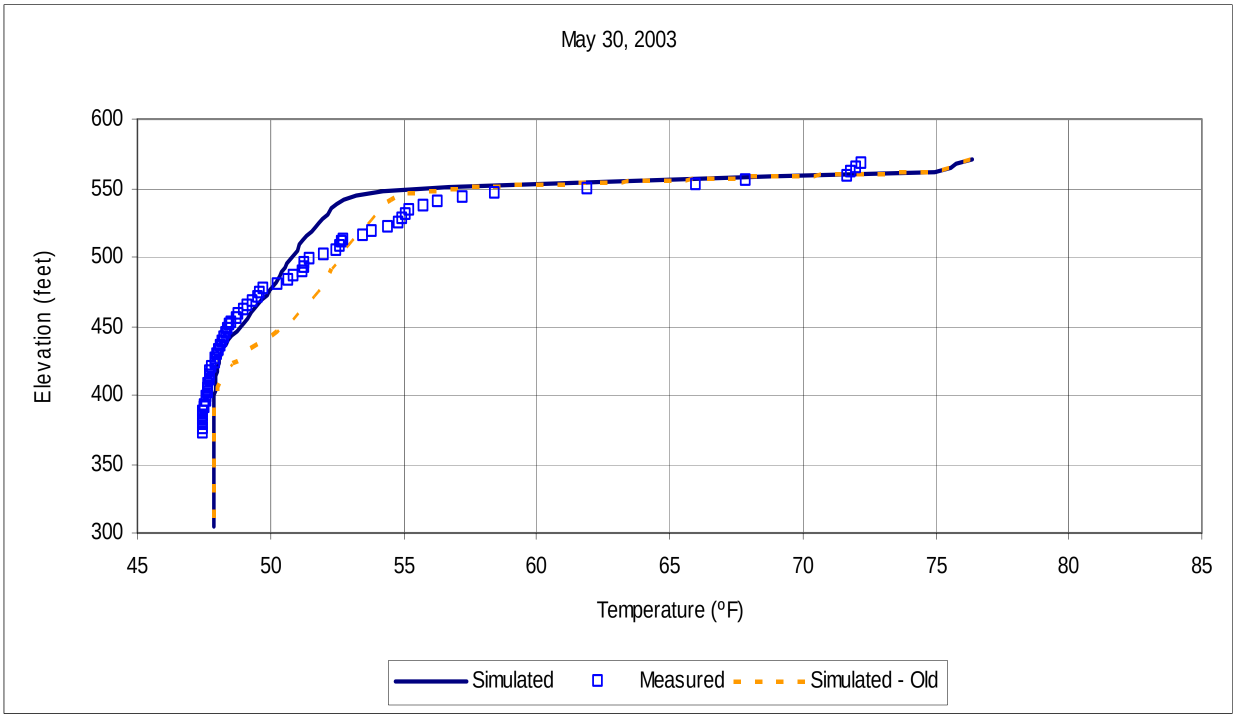


Figure 9 (Page 2 of 6)

Calibration of W2 Temperature Model to Match Measured 2003 Temperature Profiles in Millerton Lake



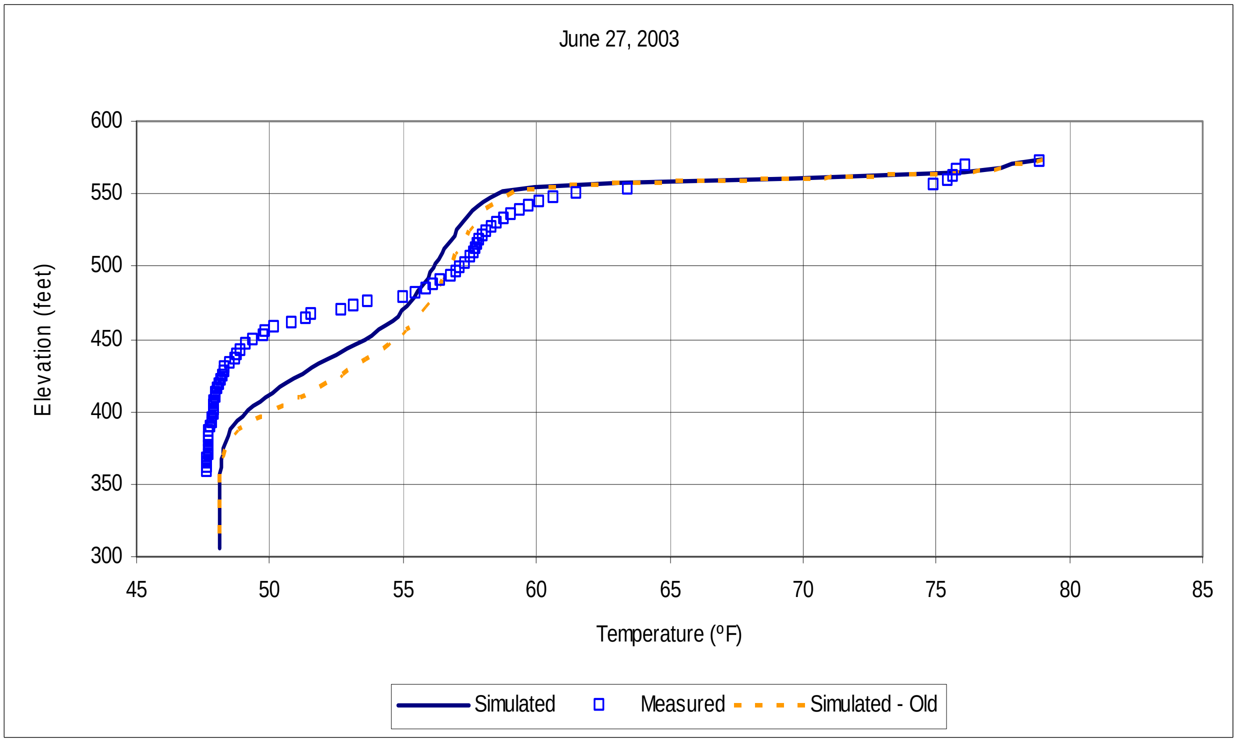


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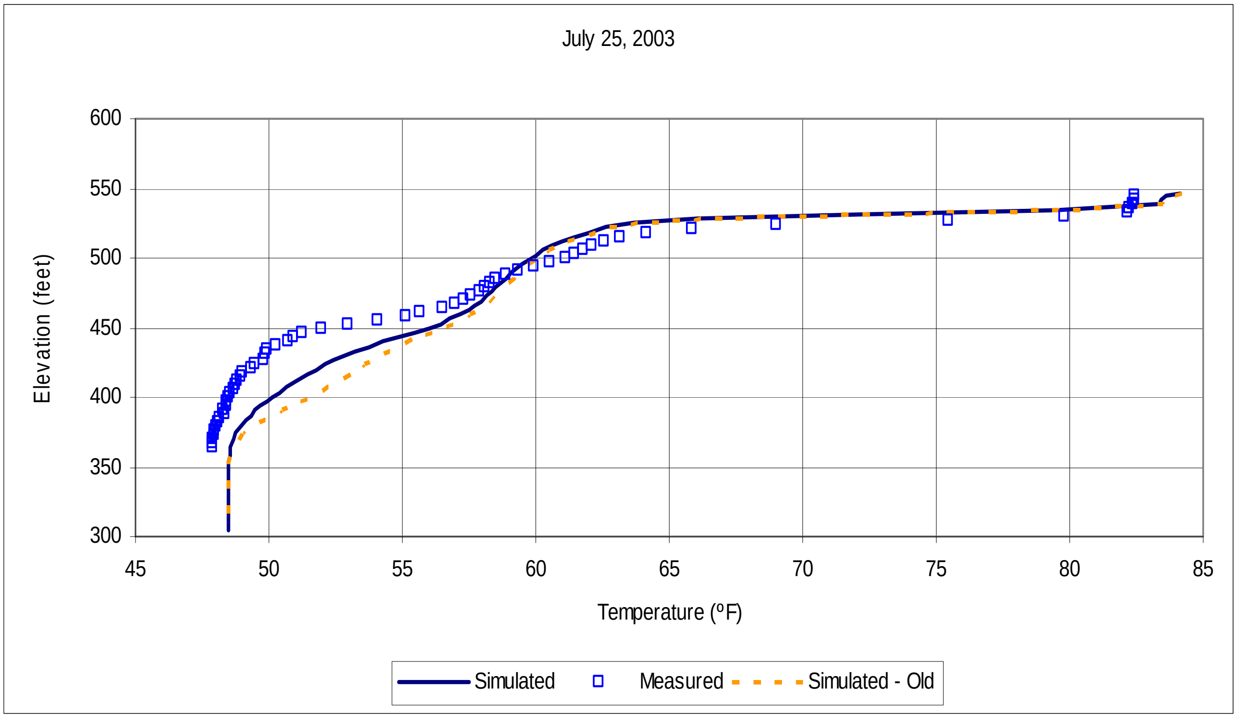
Figure 9 (Page 3 of 6)

Calibration of W2 Temperature Model to Match Measured 2003 Temperature Profiles in Millerton Lake



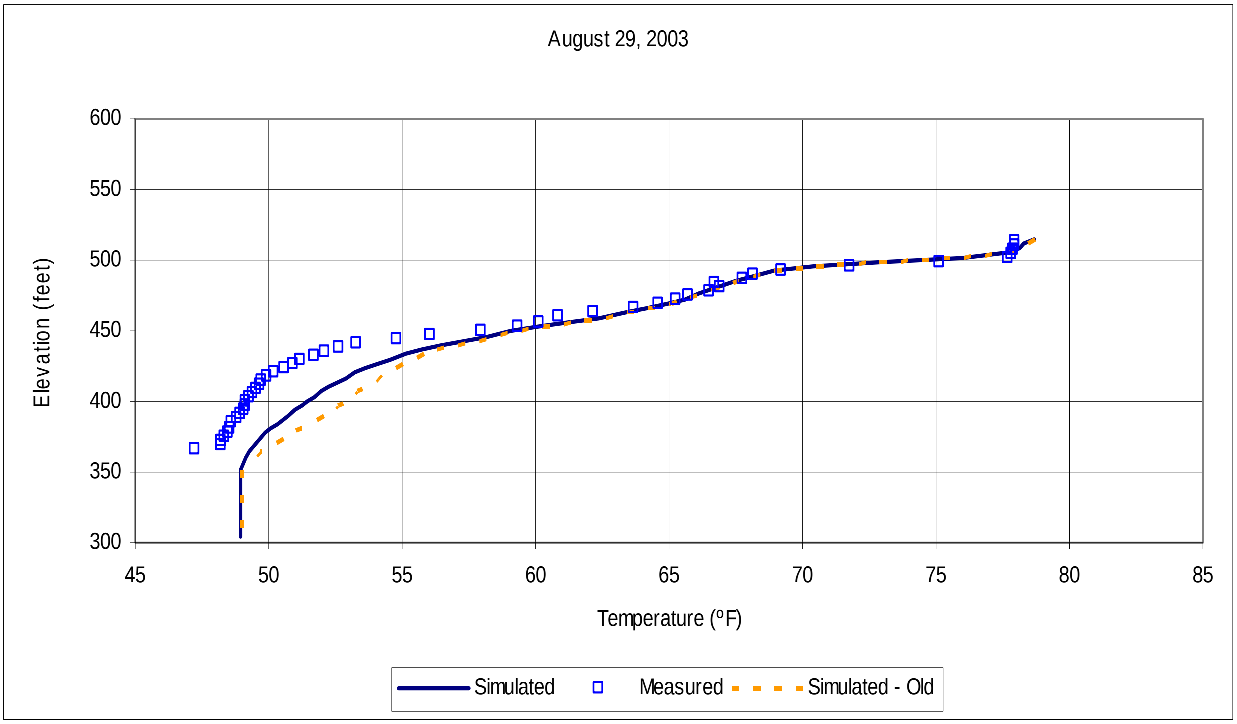


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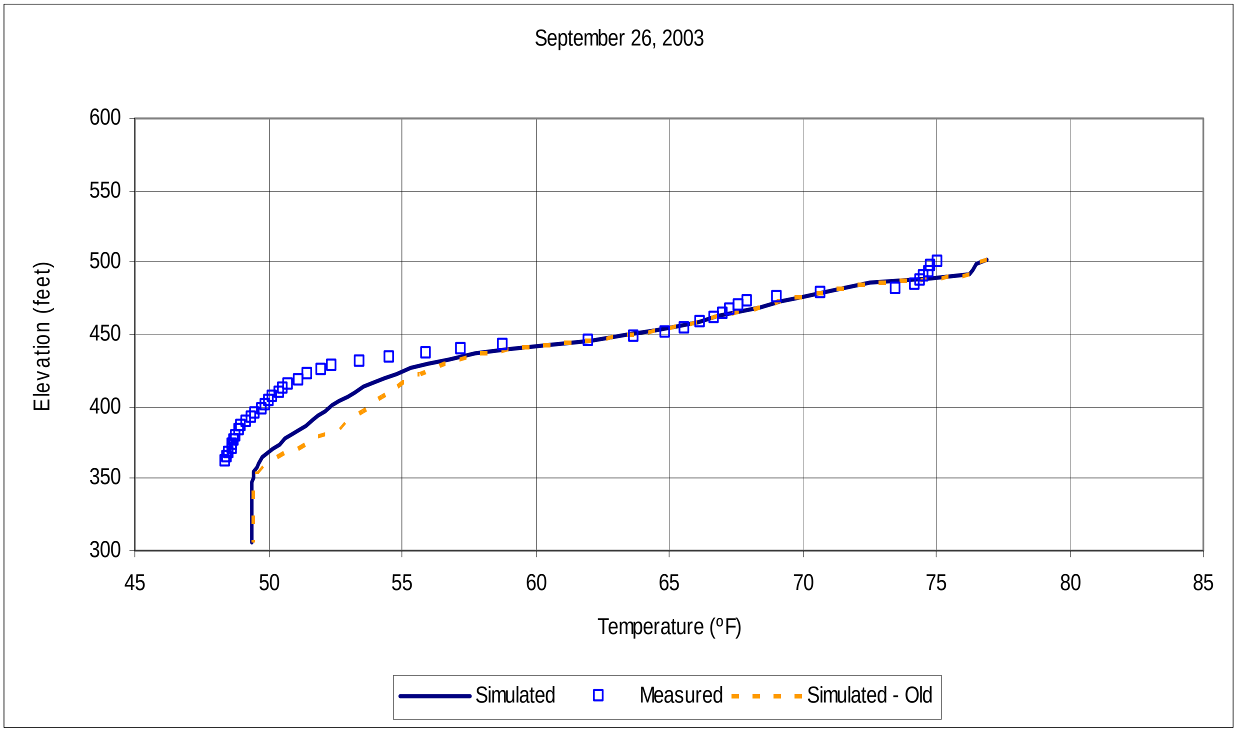
Figure 9 (Page 4 of 6)

Calibration of W2 Temperature Model to Match Measured 2003 Temperature Profiles in Millerton Lake



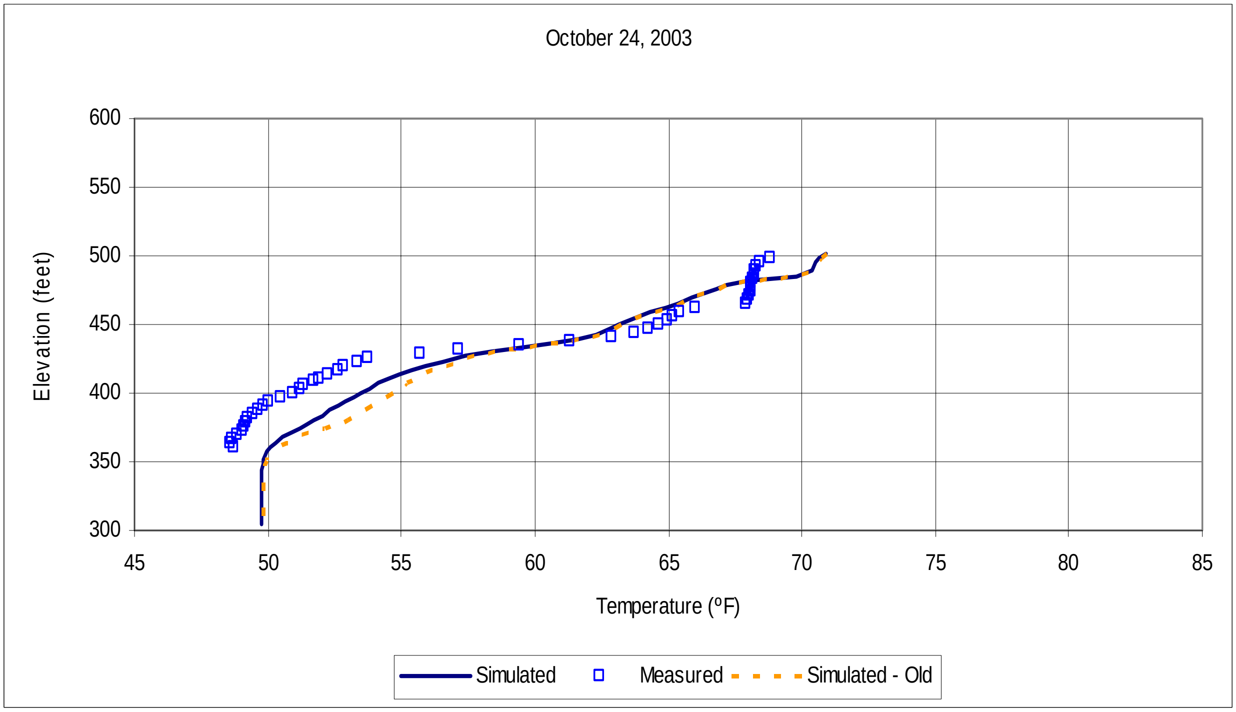
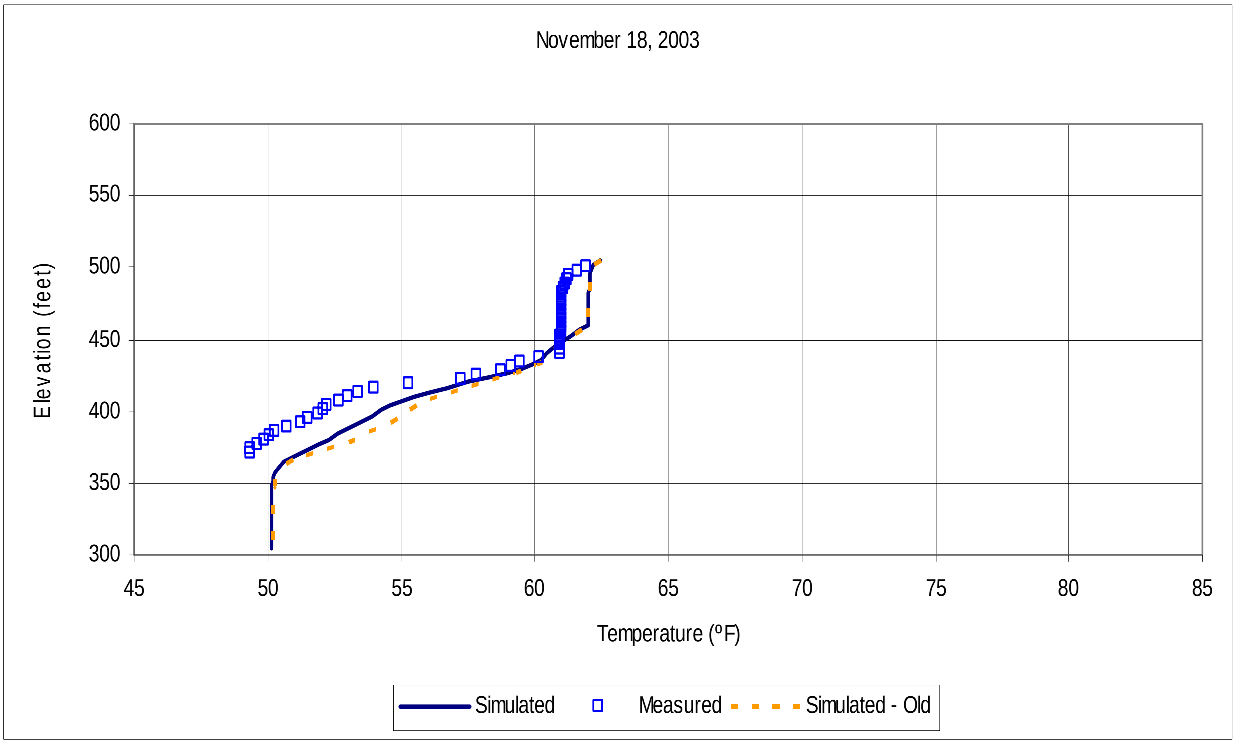


Figure 9 (Page 5 of 6)

Calibration of W2 Temperature Model to Match Measured 2003 Temperature Profiles in Millerton Lake



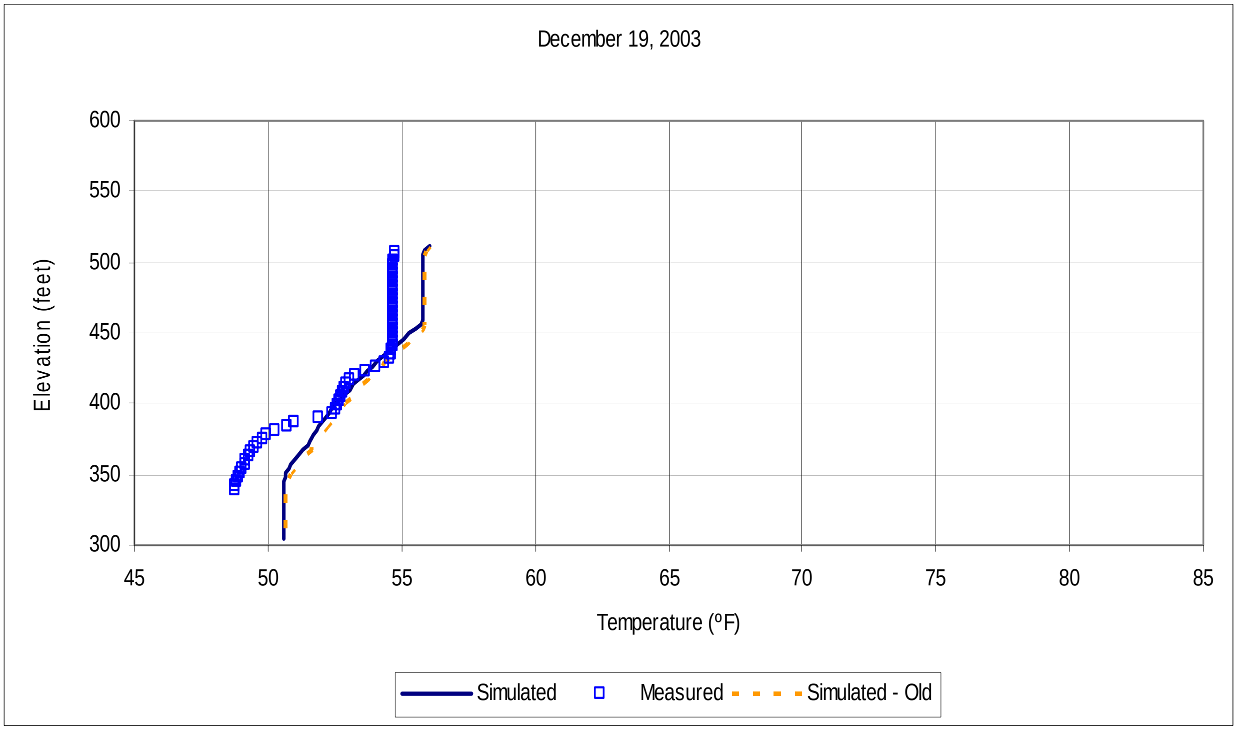


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Figure 9 (Page 6 of 6)

Calibration of W2 Temperature Model to Match Measured 2003 Temperature Profiles in Millerton Lake

