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ONS-2015-055

April 30, 2015

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10 CFR 50.54(f)

Duke Energy Carolinas, LLC (Duke Energy)
Oconee Nuclear Station, Units 1, 2 and 3
Docket Numbers 50-269, 50-270, 50-287
Renewed License Numbers DPR-38, DPR-47, and DPR-55

Subject: Second Response to Request for Additional Information dated October 23, 2014, Related to Southeastern Catalog Changes and Seismic Re-Evaluations

References:

1. Duke Energy letter to NRC, *Seismic Hazard and Screening Report (CEUS Sites), Response to NRC 10 CFR 50.54(f) Request for Information Pursuant to Title 10 of the Code of Federal Regulations 50.54(f) regarding Recommendations 2.1, 2.3 and 9.3 of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident,*"(for Oconee) dated March 31, 2014 (ADAMS Accession Number ML14092A024)
2. NRC letter, *Request for Additional Information Regarding the use of the Revised CEUS Seismic Catalogue,* dated October 23, 2014 (ADAMS Accession No. ML14268A516)
3. Duke Energy letter to NRC, *Response to the NRC's Request for Additional Information dated October 23, 2014, Related to Southeastern Catalog Changes and Seismic Re-Evaluations*, dated October 23, 2014 (ML14325A584)

Ladies and Gentlemen,

Duke Energy submitted a Seismic Hazard and Screening Report (CEUS Sites) for Oconee Nuclear Station (ONS) on March 31, 2014 (Reference 1) pursuant to the NRC's 10 CFR 50.54(f) request associated with Fukushima. The report required changes to be made to the Central and Eastern United States Seismic Source Characterization (CEUS-SSC) for Nuclear Facilities catalog.

By letter dated October 23, 2014 (Reference 2), the NRC submitted a Request for Additional Information (RAI) related to the CEUS-SSC changes. Duke Energy provided a response to the request (Reference 3) which contained one future action. That action was to provide the results of a Senior Seismic Hazard Analysis Committee (SSHAC), Level 2 study to substantiate the catalog changes made for Oconee's Seismic Hazard and Screening Report. The enclosure to this letter provides a copy of the Electric Power Research Institute's (EPRI) SSHAC Level 2 Study as requested by the RAI. It is Duke Energy's understanding that this information will also be published by EPRI at a later date.

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NRR

This letter does not create or revise a Regulatory Commitment.

Should you have any questions concerning this letter, or require additional information, please contact David Haile at (864) 873-4742.

I declare under penalty of perjury that the foregoing is true and correct. Executed on April 30, 2015.

Sincerely,

Scott L. Batson
Vice President
Oconee Nuclear Station

Enclosure

Oconee Nuclear Station Units 1, 2, and 3, Duke Energy Response to RAI:
Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 Study

cc:
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Mr. Eddy Crowe
NRC Senior Resident Inspector
Oconee Nuclear Station

Enclosure

Oconee Nuclear Station Units 1, 2, and 3

Duke Energy Response to RAI:
Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 Study

Enclosure - SSHAC Level 2 Study
ONS-2015-055
April 30, 2015

Request for Additional Information

Consistent with the request for information issued pursuant to Title 10 of the *Code of Federal regulations, Part 50, Section 50.54(f)* and the SPID guidance, please provide a revised March 2014 seismic hazard reevaluation submittal reflecting the staff endorsed CEUS-SSC *(Central and Eastern United States Seismic Source Characterization for Nuclear Facilities)* Catalog Version 7.0.

Alternatively, to ensure that the regional catalog update made for the Recommendation 2.1 seismic hazard reevaluations of H. B. Robinson, Oconee, and VC Summer plant sites represents the center, body, and range of the technically defensible interpretations, please provide a SSHAC Level 2 study. In addition to providing a detailed description of the catalog update, please describe the scope of the update and whether you also considered the impact of earthquakes in the region since the time period covered by the CEUS-SSC Catalog.

Please include in the response, in table form, control point seismic hazard curves developed using both the currently-endorsed CEUS-SSC catalog as well as the proposed updated regional catalog used for the Recommendation 2.1 seismic hazard reevaluations of H.B. Robinson, Oconee, and VC Summer plant sites.

