Craver, Patti

From: Mitman, Jeffrey
Sent: Wednesday, October 20, 2010 2:43 PM
To: Ferrante, Fernando
Subject: FW: ~~OUO/SRI-FW:~~ Information Related to an NRC External Flood Inspection Issue at Oconee
Attachments: Outside of Scope Wilson Independent Review HDR Comments.pdf; Wilson Independent Review.pdf; Young Independent Reivew HDR Comments.pdf; Young Independent Review.pdf

Among the attachments are several independent reviews of the 1- and 2-D analysis.

From: Khanna, Meena
Sent: Friday, October 08, 2010 7:12 PM
To: Mitman, Jeffrey
Subject: FW: OUO/SRI-FW: Information Related to an NRC External Flood Inspection Issue at Oconee

Jeff, here are some responses to the questions that we requested of Duke...thx

From: Wescott, Rex
Sent: Tuesday, October 05, 2010 10:47 AM
To: Khanna, Meena
Subject: FW: OUO/SRI-FW: Information Related to an NRC External Flood Inspection Issue at Oconee

From: Khanna, Meena
Sent: Friday, August 27, 2010 12:53 PM
To: Wescott, Rex; Coleman, Neil
Cc: Wilson, George
Subject: OUO/SRI-FW: Information Related to an NRC External Flood Inspection Issue at Oconee

Fyi...

From: Stang, John
Sent: Friday, August 27, 2010 7:03 AM
To: Khanna, Meena
Subject: FW: Information Related to an NRC External Flood Inspection Issue at Oconee

Here you go

From: Thomas, Jeff [mailto:Jhere you goeff.Thomas@duke-energy.com]
Sent: Thursday, August 26, 2010 8:20 PM
To: Stang, John; Khanna, Meena
Cc: McCoy, Raymond L; Earnhardt, Patsy J; Freudenberger, Richard J; Alter, Kent R; Meixell, Bob
Subject: Information Related to an NRC External Flood Inspection Issue at Oconee

John,

This email contains information (attached and below) related to an NRC External Flood Inspection Issue at Oconee. In accordance with our correspondence and FOIA procedures, the information in this email has been authorized by the appropriate Regulatory Compliance functional manager and designated "For Information Only." The information is

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provided for limited purposes and should not be used to make a regulatory finding or decision. Furthermore, it contains information that should be withheld from public disclosure under 2.390.

Should you determine that the information is needed to make a regulatory decision or finding, then we will resubmit this information on the docket (with or without a formal RAI). Just let us know how you would like to proceed. Thanks.

Jeff Thomas
Fleet Regulatory Compliance Manager, Duke Energy
704-382-3438 (Office)
(b)(6) (Mobile)
jeff.thomas@duke-energy.com

Subject: RE: Jocassee RAI clarifications for nrc

NRR's Question:

In reviewing the Oconee external flooding issue, we need the following information from Duke regarding their 2-D model. If they have already provided this information to us previously, could you pls request that they refer us to the document. Pls forward this request to Bob and Jeff. Thanks.

2-D Model:

1. Model developers and qualifications.

Shown below are the names of the individuals responsible for the origination, review and independent review of the Oconee specific 2-D model.

Originator:	*Andrew W. McCoy, Ph.D., P.E.*
Reviewer:	*John J. Engel, MS, P.E.*
Independent Reviewers:	*Nathan C. Young, Ph.D., P.E.*
	Lloyd Chris Wilson, Ph.D., P.E.

A resume for each one is attached.

2. Basic model type (finite difference or finite element) and solution method

The following information is supported by these source documents:
Oconee Nuclear Station Calculation OSC 10030,
Bureau of Reclamation Web site: http://www.usbr.gov/pmts/sediment/model/srh2d/index.html

The Oconee specific model 2-D computational hydraulic model utilizes SRH-2D, Version 2 (Sedimentation and River Hydraulics – Two-Dimensional model) (Lai 2006). Version 2 is released, but future versions with expanded capabilities remain in progress. This modeling was developed by the Bureau of Reclamation.

This model allows for solution of open channel flow equations on unstructured hybrid meshes. SRH-2D applies a finite-volume discretization to the 2-D, depth averaged St. Venant equations, and mass conservation is satisfied both locally and globally. The code can process wetting and drying of elements, steady and unsteady flows, sub-critical and super-critical flows, and complex channel geometries. This

tool uses a flexible mesh that may contain various shaped cells. The model capabilities are ideal for flow through bends, braided channel systems, determining local flow velocities, and flows over banks and levees. The model is capable of simulating all flow regimes(i.e. subcritical, etc.). Variables solved include: water depth, water surface elevation, and depth averaged velocity.

A hybrid mesh of quadrilateral and triangular cells is the most practical application(looking at the mesh in Figure 10 from the first report you can see the quadrilateral and triangular elements used for Oconee), although a model of all quadrilateral or triangular elements can be used. The best balance between solution accuracy and overall computational demands can be satisfied with the use of a hybrid mesh.

SRH-2D is a product that was derived from SRH-W (watershed runoff modeling capability).

SRH-2D version 2 Downloads (available at the above listed web site)

- SRH-2D version 2 Theory and User Manual (2.43MB pdf)
- SRH-2D v2.0 Distribution(Nov. 2008): Software, Manual, and Tutorials (3.6 MB zip)
- Papers/Presentations
  - Theory Paper (424kB pdf)
  - SRH-2D Training Presentation(10.1 MB pdf)
  - 2005 US-China Workshop Paper (670kB pdf)
  - 2006 FISC Paper on Savage Rapids Dam Removal Project(295kB pdf)
- Project Reports
  - Bountry J.A. and Lai, Y.G. (2006)."Numerical modeling of flow hydraulics in support of the Savage Rapids Dam removal."(13.7MB pdf)
  - Lai, Y.G., Holburn, E.R., and Bauer, T.R. (2006)."Analysis of sediment transport following removal of the Sandy River Delta Dam."(11.0MB pdf)
  - Lai, Y.G. and Bountry, J.A. (2006). "Numerical hydraulic modeling and assessment in support of Elwha Surface Diversion Project."(21.3MB pdf)
  - Lai, Y.G. and Bountry, J.A. (2007). "Numerical modeling study of levee setback alternatives for lower Dungeness River, Washington"(32.9MB pdf)

3. Model validation and verification

The best summary for this issue is found in our two independent reviewers reports, and the associated HDR response found in the report found on file at Oconee Document Management. The initial Independent Review (IR) was done by Dr. Young. The second IR was done by Dr. Wilson. Both reviews looked at the Oconee specific 1D model (HEC-RAS) and the 2D model. The more extensive review by Dr. Wilson covers the latest work and relates to the information submitted to the NRC on August 2, 2010. Reference attachments entitled 'Wilson' and attachments entitled 'Young'.