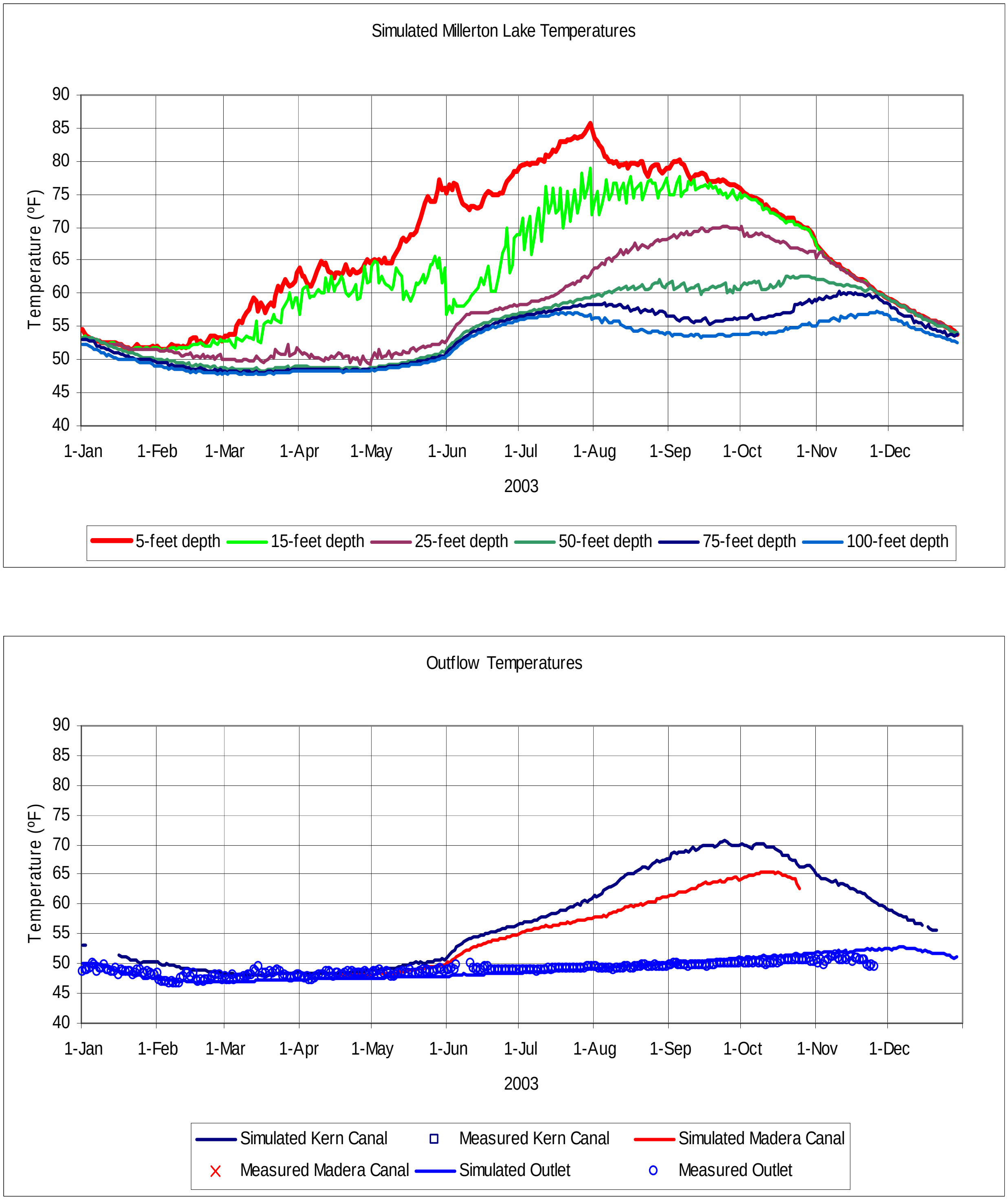

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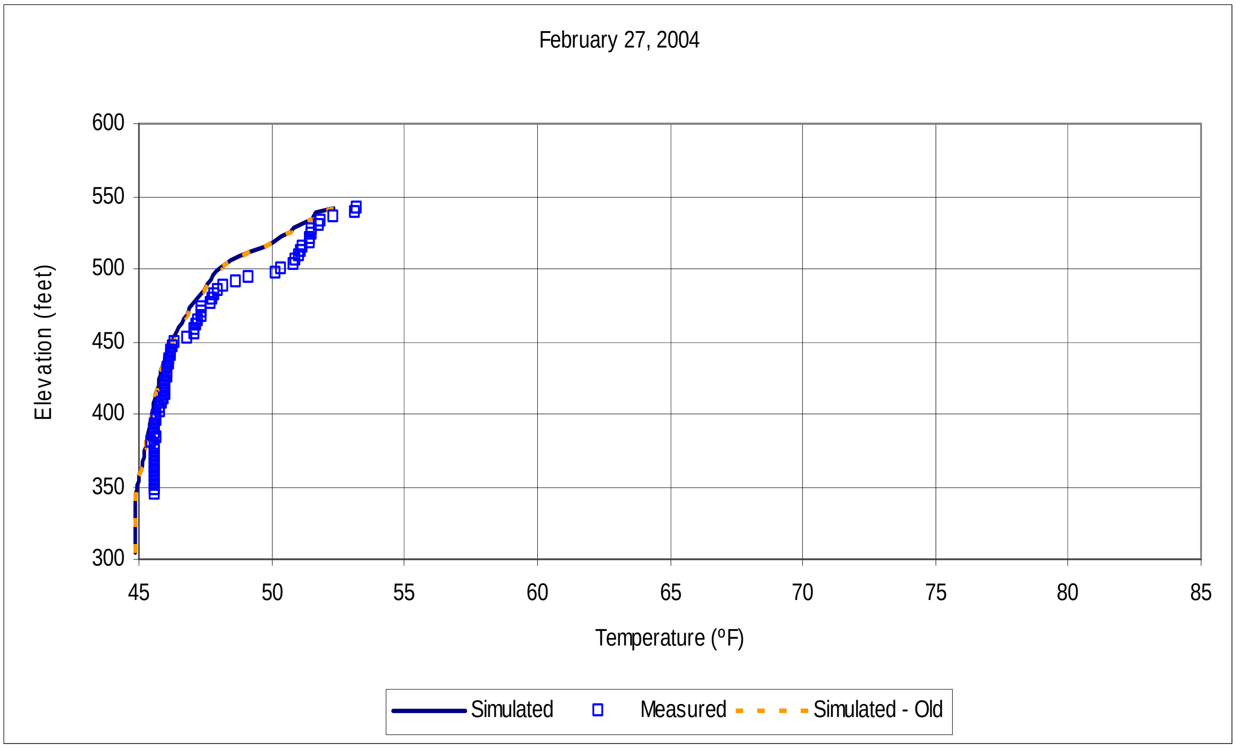
Figure 10

Simulated Millerton Lake Temperatures and Friant Dam Release Temperatures for 2003 Historical Operations Compared with DFG Measurements of River Outlet Temperatures



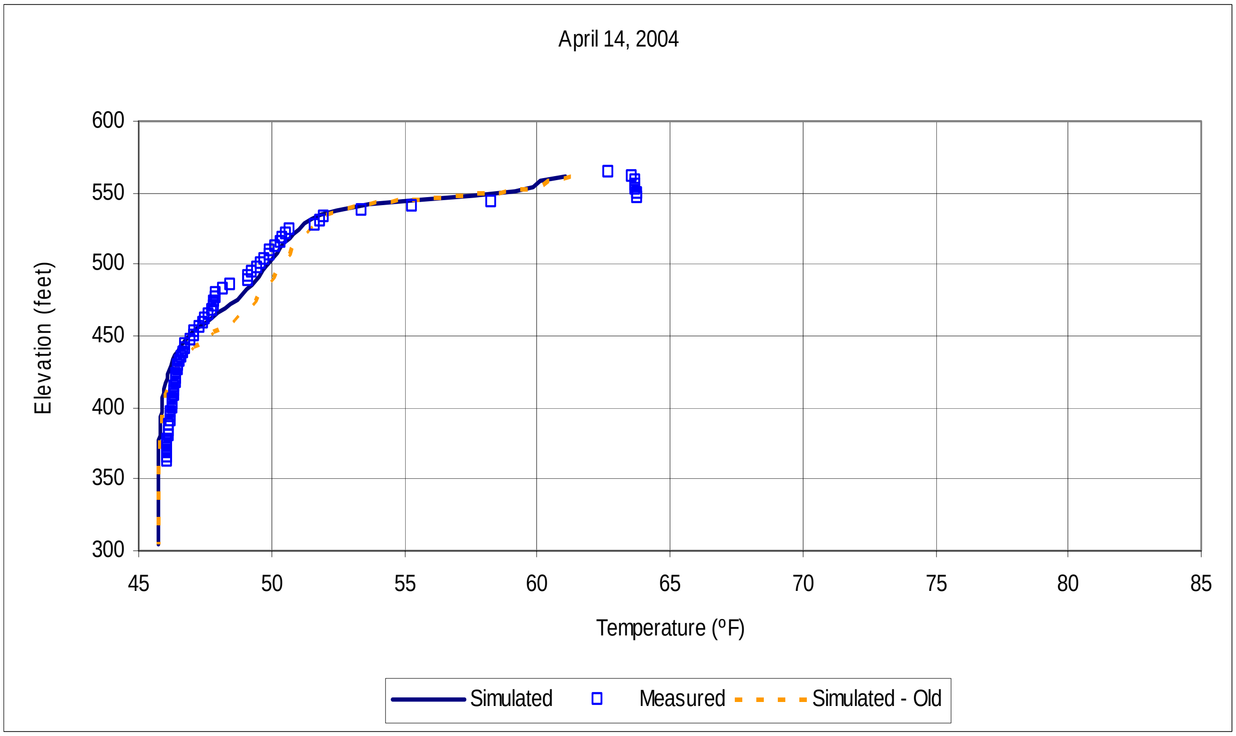


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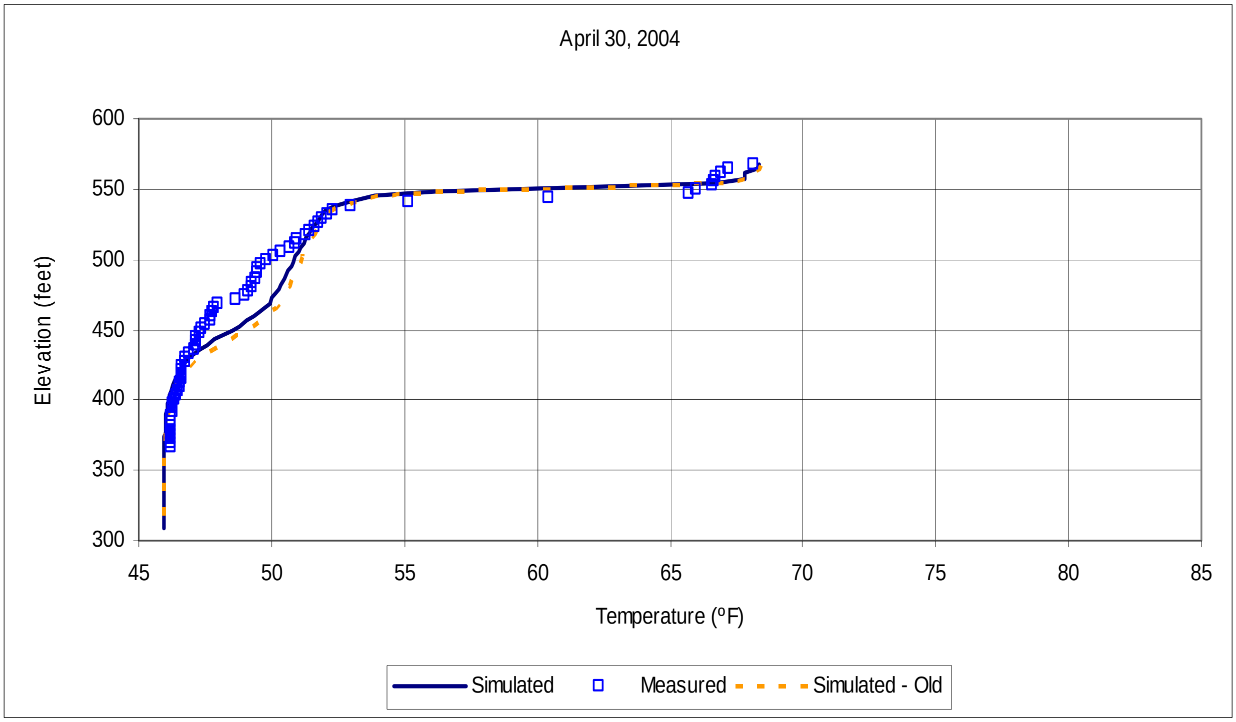
Figure 11 (Page 1 of 5)

Calibration of W2 Temperature Model to Match Measured 2004 Temperature Profiles in Millerton Lake



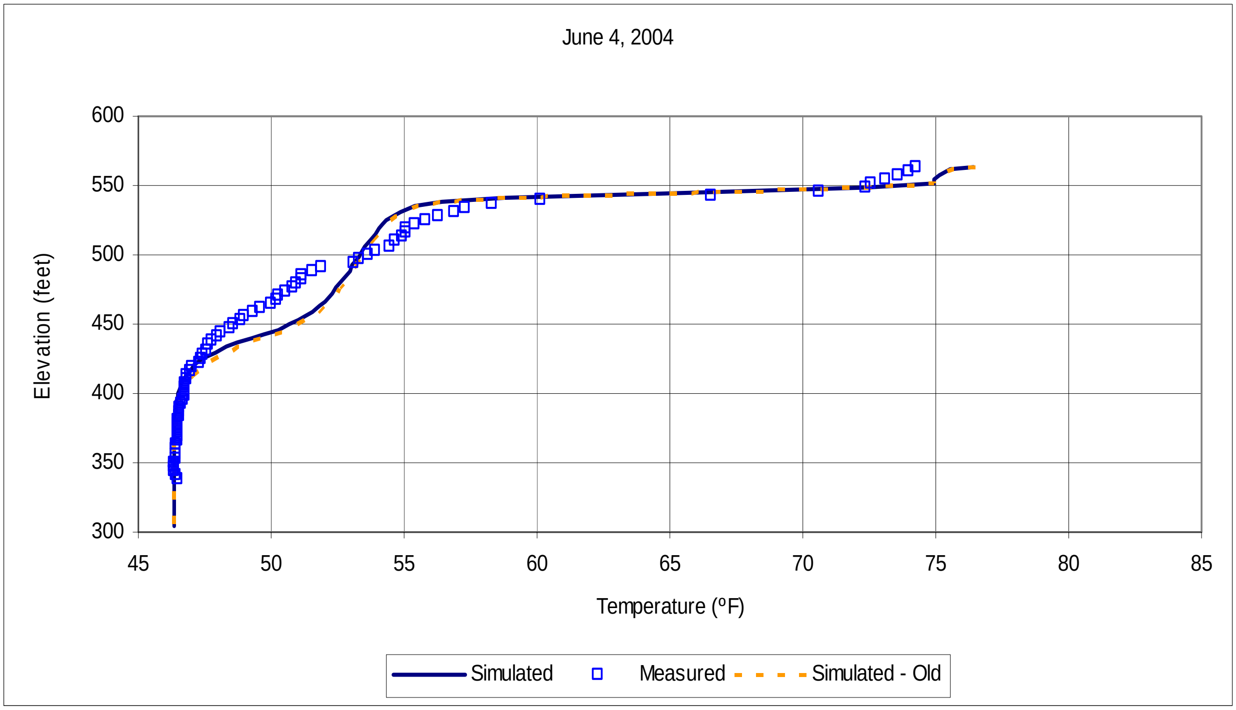


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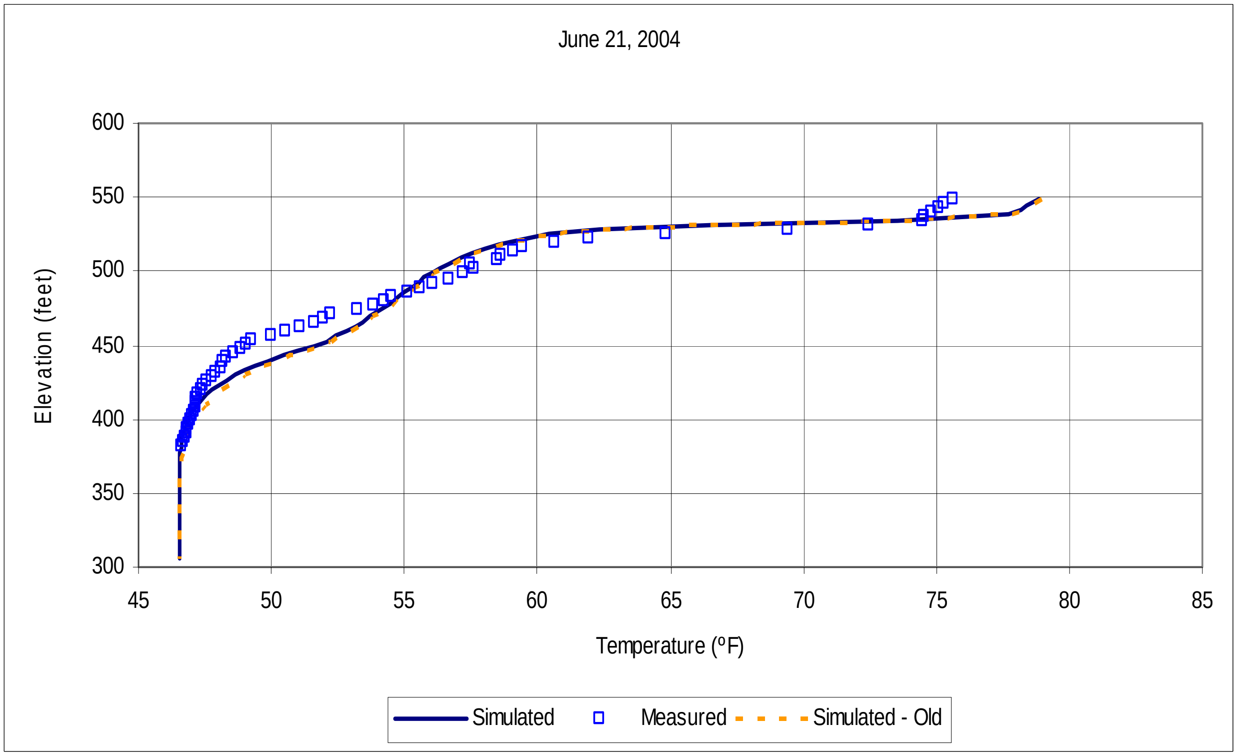
Figure 11 (Page 2 of 5)

Calibration of W2 Temperature Model to Match Measured 2004 Temperature Profiles in Millerton Lake



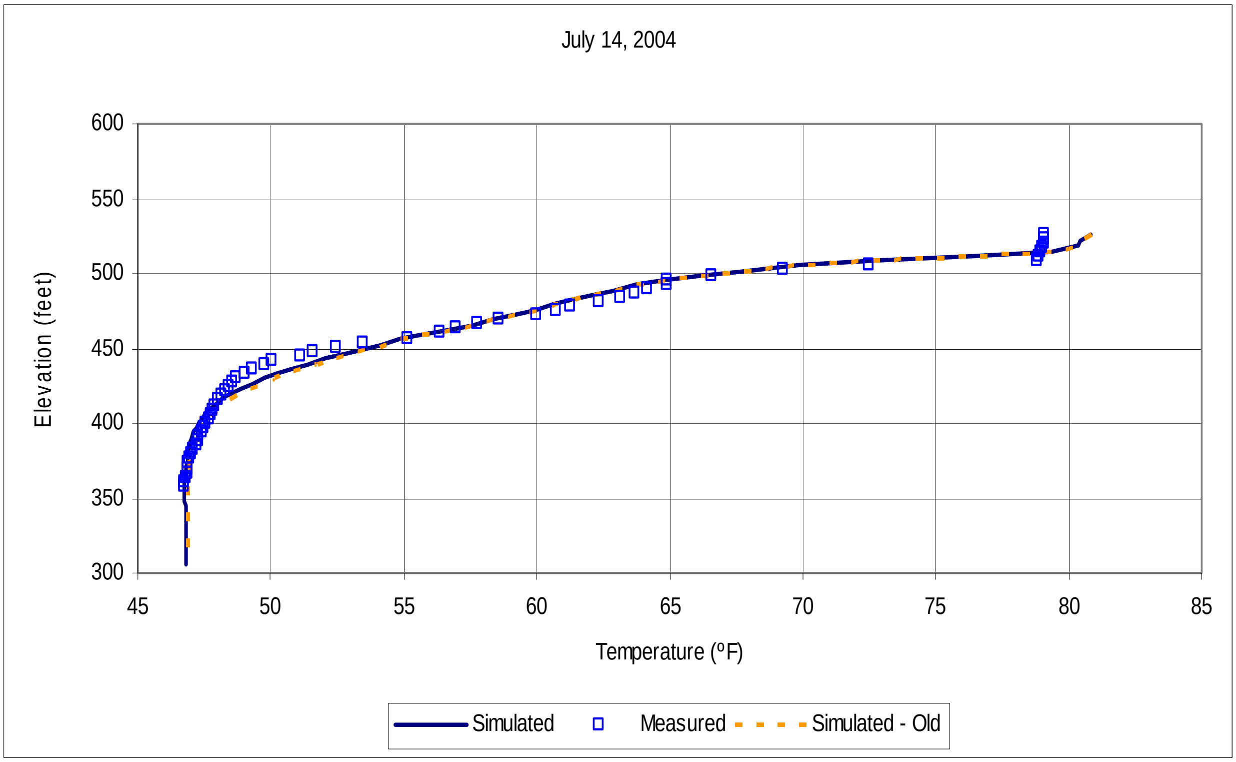
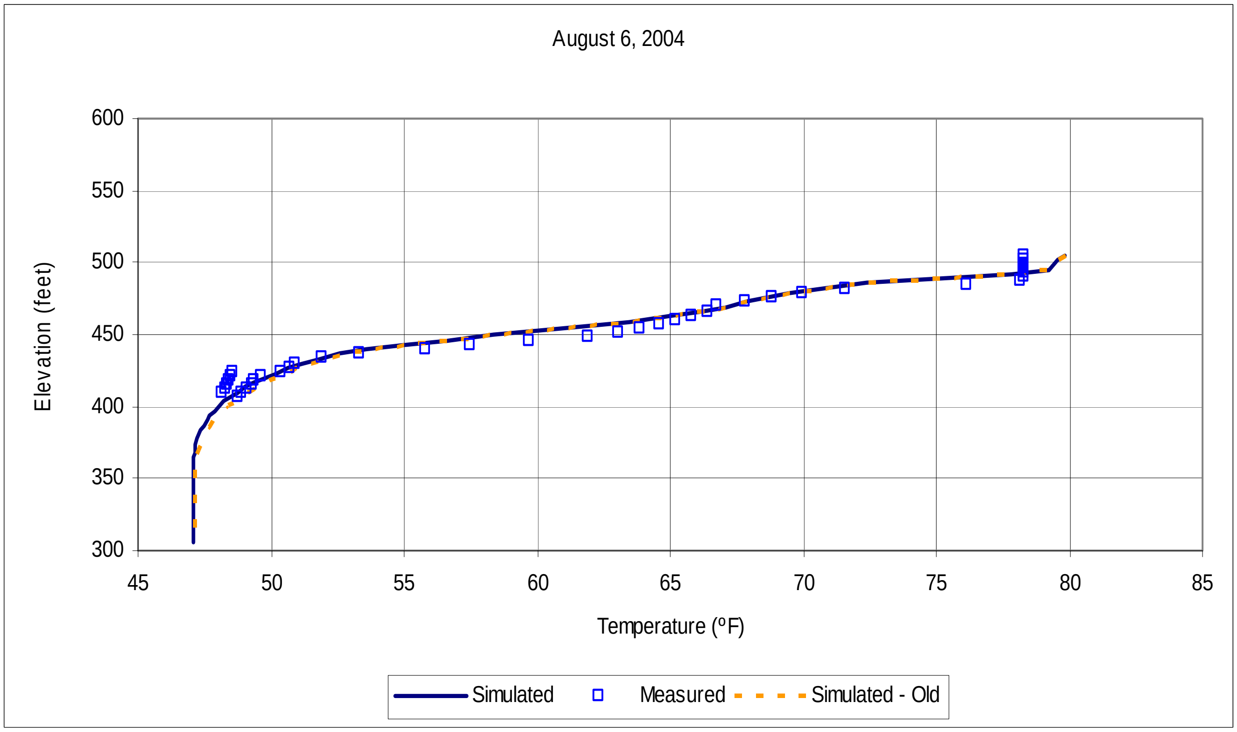
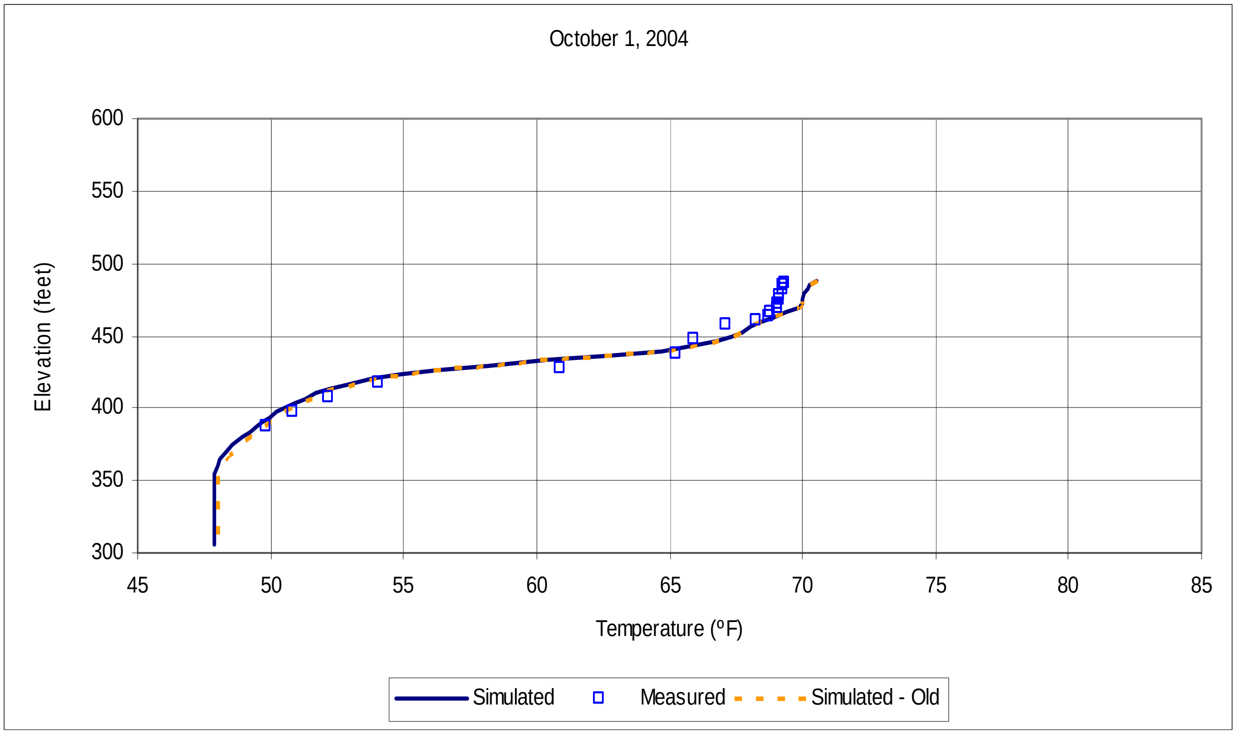


Figure 11 (Page 3 of 5)

Calibration of W2 Temperature Model to Match Measured 2004 Temperature Profiles in Millerton Lake