Oconee Nuclear Station Response

(This response addresses the SSHAC study, the balance of information requested has been provided in a previous submittal.)

For Oconee, Duke Energy elected to exercise the proposed alternate response provided in the RAI and provide a SSHAC Level 2[1] study of the updated Regional CEUS-SSC Catalog. The required study is provided as an attachment to this enclosure. Please find the following:

- EPRI Letter RSM-042115-093 dated April 24, 2015,
  Subject: "SSHAC Level 2 Review of EPRI 1021097 Earthquake Catalog Changes for RIS Earthquakes in the Southeastern U. S. and Earthquakes in South Carolina Near the Time of the 1886 Charleston Earthquake Sequence"
- AMEC Foster Wheeler project (# 8515180180) letter dated April 23, 2015
  Subject: "Review of NUREG-2115 Earthquake Catalog with regard to identification of additional Reservoir Induced Seismicity (RIS) earthquakes in the Southeastern United States and locations of earthquakes in South Carolina near the time of the 1886 Charleston, SC earthquake sequence"

[1] SSHAC Level 2 relates to "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts" through the U.S. Nuclear Regulatory Commission as NUREG/CR–6372

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

April 24, 2015
RSM-042115-093

Mr. Jeremy Graham
Design Engineering
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Jenkinsville, South Carolina 29065

Mr. Robert Keiser
Mail Code: EC01T
Duke Energy Corporation
526 South Church Street
Charlotte, NC 28202

Subject: SSHAC Level 2 Review of EPRI 1021097 Earthquake Catalog Changes for RIS Earthquakes in the Southeastern U. S. and Earthquakes in South Carolina Near the Time of the 1886 Charleston Earthquake Sequence

Please find attached an evaluation of the earthquake catalog in EPRI 1021097 (NUREG-2115, DOE/NE-0140) focusing on identification of additional reservoir induced seismicity (RIS) earthquakes in the southeastern U.S. and locations of earthquakes in South Carolina near the time of the 1886 Charleston earthquake sequence. Several RIS events were identified in the catalog and a number of South Carolina earthquakes were evaluated to be Charleston earthquake aftershocks. Further processing of the updated earthquake catalog was performed using the same procedures as in EPRI 1021097 including Magnitude evaluations, declustering, and completeness calculations. The attached evaluation provides a complete description of the earthquakes evaluated and conclusions reached.

A SSHAC Level 2 peer review was performed of the updates to the earthquake catalog in EPRI 1021097 consistent with the criteria in NUREG/CR-6372, *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*, 1997. The peer review did not identify any issues that would require a revision to the Rev 8 catalog submitted by Dr. Youngs in March 2014. Based on the results of the peer review, it is concluded that the Rev 8 CEUS SSC catalog (Youngs, 2014) constitutes an appropriate earthquake catalog for assessing earthquake recurrence rates in the southeastern U.S.

Sincerely,

John M Richards
Principal Technical Leader
Risk and Safety Management

Attachment

c: Mr. Stuart Lewis, EPRI
Mr. Robert Kassawara, EPRI

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April 23, 2015

Project 8515180180

John Richards
Electric Power Research Institute, Inc.
1300 West WT Harris Boulevard
Charlotte, NC 28262

Subject: Review of NUREG-2115 Earthquake Catalog With Regard to Identification of Additional Reservoir Induced Seismicity (RIS) Earthquakes in the Southeastern United States and Locations of Earthquakes in South Carolina Near the Time of the 1886 Charleston, SC Earthquake Sequence

Dear Mr. Richards:

At the request of EPRI, Amec Foster Wheeler performed in February and March of 2014 a review of the Central and Eastern United States Seismic Source Characterization (CEUS SSC) earthquake catalog published in NUREG-2115 (EPRI/DOE/NRC, 2012). The review was focused on two issues: (1) identification of additional reservoir induced seismicity (RIS) earthquakes in the southeastern US and (2): locations of earthquakes in South Carolina near the time of the 1886 Charleston, SC earthquake sequence. The catalog review is considered a SSHAC (Budnitz et al., 1997) Level 2 review in that researchers on South Carolina historical seismicity were contacted and provided unpublished information. Based on that review, revisions to the CEUS SSC catalog were recommended and a revised CEUS SSC catalog, Rev 8, was prepared (Youngs, 2014) for use in earthquake recurrence calculations.