NATHAN C. YOUNG (b)(6)

October 16, 2009

Dr. Andrew McCoy, PhD, PE
HDR Engineering, Inc.
300 E Locust Street
Suite 210
Des Moines, IA 50309-1823

Dear Dr. McCoy,

Please find the attached comments and recommendations on the HDR Engineering, Inc. (HDR) two-dimensional hydraulic model study of flow in the vicinity of Oconee Nuclear Station (ONS) at Lake Keowee, South Carolina following a hypothetical dam failure scenario at Lake Jocassee. Please let me know if you have any questions or concerns regarding this review.

Sincerely,

Nathan C. Young

REVIEW OF THE HDR ENGINEERING, INC. TWO-DIMENSIONAL SIMULATION OF FLOW IN THE VICINITY OF OCONEE NUCLEAR STATION RESULTING FROM A HYPOTHETICAL DAM FAILURE SCENARIO AT LAKE JOCASSEE.

Executive Summary

HDR Engineering, Inc. (HDR) is performing two-dimensional hydraulic simulations of flows in the vicinity of Oconee Nuclear Station (ONS) resulting from a sunny day dam failure at Lake Jocassee. The simulation has been developed using the United States Bureau of Reclamation (USBR) Sediment and River Hydraulics - 2D (SRH- 2D) software. The simulation uses results from a one-dimensional dam break analysis performed with Unites States Army Corps of Engineers (USACE) Hydrologic Engineering Center River Analysis System (HEC-RAS) to establish inflow and outflow boundary conditions. SRH-2D does not feature internal models for breaching of hydraulic structures. Breaching of embankments within the two-dimensional model domain was simulated by making step changes in the computational mesh.

The investigators' methodologies are sound. Application of SRH-2D is appropriate for the flow conditions represented in the simulation. The unstructured computational mesh highly resolved in the vicinity of the ONS yard, and other locations important to the objectives of the project. The geometry of ONS buildings, embankments, and nearby channels are accurately represented. Some limitations exist, associated with methods for breaching, establishing boundary conditions with one-dimensional model results, mesh density in areas further from the ONS yard, and the spatial extent of the model domain. Limitations and their effects on model predictions relevant to the project objectives should be carefully considered by the investigators.

The interruption of the simulation and restart with an altered mesh to simulate breaching appears to have created numerical instabilities and produced artificial wave phenomena. While initially a major concern, the investigators have demonstrated the waves are dampened when model time step is decreased. With the smaller time step, the waves are confined to the area in the vicinity of the breach. They do not seem to affect flows at the ONS yard.

The reviewer recommends investigators consider addressing the following model limitations by explaining their limited relevance to the project objectives, quantitatively demonstrating their limited effect on predicted flow conditions, or by making appropriate adjustments to the model:

- The one-dimensional HEC-RAS and two-dimensional SRH-2D simulations are not dynamically coupled. Therefore mass and momentum are not conserved between the two models; and

potential backflow through the inlet and outlet boundaries of the two-dimensional model cannot be represented.

- The computational domain does not extend laterally to fully include all areas inundated by the flood wave. Storage volume in these areas is therefore not represented in the model. The investigators should confirm the difference is storage is not appreciable relative to characteristic volumes associated with the simulation.
- Coarse mesh densities in areas further from the ONS yard result in greater computational efficiency but can also influence model results by reducing topographic and bathymetric resolution and introducing cell discontinuities.
- Because the simulation represents an extreme and unobserved scenario, modeled flow conditions cannot be calibrated. Analysis of sensitivity to mesh density, time step, and roughness coefficients may therefore be helpful in quantifying uncertainty and characterizing confidence in model results.

Introduction

The comments and recommendations contained herein refer to the HDR Engineering, Inc. (HDR) two-dimensional hydraulic simulation of flow in the vicinity of the Oconee Nuclear Station (ONS) resulting from a hypothetical sunny day dam failure at Lake Jocassee. HDR performed the simulations using the Sediment and River Hydraulics - 2D (SRH-2D) code developed by the United States Bureau of Reclamation (USBR). HDR provided the reviewer input files and preliminary results corresponding to model case 3, described in the draft project report.

Model Application

The investigators are prudent to note in the draft report that assumptions associated with application of the two-dimensional St. Venant equations may not be appropriate for some flow conditions represented in model. SRH-2D has been primarily used in situations where channel width is greater than 10 times the depth (Lai & Bountry, 2007), (Lai, 2006). However, testing and verification of SRH-2D included a diversion flow case with a width-to-depth ratio of approximately 5 (Lai , 2009). Additionally, SRH-2D has been used to a model river segments where width-to-depth ratios ranged from 4 to 7 (Bountry & Lai, 2005). These values are more consistent with flow conditions anticipated by the investigators for the Keowee Dam and Canal Reach, lending greater support to application of SRH-2D in the present study.

Model Use in Conjunction with Broader One-dimensional HEC-RAS Simulation

The investigators use results from a larger-scale dam break analysis performed with the one-dimensional HEC-RAS software to establish boundary conditions for the SRH-2D simulation. Use of SRH-2D in conjunction with HEC-RAS is a reasonable approach. However, mass and momentum are not conserved between the two models. Possible backflow at the two-dimensional model boundaries therefore cannot be simulated. This limitation is also relevant to the selection of the model domain and boundaries, as discussed below.

Model Boundaries

Lateral Boundaries

The lateral boundaries of the computational domain are not broad enough to include all areas inundated by the flood wave. Exclusion of these areas will reduce the available storage volume and may impact flood magnitude and timing. The investigators should evaluate the significance of the unrepresented volume relative to characteristic volumes associated with the simulation. Expansion of the computational domain to include all areas potentially inundated by the simulated dam break should be considered if the unrepresented volume is appreciable.

Inflow and Outflow Boundaries

Propagation of the flood wave through Lake Keowee has the potential to induce upstream flow at the model outflow and inflow boundaries. Investigators should evaluate the potential for return flow at the model boundaries and its impact on predicted inundation at the ONS yard.

Prior to the drainage of Lake Keowee, return flow may be possible at outflow boundary 2. However, the stage hydrograph boundary condition does not allow inflow at this location. Downstream expansion of the model domain below Little River Dam and creation of a single downstream boundary on the Keowee River would help to account for any such effects.

There is also a possibility of flow exiting the model domain at the upstream boundary as the flood wave is partially reflected by the Keowee Dam embankment and other geometric features, and reentering the domain at a later time. Expansion of the domain to incorporate the upstream portion of Lake Keowee would allow the investigators to account for this behavior in the simulation.

