Executive Summary

The US Army Engineer District, Philadelphia (NAP) requested the assistance the US Army Engineering Research and Development Center (ERDC) to develop a numerical model of the Lehigh River system including F. E. Walter Reservoir, Beltzville Reservoir, approximately 45 miles of the Lehigh River below F. E. Walter Reservoir, and approximately 4.5 miles below Beltzville Reservoir to the confluence of the Lehigh River. F. E. Walter Dam is located five miles upstream of White Haven, Pennsylvania, on the Lehigh River. Flood control was the authorized purpose for the reservoir. Later, recreation was added as an authorized purpose but is secondary to flood control operations. The reservoir operation is historically run-of-river.

During Phase I of the study CE-QUAL-W2 was calibrated for temperature, flow, and stage for the Leigh River study area. The model was calibrated and verified on two very different water years. Calibration was performed for 2001 a dry water year, and verification was performed on 2003 a wet water year. Temperature calibration results for 2001 for all stations in F. E. Walter, Beltzville, and Lehigh River were within the target AME for temperature and were considered acceptable – most predicted temperature values were within 1 ^{o} C or less of observed. In the 2003 verification simulation, boundary conditions for temperature and flow were lacking on tributaries to the Lehigh River. Consequently, tributary boundary data for 2003 were set using both reservoir temperature inflow data observed at F.E. Walter and Beltzville depending on location of a tributary to the reservoirs. Flow values for the tributaries were estimated from flow values measured in the Lehigh River. Having no boundary conditions for the tributaries, did not affect verification of reservoir temperatures since boundary data were available at the reservoir inflow station. However, in the Lehigh River section of the grid, model results compared less favorable to observed because of the use of estimated data. In spite of data shortages, temperature results were within the target AME values most of the time and percent cumulative distribution plots showed most temperature ranges being correctly predicted for both years. With favorable results for calibration and verification, the model is a good management tool to test scenarios of operational changes to in-pool and downstream temperatures in the Lehigh system. The model quite accurately captures the physics of both reservoirs and the riverine sections. Any alteration in the physics should be predicted with a high degree of accuracy.

During Phase I, six scenario simulations were run. These scenarios were:

 Scenario 1 operated with 2008 reservoir releases with no modifications to release structure (NoMod) and water surface elevation (WSEL) at 417.71 meters (m) or 1370 feet (ft).

- Scenario 2 operated with 2008 reservoir releases with a selective withdrawal structure (SW) and WSEL at 417.71 m (1370 ft).

- Scenario 3 operated with “Fisheries only” reservoir release goals with NoMod and WSEL at 417.71 m (1370 ft).

- Scenario 4 operated with “Fisheries only” reservoir release goals with both NoMod and SW and WSEL at 424.56 m (1392 ft).

- Scenario 5 operated with “Maximizing whitewater events” while augmenting flow for fisheries during non-whitewater release goals with NoMod and WSEL at 417.71 m (1370 ft).

- Scenario 6 operated with “Maximizing whitewater events” while augmenting flow for fisheries during non-whitewater release goals for both NoMod and SW and WSEL at 424.56 m (1392 ft).

Scenario results indicated that SC6–NoMod had the most affect to release temperatures when compared to the base case (SC1–NoMod) results. Improvements were considered a successful when release temperatures were 20 ^{o} C or less during the warmer summer period downstream of F. E. Walter. Release water temperatures for SC6–NoMod were cooler or of similar values to SC1-NoMod and the other scenario results. In contrast, SW release temperature results for most of the simulation period were usually warmer than NoMod release temperatures. This is counter-intuitive to what was expected since the purpose of selective withdrawal is to have more choices for elevations of water releases. Thus in Phase II adjustments to release elevations were considered with the intent of preserving cooler water in the hypolimnion for summer releases.

Phase II of the study focused on adding water quality and metal constituents to the CEQUAL-W2 (W2) models already set up in Phase I for temperature and flow. Results for water quality calibration and verification were considered acceptable given the AME values for all predicted water quality constituents and metals were within in the acceptable range of the target AME values. As discussed for temperature lack of tributary boundary conditions in 2003 predictions of water quality and metals were over or under predicted but still followed data trends of observed. Six new proposed operational scenarios jointly developed and agreed to by ACOE (Army Corps of Engineers, Philadelphia), PADCNR Parks and Pennsylvania Fish and Boat Commission (PFBC), at F.E. Walter Dam were modeled to enhance downstream and in-lake recreation and habitat. Scenario runs were conducted using initial and boundary conditions from calibration and verification runs with the new F. E. Walter reservoir releases. Also Beltzville Reservoir maintained the same reservoir release for the scenario runs that were modeled during 2001 calibration and 2003 verification runs.