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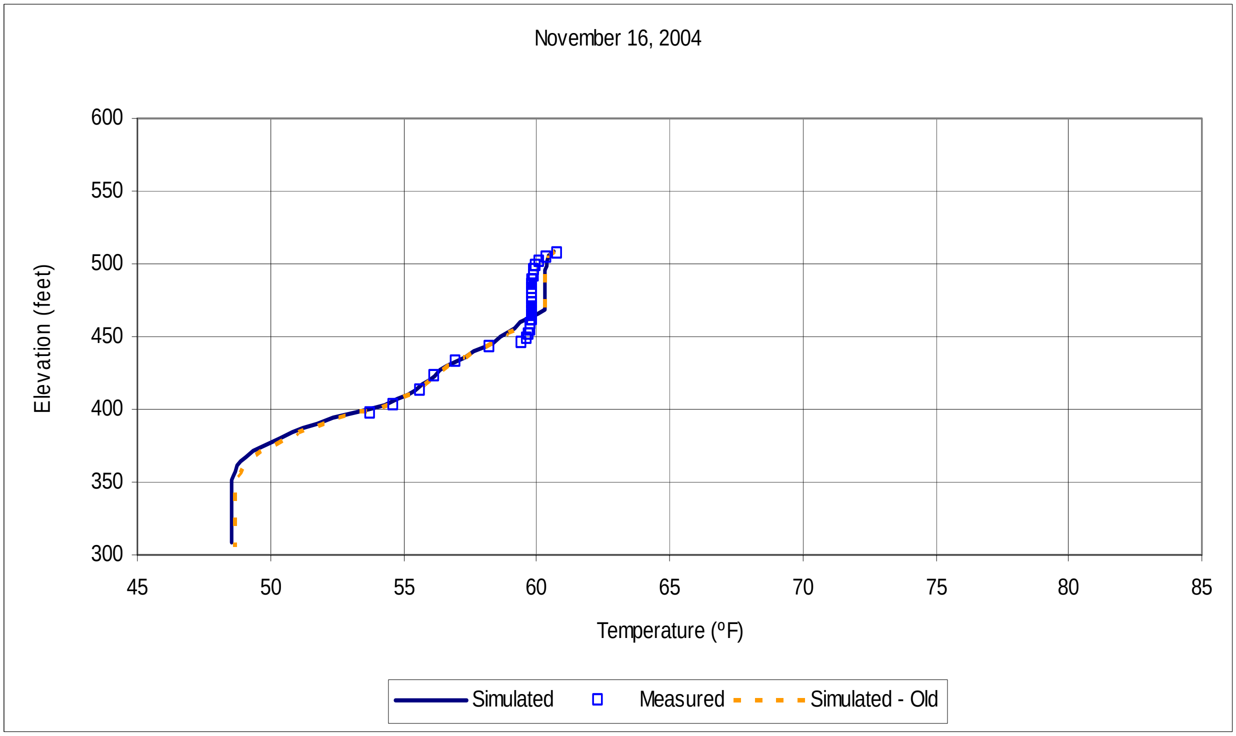
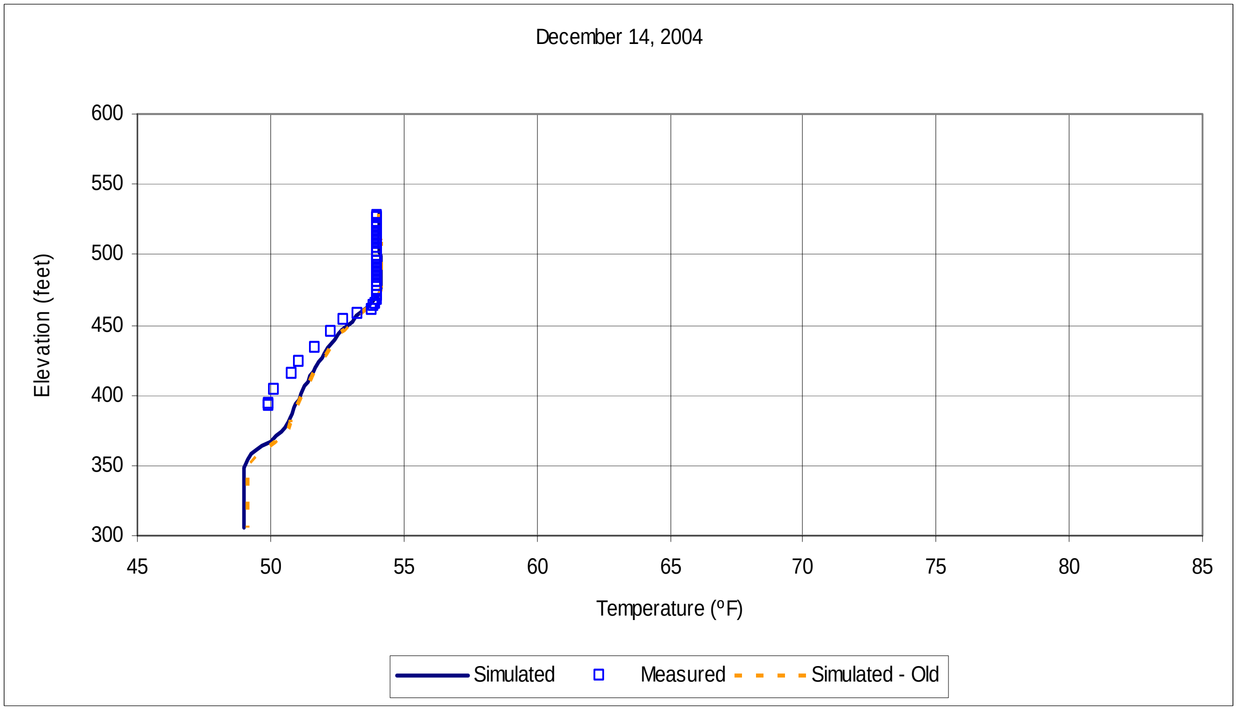
Calibration of W2 Temperature Model to Match Measured 2004 Temperature Profiles in Millerton Lake





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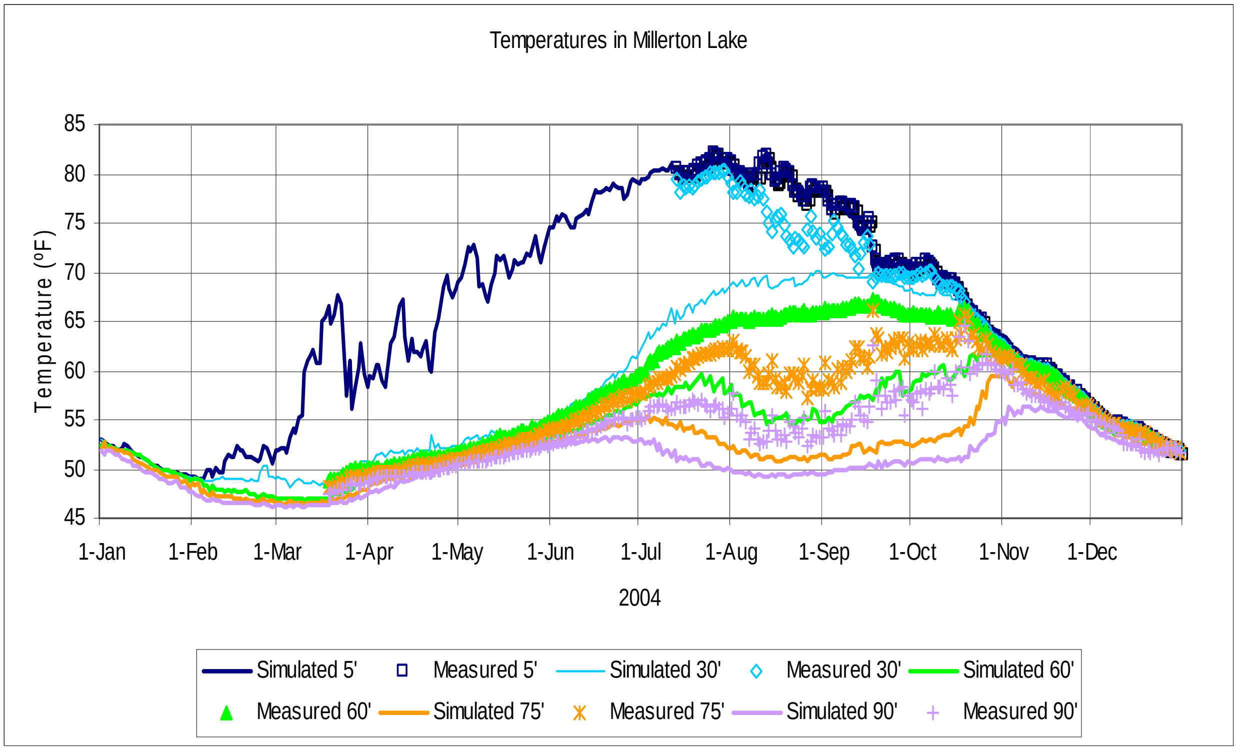
Calibration of W2 Temperature Model to Match Measured 2004 Temperature Profiles in Millerton Lake



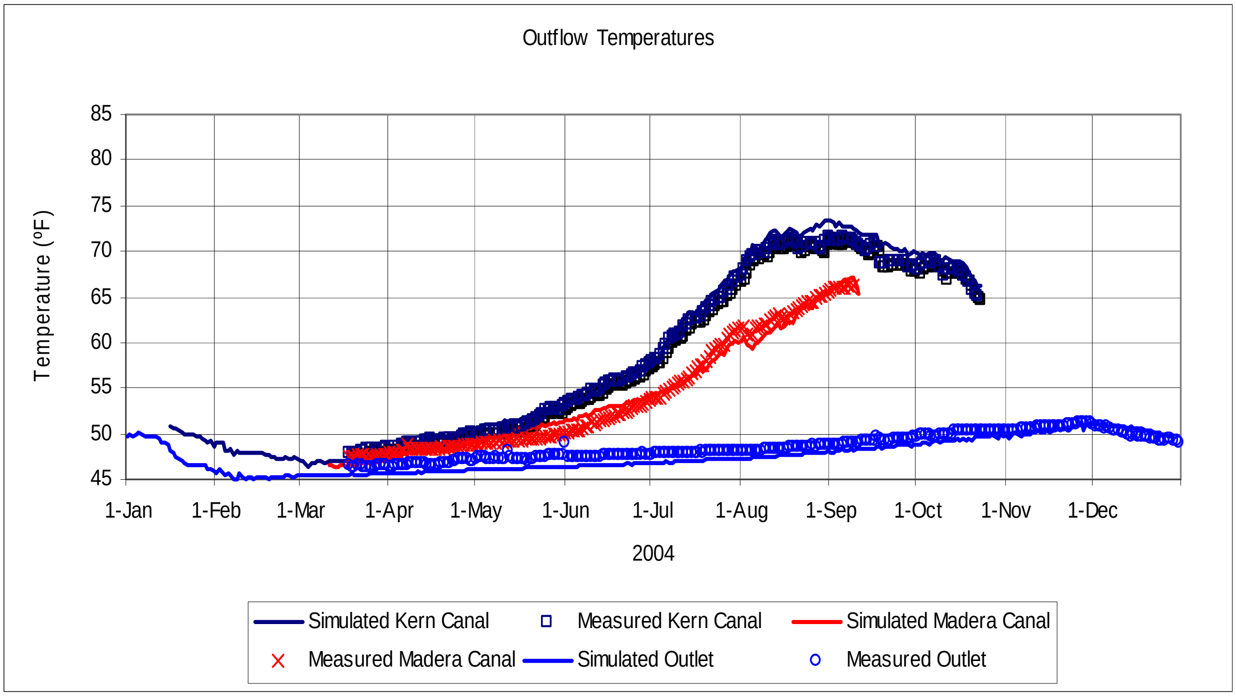


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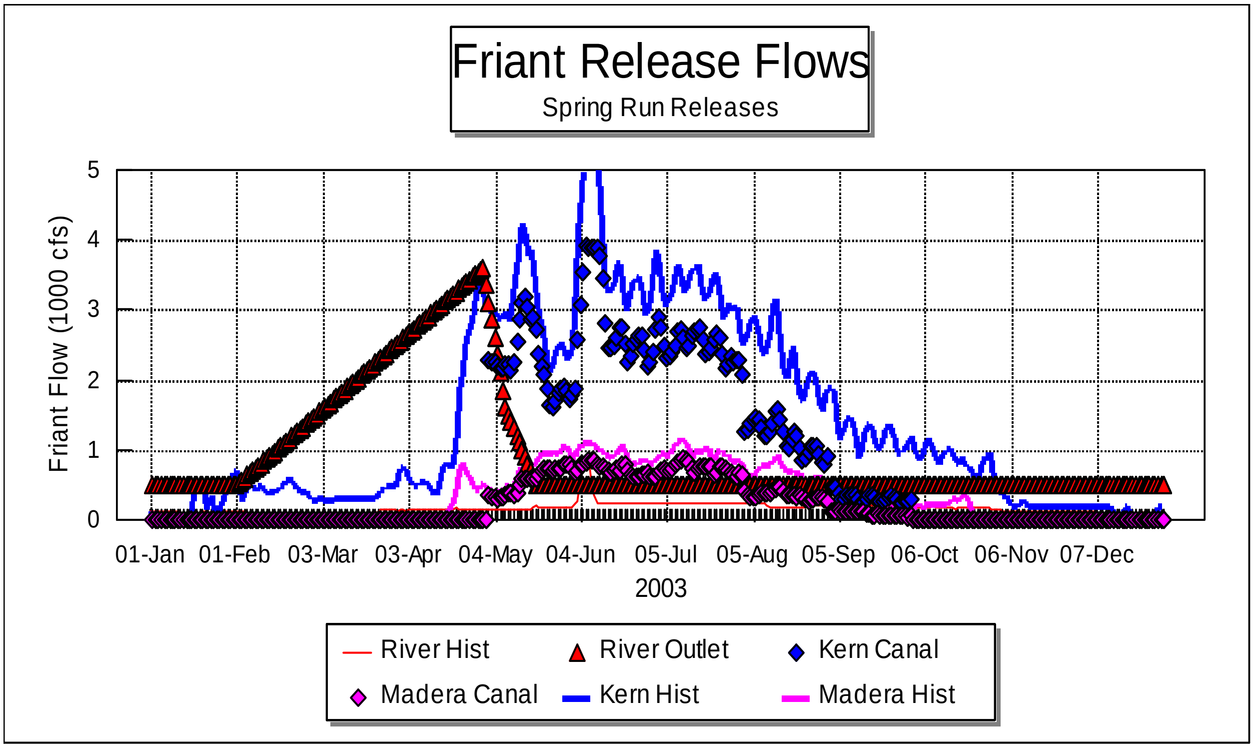
Figure 12

Simulated Millerton Lake Temperatures and Friant Dam Release Temperatures for 2004 Historical Operations Compared with Measurements of River and Canal Temperatures



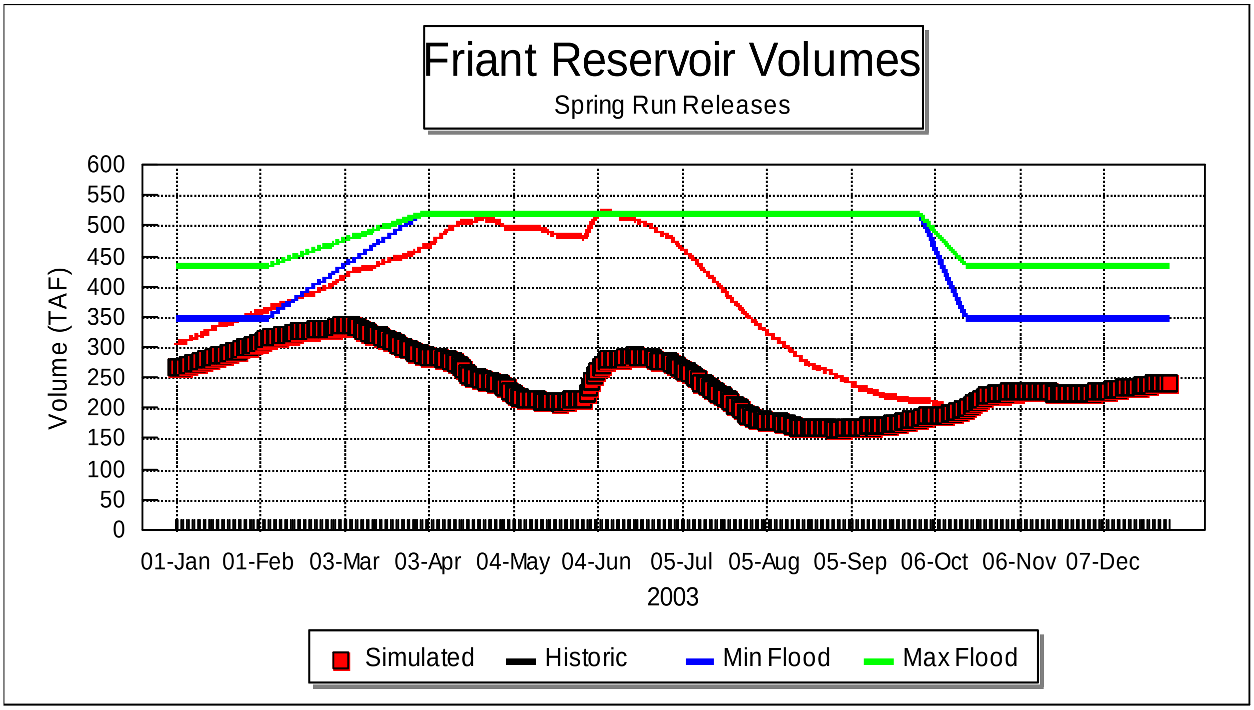


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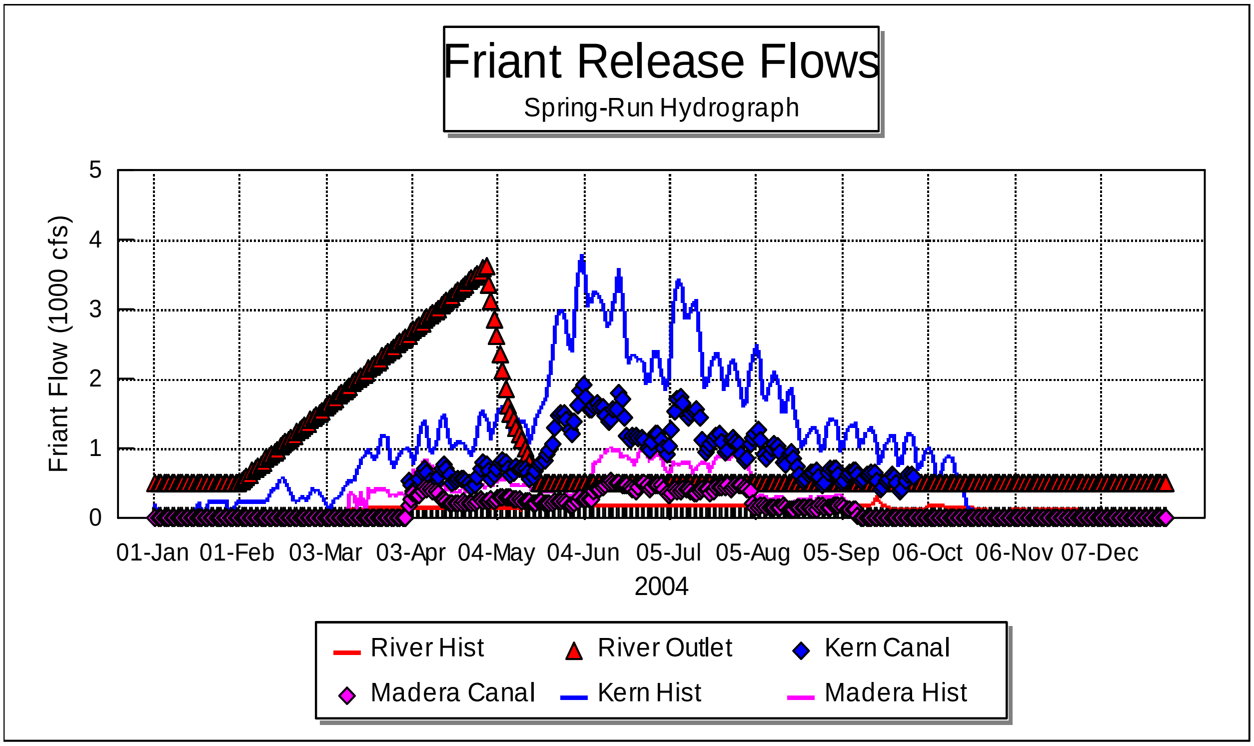
Figure 13

Simulated Friant River Release and Reduced Canal Diversions and Storage for Spring-Run Chinook Salmon Restoration Hydrograph for 2003



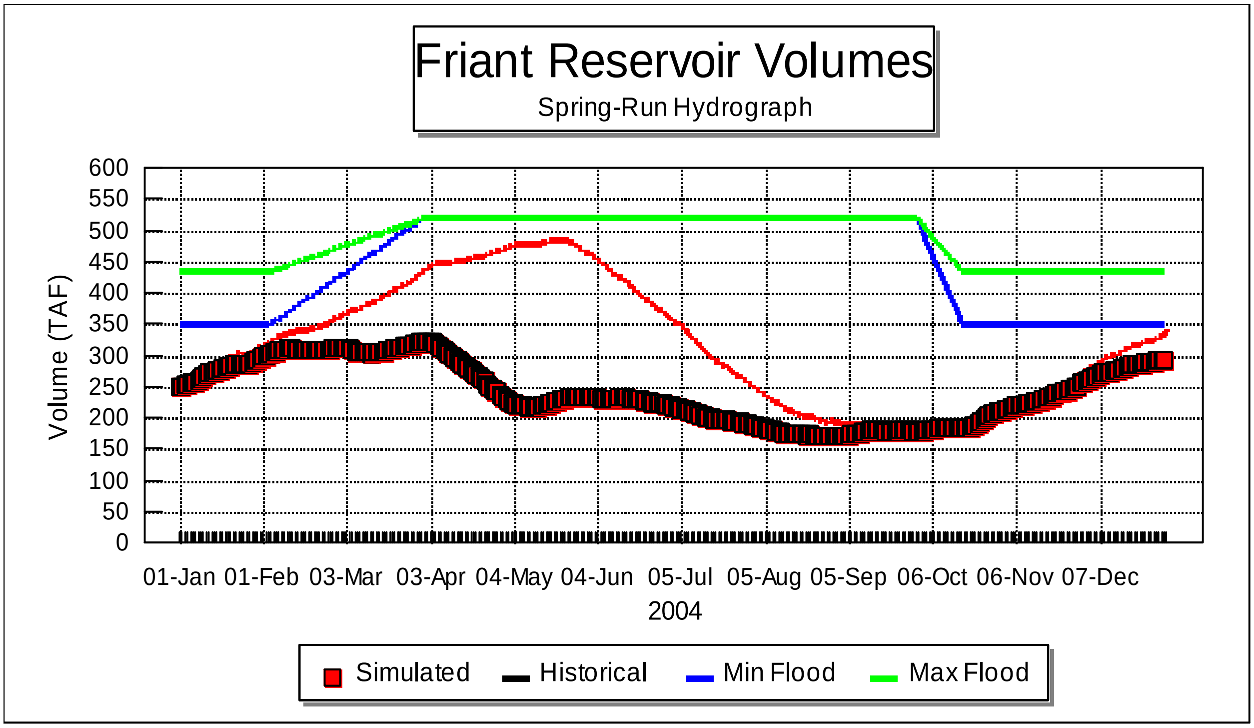


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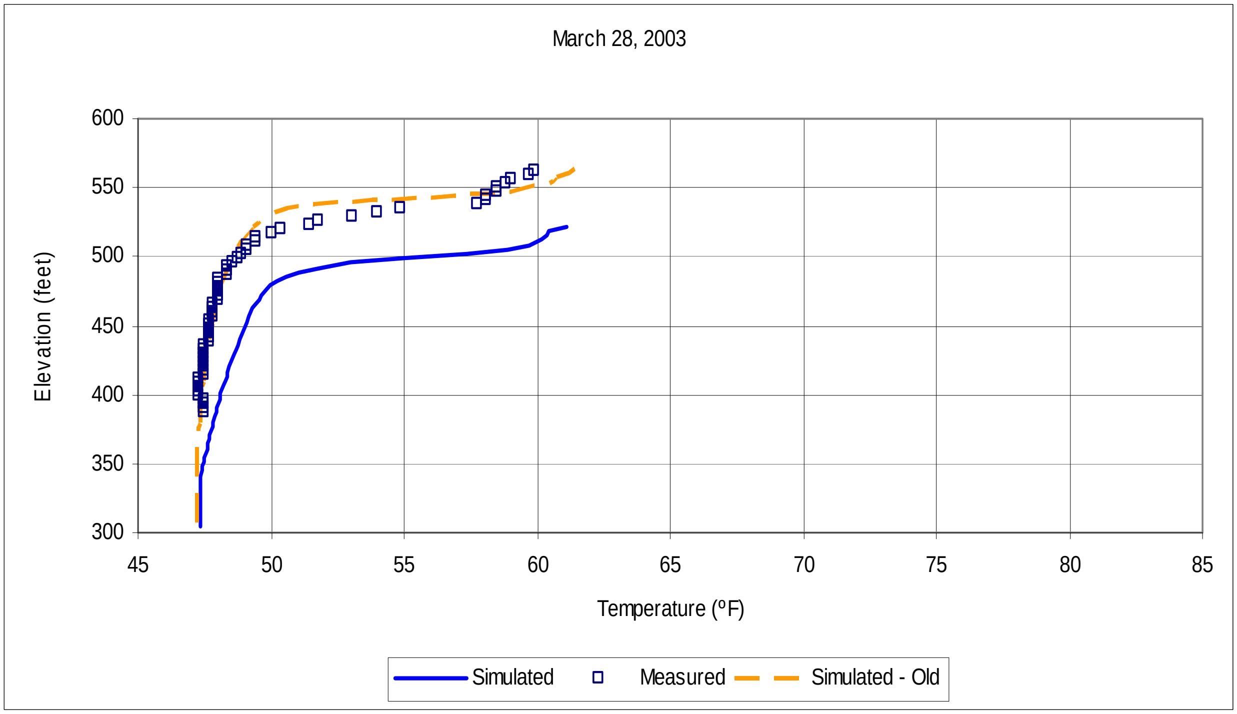
Figure 14

Simulated Friant River Release and Reduced Canal Diversions and Storage for Spring-Run Chinook Salmon Restoration Hydrograph for 2004