More recently, EPRI has requested that the revisions to the NUREG 2115 earthquake catalog proposed in Youngs (2014) be subjected to peer review. Such peer review would constitute a late-stage peer review, which is acceptable under the SSHAC guidance for projects conducted using a Technical Integrator (TI) approach (i.e. SSHAC Levels 1-3). As the CEUS SSC project was a SSHAC Level 3 project, the late-stage peer review is acceptable.

Amec Foster Wheeler engaged two peer reviewers to perform the review. Dr. Martin Chapman has extensive experience in evaluating seismicity in the southeastern portion of the US. Dr. Richard Quittmeyer has extensive experience in evaluation seismicity for seismic hazard analyses, including being a member of one of the expert teams that developed the EPRI-SOG seismic source model for the CEUS. These two experts performed a peer review of Youngs (2014). Attachment 2 to this memo contains the peer review comments received from Dr. Chapman and Dr. Quittmeyer. Attachment 3 contains Amec Foster Wheeler's responses, and Attachment 4 contains Dr Chapman's and Dr. Quittmeyer's concurrence with the response to their comments. The primary comment received from the reviewers was the need for improved documentation. In response, Amec Foster Wheeler has prepared a revision to the documentation to address the comments of the reviewers. The revised catalog review document is included as Attachment 1 to this letter.

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The peer review did not identify any issues that would require a revision to the Rev 8 catalog submitted by Youngs (2014). Dr. Chapman did identify one additional earthquake that should be classified as RIS. However, it is judged that the impact of one additional RIS earthquake on the assessed earthquake recurrence rates in the southeastern US would be minor and no revision to the Rev 8 CEUS SSC catalog is proposed. Based on the results of the peer review, it is concluded that the Rev 8 CEUS SSC catalog (Youngs, 2014) constitutes an appropriate earthquake catalog for assessing earthquake recurrence rates in the southeastern US.

Sincerely yours,
Amec Foster Wheeler Environment & Infrastructure, Inc.

Valentina Montaldo Falero
Senior Seismologist

Robert Youngs
Principal Seismic Engineer

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Attachments: Attachment 1—Review of EPRI 1021097 Earthquake Catalog for RIS and Charleston Aftershock Locations in the Southeastern United States, Rev 1
Attachment 2—Reviews by Dr. Martin Chapman and Dr. Richard Quittmeyer
Attachment 3—Amec Foster Wheeler's Responses to Review Comments
Attachment 4—Concurrence letters from Dr. Martin Chapman and Dr. Richard Quittmeyer

REFERENCES

Budnitz, R.J., Apostolakis, G., Boore, D.M., Cluff, L.S., Coppersmith, K.J., Cornell, C.A., and Morris, P.A., 1997. Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts, Report NUREG/CR-6372, Lawrence Livermore National Laboratory, sponsored by the U.S. Nuclear Regulatory Commission, U.S. Department of Energy, and Electric Power Research Institute.

Electric Power Research Institute, U.S. Department of Energy, and U.S. Nuclear Regulatory Commission (EPRI/DOE/NRC), 2012, Technical Report: Central and Eastern United States Seismic Source Characterization for Nuclear Facilities, published as NUREG-2115 by the U.S. Nuclear Regulatory Commission.

Youngs, R., 2014, Review of EPRI 1021097 Earthquake Catalog for RIS Earthquakes in the Southeastern US and Earthquakes in South Carolina Near the Time of the 1886 Charleston Earthquake Sequence." Report transmitted by EPRI letter on March 5, 2014 by J. Richards.

amec
foster
wheeler

ATTACHMENT 1

Review of EPRI 1021097 Earthquake Catalog for RIS and Charleston Aftershock Locations in the Southeastern United States

Revision History

March, 2014	Original Issue
April, 2015	Revision 1

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TABLES

FIGURES

APPENDIX

PART 1 IDENTIFICATION OF ADDITIONAL RESERVOIR INDUCED SEISMICITY (RIS) EARTHQUAKES IN THE SOUTHEASTERN U.S.