The new scenarios runs are:

- Scenario 1 can be described as “Fisheries only, with selective withdrawal to the dam” and is designed to maximized benefits to downstream fisheries. This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360, and 1380 ft and WSEL at 424.24 m (1392 ft).

- Scenario 2 can be described as “Maximizing whitewater events” while augmenting flow for fisheries during non-whitewater release goals with 2010 release schedule. This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360 and 1380 ft and WSEL at 417.71 m (1370 ft).

- Scenario 3 can be described as “Maximizing whitewater events” while augmenting flow for fisheries during non-whitewater release goals with 2010 release schedule. This scenario operated without a selective withdrawal structure (SW) with portals at elevations 1265, and 1297 ft and WSEL at 417.71 m (1370 ft).

- Scenario 4 goals are to provide whitewater releases on alternating weekends from in May and June, every weekend July through September; create optimal in-lake spawning areas in May and June by limiting the pool fluctuations to 5 feet; and maximize the benefit to cold water fisheries downstream by augmenting flows between July 1 and September 30 by a minimum of 50 cfs with the cooler water. This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360 and 1380 ft and WSEL at 424.56 m (1392 ft).

- Scenario 5 is based on the 2010 release schedule with outflow thermal targets as per Chapter 93 CWF thresholds. This operation was for producing and sustaining a fishery tailwater while satisfying whitewater interests. This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360, 1380, 1400, and 1420 ft with initial WSEL at 438.42 m (1438 ft).

- Scenario 6 is based, in part, on the 2010 release schedule. The intent is to investigate if periodic large pulses of reservoir releases, similar to the 2010 whitewater releases, can keep enough river rock substrate wetted to maintain downstream thermal target at Tannery Bridge of 68 ^{o} F (20 $^{\circ}$C). This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360, 1380, 1400, and 1420 ft with initial WSEL at 438.42 m (1438 ft).

During the Phase II study new features added to W2 were implemented which helped improve the likelihood of maximizing the benefits of selective withdrawal to improve downstream temperatures. With the new optimization routine in W2 V3.7, many simulations were made with quicker turn around to help make critical decision on reservoir operations. Criteria for judgment of improvement from one scenario to the other was again whether release temperatures were maintained at 20 ^{o} C (68 ^{o} F) or less during the warmer summer period downstream of F. E. Walter. Phase II scenarios 5 and 6 met these criteria as far downstream as LH08 and LH10, respectively. Meaning that scenario 5 river temperatures were maintained at 20 ^{o} C (68 ^{o} F) or less as far downstream as station LH08 in 2001 and scenario 6 river temperatures were maintained at 20 ^{o} C (68 ^{o} F) or less as far downstream as LH10 in 2003. Similar to results in Phase I, temperature results at stations below these were dominated by tributary inflow temperatures reducing influence from F. E. Walter dam releases. Downstream of LH08, differences in water temperature between the scenarios become minimal because tributary flows become the dominating factor for Lehigh River temperatures. As expected, water temperatures show the greatest differences immediately downstream of the dam before tributary influences begin to monopolize. Using scenario results from these simulations, the Philadelphia District will be able to make informed decisions in regard to adjustments to reservoir operations to help improve fishery habitat and boating recreation within and downstream of F. E. Walter Reservoir.

An overall statement can be made that changes to water quality releases from optimized runs are mostly attributed to release port location (i.e., actual layers release water is being pulled from) and the degree of stratification of water quality profiles. Release results for PO4, TP, TOC, and TSS for each scenario run are not very different from one scenario to the next. This is because almost isochemical conditions are present through the water column for these constituents for each scenario after Julian Day 225; thus scenario results show very little difference since water quality concentrations would be similar at any elevation released. Except for DO, most of the concentration differences for these water quality constituents at station LH02 are not detrimental to living resources downstream of F. E. Walter Reservoir. Decline in DO concentrations is noticeable in results for scenarios 5 and 6 for both runs using original and optimized release flows. Values of DO in 2003 can be as low as 2mg/L which stress living resources. From the 2003 profile results, this behavior is attributed to the formation of a DO minimum in the area of the release port elevations in the epilimnion. This may have formed through mortality, respiration, and decay from increased chlorophyll *a*, TOC and total suspended solids (TSS) concentrations in the area of the releases ports in the epilimnion of the reservoir. By the time water is transported from station LH02 to station LH03, DO concentrations have reaerated to levels of 7 mg/L or more. As water is transported downstream to station LH17, all concentration differences become diminished.