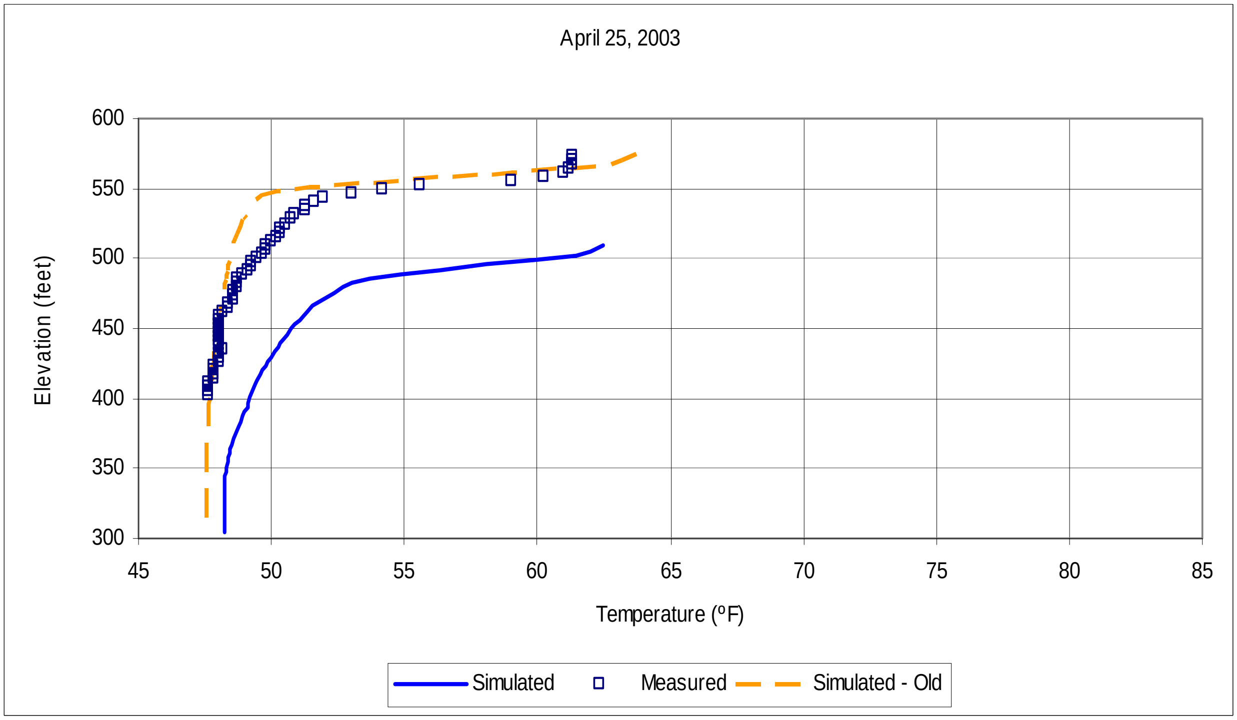


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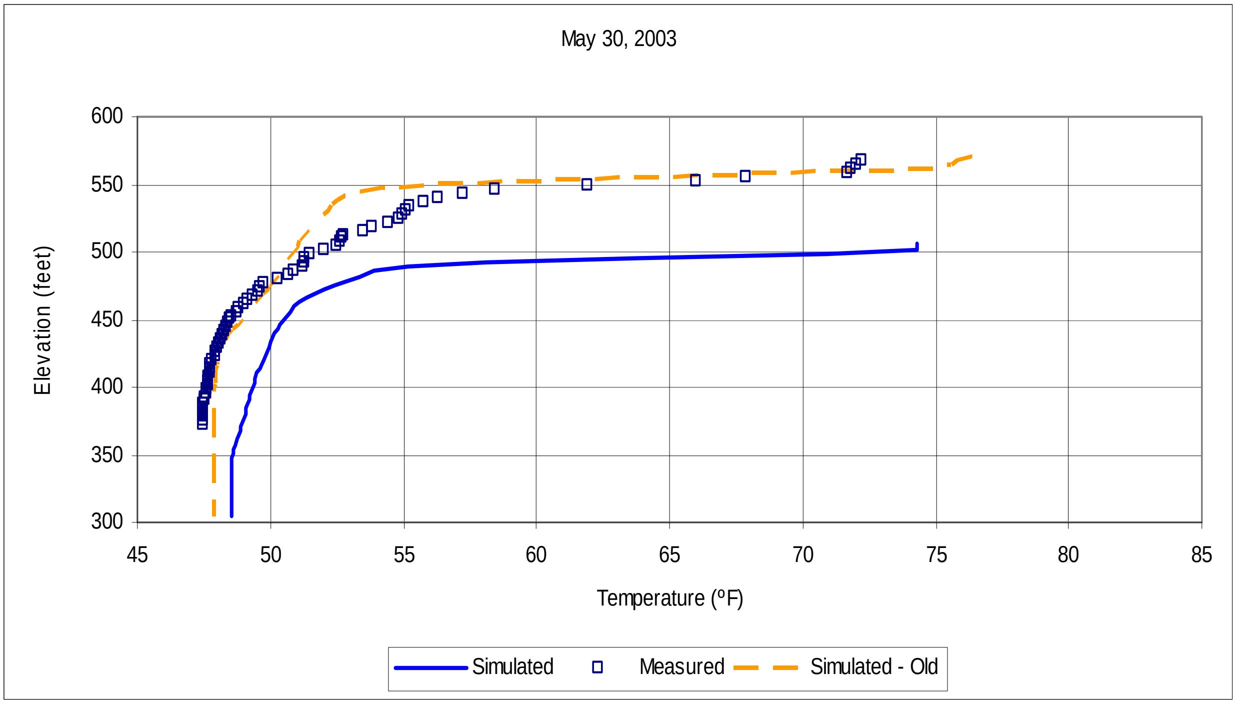
Figure 15 (Page 1 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows for 2003 Compared to Historical Temperature Simulation and Measured Data



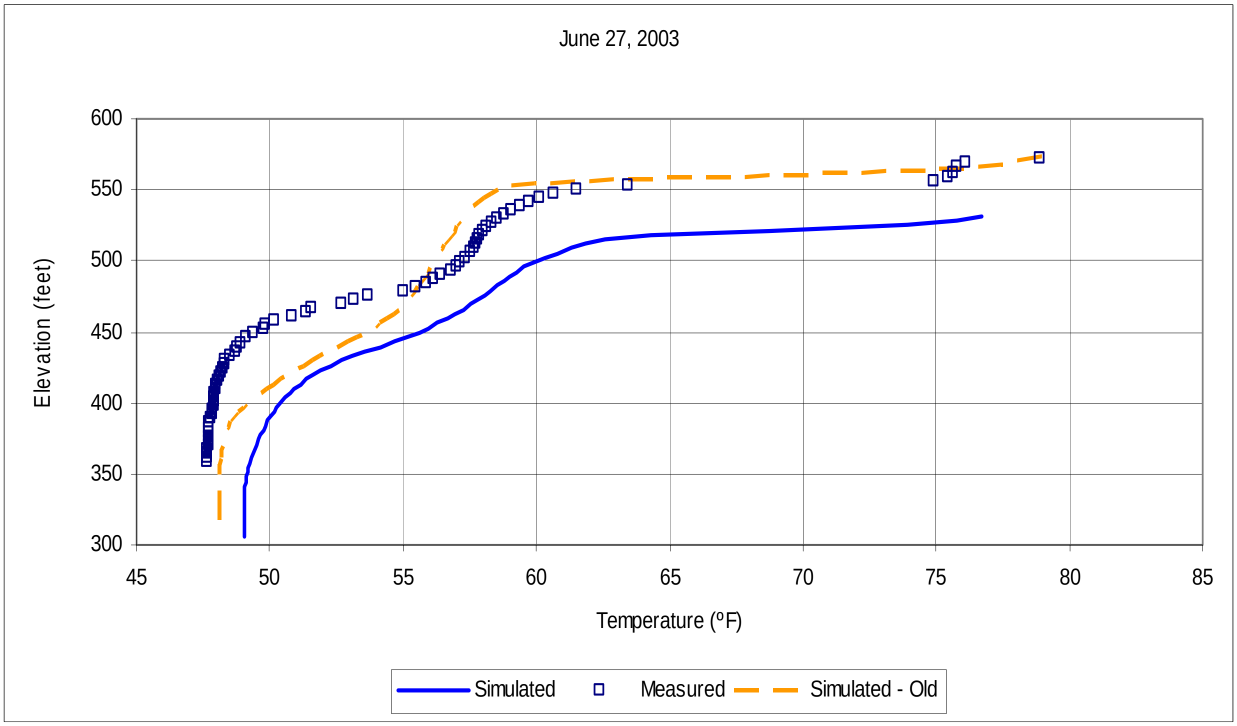


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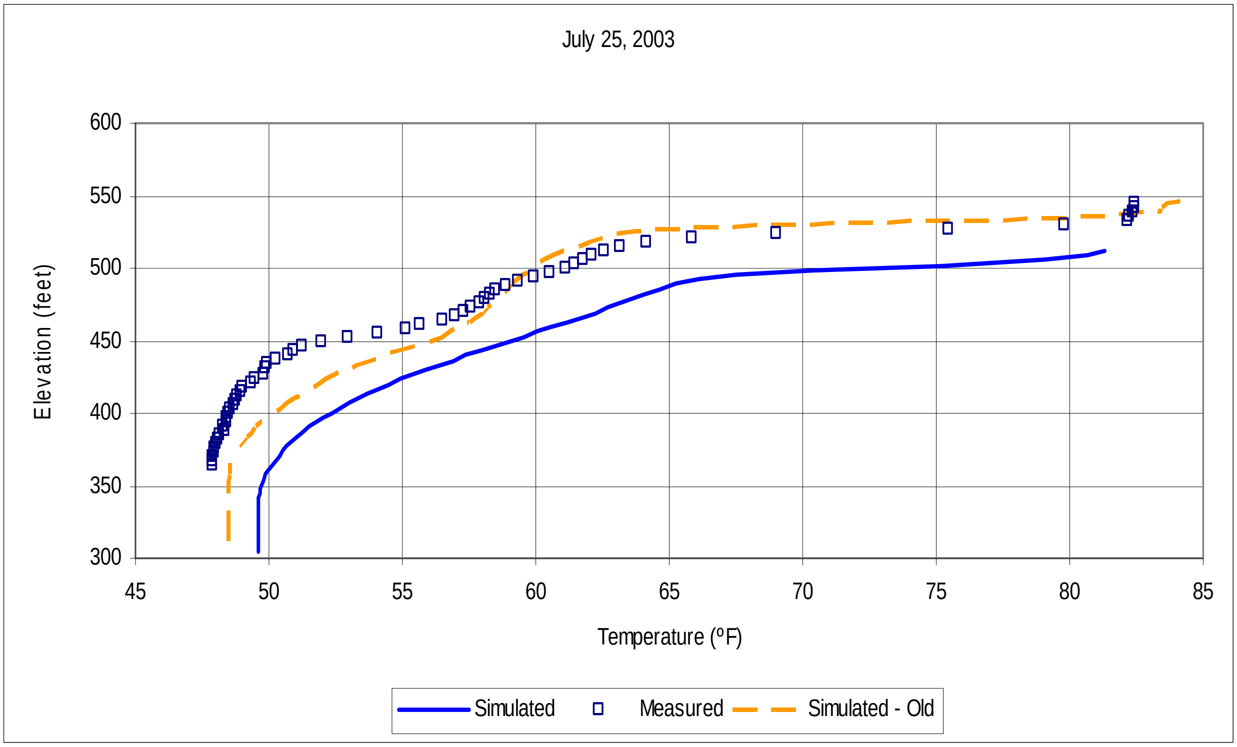
Figure 15 (Page 2 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows for 2003 Compared to Historical Temperature Simulation and Measured Data



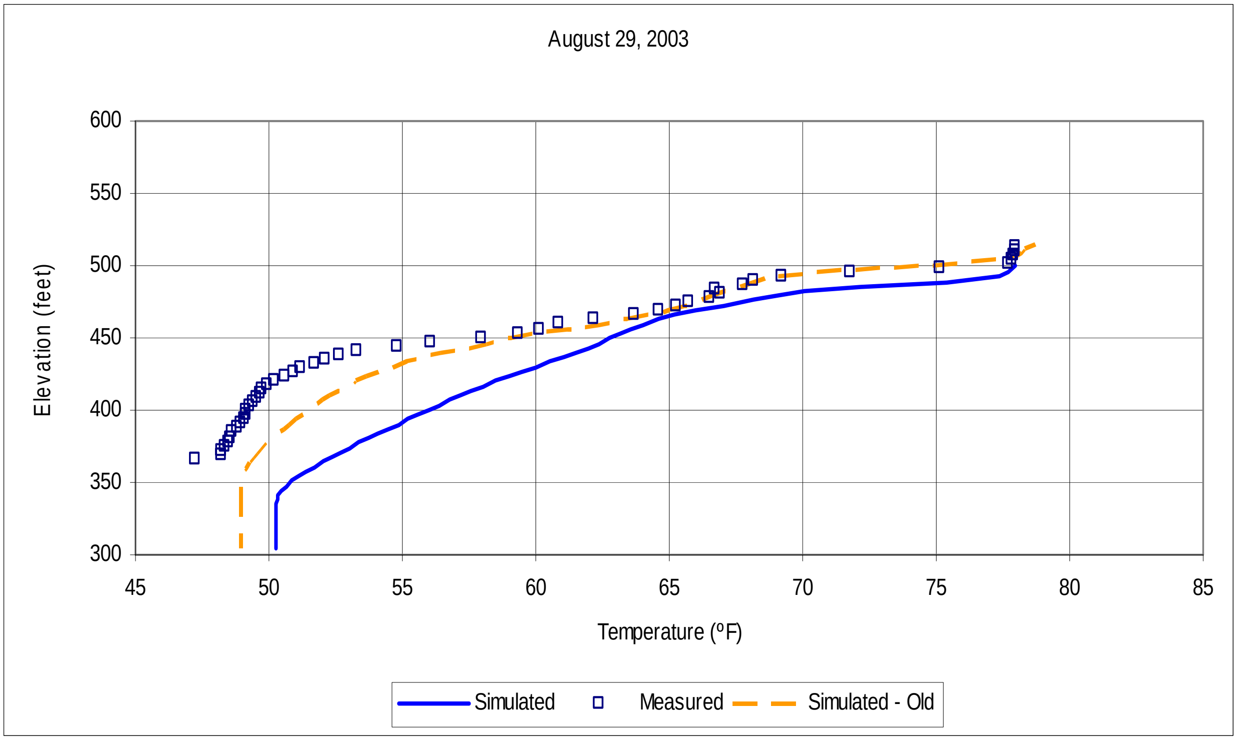
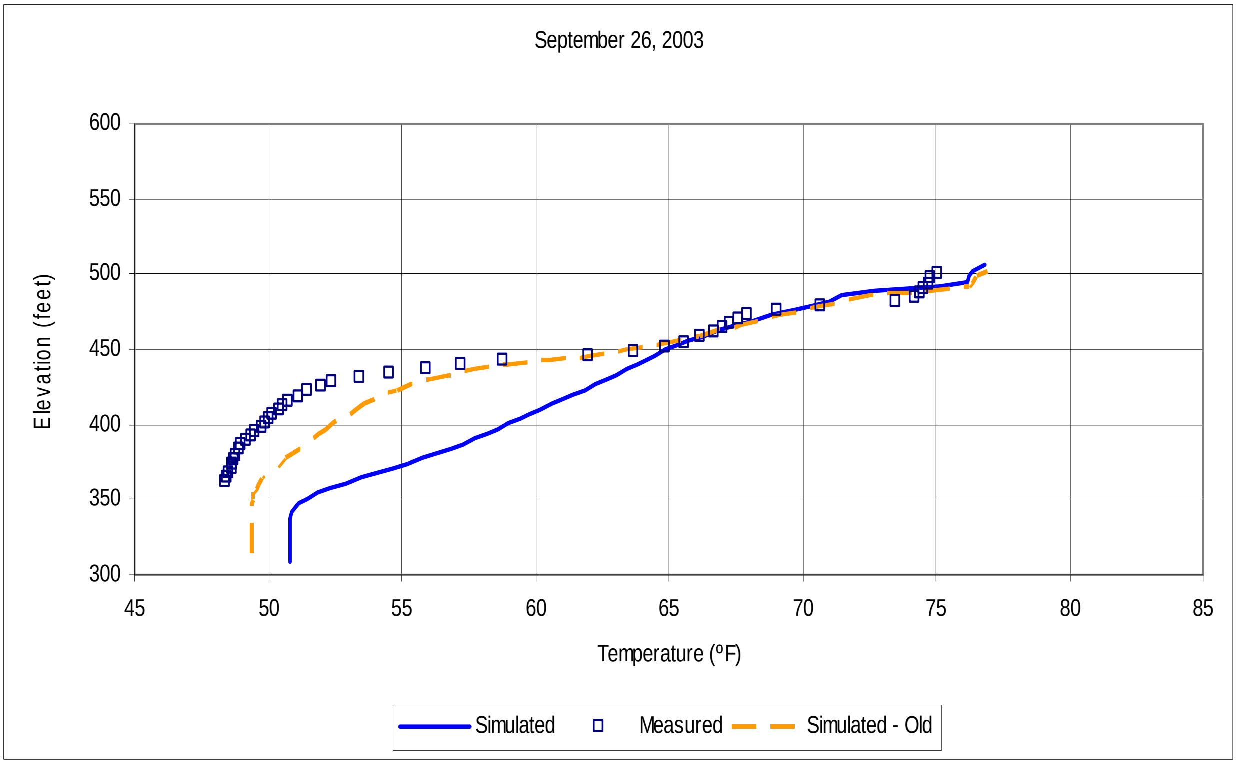


Figure 15 (Page 3 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows for 2003 Compared to Historical Temperature Simulation and Measured Data



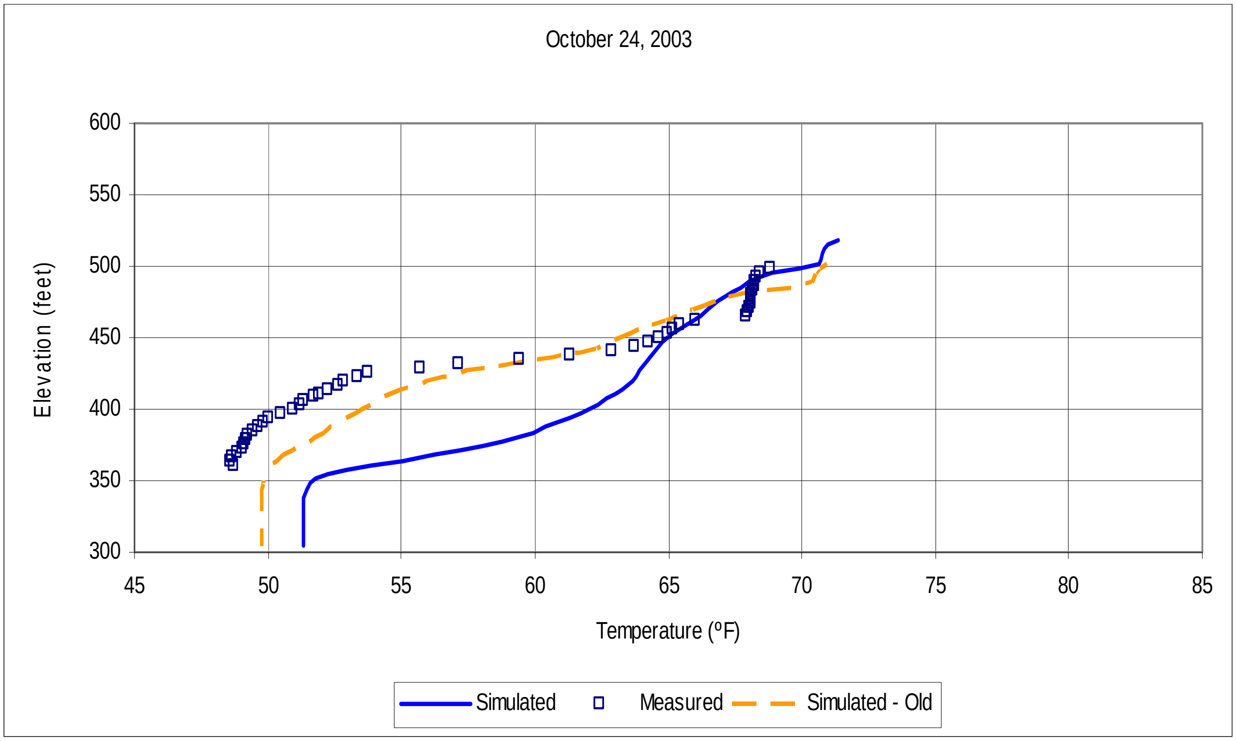


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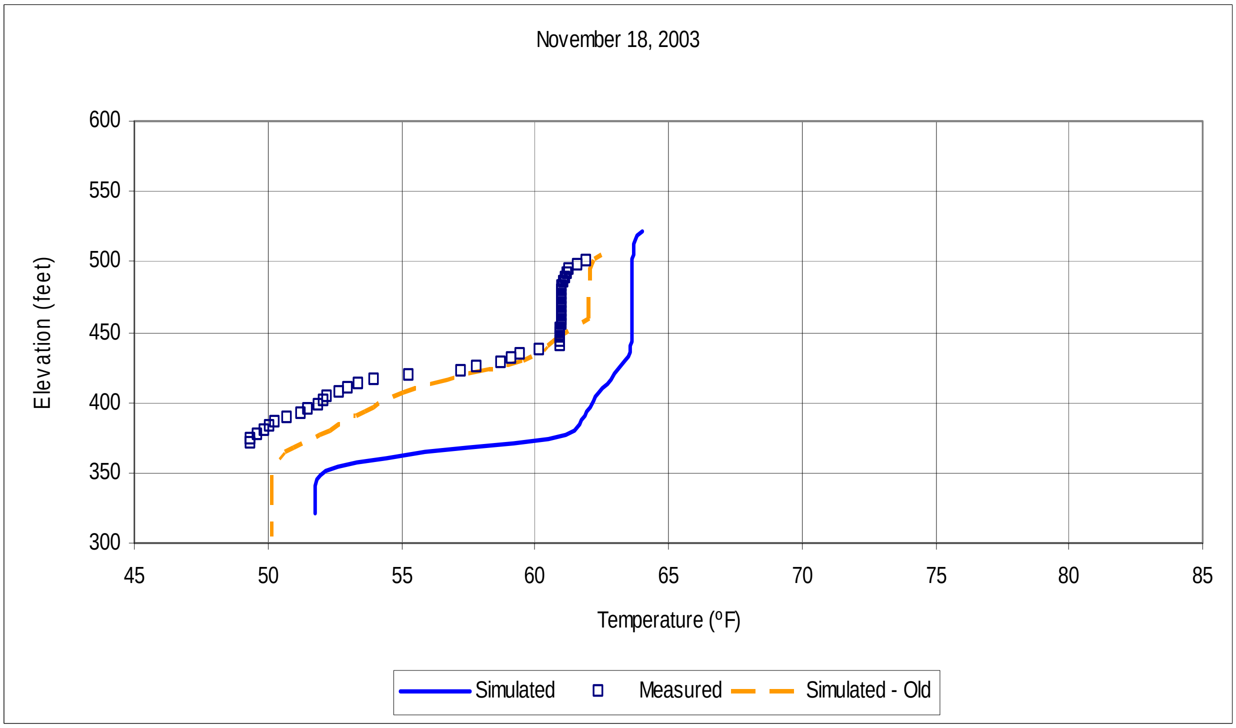
Figure 15 (Page 4 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows for 2003 Compared to Historical Temperature Simulation and Measured Data



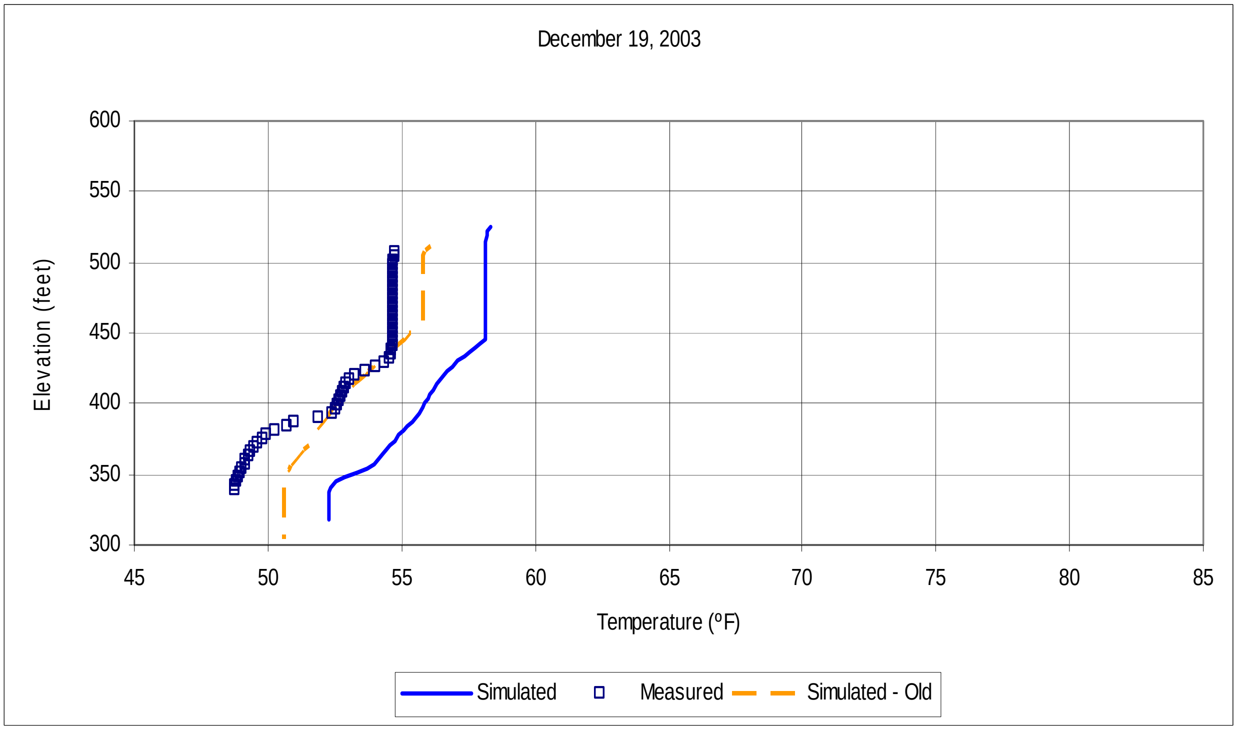


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Figure 15 (Page 5 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows for 2003 Compared to Historical Temperature Simulation and Measured Data

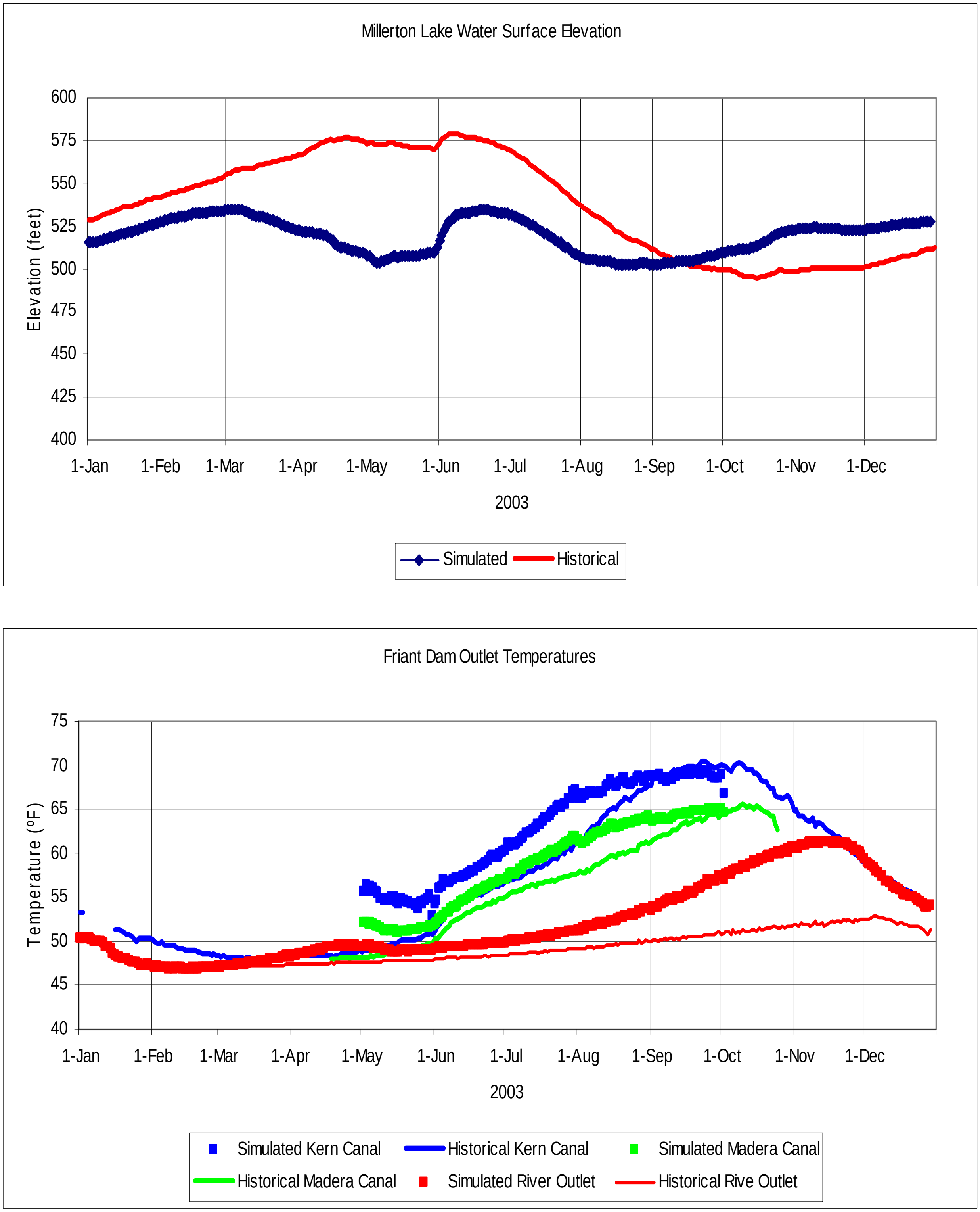

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Figure 16

Simulation of Millerton Lake Elevation and Outlet Temperatures with Spring-Run Chinook Salmon River Restoration Outflows for 2003 Compared to Historical Outlet Temperature Simulations