Computational Mesh

The unstructured computational mesh used in the model study is a good compromise between numerical efficiency and accurate geometric representation. The investigators use a fine mesh resolution in the vicinity of the ONS and other features of major importance to the study objectives, such as locations of simulated breaches. The mesh accurately represents the geometry of buildings, embankments, and other features that may influence the local flow field at these locations. The mesh density decreases gradually with distance from these features and becomes fairly coarse near the outer boundary of the computational domain, decreasing simulation times.

The investigators should consider some possible effects of the coarse mesh near the model boundaries. Large, irregularly-shaped elements may have an effect on computational performance and model results. This may be an important consideration for the initially impounded areas of Lake Keowee. Mesh refinement in remnant river channels within impounded areas may improve model performance, especially near the end of the simulation when flow becomes more constrained by channel geometry.

Refinement of the mesh near the domain boundary may improve the geometric representation of the bathymetry and topography in these areas. This may benefit model performance by improving the accuracy of available storage volume, affecting the timing and magnitude of flood peaks. It may also improve cell connectivity, reducing occurrence of artificial ponding as water recedes from these areas.

The investigators have introduced stepped changes in the computational mesh to simulate embankment failures. While this is a practical solution to modeling embankment failure scenarios, interruption and restart of the simulation with slightly altered geometry may introduce numerical instability. This may contribute to the wave phenomena discussed in more detail below.

Model Time Step

Because SRH-2D uses an implicit scheme to perform numerical calculations, the **Courant–Friedrichs–Lewy** (CFL) condition need not be satisfied to ensure model stability. However, when time steps are very large relative to mesh cell size, the model can still produce erroneous results. Analysis of model sensitivity to mesh density and time step may be valuable in identifying and eliminating such errors (see below).

Observed Wave Phenomena

HDR noted the presence of relatively high-frequency waves propagating through the model domain. Waves appear following abrupt changes made to the mesh during the simulation, representing breaching of

embankments. After initial model review discussions, the 1.0-second model time step was incrementally reduced to evaluate its potential role in wave phenomena. Reduction in model time step from 1.0 to 0.25 seconds resulted in more rapid attenuation of the waves. However, short-lived waves with roughly 5-foot maximum amplitude are still produced near the Keowee Dam at the time of the initial embankment breach. More recently, the time step was reduced to 0.1 seconds. This appears to attenuate the waves more rapidly, limiting their influence to the immediate vicinity of the breach.

Sensitivity Analyses

Because the simulation represents an extreme and unobserved event, it is not possible to calibrate or validate for the modeled flow conditions. Therefore, it may be valuable to perform sensitivity analyses to evaluate variability in results according to reasonable changes in model parameters. This would help to quantify uncertainty and characterize confidence in model predictions. Sensitivity analyses may also help to identify maximum thresholds in mesh density and time step at which numerical error does not affect model results.

If performed, sensitivity analyses should include mesh density, and time step, and roughness coefficients. Potential effects of mesh density and time step have been described above. Sensitivity to roughness coefficients may also be an important consideration. The reviewer's experience suggests Manning's roughness coefficients are somewhat lower than published values for two-dimensional simulations. The SRH-2D turbulence parameter α may also be considered in the analysis. However the SRH-2D user manual indicates minimal sensitivity to α.

References

Bountry, J. A., & Lai, Y. G. (2005). *Numerical Modeling of Flow Hydraulics in Support of the Savage Rapids Dam Removal.* Denver, CO: Bureau of Reclamation Technical Service Center.

Lai, Y. G. (2009). *Two-Dimensional Depth-Averaged Flow Modeling with an Unstructured Hybrid Mesh.* Denver, CO: Bureau of Reclamation Technical Service Center, Sedimentation and River Hydraulics Group.

Lai, Y. G., & Bountry, J. (2007). *Numerical Modeling Study of Levee Setback Alternatives for Lower Dungeness River, Washington.* Denver, CO: Bureau of Reclamation Technical Service Center, Sedimentation and River Hydraulics Group.

Yong G. Lai, J. A. (2006). *Numerical Hydraulic Modeling and Assessment in Support of Elwha Surface Diversion Project.* Denver, CO: Bureau of Reclamation Technical Service Center, Sedimentation and River Hydraulics Group.

Wilson Engineering
Water Resources Specialists
WE

June 14, 2010

Mr. Raymond L. McCoy
Duke Energy
529 South Church St.
Charlotte, NC 28202

Subject: **Independent Technical Review**
HEC-RAS and SRH-2D Hydraulic Modeling
Wilson Engineering Project WE10009

Dear Mr. McCoy:

I have performed an independent technical review of the HEC-RAS and SRH-2D modeling performed by your consultant, HDR|DTA. Work was performed in accordance with the Independent Consulting Agreement and scope of work dated May 3, 2010. This letter is written to present my findings.

EXECUTIVE SUMMARY

Wilson Engineering reviewed reports, documents, model input and model output files to evaluate the hydraulic modeling performed by HDR|DTA associated with a simulated sunny-day breach of Jocassee Dam and its impacts on downstream hydro facilities and the Oconee Nuclear Station (ONS). As the designated independent reviewer I found the study to be performed in accordance with generally accepted engineering practice and to be an unbiased appraisal of the impacts of a wide range of breach scenarios. Considering the challenges of developing both 1-D and 2-D hydraulic models for the very complicated system in the study area, HDR|DTA should be commended for their thorough approach.

There are a few areas in which the modeling could be improved, however these recommendations are not likely to impact conclusions that have been drawn to date using the hydraulic models. It is my understanding that many of the recommendations presented in this report have are already being implemented in new modeling efforts by HDR|DTA.

BACKGROUND

HDR|DTA prepared both one-dimensional and two-dimensional dynamic hydraulic computer models to simulate the downstream impacts of a hypothetical sunny-day breach of Lake Jocassee Dam on the Oconee Nuclear Station (ONS) located adjacent to Lake Keowee which is impounded by Keowee Dam, Oconee Intake Dike and Little River Dam (as well as several smaller dikes along the Little River Arm). The 1-D model utilized the HEC-RAS computer program developed and maintained by the U.S. Army Corps of Engineers; the 2-D model utilized the SRH-2D computer program developed and maintained by the Bureau of Reclamation.