In developing the CEUS SSC catalog, earthquakes identified as reservoir induced (RI) were removed from the final earthquake listing. The sole source for this identification in the southeastern US was the set of available Southeast US Seismic Network (SEUSSN) Bulletins that contain 120 RI earthquakes. Sixteen of these were large enough to be included in the CEUS SSC catalog; these earthquakes occurred primarily near Monticello Reservoir and Lake Keowee. These earthquakes were removed from the final (Rev 7) CEUS SSC catalog published in NUREG-2115.

At the request of EPRI, we have performed additional reviews of publicly available sources to identify additional RI earthquakes that are in the CEUS SSC catalog. In addition to the references listed in the following section, the SEUSSN Bulletins from 1979 to 1980 were re-examined. In cases where the references consulted are not in agreement, expert judgment is used to classify an earthquake as RI on other considerations, such as the proximity to a reservoir and shallow focal depth, or the temporal relation to the reservoir filling.

1.1 REFERENCES

The following list contains the additional reference material consulted to identify potential RI earthquakes in the CEUS SSC catalog.

[1] Acree, S.D., Acree, J.R., and P. Talwani, 1988, The Lake Keowee, South Carolina earthquakes of February through July 1986, Seismological Research Letters, 59 (2), 63-70.

[2] Talwani, P., 1981, Earthquake Prediction Studies in South Carolina, in "Earthquake Prediction: An International Review". American Geophysical Union.

[3] Talwani, P., 1990, Appendix D in Krinitzsky, E.L. and J.B. Dunbar (1990): "Geological Seismological Evaluation of Earthquake Hazards at Hartwell and Clemson Upper and Lower Dams, South Carolina". Technical Report GL-90-11, Final Report prepared for US Army Engineer District Savannah, Savannah, Georgia.

[4] Talwani, P., 1997, On the Nature of Reservoir-induced Seismicity, Pure and Applied Geophysics, 150, 473-492.

[5] Talwani, P., Stevenson, D., Amick, D., and J. Chiang, 1979, An Earthquake Swarm at Lake Keowee, South Carolina, Bulletin of the Seismological Society of America, 69 (3), 825-841.

[6] Long, L.T., Kocaoglu, A., Hawman, R., and P.J.W. Gore, The Norris Lake earthquake swarm of June through September, 1993; Preliminary Findings. Seismological Research Letters, 65 (2), 167-171.

[7] Fletcher, J.B., Boatwright, J., and W.B. Joyner, 1983, Depth dependence of source parameters at Monticello, South Carolina, Bulletin of the Seismological Society of America, 73 (6), 1735-1751.

[8] Chen L., and P. Talwani, 2001, Mechanism of Initial Seismicity Following Impoundment of the Monticello Reservoir, South Carolina, Bulletin of the Seismological Society of America, 91 (6), 1582-1594.

[9] Rajendran, K., and P. Talwani, 1992, The role of elastic, undrained, and drained responses in triggering earthquakes at Monticello Reservoir, South Carolina, Bulletin of the Seismological Society of America, 82 (4), 1867-1888.

[10] Shedlock, K.M., 1988, Seismicity in South Carolina, Seismological Research Letters, 59 (4), 165-171.

[11] Tarr, A.C., Talwani, P., Rhea, S., Carver, D., and D. Amick, 1981, Results of recent South Carolina seismological studies, Bulletin of the Seismological Society of America, 71 (6), 1883-1902.

[12] Chen L., and P. Talwani, 2001, Renewed seismicity near Monticello Reservoir, South Carolina, 1996-1999, Bulletin of the Seismological Society of America, 91 (1), 94-101.

[13] Marion, G.E., and L.T. Long, 1980, Microearthquake spectra in the Southeastern United States, Bulletin of the Seismological Society of America, 70 (4), 1037-1054.

[14] Reinbold, D.J., and Johnston, A.C., 1987, Historical Seismicity in the Southern Appalachian Seismic Zone: U.S. Geological Survey Open-File Report 87-433.

[15] Stover, C.W., and Coffman, J.L., 1993, Seismicity of the United States, 1568-1989 (Revised): U.S. Geological Survey Professional Paper 1527, 418 pp.

1.2 REVIEW RESULTS

The documents listed above were reviewed to identify events in the CEUS SSC catalog that should be classified as RI events. It should be noted, though, that these references often list the earthquakes vaguely by month and year, without a precise date or magnitude. Epicentral coordinates are usually not listed. As an example: [4], [9], [10], [12] do not identify any individual earthquake. In addition, most of the RIS is low magnitude (less than 2), which was typically not included in the CEUS-SSC catalog.