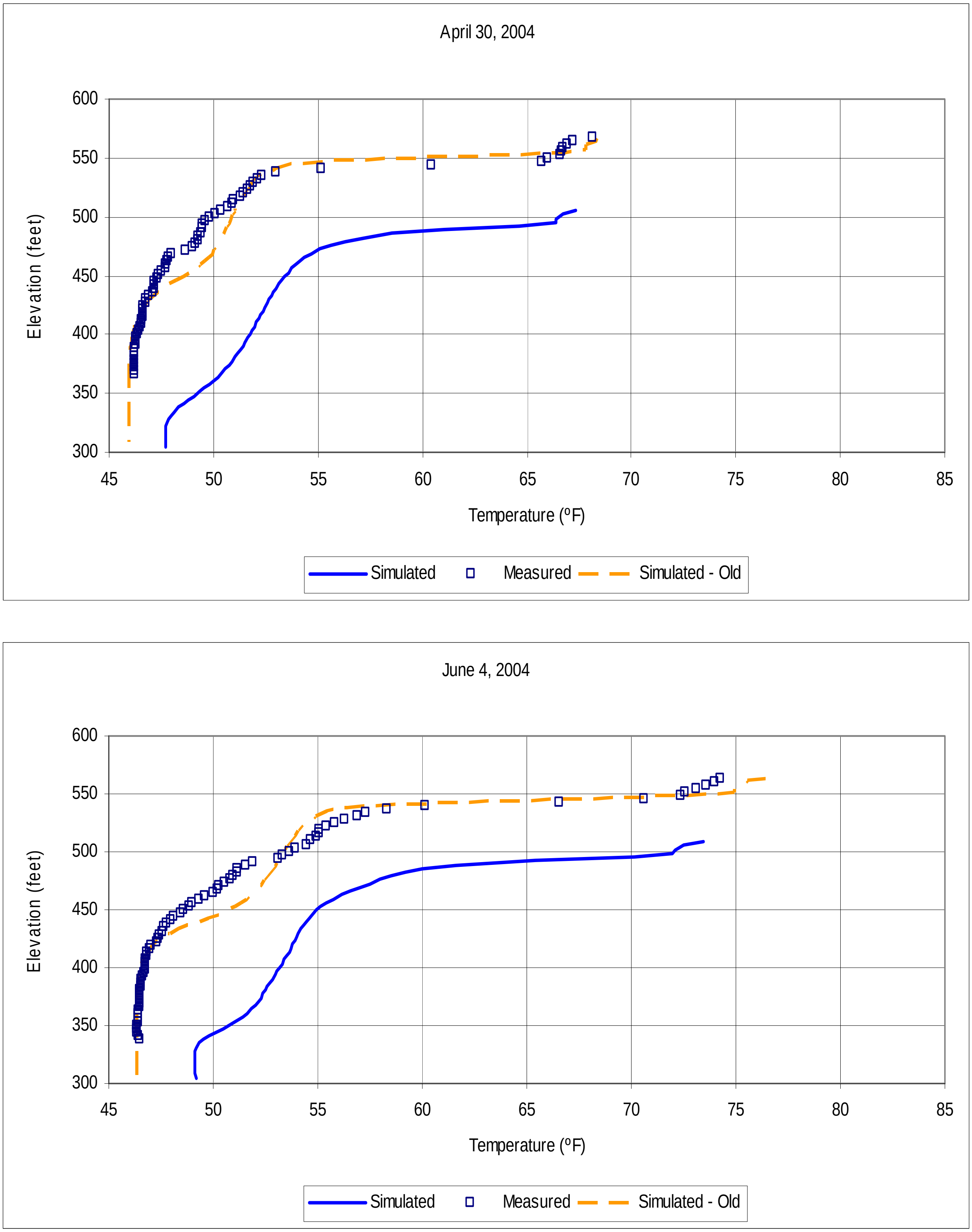

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Figure 17 (Page 1 of 3)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows for 2004 Compared to Historical Temperature Simulation and Measured Data

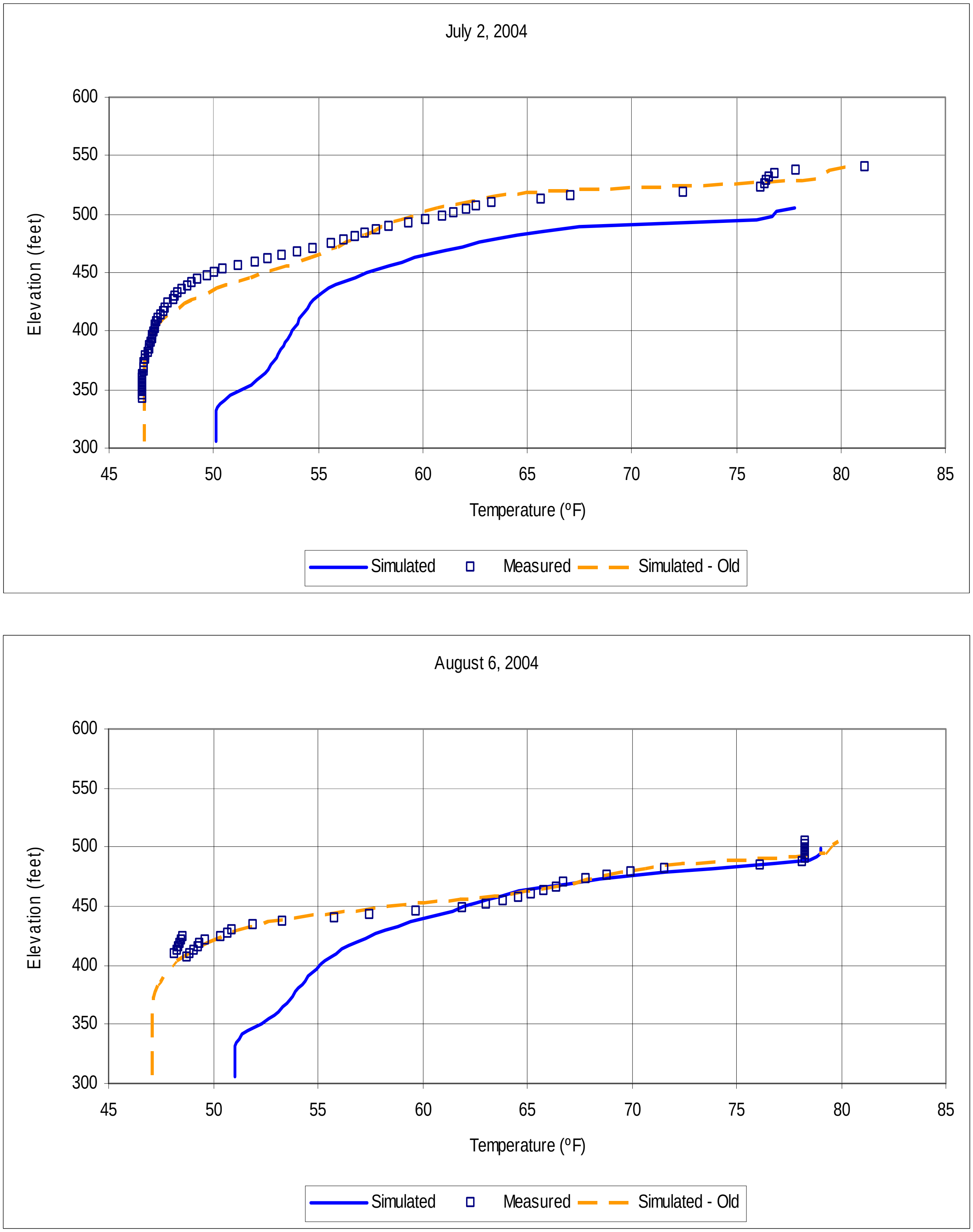

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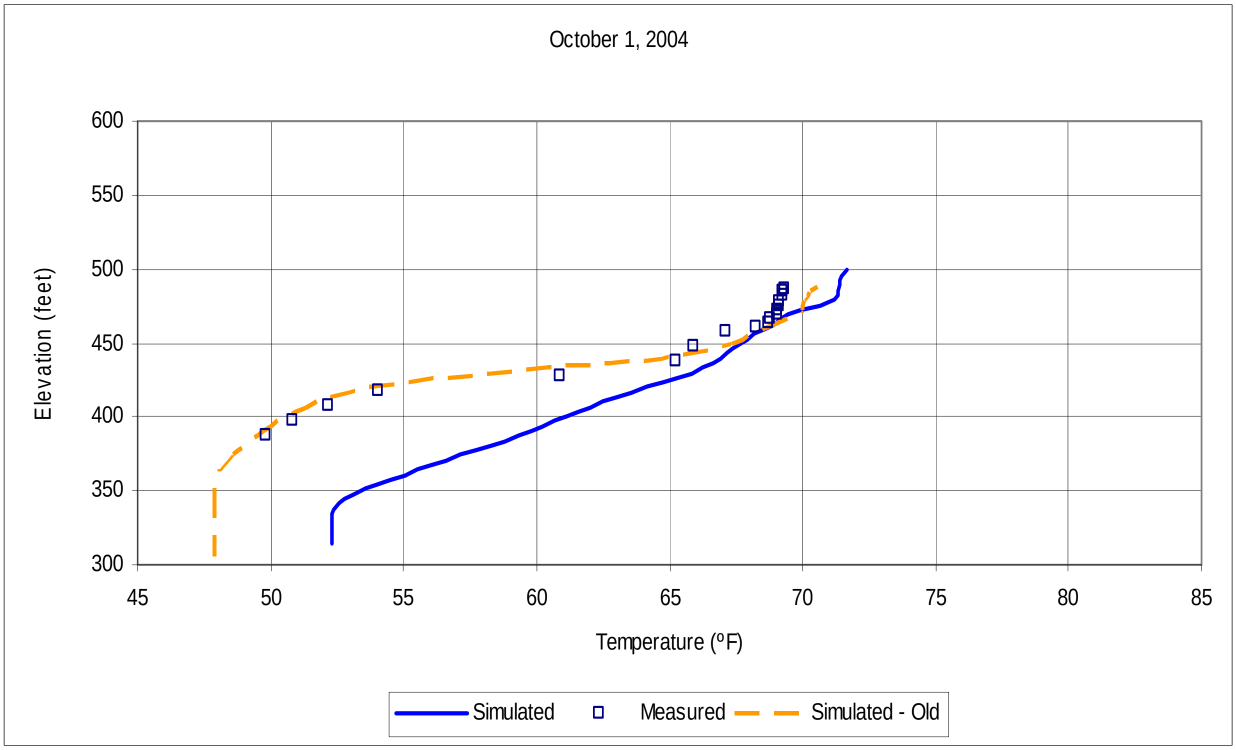
Figure 17 (Page 2 of 3)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows for 2004 Compared to Historical Temperature Simulation and Measured Data



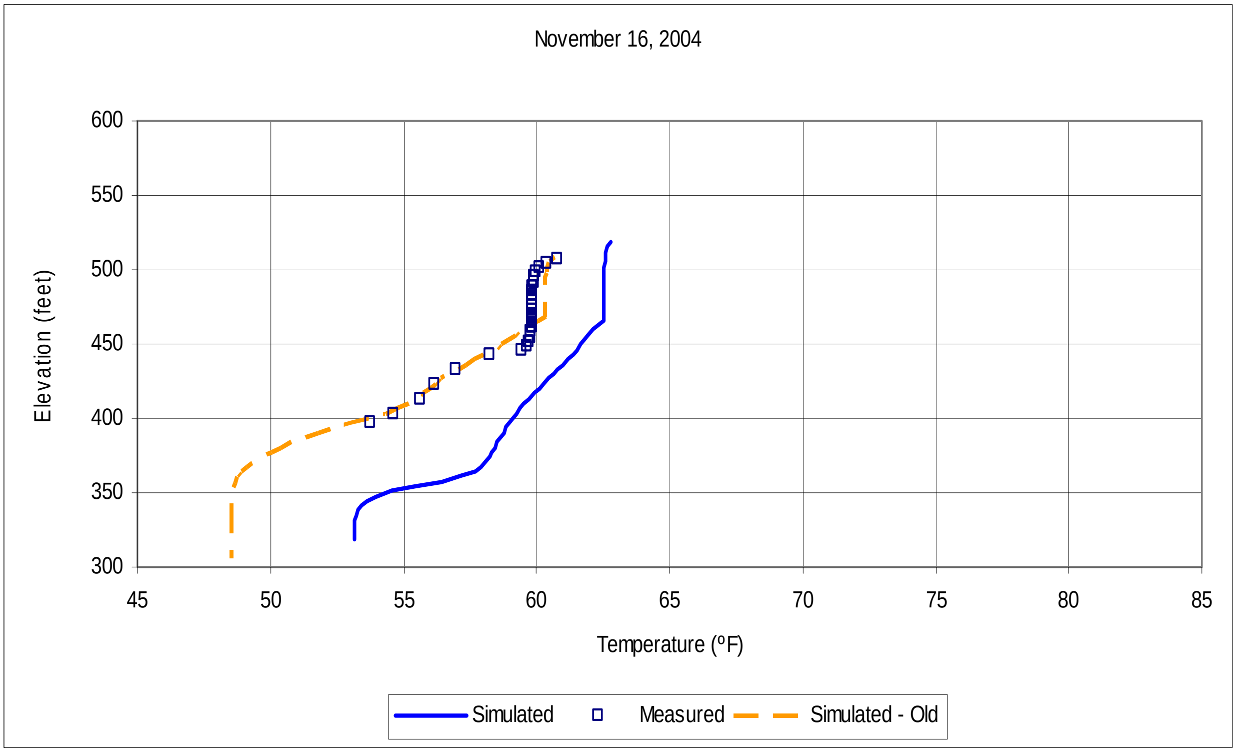


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Figure 17 (Page 3 of 3)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows for 2004 Compared to Historical Temperature Simulation and Measured Data

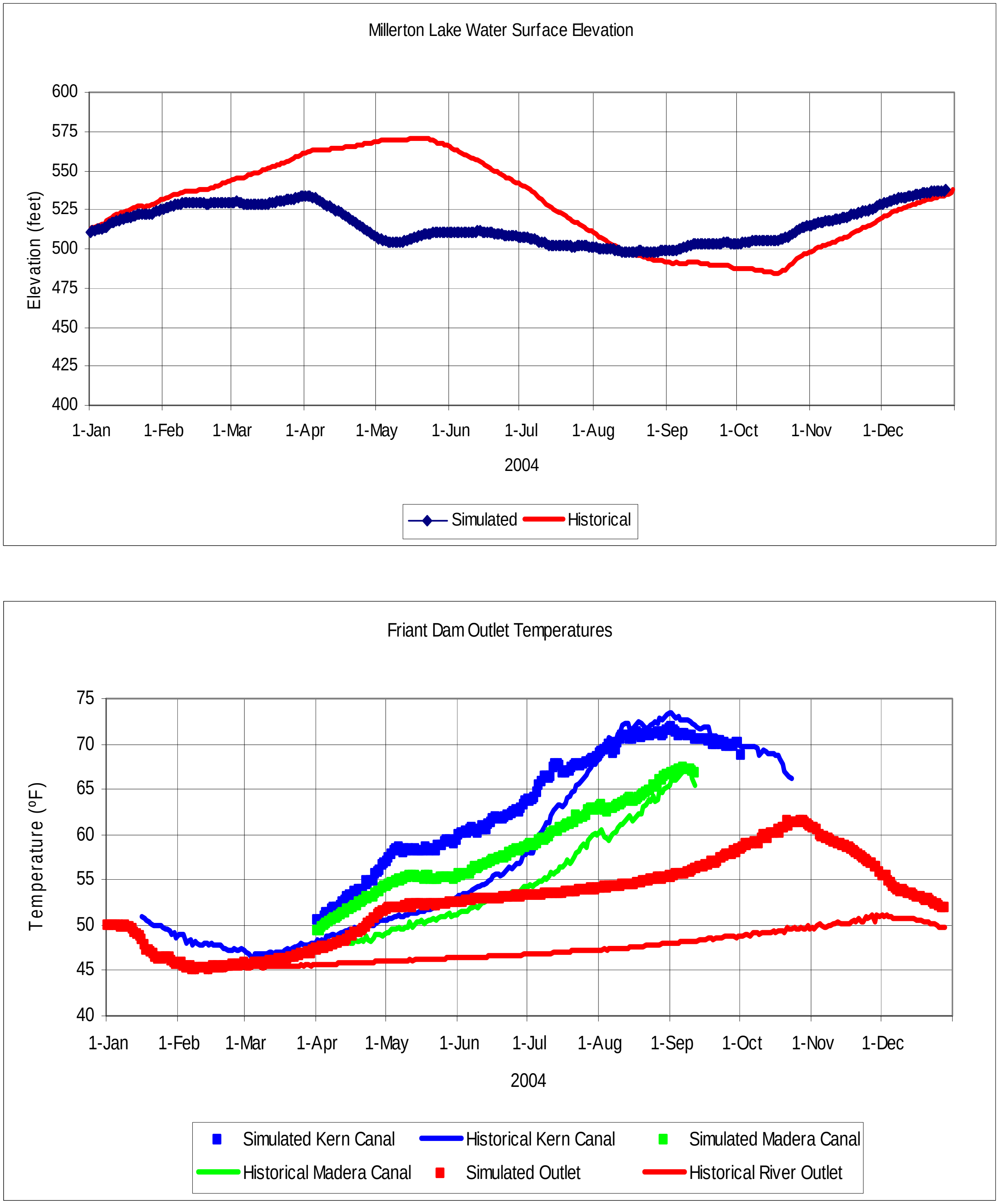

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Figure 18

Simulation of Millerton Lake Elevation and Outlet Temperatures with Spring-Run Chinook Salmon River Restoration Outflows for 2004 Compared to Historical Outlet Temperature Simulations

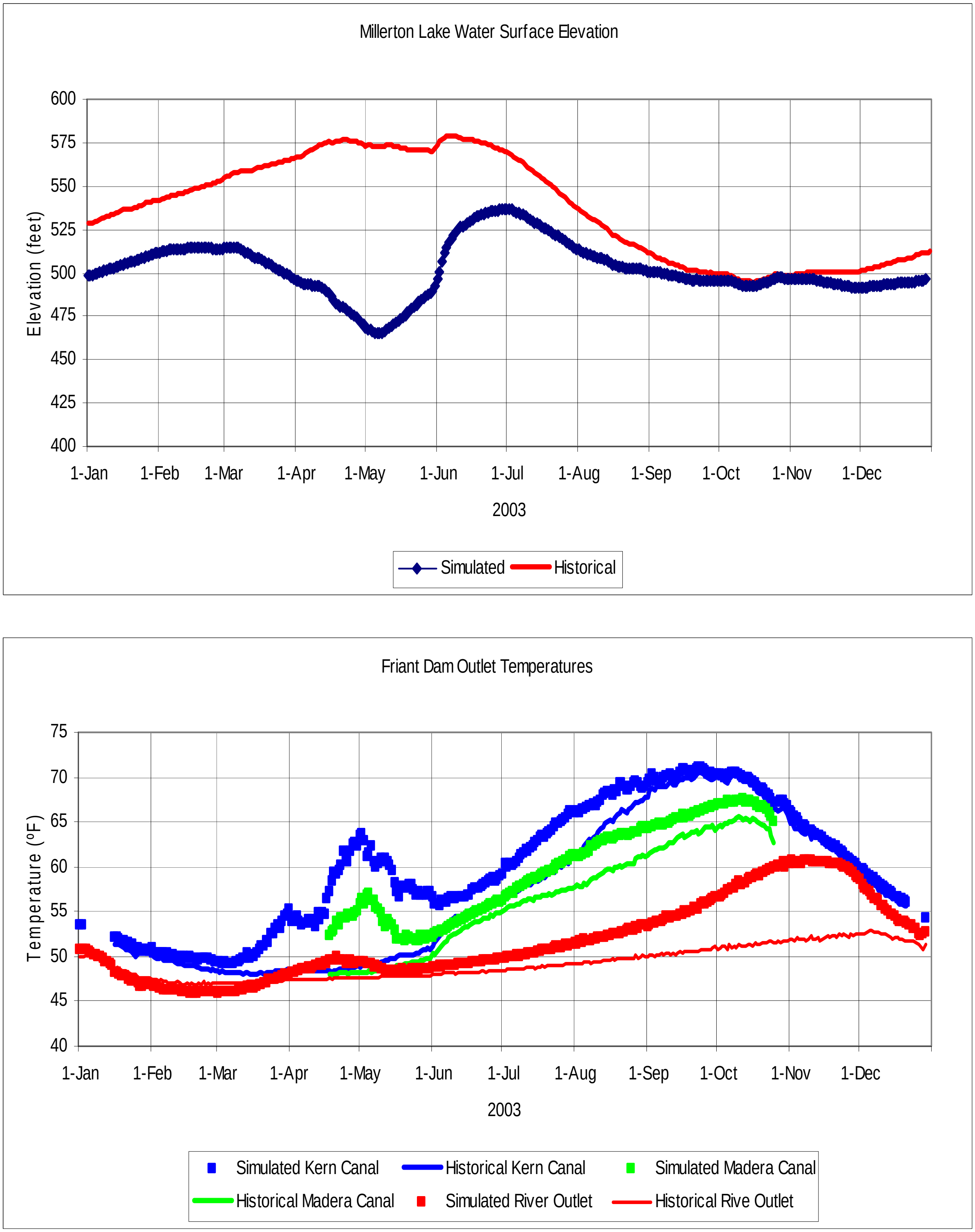

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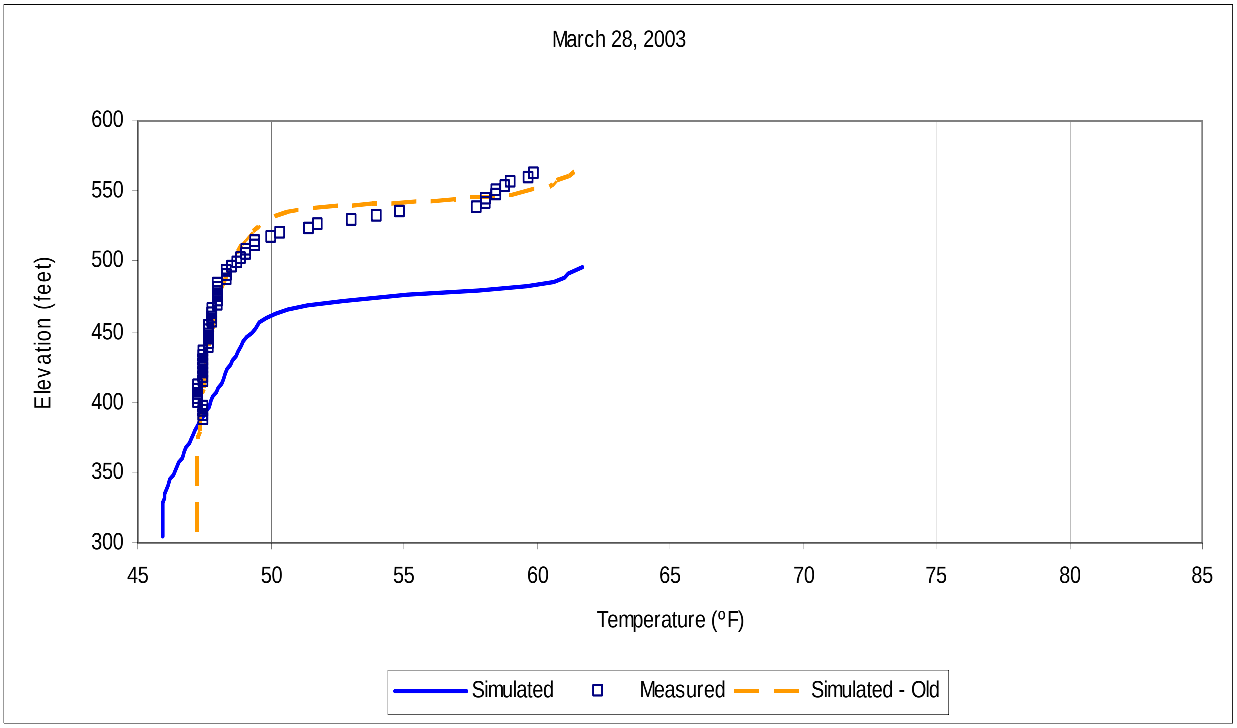
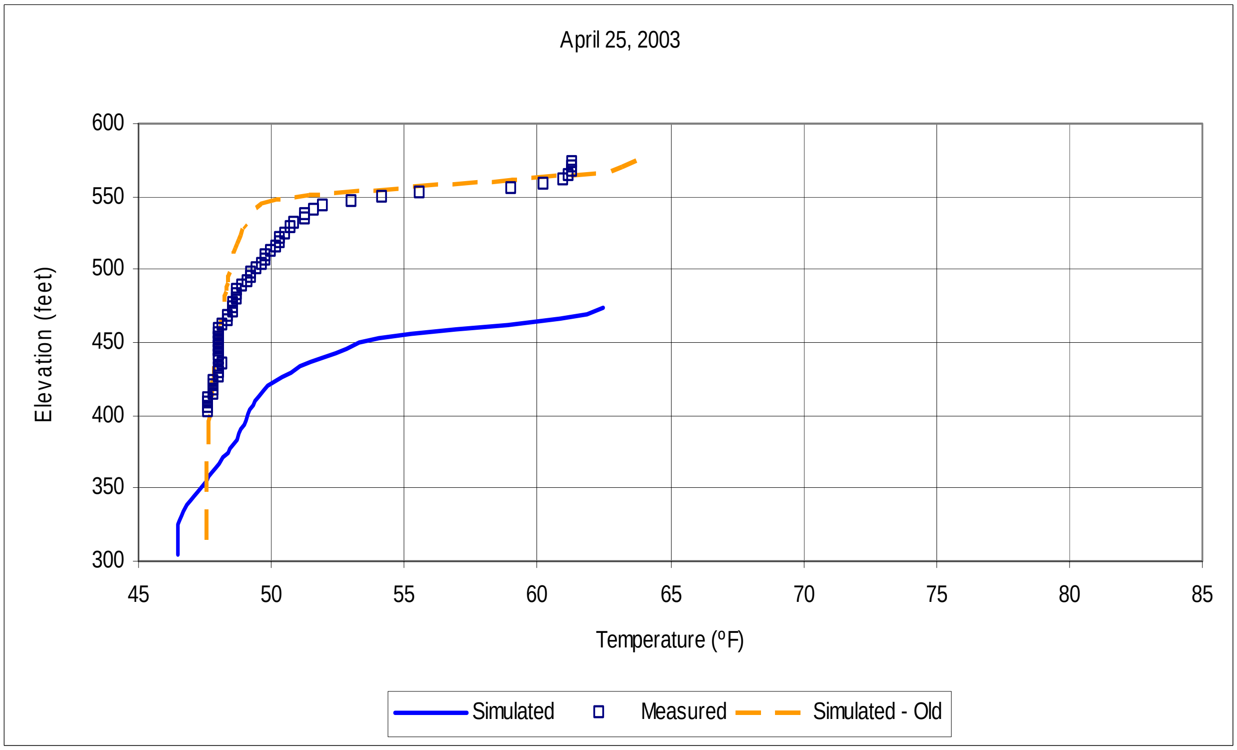
Figure 19