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The modeling effort was documented primarily in these reports:

- *Oconee Nuclear Station, Jocassee-Keowee Dam Breach Model Report*, March 2009,
- *Oconee Nuclear Station, Jocassee-Keowee Dam Breach Study, March 2009 Report Addendum, HEC-RAS Breach Parameter Matrix and Model Results*, April 2010 (hereafter referred to as the *HEC-RAS report*), and
- *Oconee Nuclear Station, Jocassee 2-D Hydraulic Model Study, Hydraulic Modeling Report, Technical Report*, April 2010 (hereafter referred to as the *SRH-2D report*).

The complete background of the Jocassee/Keowee hydro system and HDR|DTA modeling effort is contained in these documents, and will not be repeated here. The remainder of this letter report is written with the assumption that the reader is very familiar with the contents of these reports.

Wilson Engineering was retained to review the technical analyses performed by HDR|DTA based on my background and experience (please see attached c.v.) and familiarity with the hydrologic system. During prior employment, I acted as project manager on the Jocassee Dam Hydrologic Analysis and project principal on the Lake Keowee Dam Probable Maximum Flood Study which included a technical review of Duke's PMF study. I was also the co-developer of the Duke Hydro Management System which is a software tool to perform real-time hydrologic simulation of many of Duke Energy's hydro systems including the Keowee-Toxaway facilities. I am very experienced with HEC-RAS and have used it on numerous occasions. Although I had previously no experience with the SRH-2D computer model, I have used RMA-2 which is similar.

The Federal Energy Regulatory Commission (FERC) mandates that Independent Technical Reviews be performed associated with FERC relicensing of hydropower facilities, and this review was performed in accordance with those requirements. The objective of my review was to evaluate and comment on the appropriateness of the model geometry, cross section/grid density, boundary conditions, roughness parameters, and proposed breach parameters.

Following a preliminary kick-off meeting at HDR|DTA's office in Charlotte, work was conducted over a six-week period in May and June 2010. HDR|DTA provided office space for an intensive review of all requested documents and models for four days in Charlotte, NC, and four days in Des Moines, IA. Additional reviews and analyses were conducted in my office in St. Louis, MO. I was given full access to computer model inputs and outputs, QA/QC documents, raw data, intermediate emails, memos, and reports, and was able to make many computer simulations using their models as well as additional "what-if" simulations that I developed for testing purposes.

On-site visits were conducted in 2007 as part of the Duke Hydro Management System (DHMS) project, which provided me with sufficient familiarity to conduct this review.

FINDINGS

GENERAL

Geometry for both the 1-D and 2-D models was taken from publicly available Digital Elevation Models (DEMs), and the cross sections and volumes compared favorably to prior values. Manning's n roughness values were well documented and are considered to be appropriate for the field conditions. The dam breach parameters were chosen after a thorough literature review and an ongoing Probability Risk Assessment. A careful sensitivity analysis was also performed and documented.

HDR|DTA developed the most complex HEC-RAS model in my experience. As detailed in the April 2009 report, the model consisted of 1,411 primary and 5,762 interpolated cross sections, 10 storage areas, and a multi-branch model organized into a non-dentritic network. Similarly, the SRH-2D model was developed at a high density, consisting of about 40,000 grid meshes.

In general, the models showed a high level of diligence and professionalism in their development. During interviews it was apparent that the engineers were experienced with their application and knowledgeable about their limitations. Overall, the models are a good representation of the hydraulic system.

Before detailing my findings and recommendations, I want to emphasize that applications of complex hydraulic models is an art. The objective of water resources modeling is to simplify an impossibly complex natural system so that it can be simulated using a computer program. Not all of the laws of physics are even represented in the mathematical models, and those that are often involve the application of empirical equations rarely calibrated to extreme conditions such as those associated with a dam breach. The models cannot be calibrated using observed data because the regulated stream system has never exceeded full pond elevation.

With the amount of judgment and experience that goes into the development of a hydraulic model, it would be easy to nitpick individual representations or decisions that are made. Instead, this report will focus on modeling issues that may have a significant impact on the results, deserve additional study, and should be considered for adoption as the hydraulic models are further developed and revised.

HEC-RAS Findings

Cross Section Placement

HEC-GeoRAS was used to acquire cross sections from a DTM and specified cut lines. This approach allowed a great deal of geometric information to be represented in the HEC-RAS model. Spot-checking of the cross section alignments revealed a few areas where cross section alignment should be reconsidered. Figure 1 illustrates one such location downstream from Keowee Dam: the cross sections were located in the vicinity of "Big Bend" assuming that the saddle between Old Pickens and Big Bend would be overtopped and during the peak event would act as the main channel. Although this may be true, the normal flow channel would be better represented using the four cross sections overlaid as thick red lines.

The ONS model was purposely developed for a dam break scenario, and detailed bridge modeling was not done because it was correctly assumed that the bridge decks would likely wash out early in the event. However, the highway embankments would not necessarily wash out (in fact, all cross sections except where dam breaches occur are assumed to be unchanged), and the HEC-RAS model did not accurately represent the Highway 183 embankment located at cross section 26152. These issues are expected to have a significant impact on predicted water surface elevations in the reach just below Keowee Dam.

Roughness Coefficients

The selection of Manning's n roughness coefficients was generally reasonable, however the assignment of the coefficients was in some places was incorrect. For example, in the reach which comprised Keowee Lake, cross section n values were assigned based on bank station placement, and in some places the banks were set too far from the normal pool lake extents, thus causing areas that are currently heavily wooded to be assigned too low n values. Similarly, n values in the vicinity of Big Bend (Figure 1) were inappropriate.

BREACH FORMATION SETTINGS

Breach parameter selections were guided by members of the Jocassee Probability Risk Assessment (PRA) Team. I reviewed their breach parameter selection methodology and found the team's approach to be thorough and parameters to be appropriate.

NUMERICAL STABILITY

The ONS HEC-RAS model is quite complex in terms of the number of cross sections and reach configuration. Simulation of a sunny-day dam breach also adds extraordinary challenges to the numerical solution technique, despite HEC-RAS's reputation as a very stable model.