Also not being capture by the model is the natural reaeration occurring through the pipes in the dam. This is why calibration DO results at this station are about 1 mg/L lower than observed. At the end of the study reach (station LH17), DO concentration differences are minimal for all scenario runs. Since the objective of this study was to conserve cooler water for warmer periods to maintain temperature criteria of 20 ^{o} C as far downstream as possible, maintaining DO concentrations were not considered. However, results from this study can be used as an indicator of the type of conditions that could result from maintaining a higher conservation pool having a selective withdrawal component when operating. Maintaining higher conservation pools may lead to the necessity of more frequent profile monitoring to avoid releasing low DO water from increased chlorophyll concentrations and the related processes influencing low DO concentrations.

Over all, the total metals modeled during scenario runs at stations in the Lehigh River have concentrations that are below the levels considered to be harmful to the living resources if they were all assumed to be in the dissolved metal forms. Improved monitoring for dissolved metals data is recommended for in-pool, downstream stations at F. E. Water and Beltzville Reservoirs, and tributaries to the Lehigh River. Any metal considered to be bioavailable to living organisms should be monitored as frequently as other water quality constituents.

It is still recommended that for future modeling studies of F. E. Walter Reservoir, Beltzville Reservoir and riverine sections below, the District monitor inflow temperatures and water quality parameters to major tributaries and inflow points to the reservoir to improve on this calibration. W2 did extremely well at F. E. Walter, Beltzville and the Lehigh River for 2001. W2 results for 2003 were favorable in the reservoirs but lack of data from tributaries entering into the Lehigh River below F. E. Walter caused predicted values to be less favorable compared to results in 2001. As presented and discussed above, calibration/verification results were considered quite good considering tributary boundary data for 2003 used both F.E. Walter and Beltzville reservoir inflow data depending on location of tributary to the reservoirs. W2 was able to predict behavior trends of constituents if not always the exact value. AME values were within acceptable values of the target AME values. Although W2 performance is quite acceptable for this study, better boundary data to improve on this calibration would help improve model predictions and reduce the uncertainty associated with the lack of data.

Summary and Conclusions

CE-QUAL-W2 has been calibrated for temperature, flow, and water quality at F. E. Walter and Beltzville Reservoirs and 45 miles downstream of F.E. Walter Reservoir on the Lehigh River. The model was calibrated and verified on two very different water years. Calibration was performed for 2001 a dry water year, and verification was performed on 2003 a wet water year. W2 performed well for calibration and verification. When using the calibrated model as a management tool, one would have the most confidence using the model to investigate how operational changes would affect temperature. The model quite accurately captures the physics of both reservoirs and the riverine sections. Any alteration in the physics should be predicted with a high degree of accuracy.

The primary focus of this study was to add water quality and metal constituents to the temperature and flow CE-QUAL-W2 (W2) models developed for two reservoirs (F. E. Walter and Beltzville) and approximately 60 river miles on the Lehigh River and Pohopoco Creek. Additionally, six new proposed operational scenarios agreed upon by the study partners at F.E. Walter Dam were modeled to enhance downstream and in-lake recreation and habitat.

Although temperature, water quality and flow boundary conditions were lacking on tributaries to the Lehigh River for 2003, verification water quality results compared favorably in both reservoirs to observed data. In the Lehigh River, model results it is believe would have been closer to observed data if tributary boundary conditions had been available. In spite of the lack of tributary boundary data most variables followed the trends of observed water quality behavior. Comparison of model profile results for both reservoirs showed good agreement for both years. Most water quality constituent results were within the target AME values and percent cumulative distribution plots showed most concentration ranges being correctly predicted. There were some exceptions. All in all for calibration and verification, results were considered favorable given limited data for verification.

Once the system was calibrated and verified, scenario runs looking at temperature in the Lehigh River were conducted using initial and boundary conditions from calibration and verification runs with new F. E. Walter reservoir releases. A total of six scenario runs, jointly developed and agreed to by ACOE (Army Corps of Engineers, Philadelphia), PADCNR Parks and Pennsylvania Fish and Boat Commission (PFBC), were made for each year and included:

- Scenario 1 can be described as “Fisheries only, with selective withdrawal to the dam” and is designed to maximized benefits to downstream fisheries. This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360, and 1380 ft and WSEL at 424.24 m (1392 ft).

- Scenario 2 can be described as “Maximizing whitewater events” while augmenting flow for fisheries during non-whitewater release goals with 2010 release schedule. This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360 and 1380 ft and WSEL at 417.71 m (1370 ft).