The following Tables 1, 2 and 3 show all the RI earthquakes that are reported with a date and occasionally magnitude in the references above. In particular, Table 1 contains earthquakes identified as RI that were too small to be included in the CEUS SSC Rev 7 catalog; Table 2 lists three earthquakes that we consider to have been correctly classified in the Rev 7 CEUS SSC catalog; and Table 3 contains additional earthquakes described in the above references that are not classified as RI earthquakes in the CEUS SSC Rev 7 catalog.

TABLE 1

EARTHQUAKES IDENTIFIED AS RI THAT ARE TOO SMALL TO BE INCLUDED IN THE CEUS-SSC CATALOG

Earthquake	Reference
1978/10/27	[7]
1979/1/19	[1]
1976/1/14	[2]
1977/2/23	[2]
1987/12/24	[3]
1988/1/26	[3]
1993/9/23	[6]
Events 1 through 40 and 42 through 53 in Table 1	[8]
All events listed in Table 1	[13]

TABLE 2

EARTHQUAKES CORRECTLY CLASSIFIED IN REV 7 OF THE CEUS-SSC CATALOG

ID	Date	Magnitude	Comment
TMP10113	1979/10/16	M 3.0	Ref. [7] analyzed four well-recorded reservoir induced earthquakes near the Monticello reservoir to determine stress drop. The events are taken from Fletcher (1982). This earthquake was identified as RI in the Rev 7 CEUS-SSC catalog.
TMP14740	1986/2/16	E[**M**] 3.32	Ref [1] states there is no correlation between reservoir level and the onset of seismicity (this event), while rapid fluctuations in the water levels were observed before the subsequent events in June (see below) and July. The SEUSSN Bulletins do not classify this as RI, therefore the earthquake was included in the Rev 7 CEUS-SSC catalog as a tectonic earthquake. We note that Dr. Martin Chapman considers this to be RI earthquake due to its location at the shoreline of Lake Keowee.
TMP14964	1986/6/11	Md 2.8	This event was identified as RI in the Rev 7 CEUS-SSC catalog from the SEUSSN Bulletins.

TABLE 3

EARTHQUAKES CLASSIFIED AS RI IN THE REFERENCES CONSULTED IN THIS REVIEW, BUT CONSIDERED TECTONIC IN REV 7 OF THE CEUS-SSC CATALOG

ID	Date	Magnitude	Comment
TMP07012	1969/12/13	E[M] 3.46	Ref. [5] argues that location of this event is based on "meager macroseismic data" and the earthquake could be a RI event at Lake Keowee. This earthquake is too old to be listed in the SEUSSN Bulletins therefore it was not classified as RI in Rev 7 of the CEUS-SSC Catalog. Because the event is poorly located and Ref. [5] does not conclusively classify it as RI, our recommendation is that it should remain in the catalog as a tectonic earthquake.
TMP07159	1971/7/13	E[M] 3.63	Ref. [5] suggests that the location of the Seneca earthquake by Bollinger (1972) is less accurate than the location by Sowers and Fogle (1978), which is based on detailed macroseismic studies. The Sowers and Fogle (1978) location coincides with observed RIS. This earthquake was considered a tectonic event in Rev 7 of the CEUS SSC catalog because: 1) it is too old to be listed in the SEUSSN Bulletins, and 2) it appears (as a tectonic event) in a number of catalogs: EPRI, NCEER91, USGS, SEUSSN, South Carolina seismic network, Reagor, Stover and Coffman, and Hopper. Our conclusion is that the more precise location by Sowers and Fogle (1978) suggests that it may be a RI earthquake and the recommendation is to identify it as a probable RI (non-tectonic) earthquake.
TMP07565	1974/8/2	E[M] 3.91	The earthquake is mentioned in Ref. [11] with references to existing literature (by Dr.Talwani) suggesting that the earthquake is RI, caused by variation in pore-pressure caused by fluctuations of the water level in the reservoir. More recently, Ref. [3] says that despite the excellent correlation between water fluctuations and earthquakes, "The observation that the seismicity occurred 43 km upstream of the Clarks Hill dam and 22 years after its impoundment led to the questioning of the suggestion that the activity was induced". The earthquake is too old to appear in the SEUSSN Bulletin therefore it was not classified as RI in Rev 7 of the CEUS-SSC Catalog. Based on Ref [3] the categorization of this