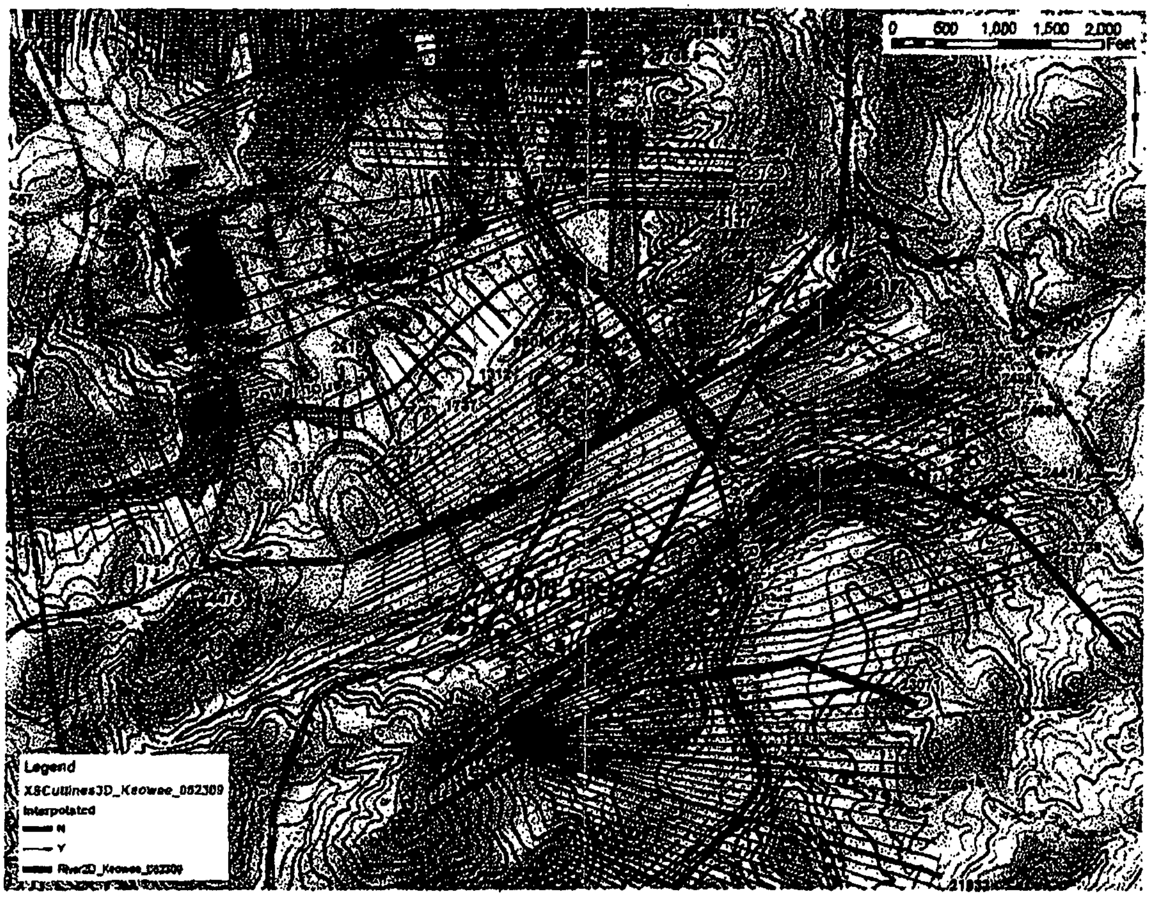

FIGURE 1 - CROSS SECTION PLACEMENT DOWNSTREAM FROM KEOWEE DAM

Early versions of the model were not able to complete the simulation successfully until the momentum equation was adopted for solution at junction nodes. After this was done, during the massive dam breach flood wave release, HEC-RAS still reported that the maximum number of iterations was exceeded at numerous cross sections along with the associated elevation error. In some cases, the more serious error "solver went unstable" message was also displayed.

I spent a considerable amount of time investigating the cause of these numerical instabilities in an effort to reduce their impact on the simulation results. The only numerical solution setting that positively impacted the review model stability was the "exponent for Froude number reduction factor" (m variable).

Use of the HEC-RAS mixed flow regime was necessary due to the fact that water flows in both the subcritical and supercritical states. The Local Partial Inertia (LPI) technique is used to reduce the inertia terms in the momentum equation as the Froude number goes towards 1.0. The HEC-RAS Manual indicates that smaller values increase stability but decrease accuracy.

I changed the mixed flow exponent, m, from the default value of 10 to 4 to determine the impact on the occurrence of non-convergence errors, average error, and predicted peak elevations. All "solver went unstable" messages were eliminated and the errors associated with the "iterations exceeded" messages and predicted water surface elevations were significantly reduced:

Mixed Flow Exponent, m	"Iterations Exceeded" Convergence Error (ft)		Peak Water Surface Elevation (ft msl)	
	Maximum	Average	Jocassee Downstream	Keowee Upstream
10	7.74	2.53	944.26	842.20
4	2.57	0.53	935.58	840.19

Reduction of this factor decreased the numerical error in the solution and caused a substantial dampening of the predicted peak elevations. An examination of two hydrographs illustrates that the results from the analysis using m=4 produces more realistic, monotonic hydrographs. Both hydrographs are taken from a typical HEC-RAS model run which experienced numerical oscillations on the Keowee River (Breach Case 1), just upstream and downstream from the confluence with the Eastatoe River, are shown in Figure 2 and Figure 3.

Based on this analysis, use of the non-default mixed flow exponent yields more reasonable results, and should be used in future.