- Scenario 3 can be described as “Maximizing whitewater events” while augmenting flow for fisheries during non-whitewater release goals with 2010 release schedule. This scenario operated without a selective withdrawal structure (SW) with portals at elevations 1265, and 1297 ft and WSEL at 417.71 m (1370 ft).

- Scenario 4 goals are to provide whitewater releases on alternating weekends from in May and June, every weekend July through September; create optimal in-lake spawning areas in May and June by limiting the pool fluctuations to 5 feet; and maximize the benefit to cold water fisheries downstream by augmenting flows between July 1 and September 30 by a minimum of 50 cfs with the cooler water. This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360 and 1380 ft and WSEL at 424.56 m (1392 ft).

- Scenario 5 is based on the 2010 release schedule with outflow thermal targets as per Chapter 93 CWF thresholds. This operation was for producing and sustaining a fishery tailwater while satisfying whitewater interests. This scenario operated with a selective withdrawal structure (SW) with portals at elevations 1300, 1320, 1340, 1360, 1380, 1400, and 1420 ft with initial WSEL at 438.42 m (1438 ft).

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Beltzville Reservoir maintained the same release discharges for the scenario runs as were used during 2001 calibration and 2003 verification runs.

Using scenario results from these simulations, the Philadelphia District will be able to make informed decisions in regard to adjustments to reservoir operations to help improve fishery habitat and boating recreation within and downstream of F. E. Walter Reservoir. With the new optimization routine in W2 V3.7, many simulations can be made with quicker turn around to help make critical decision on reservoir operations.

Criteria for judgment of improvement from one scenario to the other was whether release temperatures were maintained at 20 ^{o} C (68 ^{o} F) or less during the warmer summer period downstream of F. E. Walter. Scenarios 5 and 6 met these criteria as far downstream as LH08 and LH10, respectively. Meaning that scenario 5 river temperatures were maintained at 20 ^{o} C (68 ^{o} F) or less as far downstream as station LH08 and during the wet year scenario 6 river temperatures were maintained at 20 ^{o} C (68 ^{o} F) or less as far downstream as LH10. As seen in Phase I, beyond these stations tributary inflows dominated flow in Lehigh River reducing influence from the dam. Downstream of LH08, differences in water temperature become minimal. As expected, water temperatures show the greatest differences immediately downstream of the dam before tributary influences begin to monopolize.

An overall statement can be made that changes to water quality releases from optimized runs are mostly attributed to release port location (i.e., actual layers release water is being pulled from) and the degree of stratification of water quality profiles. Release results for PO4, TP, TOC, and TSS for each scenario run are not very different from one scenario to the next. This is because almost isochemical conditions are present through the water column for these constituents for each scenario; thus scenario results will show very little difference since water quality concentrations would be similar at any elevation released. Except for DO, most of the concentration differences for these water quality constituents at station LH02 are not detrimental to living resources downstream of F. E. Walter Reservoir. Decline in DO concentrations is noticeable in results for scenarios 5 and 6 for both runs using original and optimized release flows. Values of DO can be as low as 2mg/L which stress living resources. From the 2003 profile results, this behavior is attributed to the formation of a DO minimum in the area of the release port elevations in the epilimnion. This may have formed through mortality, respiration, and decay from increased chlorophyll *a*, TOC and total suspended solids (TSS) concentrations in the area of the releases ports in the epilimnion of the reservoir. By the time water is transported from station LH02 to station LH03, DO concentrations have reaerated to levels of 7 mg/L or more. As water is transported downstream to station LH17, all concentration differences become diminished. Over all, the total metals modeled during scenario runs have concentrations that are below the levels considered to be harmful to the living resources for dissolved metal forms.

It is still recommended that for future modeling studies of F. E. Walter Reservoir, Beltzville Reservoir and riverine sections below, the District monitor inflow temperatures, metals and water quality parameters to major tributaries and inflow points to the reservoir to improve on this calibration. W2 did extremely well for 2001 but for 2003 lack of data from tributaries entering into the Lehigh River below F. E. Walter caused predicted values to be less favorable compared to results in 2001. As presented and discussed above, calibration/verification results were considered quite good considering tributary boundary data for 2003 used reservoir inflow data depending on location of tributary to the reservoirs. W2 was able to predict behavior trends of constituents if not always the exact value. Most of the time AME values were within target AME values. Although W2 performance is quite acceptable, better boundary data to drive the model would help improve model predictions and reduce the uncertainty associated with the lack of data.