Simulation of Millerton Lake Surface Elevation and Outlet Temperatures with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2003 Compared to Historical Surface Elevation and Outlet Temperature Simulations





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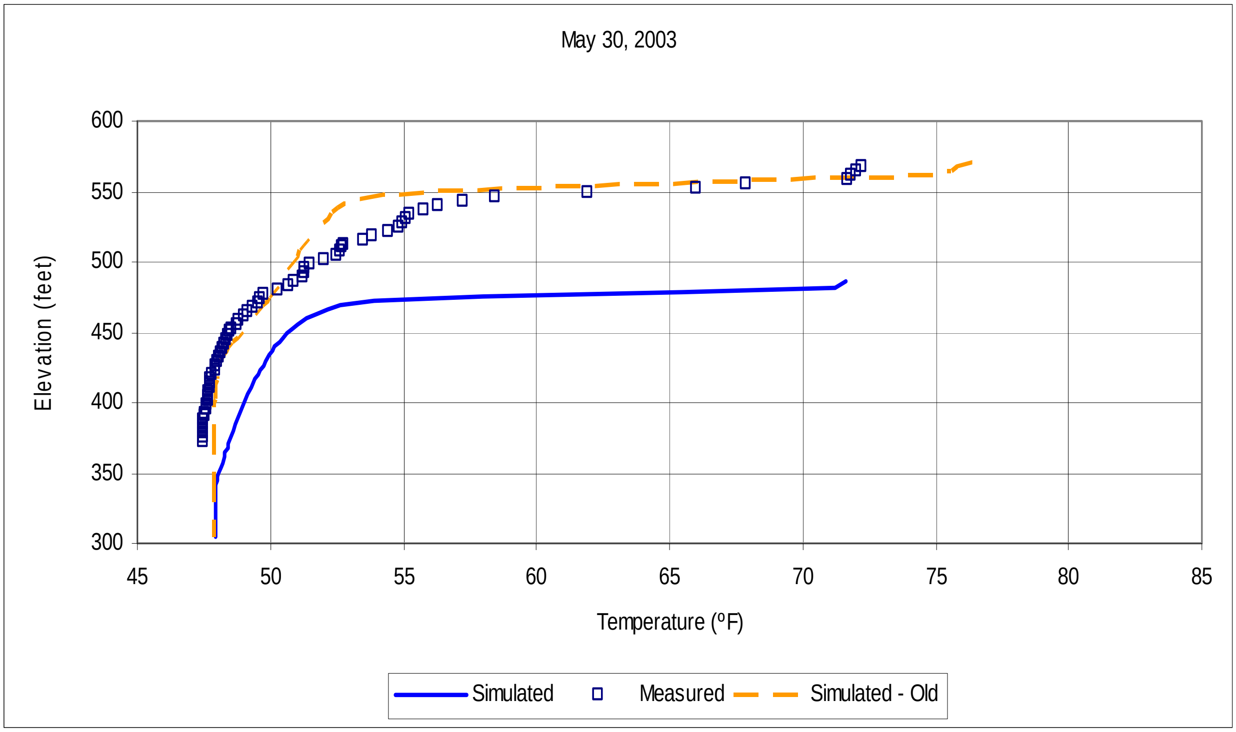
Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2003 Compared to Historical Temperature Simulation and Measured Data



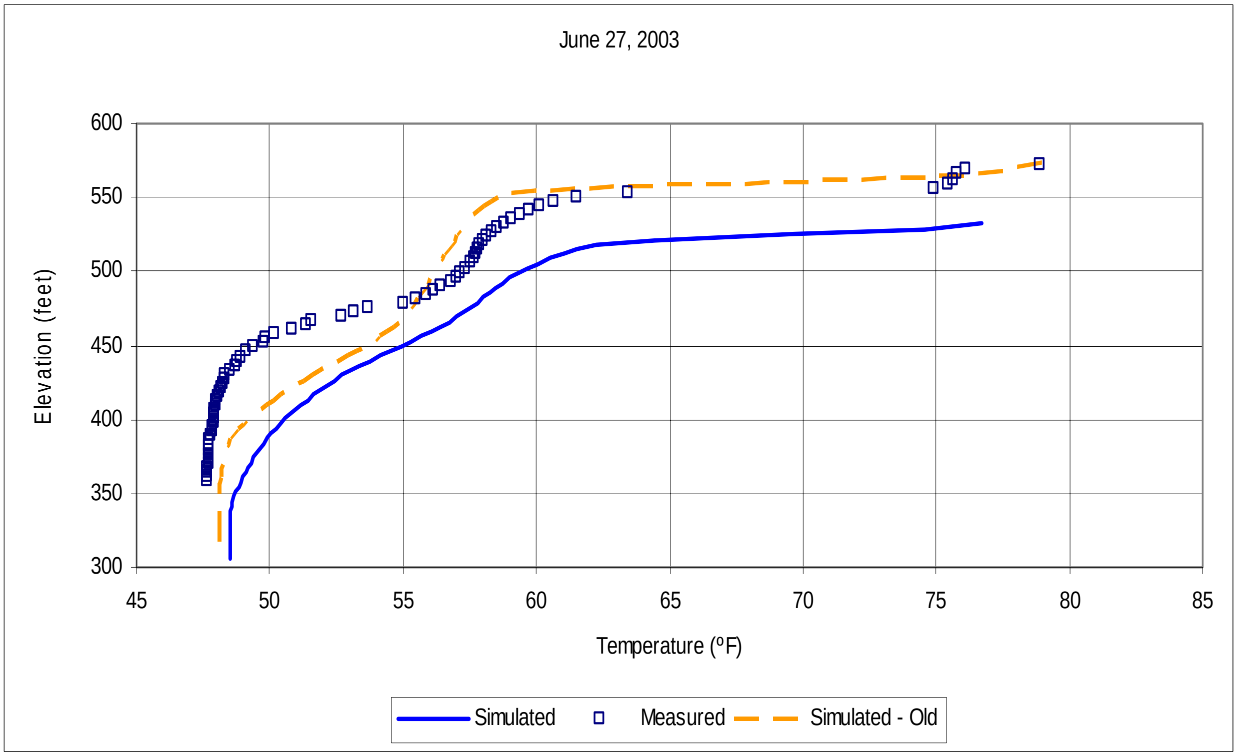


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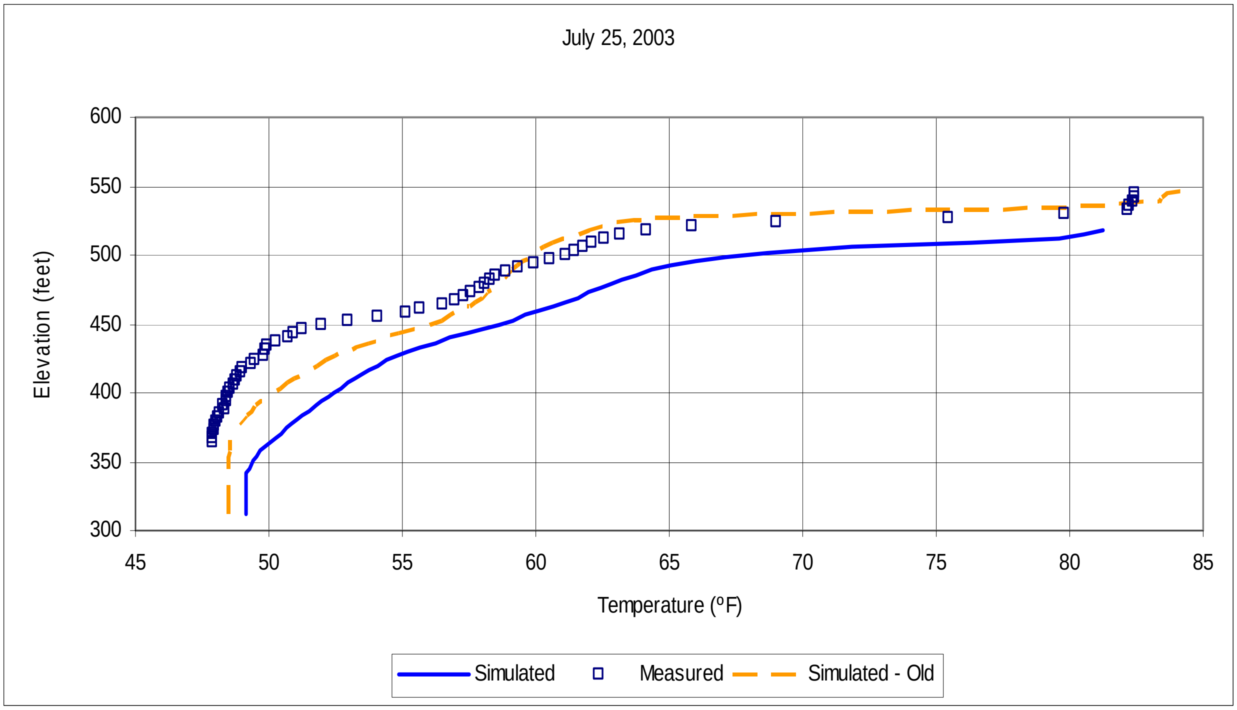
Figure 20 (Page 2 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2003 Compared to Historical Temperature Simulation and Measured Data



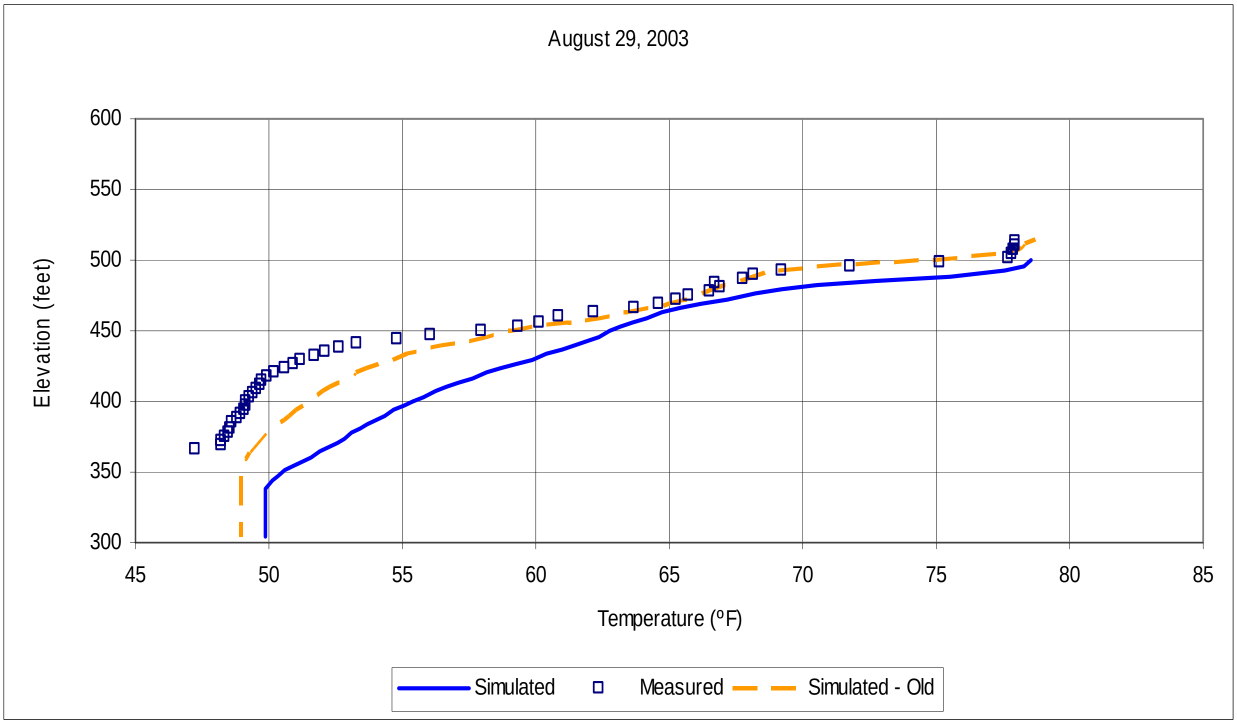


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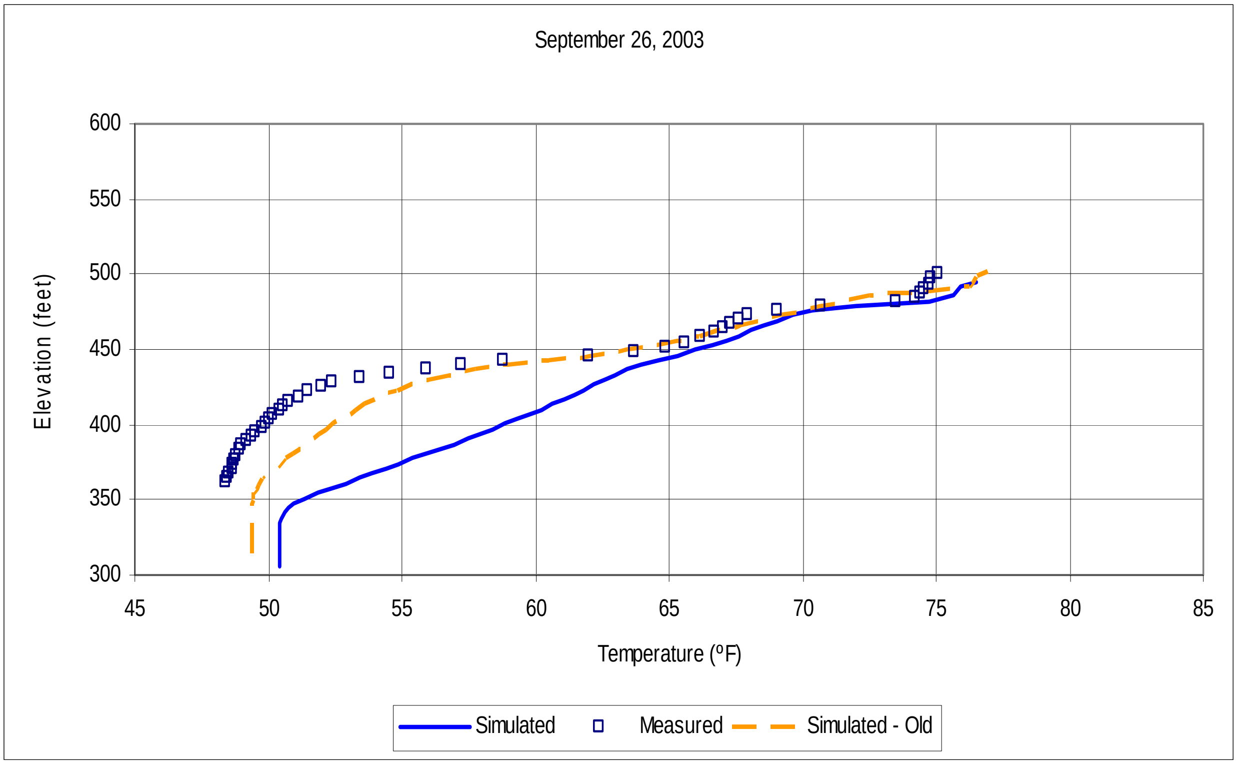
Figure 20 (Page 3 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2003 Compared to Historical Temperature Simulation and Measured Data



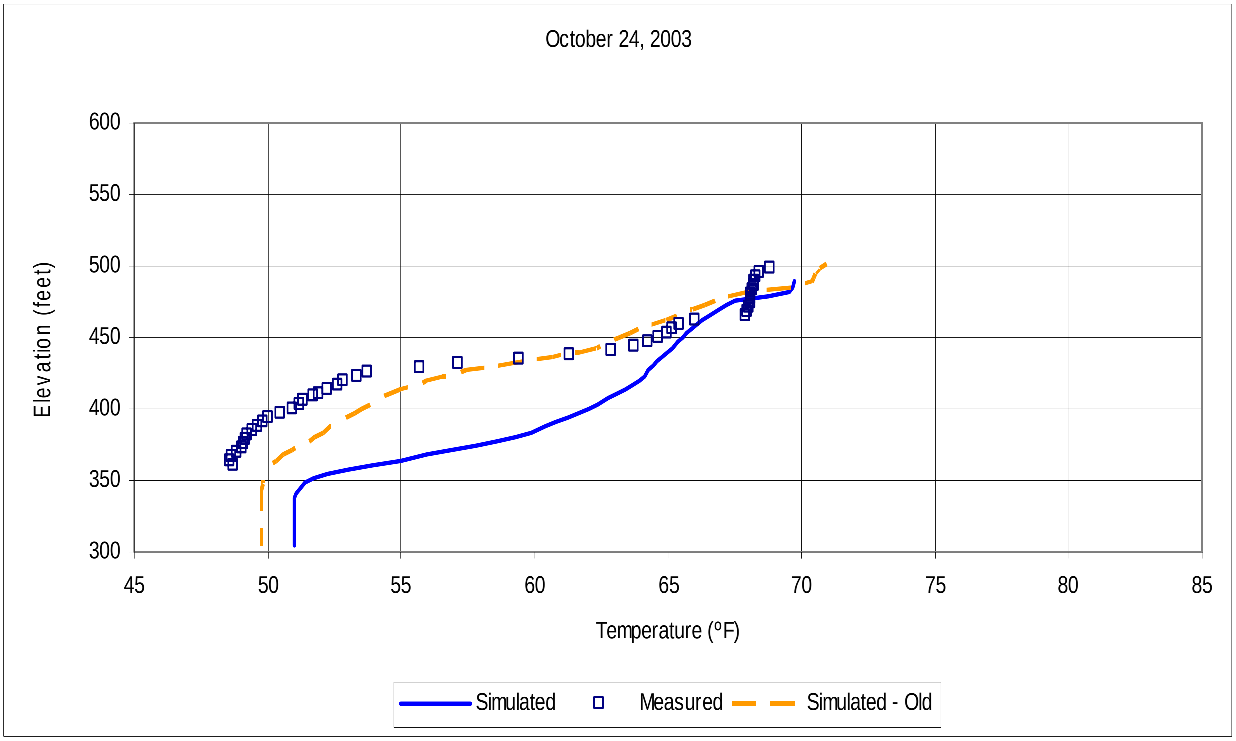


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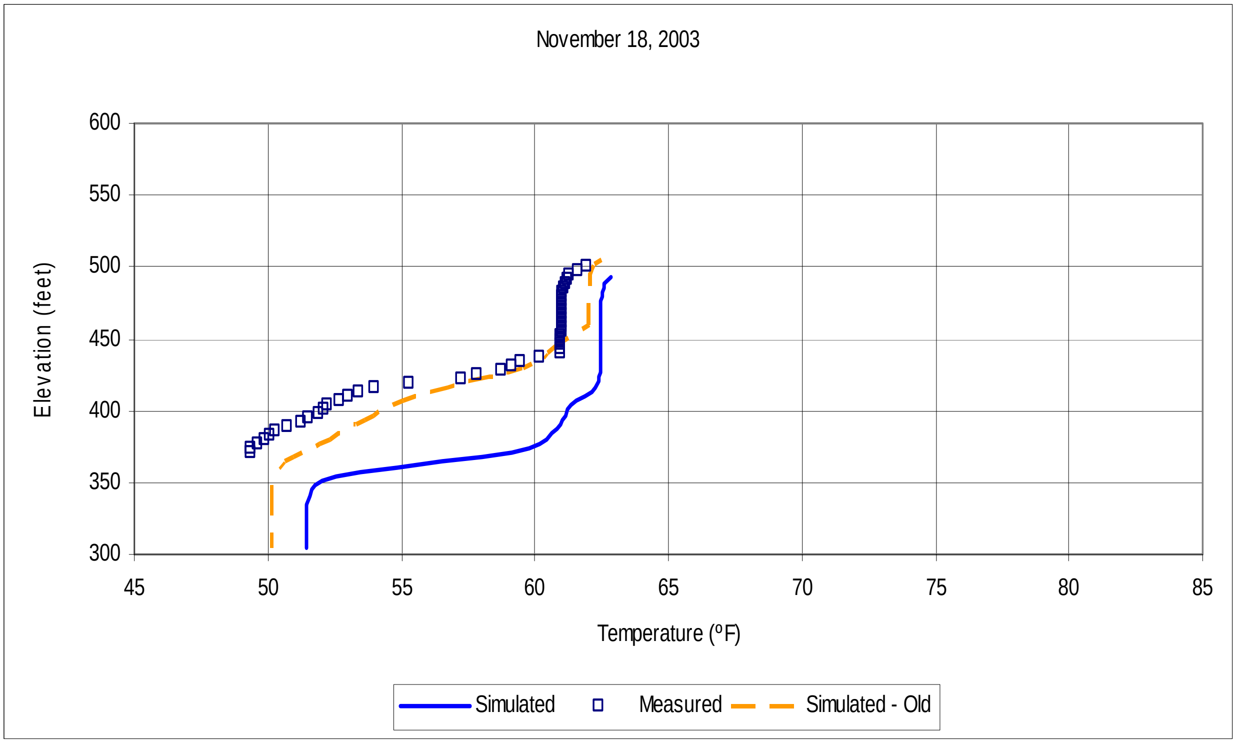
Figure 20 (Page 4 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2003 Compared to Historical Temperature Simulation and Measured Data



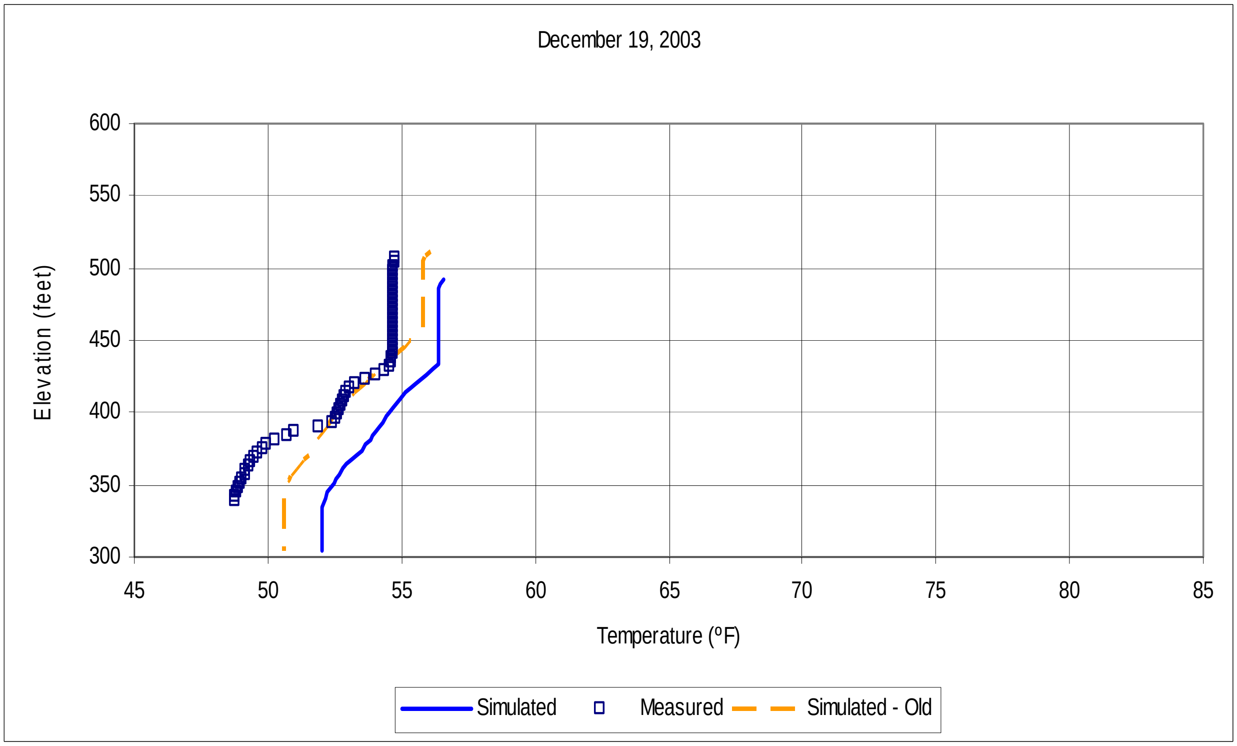


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Figure 20 (Page 5 of 5)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2003 Compared to Historical Temperature Simulation and Measured Data