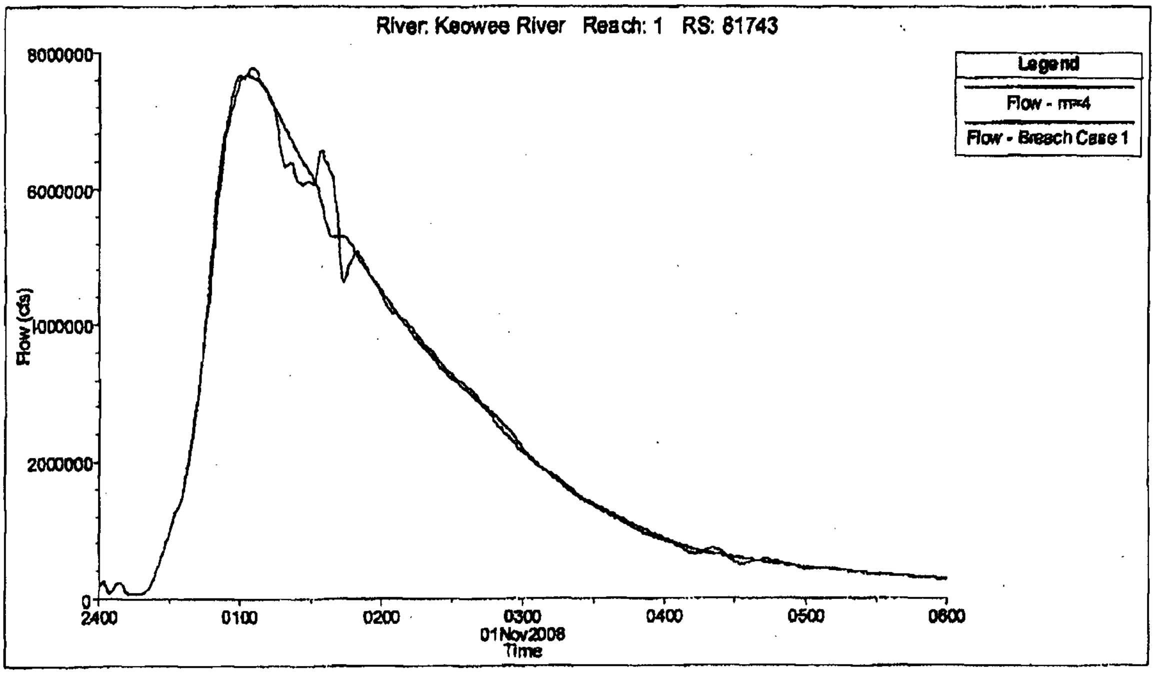

FIGURE 2 - MIXED FLOW EXPONENT COMPARISON, KEOWEE RIVER - UPSTREAM OF EASTATOE RIVER

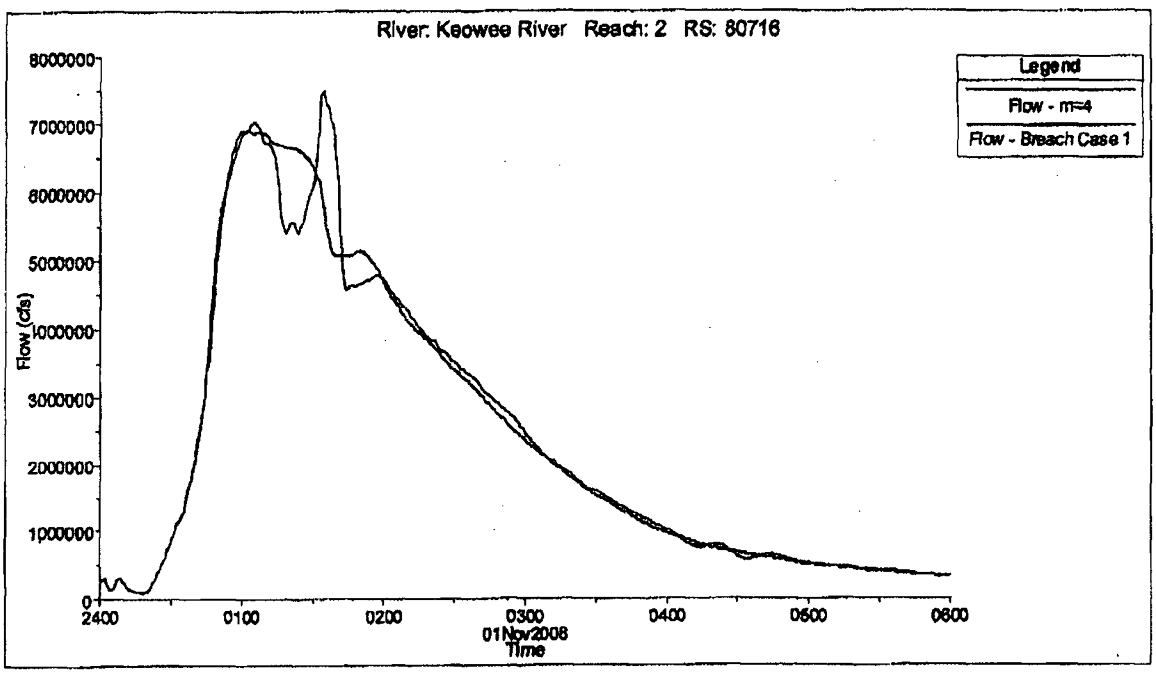

FIGURE 3 - MIXED FLOW EXPONENT COMPARISON, KEOWEE RIVER - DOWNSTREAM OF EASTATOE RIVER

COMPARING STEADY AND UNSTEADY SIMULATION RESULTS

The HEC-RAS model uses a different internal representation of energy losses and solution technique when performing unsteady as compared to steady state computations (which are used more frequently and are

presumably better tested). It is therefore recommended that a pseudo-steady state model consisting of constant boundary inflows and water surface elevations be prepared and run for a sufficient time for all computed flows and stages to reach equilibrium. Results from this run should be compared to a steady state simulation using the identical geometry, roughness coefficients, and flows. The resulting water surface profiles should be plotted and compared. The performance of this simplified test should be conducted for a few flows representative of the range of conditions for which the unsteady simulation is performed. It is assumed that using this test should produce a similar result for the discharge snapshot and without the complications associated with the numerous parameters associated with numerical stability of the unsteady solution (mentioned previously), the steady flow simulations may provide greater confidence in the results and geometry that is being used to estimate the complex flows being routed.

SRH-2D Findings

Even though the 2-D model is internally more sophisticated and computationally intensive than the 1-D model, it is easier to understand because of the lower degree of abstraction. In other words, the full 2-D St. Venant equations are being solved so it is not necessary to approximate the natural system with a 1-D representation and the associated empirical equations. Consequently, once the extent of the node mesh is determined and represented using DEM data, the only remaining variable is the roughness coefficient (and the turbulence coefficient to which the model is non-sensitive according to the developer).

Model Geometry

The same DTM used by HEC-GEORAS to develop the HEC-RAS cross sections was used to create the SRH-2D mesh. In the 2-D report, HDR|DTA showed a single comparison of cross sections; two additional comparisons were made during this review (at Keowee River sections 20286 and 24635) and they were found to be nearly identical.

The HEC-RAS storage area associated with Four Mile Creek just southeast of Keowee Dam (4 Mile) was modeled using a 2-D mesh with SRH-2D. The areal extent of that storage area appeared to be insufficient to completely represent the storage associated with the corresponding storage area in HEC-RAS, but it was not possible to easily compare the total volumes. Considering the impact this storage area may have on tailwater elevations, I recommend that the mesh be extended in this area to the northeast; the mesh can be coarse and still adequately represent the off-channel storage at this location.

Roughness Coefficients

The SRH-2D model was checked to verify that the same geometry was used as in HEC-RAS. The same Manning's n values were adopted, however the extents of the n values was not necessarily identical. As previously mentioned, in some cases the bank stations for HEC-RAS cross sections were somewhat wider than they should have been at:

- Lake Keowee Reservoir
- Big Bend downstream of Keowee Dam

The SRH-2D model used the correct pool extents when assigning n values within the Lake and channel extents at Big Bend. The HEC-RAS model adopted Manning's roughness coefficients of 0.07 for about 1000 feet downstream of breached embankments (gradually transitioning to 0.025); however this was not done in SRH-2D.

Boundary Conditions

SRH-2D boundary conditions were set to match the HEC-RAS model as follows: downstream boundaries used computed water surface elevations and upstream boundaries used computed flow hydrographs. The SRH-2D

report details the mass balance checks that were done. As an additional check, the upstream boundary stage hydrographs were compared for both HEC-RAS and SRH-2D and shown in Figure 4. SRH-2D computes a peak water surface elevation about 13 feet higher than HEC-RAS. This may be due to the differences in Manning's n values between the models or the fact that mass and momentum are not conserved between the two models (as mentioned in Dr. Young's review of the 2-D model dated October 16, 2009). I concur with Dr. Young's assessment that the use of the two models is a reasonable approach, but believe that HDR's extent and density of the 2-D model mesh is as large as can be practically applied.

(b)(7)(F)

FIGURE 4 - UPSTREAM BOUNDARY STAGE HYDROGRAPH COMPARISON FOR CASE 2

STAGE HYDROGRAPHS

Tailwater stage hydrographs in the vicinity of the ONS downstream from Keowee Dam were compared for the HEC-RAS and SRH-2D models. Figure 5 is a modification of Figure 35 in the SRH-2D report which adds HEC-RAS simulation results. The SRH-2D Case 2 predicted stage values were about 25 feet higher than those of HEC-RAS. This is likely due to the HEC-RAS geometry discrepancies in this reach that were previously mentioned.

(b)(7)(F)

FIGURE 5 – TAILWATER WATER SURFACE PROFILE COMPARISON FOR CASE 2

Breach Formation

Section 3.4 of the SRH-2D report described how the breaches had to be simulated using the 2-D model: the sine wave breach formation was approximated using a 6-part step function by stopping the model at a specific time, adjusting the mesh to represent the partial breach, and restarting the simulation. As shown in Figure 8 of that report, the timing of these manual steps lagged the HEC-RAS sine-curve function. In my opinion, a better approach would have been to have the steps straddle the sine curve, as indicated in Figure 6 as a green dotted line. This would have enabled a slightly more faithful representation of the HEC-RAS breach formation, shifting it about 10% of the total breach formation time (in the case of Keowee, about 15 minutes). The impact of this time shift was not determined, but it is not expected to be large, relatively speaking.

The fine mesh and short time step caused a single SRH-2D model run time to exceed several days, taking it to the edge of practicality. If additional 2-D modeling is to be performed, I recommend that Duke Energy consider funding some additional software development so HDR can enhance the SRH-2D code to add a breach formation algorithm. Not only would it allow the 2-D model to better match the HEC-RAS breach formation results, but it is likely that a smooth adjustment of the mesh would introduce less shock to the numerical algorithm compared to the step function. This would allow the model to be run using a larger time step and allow the simulations to be done in less time. Another possible avenue to decrease overall runtimes would be to implement parallel processing features in the code to enable it to utilize multiple cores and processors.

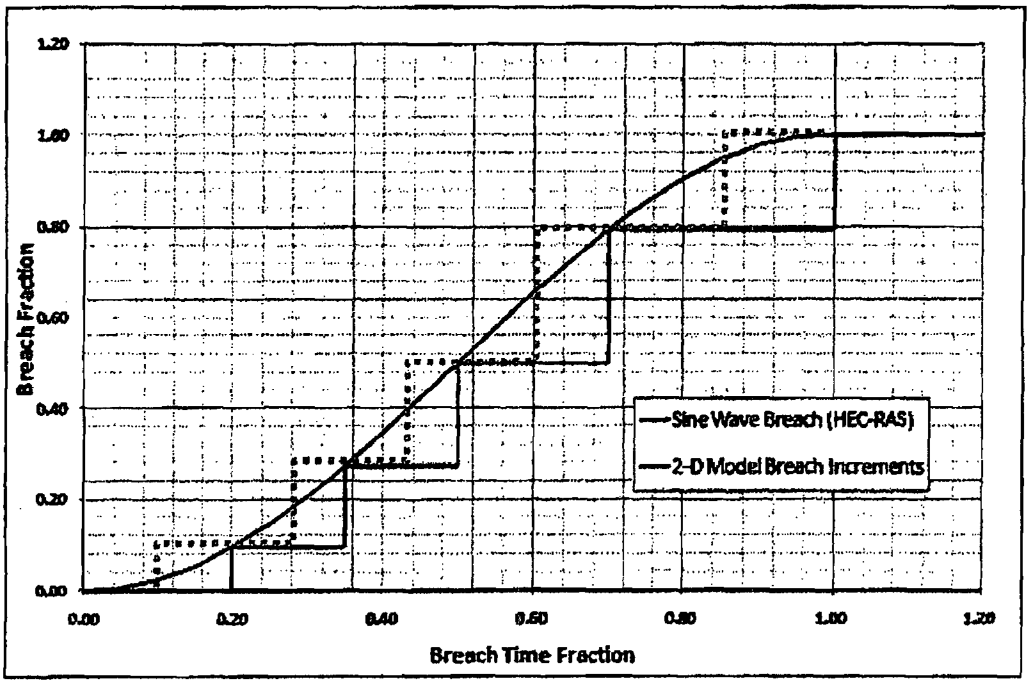

FIGURE 6 - BREACH FORMATION STEP FUNCTION

COMPARING PSEUDO-STEADY SIMULATION RESULTS

A relatively simple means to perform a QA/QC check between the HEC-RAS and SRH-2D model would be to create pseudo-steady simulations for each model and compare the water surface profiles. As previously mentioned, this is done by taking the unsteady models and applying constant value flow and stage boundary conditions for a very long time, running the models until equilibrium is established. This should be done for a few flows representative of the range of conditions for which the unsteady simulation is performed. By comparing pseudo-steady state runs for each model, it would be much easier to verify correct entry of geometry and roughness coefficients without the complications of unsteady flow simulations and possibly numerical stability issues. In particular, the stage hydrograph discrepancies between the two models at the upstream boundary (Figure 4) and tailwater reach downstream of Keowee Dam (Figure 5) could more easily be explained and hopefully corrected for.

CONCLUSIONS

As the designated independent reviewer I found the study to be performed in accordance with generally accepted engineering practice and to be an unbiased appraisal of the impacts of a wide range of breach scenarios. This report presented some recommendations where the modeling could be improved or additional analyses to facilitate comparisons of the 1-D and 2-D models; however these recommendations are not likely to impact conclusions that have been drawn to date using the hydraulic models. Nevertheless, it is my understanding that many of these recommendations are planned for implementation as HDR|DTA continues to refine their hydraulic models.

It has been a pleasure assisting Duke Energy with this important project. Please call me if I can be of more service.