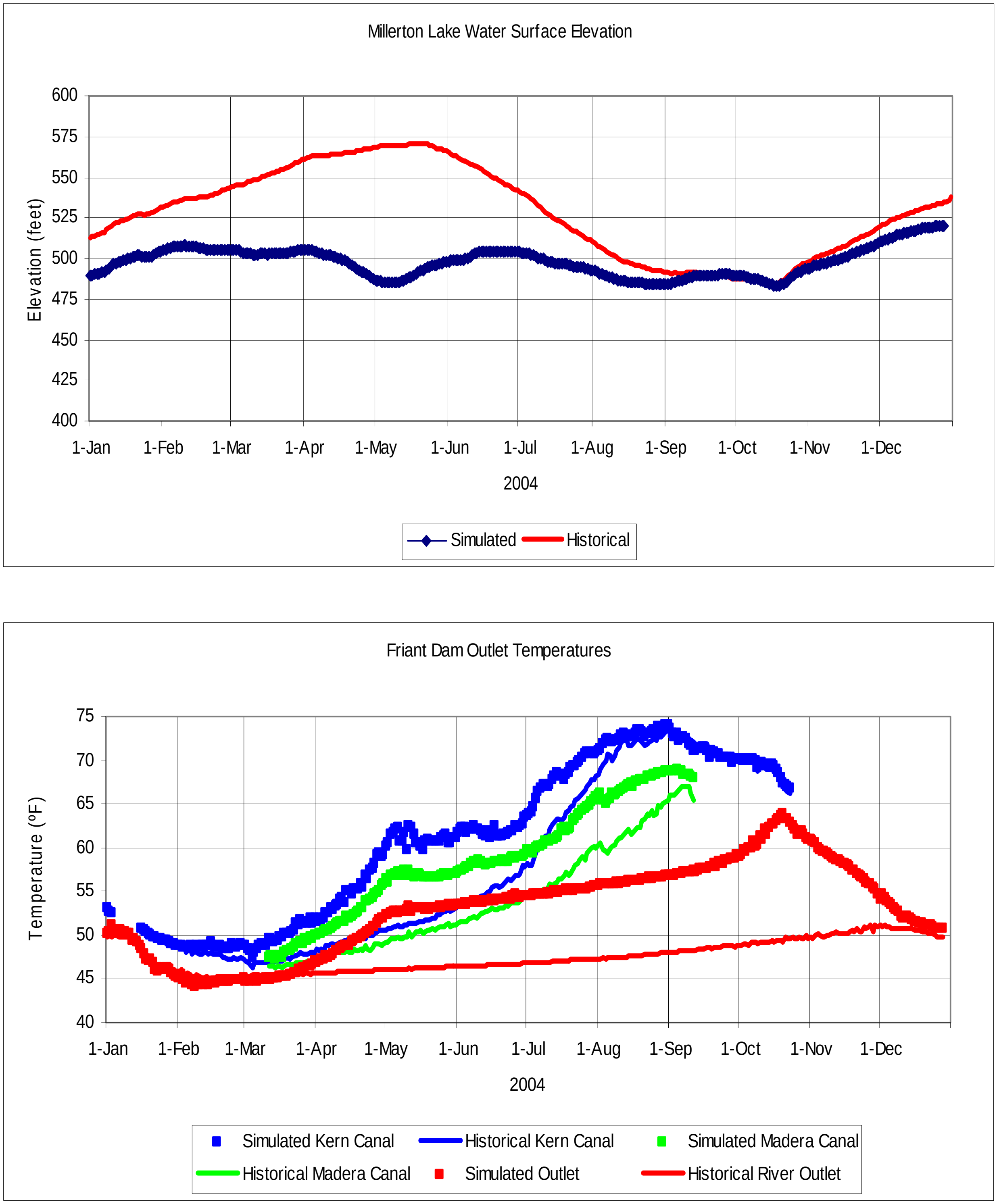

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Figure 21

Simulation of Millerton Lake Surface Elevation and Outlet Temperatures with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2004 Compared to Historical Surface Elevation and Outlet Temperature Simulations

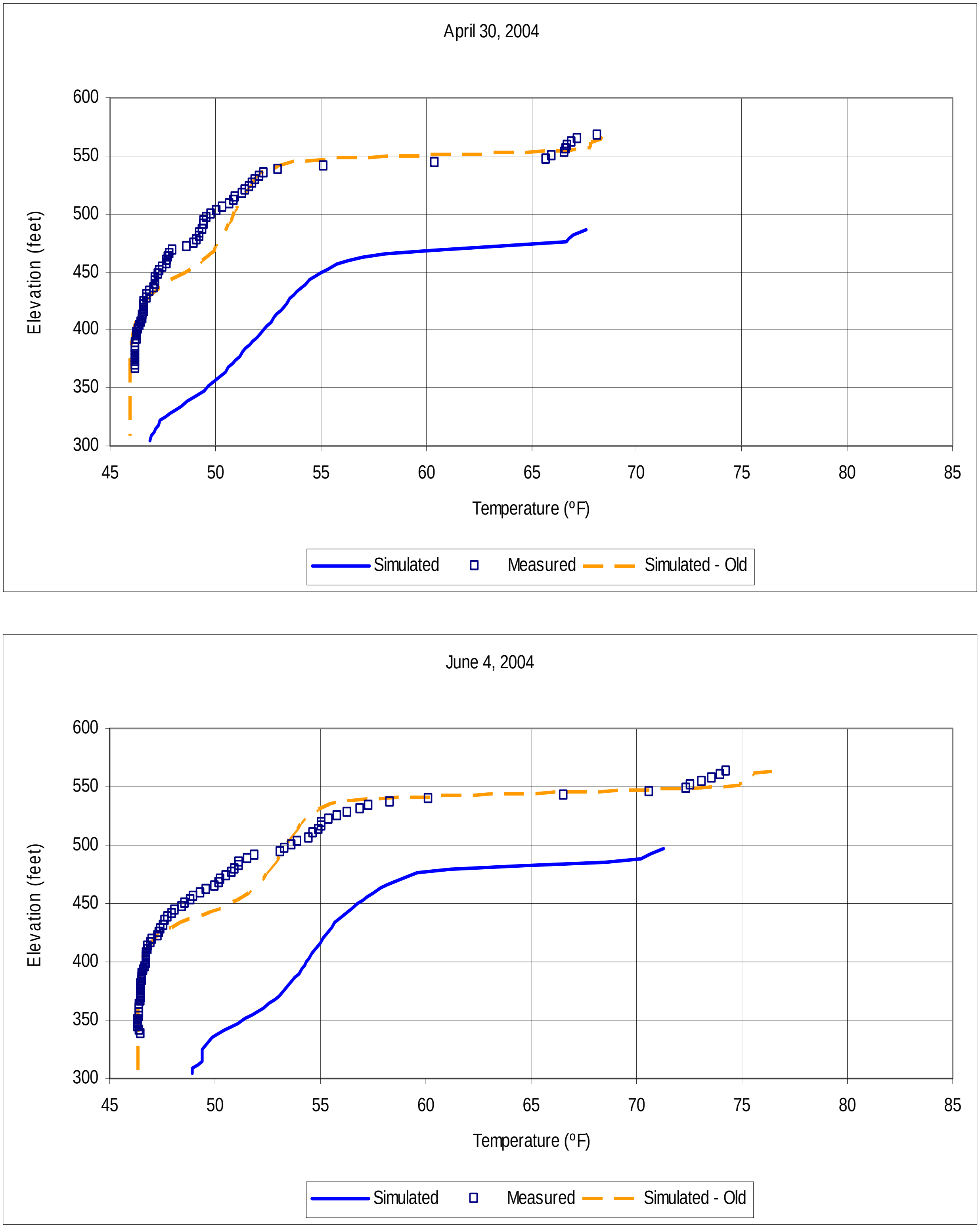

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Figure 22 (Page 1 of 3)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2004 Compared to Historical Temperature Simulation and Measured Data

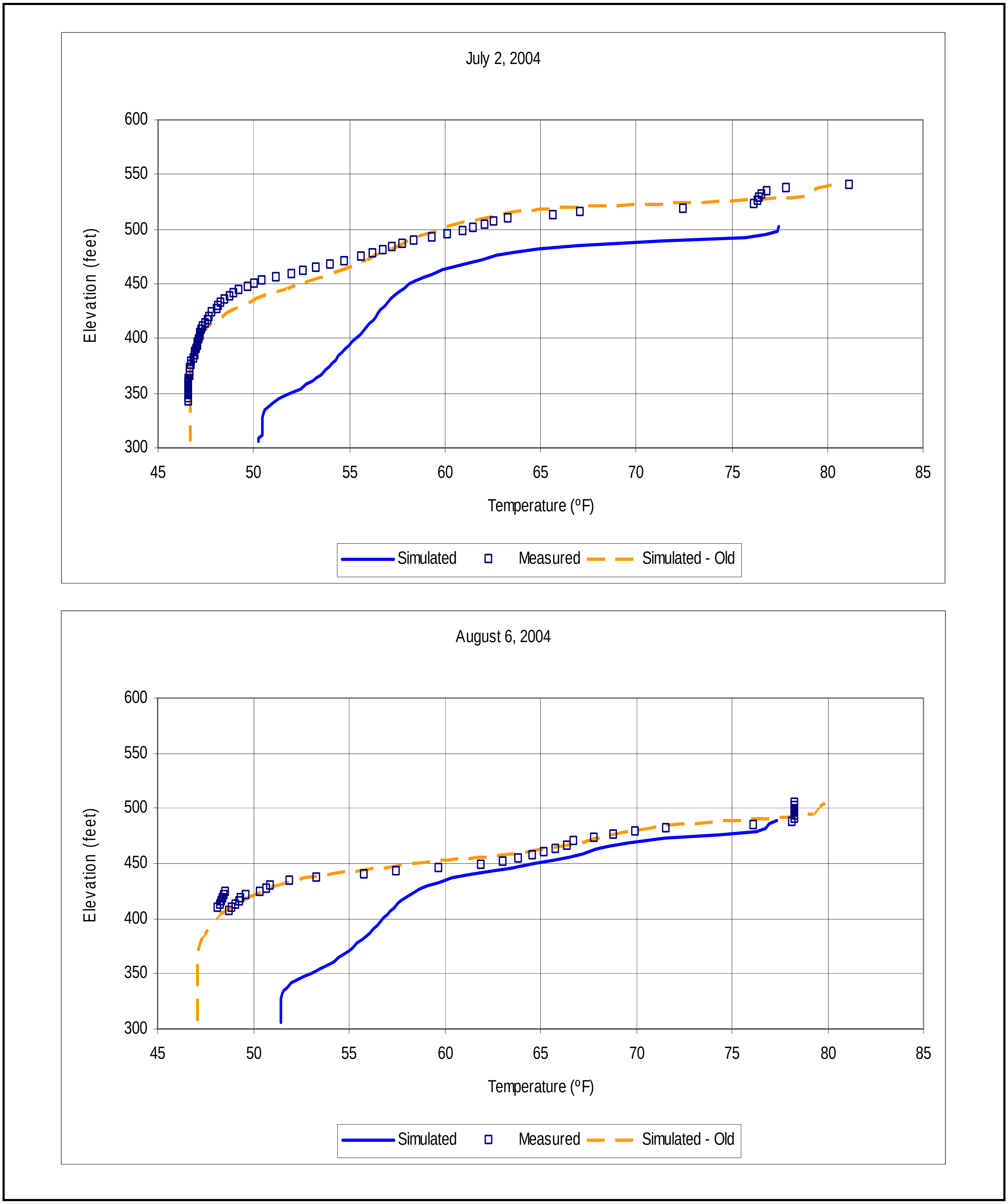

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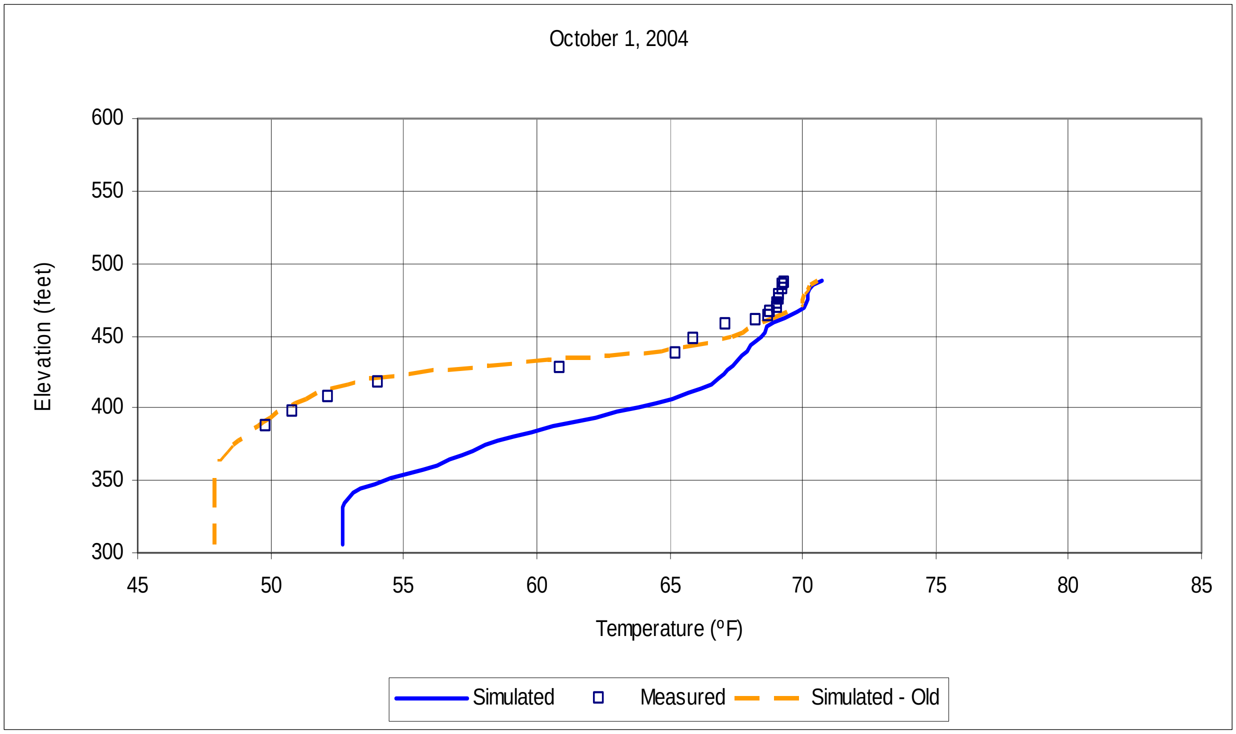
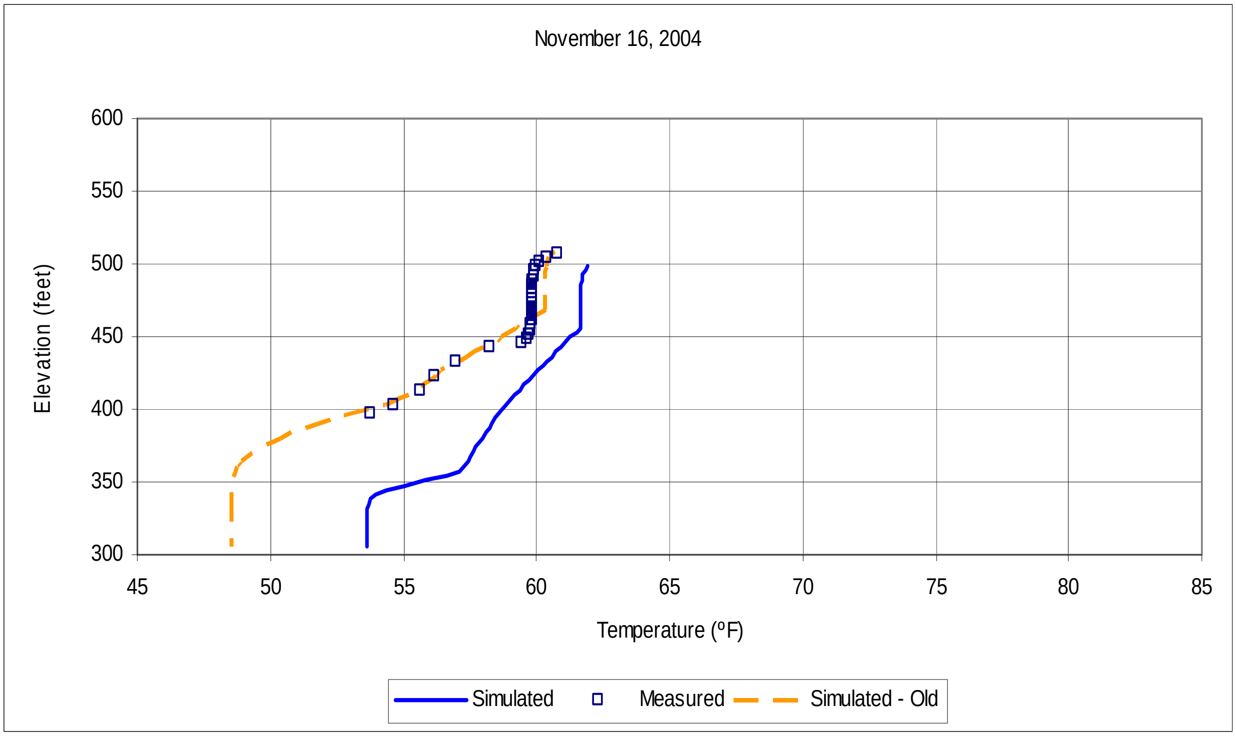
Figure 22 (Page 2 of 3)

Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2004 Compared to Historical Temperature Simulation and Measured Data





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Simulation of Millerton Lake Temperature Profiles with Spring-Run Chinook Salmon River Restoration Outflows and Minimum Canal Diversions for 2004 Compared to Historical Temperature Simulation and Measured Data

Appendix A

CE-QUAL-W2 Temperature Model Description and Calibration Procedures

CE-QUAL-W2 Introduction

Computer Files CE-QUAL-W2 is a two-dimensional (longitudinal/vertical) hydrodynamic and water quality model. Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow reservoirs, lakes, or estuaries. CE-QUAL-W2 has been under continuous development by the U.S. Army Corps of Engineers since 1975. The original model was known as LARM (Laterally Averaged Reservoir Model) developed by Edinger and Buchak (1975). The first LARM application was on a reservoir with no branches. Subsequent modifications to allow for multiple branches and estuarine boundary conditions resulted in the code known as GLVHT (Generalized Longitudinal-Vertical Hydrodynamics and Transport Model). Addition of the water quality algorithms by the Water Quality Modeling Group at the U.S. Army Engineer Waterways Experiment Station (WES) resulted in CE-QUAL-W2 Version 1.0 (Environmental and Hydraulic Laboratories 1986).

Version 2.0 was a result of major modifications to the code to improve the mathematical description of the prototype and increase computational accuracy and efficiency. New capabilities were added, including: an algorithm that adjusted the timestep to ensure hydrodynamic stability; a selective withdrawal algorithm that calculated a withdrawal zone based on outflow, outlet geometry, and upstream density gradients; a higher-order transport scheme (QUICKEST) that reduced numerical diffusion (Leonard 1979); time-weighted vertical advection and fully implicit vertical diffusion; step or linear interpolation of inputs; improved ice-cover algorithm; internal calculation of equilibrium temperatures and coefficients or a term-by-term accounting of surface heat exchange; variable layer heights and segment lengths; input data accepted at any frequency; and a sediment/water heat exchange.

Version 3.1 was the result of additional improvements to the numerical solution scheme and water quality algorithms, including an implicit solution for the effects of vertical eddy viscosity in the horizontal momentum equation; addition of Leonard's ULTIMATE algorithm that eliminates over/undershoots in the transport solution scheme; inclusion of momentum transfer between branches; internal weir algorithm for submerged or skimmer weirs; user-defined arbitrary constituents defined by a decay rate, settling rate, and temperature rate multiplier; and a graphic (tabular) preprocessor.

Version 3.2 new capabilities include: internal code rewrite to reduce code size, simplify code maintenance, and improve model execution speed; new screen display during model run-time; reorganization of the graph.npt file to allow more output control formatting possibilities; and addition of a new kinetic energy–turbulent dissipation turbulence closure model.

CE-QUAL-W2 Computer Files

All files on the CE-QUAL-W2 web site (http://www.ce.pdx.edu/w2) are archived in compressed zip files. To install CE-QUAL-W2, download the file “W2V3.zip” from the web site to a hard disk, copy over the compressed file “W2V3.zip” onto a hard disk and unzip the file. The “read me file for W2V3-2.doc” file contains an explanation of the subdirectory structure and files that will be set up on the PC. The “manual.zip” file contains the User’s Manual in PDF format and should also be downloaded. The “gui.zip” file includes a GUI preprocessor, a bathymetry editor, and a separate User’s Manual for the GUI.

Several example applications are included in the subdirectory “EXAMPLES”. The DeGray application is a reservoir with a single branch and a complete water quality application. The Spokane River is an example of a complicated river system with multiple river sections and run-of-the-river dams that flows into Long Lake, a deep-storage reservoir.

The following FORTRAN files are located in the SOURCE subdirectory:

- PRE_CVF.F90—preprocessor source code for use in a Windows environment
- PRE_CVF.EXE—preprocessor executable for use in a Windows environment
- W2_CVF.F90—CE-QUAL-W2 source code for use in a Windows environment
- W2_CVF.EXE—CE-QUAL-W2 executable for use in a Windows environment

The following input files come with each application:

- w2_con.npt—control file for each application
- bth.npt—bathymetry file
- met.npt—meteorological file

A subset of the following input files comes with each application:

- qin_br1.npt—inflows

- tin_br1.npt—inflow temperatures
- cin_br1.npt—inflow constituent concentrations
- qtr_tr1.npt—tributary inflows
- ttr_tr1.npt—tributary inflow temperatures
- ctr_tr1.npt—tributary inflow constituent concentrations
- euh_br1.npt—upstream head elevations
- tuh_br1.npt—upstream head boundary temperatures
- cuh_br1.npt—upstream head boundary constituent concentrations
- edh_br1.npt—downstream head elevations
- tdh_br1.npt—downstream head boundary temperatures
- cdh_br1.npt—downstream head boundary constituent concentrations
- qot_br1.npt—outflows
- ext_wb1.npt—light extinction
- qwd.npt—withdrawals
- vpr.npt—vertical profile at dam for specifying initial conditions
- lpr.npt—longitudinal and vertical profiles specifying initial conditions for each cell
- wsc.npt—wind sheltering
- shd.npt—solar radiation shading
- qgt.npt—gate flows/operation

If more than one branch or tributary is modeled, corresponding files using “br2”, “br3”, etc. (or “TR2, “TR3”, etc.) in the filename will also be included.

CE-QUAL-W2 Capabilities

The model predicts water surface elevations, velocities, and temperatures. Temperature is included in the hydrodynamic calculations because of its effect on water density and cannot be turned off. An accurate water balance must be prepared before running the model. A large group of inorganic water quality parameters are simulated (none were turned on for the Millerton Lake simulations). The water surface elevation is solved implicitly, which eliminates the surface gravity wave restriction on the timestep. This permits larger timesteps during a simulation, resulting in decreased computation time. The vertical diffusion criteria from stability requirements have also been eliminated allowing for even larger timesteps. The model can be applied to estuaries, rivers, or portions of a water body by specifying upstream or downstream head boundary conditions. The branching algorithm allows application to geometrically complex water bodies such as dendritic reservoirs or estuaries. Variable segment lengths and layer thicknesses can be used, allowing specification of higher resolution where needed. The model will adjust surface layer and upstream segment locations for a rising or falling water surface during a simulation. Provisions are made for inflows and inflow loadings from point/nonpoint sources, branches, and precipitation. Outflows are specified either as releases at a branch's downstream segment or as lateral withdrawals. Although evaporation is not considered an outflow in the strictest sense, it can be included in the water budget. The model can calculate onset, growth, and breakup of ice cover. The model can calculate the vertical extent of the withdrawal zone based on outlet geometry, outflow, and density.

The model accepts a given set of time-varying inputs at the frequency they occur, independent of other sets of time-varying inputs. The model allows the user considerable flexibility in the type and frequency of outputs. Output is available for the screen, hard copy, plotting, and restarts. The user can specify what is output, when during the simulation output is to begin, and the output frequency. A graphic pre- and postprocessor for plotting/ visualization is provided. Details of these capabilities are discussed in Appendix C of the Modeling Manual.

Application of CE-QUAL-W2 to Millerton Lake

The following data are needed for model application:

1. geometric data
2. initial conditions
3. boundary conditions
4. hydraulic parameters
5. kinetic parameters
6. calibration data

The first input task involves assembling geometric data. A topographic map or sediment range surveys are used to generate bathymetric cross sections that are input into the model. The project volume-area-elevation table is used for comparison with the volume-area-elevation table generated by the model. The computational grid is the term used for the finite difference representation of the water body. Grid geometry is determined by four parameters:

1. longitudinal spacing (segment length) [DLX]
2. vertical spacing (layer height) [H]
3. average cross-sectional width (cell width) [B]
4. water-body slope [SLOPE]

The longitudinal and vertical spacing may vary from segment to segment and layer to layer, but should vary gradually from one segment or layer to the next to minimize discretization errors. With the development of the bathymetry editor, finely discretized grids can be easily coarsened. The coarser grid will have fewer computational cells and larger average timesteps, resulting in decreased runtimes. The computational grid should initially be of high resolution and, if runtimes are excessive, reduced in resolution until the results change substantially. Results should never be a function of the grid resolution. Previous applications have used a horizontal grid spacing of 100 to 10,000 m and a vertical grid spacing of 0.2 to 5 m.

The next step after determining horizontal and vertical cell dimensions is to determine average cross-sectional widths for each cell. This is an iterative procedure whereby initial bathymetry is input into the preprocessor and the volume-area-elevation table is then generated by the preprocessor. This table is compared to the project table and widths are adjusted to better match the project table. Several methods have been used for determining average widths. Transects along the water body centerline can be drawn on a topographic map. A contour at the elevation corresponding to the *center* of a grid cell is located and the area encompassed by the contour line and the upstream and downstream transect is determined by planimeter. This area divided by the segment length is the average width of the grid cell. The process is repeated for each grid cell.

Each segment must have a zero width for the cell in layer 1 and a zero width for every cell located below the bottom active cell. In addition, each branch must have zero widths for upstream boundary and downstream boundary segments. Note this requirement results in *two segments* of boundary cells between each branch. Cell widths *cannot increase* with depth. A *branch* may connect to other branches at its upstream or downstream segment, but a branch *may not enter or leave* itself. Two branches may not connect at the same segment of another branch. The bathymetry input file contains the longitudinal grid spacing [DLX], initial water surface elevation [WSEL], segment orientations [PHI0], vertical grid spacing [H], bottom friction [FRICT], and average cell widths [B]. After the bathymetry is generated, it should be checked to match the elevation-volume data for the reservoir. Reclamation had already developed a geometry file for Millerton Lake, with 1-m layers. The Millerton Lake geometry file uses three branches, and the overall surface area and volume match the Millerton surface area and volume tables. The W2 model uses only metric units for elevation, area, and volume.

Initial conditions are specified in the control, bathymetry, and vertical and/or longitudinal profile input files. The initial temperatures on January 1 were specified as a vertical profile. The model recognizes the following inflows:

1. **Upstream inflows** (optional). Upstream inflows occur only at a branch's current upstream segment [CUS], which may vary during a simulation. The model provides the option to distribute inflows evenly throughout the inflow segment or place inflows according to density [PQC]. If the upstream inflow option is used, a separate file for inflow [QIN] and a separate file for temperature [TIN] for each branch are required.

2. **Tributary inflows** (optional).
3. **Distributed tributary inflows** (optional).
4. **Precipitation** (optional).
5. **Internal inflows** (optional).