Sincerely,

WILSON ENGINEERING

Lloyd (Chris) Wilson, Ph.D., P.E.
President

FIGURE 15

(b)(7)(F)

3.8 Independent Technical Review

An independent Technical Review was undertaken and can be reviewed in entirety in Appendix A. The main points that the reviewer made with respect to the modeling effort to date were made within a context of how to further refine the model given an extension in the project schedule and specific need for improved numerical efficiency. The reviewer concluded that the modeling methodology was sound. Application of SRH-2D is appropriate for the flow conditions represented in the simulation. The unstructured computational mesh is highly resolved in the vicinity of the ONS yard, and at other locations important to the objectives of the project. The geometry of ONS buildings, embankments, and nearby channels is accurately represented.

The reviewer also commented on areas that could be improved to strengthen the model in the future.

1. The interruption of the simulation and restart with an altered mesh to simulate breaching appears to have created numerical instabilities and produced artificial wave phenomena. While initially a major concern, the investigators have demonstrated the waves are dampened when model time step is decreased. With the smaller time step, the waves are confined to the area in the vicinity of the breach. They do not seem to affect flows at the ONS yard.
2. The 1-D HEC-RAS and 2-D SRH-2D simulations are not dynamically coupled. Therefore mass and momentum are not conserved between the two models; and potential backflow through the inlet and outlet boundaries of the 2-D model cannot be represented.
3. The computational domain does not extend laterally to fully include all areas inundated by the flood wave. Storage volume in these areas is therefore not represented in the model. The investigators should confirm the difference is storage is not appreciable relative to characteristic volumes associated with the simulation.
4. Coarse mesh densities in areas further from the ONS yard result in greater computational efficiency but can also influence model results by reducing topographic and bathymetric resolution and introducing cell discontinuities.
5. Because the simulation represents an extreme and unobserved scenario, modeled flow conditions cannot be calibrated. Analysis of sensitivity to mesh density, time step, and roughness coefficients may therefore be helpful in quantifying uncertainty and characterizing confidence in model results.

With respect to improvement suggestion 1, the decreases in time step dealt with the problem of widespread numerical instability in the form of widespread surface waves. Figure 15 demonstrates this result.

With respect to improvement suggestion 2, while mass and momentum are not conserved between the 1-D and 2-D model, any impact of a wave reflecting off the dam is passed to the 2-D model in the form of the boundary conditions extracted from HEC-RAS.

With respect to improvement suggestion 3, the reviewer points out that the computational domain does not extend laterally to fully include all areas inundated by the flood wave. While this is a true statement, inspection of Figure 10 reveals that there are a few coves that are not included within the computational domain. This is insignificant because the depths in the coves in question are small and thus the total storage volume left out of the 2-D model is insignificant.

With respect to improvement suggestion 4, the coarse mesh densities are far away from the ONS yard (~2 miles). The magnitude of impact due to coarse mesh elements is diminished by the time the (b)(7)(F) [redacted]

With respect to improvement suggestion 5, it is true that the flow conditions cannot be calibrated. The reviewer points out that analysis of sensitivity to mesh density, time step, and roughness coefficients may therefore be helpful in quantifying uncertainty and characterizing confidence in model results. The sensitivity to time step was found to be very important and was dealt with sufficiently. The sensitivity to roughness coefficients was investigated during the HEC-RAS analysis and found to have minimal impact on the timing and depth of the (b)(7)(F) [redacted] With respect to sensitivity to mesh element size, the impacts of decreasing or increasing the mesh elements in the ONS yard were not explicitly analyzed. External to this project, an analysis of mesh sensitivity on water surface elevations was performed on a stream reach with elements ranging from 1.5 to 3.5 feet (Tolossa et al. 2009). The impact to the water surface elevation associated with varying the characteristic size of the element in this range were on the order of 0.05 to 0.1 feet. In the ONS Yard, the characteristic size of the elements are on the order of 5 to 15 feet. Based on the results of this analysis (Tolassa et al. 2009), the conclusion was drawn that mesh element size does indeed impact water surface elevations, but on a much smaller order than what is required for the current analysis.

Section 4

Addressing Review Comments from Independent Review

The following section addresses results of a re-run of the 2-D model using results from a modified 1-D HEC-RAS model (June 2010) for Case 100. The re-run was performed to show the sensitivity of the 2-D model results to changes in the 1-D model that were recommended in an independent review commissioned by Duke Energy. The independent review of the 1-D model by Wilson Engineering provided several recommendations addressing hydraulic characteristics of cross section downstream of Keowee Dam. HDR|DTA incorporated the recommendations in a modified 1-D model noted as the June 2010 model. The results of the 1-D model are discussed in the companion report "Oconee Nuclear Station, Jocassee-Keowee Dam Breach Study, March 2009 Report Addendum 2, Breach Scenarios 100A through 100F, HEC-RAS Model Results. July 2010". HDR|DTA performed a new 2-D assessment using the necessary output from the 1-D model to supply boundary parameters to the new 2-D run, or Case 100W.

Table 7 compares 2-D Case 100M (prior to Independent Review) and 2-D Case 100W (post Independent Review). This is a valid relationship since Case 100M values were derived with inputs from a March 2009 HEC-RAS model using parameters associated with run 100, and Case 100W values were derived with inputs from a June 2010 HEC-RAS model using parameters associated with run 100. Identical parameter inputs were used in all evaluations for this table.

The time to (b)(7)(F) [redacted] decreased slightly and followed the same trend as the scenario output using the revised June 2010 1-D HEC-RAS model. The maximum water surfaces reached in Case 100W in the Keowee Reservoir (upstream of the dam) and the Intake Dike Canal were within 1 feet of the surfaces reached in Case 100M and timing comparison between the 2-D model and the 1-D model is closer in Case 100W than it was in Case 100M. The maximum elevation reached at the swale, tailwater, and SSF does not change substantially from Case 100M to Case 100W in the 2-D model. However, the timing

comparison of these reference events between Case 100M and Case 100W indicates that the 1-D model is producing results that are more similar to the 2-D model in Case 100W.

Figure 25 illustrates that the (b)(7)(F) [redacted] during Cases 100M and 100W are nearly equivalent.

Overall, using the results from 1-D scenario Case 100 using the June 2010 modified 1-D model (changes recommended by Wilson Engineering) and the modified mesh 2-D model (2010) (Case 100W) does not produce significant changes in results when comparing the two similar scenarios (Case 100M and Case 100W). Therefore, it is concluded that the results from the previous scenarios documented in the April 2010 Report are still valid.

TABLE 7

(b)(7)(F)

FIGURE 25

(b)(7)(F)