The model recognizes the following types of outflows:

1. **Downstream outflows** (optional). Downstream outflows [QOUT] occur only at the downstream segment [DS] of a branch. Selective withdrawal where the vertical extent of and flow distribution in the withdrawal zone are calculated by the model is used for all outflows. Additionally, the bottom [KBSTR] and top layers [KTSTR] below and above which outflow cannot occur can be specified by the user to include the effects of upstream structures that restrict the selective withdrawal zone. Outflow will occur even if the outlet location is above the current water surface layer [KT]. This is a necessity when calibrating water surface elevations. A separate file for each branch outflow is required. All outflow from a branch is mixed to provide a single outflow temperature.
2. **Lateral withdrawals** (optional). Lateral withdrawals [QWD] may be specified for any active cell. The number of withdrawals [NWD], their segment location [IWD], and their centerline elevation [EWD] must be specified in the control file. If this option is used, a separate file for each withdrawal is required. Selective withdrawal is used for lateral withdrawals.
3. **Evaporation** (optional).
4. **Internal outflows** (optional).

The model requires the following surface boundary conditions:

1. **Surface heat exchange.** Surface heat exchange is calculated by either of two methods using the input variable [SLHTC] in the control file. The first method uses equilibrium temperatures [ET] and coefficients of surface heat exchange [CSHE] to calculate surface heat exchange (Brady and Edinger 1975). The second method uses a term-by-term accounting for calculating surface heat exchange. For both methods, latitude [LAT] and longitude [LONG] are specified in the control file and values for air temperature [TAIR], dew point temperature [TDEW], wind speed [WIND] and direction [PHI], and cloud cover [CLOUD] must be included in the meteorological file. If available, short wave solar radiation can be input directly into the model.
2. **Solar radiation absorption.** Distribution of solar radiation in the water column is controlled by the fraction of solar radiation absorbed in the surface layer [BETA] and the attenuation rate attributable to water [EXH2O], inorganic suspended solids [EXINOR], and organic suspended solids [EXORG]. Values for [EXINOR] and [EXORG] affect solar radiation only if constituents are modeled. These values are specified in the control file.

3. **Wind stress.** Wind speed [WIND] and direction [PHI] must be supplied in the meteorological file [METFN]. Wind stress is an extremely important physical process and should be included in all applications. The model allows the user to specify a wind-sheltering coefficient [WSC] which, when multiplied with the wind speed, reduces effects of the wind to take into account differences in terrain from the met station and the prototype site. The sheltering coefficient is specified in the wind-sheltering file [WSCFN].

Model Parameters. The horizontal dispersion coefficients for momentum [AX] and temperature/constituents [DX] are specified in the control file. They are presently time and space invariant. Sensitivity analyses on numerous applications have shown the model is relatively insensitive to variations in the default values for reservoirs but can be important in rivers and estuaries. The vertical diffusion coefficients for momentum [AZ] and temperature/constituents [DZ] vary in space and time and are computed by the model. The current version allows for a number of different vertical turbulence algorithms for sloping river sections and estuaries. The user may specify longitudinally varying values for the Chezy coefficient or Manning's N for bottom friction (the friction type is specified in the control file [FRICC]). They are used in calculating boundary friction that varies spatially as a function of exposed bottom area and temporally as a function of the flow field. The values are specified in the bathymetry file.

CE-QUAL-W2 Calibration Procedures

Calibration data are used to provide initial and boundary conditions and assess model performance during calibration. Model results will be suspect at best and will not withstand scrutiny at worst if the model is applied with insufficient and/or inadequate calibration data. Proper application of mechanistic water quality models requires at least one set of in-pool observed data. The preferred method is *at least* two sets of data encompassing different extremes in the prototype (i.e., high- and low-flow years, warm and cold years, etc.). In-pool data is used to set initial conditions and assess the model's ability to reproduce observed conditions. Given sufficient time and funding, *all years* in which sufficient data are available should be included during model calibration. Model all the years and model them continuously (with same coefficients). Modeling them continuously would eliminate separate calibration and verification years or data sets so the model could not be considered "calibrated and verified." However, if the model reproduces the wide variation in prototype behavior between all the years, a lot more confidence can be placed in the model's ability to reproduce prototype behavior for the "right" reasons than if the model were calibrated for one year and verified for another year.

The data used to drive the model need to be as accurate as possible. For temperature calibration, this typically means using continuous inflow temperatures or developing regression relationships for inflow temperatures based on flow and air or equilibrium temperature to generate at least daily inflow temperatures (see Ford & Stein 1984). For meteorological data, use the most frequent data available. Previously, daily average values were used to drive the model because earlier 1-D models used daily timesteps. Many modelers still take hourly or three-hour data and generate daily averages for model input. For most reservoirs, thermocline depth and shape are functions of two physical mechanisms—wind mixing and convective cooling. Using daily average air temperatures eliminates nighttime convective mixing, which can be a very important physical process affecting epilimnetic depths and thermocline shapes for reservoirs. As another example, applying a daily average wind speed and direction can generate an artificial water surface slope that incorrectly drives hydrodynamics. Daily averaging of wind speeds also can result in much less energy input into the model because the energy input by wind is a function of the wind speed cubed.

The model produces the following output files for displaying results:

1. Profile file [PRFFN]. This file is used to plot observed versus predicted vertical profiles of temperature and constituents at a given segment.
2. Time series file [TSRFN]. This file is used to plot time histories of water surface elevations, flows, temperatures, and constituent concentrations for user-specified computational cells. This file also contains information to plot out the time history of the variable timestep and average timestep.
3. Contour plot file [CPLFN]. This file is used to plot contours of temperature and constituents along the water-body length.
4. Vector plot file [VPLFN]. This file is used to plot velocity vectors determined from horizontal and vertical velocities. The output is useful in analyzing flow patterns in the water body.
5. Spreadsheet file [SPRFN]. This file is similar to the profile except the output is suitablefor importing into a spreadsheet type database for subsequent plotting. A description of the output from each file and how to use the information is given in Appendix C of the Modeling Manual. The current release version requires the user to develop plotting capabilities from these files. This is most often done using the spreadsheet output file and time series output file and developing macros to process the data. The Millerton results were imported into an Excel file called “2003_Performance_case_description.xls” that contains the timeseries and profile plots.

Calibration is an iterative process whereby model coefficients are adjusted until an adequate fit of observed versus predicted data is obtained. Unfortunately, there are no hard and fast guidelines for determining when an adequate fit is obtained. The user must continually ask himself or herself, “Is the model giving useful results based on model formulations, assumptions and input data?” If it is not, the user must determine whether the inability of the model to produce useful results is attributable to model formulations that are insufficient to describe known prototype behavior, or input data are insufficient to describe the system dynamics.

The water budget is checked by comparing the predicted elevations with the observed elevations. Errors in the water budget may be generated by: incorrect bathymetry, incomplete or inaccurate inflow or outflow data, evaporation, or seepage. The Millerton Lake daily inflows and outflows compiled by Reclamation appear to provide an accurate water balance for both 2003 and 2004.

The earliest one-dimensional mechanistic reservoir models included only temperature. As a result, temperature was the only model prediction that could be used for hydrodynamic calibration. Because temperature is affected by surface and bottom heat exchange and is therefore not conservative, it is not the best parameter for calibrating hydrodynamics. Salinity, which is conservative, historically has been considered the ideal constituent for hydrodynamic calibration. However, this is generally feasible only for estuarine applications where salinity is routinely monitored. Dissolved solids are not conservative and are generally not a good substitute for salinity during calibration except in water bodies where the conservative assumption is appropriate. The previous three sentences echo the prevailing sentiment of hydrodynamic modelers. In reality, there is no “ideal” constituent that should be used for hydrodynamic calibration. Each constituent can contribute knowledge about the system and can have an impact on the hydrodynamic calibration. Experience has shown that dissolved oxygen and phytoplankton are often much better indicators of proper hydrodynamic calibration than either temperature or salinity. However, for Millerton Lake, only temperature profiles were available for calibration.

Temperature and/or salinity should always be the first step during hydrodynamic calibration, with the hydrodynamic calibration further refined during water quality calibration. Computed velocities can be compared with velocity and flow measurements obtained from an acoustic Doppler current profiler (ADCP) to additionally evaluate the model’s hydrodynamic performance. However, care must be taken when comparing model velocities with observed velocities to ensure ADCP measurements are comparable to the laterally averaged velocities generated by the model.

Coefficients affecting temperature and their default values are given in Table 3 of the Modeling Manual. The eddy viscosities, Chezy coefficient, and wind-sheltering coefficient directly affect hydrodynamics, which affect heat and constituent transport. The remaining coefficients directly affect temperature, which affects hydrodynamics.

In addition to the above coefficients, temperature predictions are also affected by the surface heat exchange algorithm specified, mainstem and tributary inflows, inflow temperatures and their placement, outlet and withdrawal specifications, the numerical solution scheme, and bathymetric and meteorological data. Again, always represent the prototype as accurately as possible.

Applications on more than 400 water bodies under a wide variety of conditions have shown the model generates remarkably accurate temperature predictions using default values when provided accurate geometry and boundary conditions.

The wind-sheltering coefficient [WSC] has the most effect on temperature during calibration and should be adjusted first. Previous applications varied the wind-sheltering coefficient from 0.5 to 0.9 for mountainous and/or dense vegetative canopy and 1.0 for open terrain. In a very few cases, the wind-sheltering coefficient [WSC] has been increased above 1.0 to account for funneling effects on systems with steep banks.

Difficulties during temperature calibration can often be traced to the following:

1. **Inflows and Inflow temperatures.** Accurate inflows and inflow temperatures are desirable for all applications, but they are critical for water bodies with short residence times or during high inflow periods. Temperature calibration will be difficult using monthly inflow temperatures for a water body with a 1-week residence time. Methods exist for generating more frequent inflow temperatures based on flow and meteorological data (Ford and Stein, 1986), but there is no substitute for actual measurements.
2. **Meteorological data.** Many difficulties are associated with extrapolating weather station meteorological data to a water-body site. Weather stations are typically located in different terrain and at large distances from the prototype. Frontal movements can occur at different times over the water body and meteorological station, resulting in model predictions that are in closer agreement either earlier or later than the actual comparison date. Methods for addressing these problems include adjustment of the wind-sheltering coefficient [WSC], use of an alternative meteorological station, averaging data from several meteorological stations, separating a water body into regions and applying data from different meteorological stations, and comparing observed data using model output either before or after the observed date. If the user has the luxury of obtaining calibration data before applying the model, portable weather stations exist that can be deployed on the water body. Obviously, this is the preferred method.
3. **Outflow data.** The addition of the selective withdrawal algorithm in Version 2.0 has reduced many of the previous problems of accurately representing outflows. However, problems still arise. In the application of CE-QUAL-W2 to Bluestone Reservoir, Tillman and Cole (1994) were unable to reproduce observed temperature stratification without limiting the lower withdrawal layer. Subsequent investigation showed that withdrawal was limited by trash accumulation that effectively acted as a submerged weir. This was a problem generated by inadequate knowledge of the prototype and not a problem with the model. Indeed, this is an example of a model giving insight into the behavior of the prototype.
4. **Bathymetry.** Several previous applications of the model encountered difficulties during temperature calibration until the bathymetry was revisited. Check the assumptions made during the development of the bathymetry to ensure they are not the source of the problem. Starting points include grid resolution that affects the models ability to define sharp thermal gradients and bottom slope, volume-area-elevation accuracy that can have a marked effect on hypolimnetic temperatures as the volumes are generally small near the bottom, and water surface areas that affect the area available for surface

heat exchange. Branch definition has also been found to have an effect on temperature predictions.

Pineflat Reservoir results (Kings River) are given in the Modeling Manual as an example of W2 temperature calibration results. Pineflat Reservoir is located east of Fresno. One of its primary uses is providing irrigation water during the summer growing season. Consequently, the reservoir is drawn down as much as 70 m over the summer during drought years. The model was used to provide operational guidance for a temperature control device that will be installed in the reservoir to optimize the storage of cold water for downstream releases at the end of summer. Figure A-1 shows the results of temperature predictions for 1989. The thermal regime exhibits a “double” thermocline starting in early spring. As can be seen, the reservoir was drawn down over 40 m during the summer. During 1993, the development of the double thermocline was delayed until the end of summer (Figure A-2). The W2 model correctly matched the thermal regimes for both years and the differences in the thermal regimes between the two years. Sensitivity analyses showed that temperature predictions were very sensitive to inflow temperatures. Calibration consisted of adjusting inflow temperatures to more closely match in-pool temperature profiles. Because calibration showed the importance of accurate inflow temperatures in order to properly calibrate the model, additional fieldwork was done to obtain accurate inflow temperatures. During this effort, it was discovered that the location where inflow temperatures were taken showed a lateral variation in the river of more than 5°C because of hypolimnetic discharges from an upstream reservoir that did not completely mix laterally. Additionally, during extreme drawdown, it was shown that inflow temperatures increased by nearly 2°C from measured temperatures as the upstream boundary of the model moved downstream approximately 10 km because of the large drawdowns that the reservoir was periodically subjected to.

The Calibration of Millerton Lake model for 2003 and 2004 included adjustment of the wind-shelter coefficient for each segment to 0.75 to match the measured surface temperatures in the 2003 and 2004 profiles and surface temperature probe in 2004.

The second major calibration factor was adjustments in the inflow temperatures during periods when it was not measured (measurements started in March 2004). A third calibration effort placed a bottom limit on the Madera Canal and Kern Canal outflow zone. The calibration results appear to be quite good, judging by the match with measured profiles, and are comparable to those shown in the W2 Modeling Manual for other reservoirs, including Pineflat Reservoir.

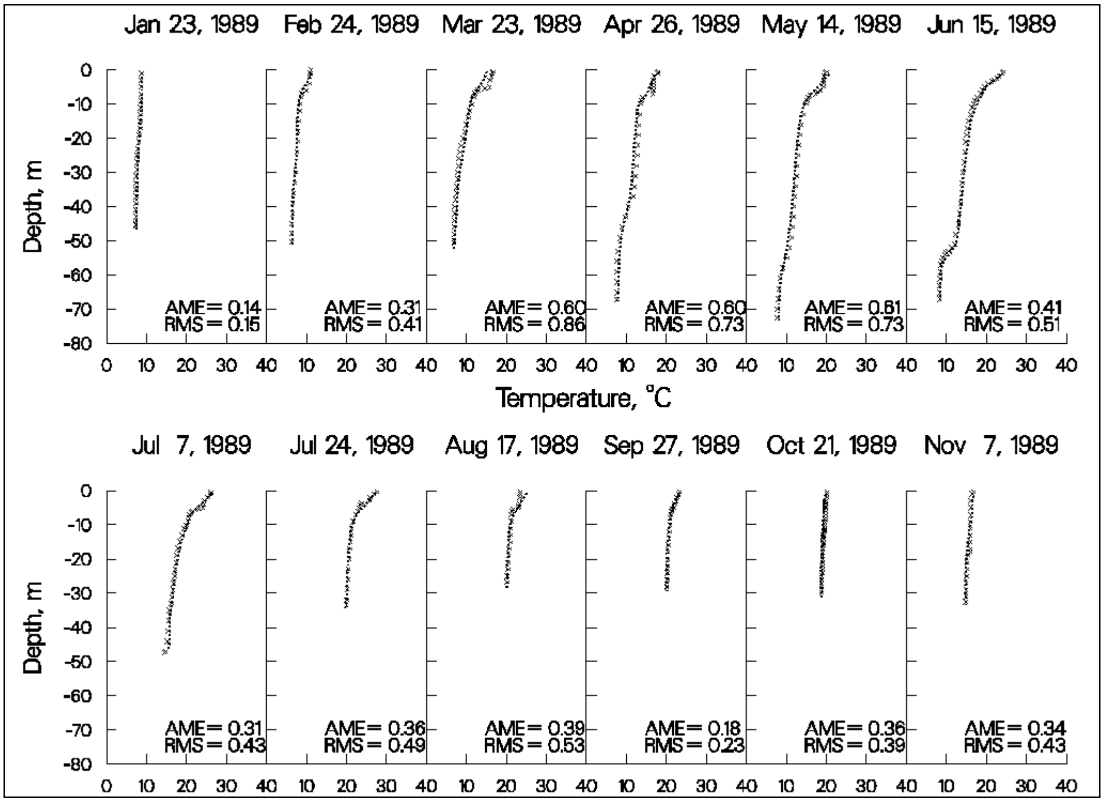

Figure A-1. 1989 Pineflat Reservoir Computed versus Observed Temperatures (Source: Modeling Manual)

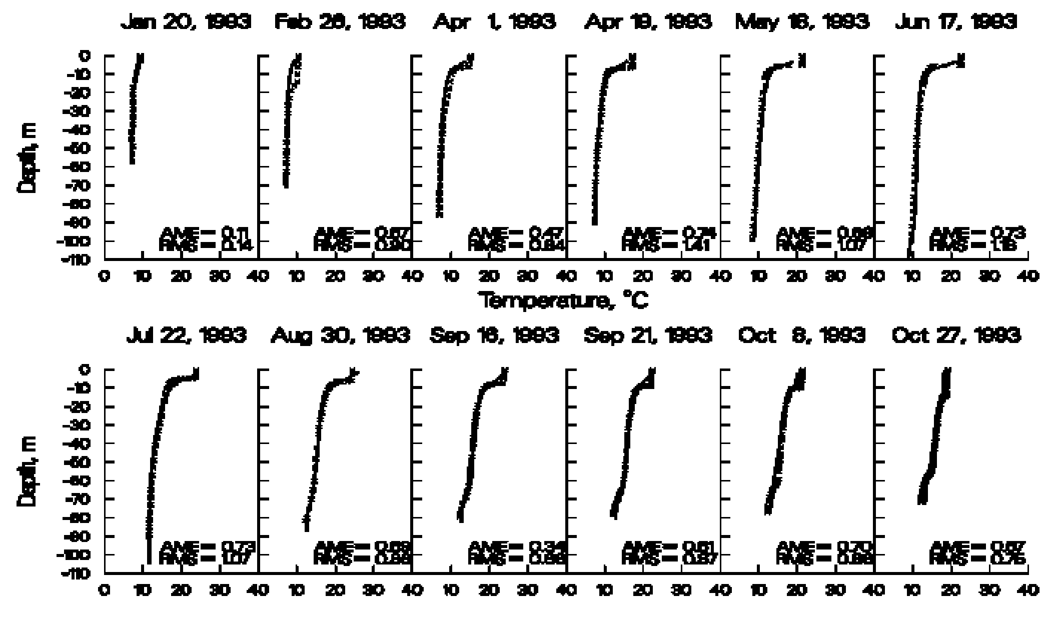

Figure A-2. 1993 Pineflat Reservoir Computed versus Observed Temperatures (Source: Modeling Manual)

Resume for

Russell T. Brown, Ph.D.

Senior Environmental Scientist

Russell T. Brown, Ph.D.

Senior Environmental Scientist

Education

Ph.D. Civil Engineering and Water Resources, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1978.

M.S. Ocean Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1974.

B.S. Civil and Environmental Engineering, University of California, Irvine, 1972.

Professional Memberships

California Water and Environmental Modeling Forum

Russ Brown's areas of expertise include delta hydrodynamics, water quality, aquatic habitat and transport evaluations, water resources operations and planning models, reservoir and river temperature and water quality modeling, chemical transport and fate modeling, watershed erosion and sediment transport processes, nonpoint source pollution controls, water quality sampling designs, water resource problem solving, and effluent discharge and mixing systems. He manages, designs, and conducts projects requiring delta, reservoir, river, watershed erosion, sediment transport, hydrologic, and pollutant fate modeling. Russ also develops simulation models to integrate and interpret hydrologic, water quality, and ecological data for environmental assessments. He uses biological criteria to develop flow, temperature, dissolved oxygen, and nutrient models appropriate for predicting biological impacts under alternative project operations; plans water quality sampling, monitoring, and modeling efforts for projects; and evaluates existing water quality and hydrologic data for relationships useful for predicting project impacts. Russ also performs sensitivity analyses to test model validity and limitations and leads (or participates as a member of) multidisciplinary teams to solve water resource conflicts, developing alternative water management scenarios based on input from various user groups.

Project Experience

Delta Hydrodynamics and Water Quality. Prepared hydrologic, hydrodynamic, and water quality impact assessment of the proposed Sacramento–San Joaquin River Delta (Delta) Wetlands In-Delta Storage Project for the State Water Resources Control Board (SWRCB) and the U.S. Army Corps of Engineers. Utilized the Resources Management Associates hydrodynamic Delta model to provide detailed summary of Delta flow and salinity conditions. Developed a spreadsheet model (DeltaSOS) to investigate the effects of alternative Delta water quality standards on Delta channel flows and exports with historic or simulated hydrologic conditions. Conducted experiments to determine the contribution of dissolved organic carbon (DOC) from Delta peat soil and vegetation. Evaluated data from the Department of Water Resources' municipal water quality investigations samples of Delta agricultural drainage and channel water and developed a monthly Delta agricultural drainage water quality model that links the water, salinity, and DOC concentrations. Evaluated the effects of proposed Mountain House wastewater effluent in south Delta channels. Reviewed and summarized historical water quality data from the Stockton Deepwater Ship Channel for the City of Stockton.

Prepared the water supply, Delta tidal hydraulics, and water quality existing conditions descriptions and impact assessments for the DWR South Delta Improvements Program that includes tidal gates for water level control and fish migration protection. Utilized the CALSIM and DSM2 model results to provide accurate evaluations of natural and modified tidal conditions in the Delta.

Water Temperature Modeling. Applied a daily two-dimensional reservoir flow and temperature model (BETTER) to the Lewiston Reservoir on the Trinity River and Lake McClure on the Merced River for evaluating effects of release temperatures on downstream river temperatures. Developed and applied an hourly river temperature model (STREAM) for fisheries evaluations on the Owens River, Putah Creek, Merced River, and Guadalupe River. Each application was calibrated with measured temperatures and used to demonstrate effects of various flow and reservoir management alternatives. The Putah Creek and Guadalupe River applications investigated the effects of riparian vegetation and low-flow pools on water temperatures. The JSATEMP model has been peer-reviewed by the Corps Waterways Experiment Station for application on the Guadalupe River downtown flood control project. The Guadalupe River model was extended to include Alviso Slough and tidal flow effects on temperature and salinity.

Developed and applied a reservoir temperature and water quality model for Olivenhain Reservoir to help San Diego County Water Authority design the selective withdrawal facilities. Thermal stratification as well as salinity gradients that may control mixing in the reservoir were evaluated. Used the CE-QUAL-R2 model to evaluate the stratified reservoir water quality (temperature and dissolved oxygen) of Lake Almanor for PG&E and of San Luis Reservoir for the Santa Clara Valley Water District.

Developed a daily water temperature model of the San Joaquin River from Friant Dam to the Merced River. Applied this daily flow and hourly water temperature model for evaluating restoration actions using chinook salmon and steelhead temperature criteria and habitat assessment calculations.

Water Quality Assessment. Prepared water quality assessment for SWRCB revisions to the City of Los Angeles diversions from Mono Lake tributary streams, including the effects on Crowley Lake nutrients and arsenic concentrations at the city's drinking water treatment plant.

Developed a model for the assessment of the fate of nutrients and metals in the constructed wetlands at the Sacramento Regional Wastewater Treatment Plant. Developed models to assess the transport and fate of sediment and mercury in the Holston River, Virginia, that included daily rainfall-runoff, sediment transport, and mercury partitioning calculations.

Participated in special studies of the Stockton Deep Water Ship Channel (DWSC) to determine the sources and causes of low DO concentrations for the SJR DO TMDL stakeholder process. Assisted the City of Stockton in evaluating these data and conducted two CALFED-sponsored research evaluations of the tidal exchange near Turner Cut and the potential for aeration and oxygenation of the DWSC to improve DO concentrations during the summer and fall. Assisted in the design of an oxygenation system (i.e., U-tube device with diffuser) to increase the dissolved oxygen concentrations in the DWSC.

Prepared a summary and review of historical daily suspended-sediment data collected in the 1930s and 1960s by the Tennessee Valley Authority. Prepared files for the USGS database and compared the daily patterns of sediment concentrations during storm flows from the 15 watersheds with at least 3-years of daily flow and sediment data.

Hydrological and Ecological Modeling. Prepared habitat water quality evaluation for U.S. Bureau of Reclamation's Central Valley Project Improvement Act programmatic environmental impact statement (EIS) that linked reservoir and Delta operations and associated temperature and salinity conditions that govern habitat water quality fish responses. Developed life-stage model of Mono Lake alkaline fly population (POPFLY) to evaluate the effects of larval substrate and salinity changes from various lake elevations. Developed Delta transport and entrainment model (DeltaMOVE) for assessment of plankton and larval fish life-stages resulting from Delta flows and export pumping operations and applied this model to evaluate effects of Pacific Gas and Electric's Delta power plant and Delta Wetlands operations. Assisted in the selection of appropriate hydrologic, water quality, and ecological assessment tools for the CALFED Bay-Delta Program Programmatic EIS/environmental impact report (EIR). Developed a daily model of alternative PG&E operations of Lake Almanor and the North Fork Feather River hydroelectric facilities to support a water right application by Plumas County for increased fish flows.

Developed a daily model of Delta exports and San Luis Reservoir operations for use in interactive simulation (i.e., gaming) of export restrictions to protect endangered fish species for the CALFED environmental water account. The daily model combines historic salvage data with historic hydrology and Central Valley Project and State Water Project operations data to provide an integrated assessment tool. Project operators and fish resource managers change the initial export pattern to reduce entrainment during periods of high fish density, and then allow higher pumping during periods of reduced fish density. The daily model accurately simulates many of the operational constraints and allows adaptive management actions to be evaluated.

Prepared an evaluation of the Salton Sea restoration alternatives for Salton Sea Authority. Simulated water and salt management alternatives using the USBR water and salt accounting model and compared these alternatives with possible on-shore solar salt ponds, similar to those used by salt industry in San Francisco Bay.

Prior Experience

Tennessee Technological University. Associate professor of civil engineering. Developed research proposals and participated in research activities at the Center for the Management, Utilization, and Protection of Water Resources. Conducted water quality data collection, data analysis, and modeling. Authored numerous technical reports on reservoir water-quality modeling for the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, Tennessee Valley Authority, and Oak Ridge National Laboratory. Directed graduate student research projects and taught courses in hydrology and water quality modeling.

Tennessee Valley Authority Engineering Laboratory. Research engineer. Conducted engineering studies of water temperature effects from thermal power plant discharges and hydropower dam releases. Analyzed data obtained from hourly water temperature monitoring systems. Participated in multi disciplinary water resource studies, assisted in planning field data collection activities, and developed and applied reservoir water quality models to evaluate environmental concerns.

U.S. Army Corps of Engineers Waterways Experiment Station. Graduate fellow. Studied the range of reservoir water quality model predictions resulting from uncertain river loadings. Investigated data requirements for reservoir inflow concentrations and coefficient estimates. Participated in reservoir water quality model development and calibration.

Selected Publications

Brown, R.T., A. Huber. 2004. The Effects of Riparian Shade on Stream Water Temperature. In *Proceedings of 2004 Riparian Ecosystems and Buffers: Multi-Scale Structure, Function, and Management.* American Water Resources Association Specialty Conference, Olympic Valley, California

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