TABLE 3

EARTHQUAKES CLASSIFIED AS RI IN THE REFERENCES CONSULTED IN THIS REVIEW, BUT CONSIDERED TECTONIC IN REV 7 OF THE CEUS-SSC CATALOG

ID	Date	Magnitude	Comment
			earthquake as RI is questionable and our recommendation is to retain the event in the CEUS SSC catalog as a tectonic earthquake.

TABLE 3

EARTHQUAKES CLASSIFIED AS RI IN THE REFERENCES CONSULTED IN THIS REVIEW, BUT CONSIDERED TECTONIC IN REV 7 OF THE CEUS-SSC CATALOG

ID	Date	Magnitude	Comment
TMP08078	1975/11/25	E[**M**] 3.21	Ref. [11] references this earthquake among those correlated to reservoir activity and indicates that following this event a monitoring program was carried out in the vicinity of Lakes Jocassee and Keowee. This earthquake is too old to appear in the SEUSSN Bulletin therefore it was not classified as RI in Rev 7 of the CEUS-SSC Catalog. Our recommendation is to identify the event as a RI earthquake.
TMP08787	1977/9/7	E[**M**] 2.77	Ref. [2] says this event was found to be associated with changes in water levels at a 100 m deep observation well. The water level was smoothed and corrected for recharge from Lake Keowee and barometric pressure, and the effect of earth tides, ocean tides and winds was found to be negligible. Ref. [2] finds that the water level changes (in the order of 9 cm) are correlated with magnitude and hypocentral distance. This earthquake does not appear in the SEUSSN Bulletin. Recommendation is to identify the event as a RI earthquake, although it is smaller than earthquakes used in recurrence calculations.
TMP08971	1978/1/25	E[**M**] 2.6	This earthquake is #41 in Table 1 of [8], which lists events recorded during the impounding of the Monticello Reservoir by the local monitoring seismic network. SEUSSN Bulletin reports the earthquake as 25 January 1978 Jenkinsville, South Carolina, ML 2.8 (USC), Lat 34.3 N, Long 81.3W at 3:29:38.7 and depth of 2 km. A note in parenthesis reads: "Same event as the 8/29/38.9 shock in the microearthquakes in South Carolina listing?". Because the SEUSSN Bulletin does not classify this event as RI, the earthquake was retained to be tectonic in Rev 7 of the CEUS SSC catalog. Recommendation is to identify the event as a RI earthquake, although it is smaller than earthquakes used in recurrence calculations.
TMP09000	1978/2/11	E[**M**] 2.93	This earthquake is not classified as RI in the SEUSSN Bulletins, but its location and shallow depth suggests in may be RIS. Recommendation is to identify the event as a probable RI earthquake.

TABLE 3

EARTHQUAKES CLASSIFIED AS RI IN THE REFERENCES CONSULTED IN THIS REVIEW, BUT CONSIDERED TECTONIC IN REV 7 OF THE CEUS-SSC CATALOG

ID	Date	Magnitude	Comment
TMP09354	1978/8/27	E[**M**] 2.93	This earthquake is not listed in the SEUSSN Bulletin. This earthquake is one of the four events studied in [7]: its location is obtained from Fletcher (1982). Recommendation is to identify the event as a RI earthquake.
TMP09355	1978/8/27	E[**M**] 2.77	This earthquake is not listed in the SEUSSN Bulletin. This earthquake occurred immediately after TMP09354 in nearly the same location and was flagged as a dependent event. It has an assigned depth of 7 km, which is much deeper than typical RIS. Recommendation is to identify the event as a probable RI earthquake, although it is smaller than earthquakes used in recurrence calculations.
TMP09460	1978/10/27	E[**M**] 3.08	This earthquake is not listed in the SEUSSN Bulletin. This earthquake is one of the four events studied in [7]. Location is obtained from Fletcher (1982). Recommendation is to identify the event as a RI earthquake.
TMP10034	1979/8/26	E[**M**] 3.64	This earthquake is listed in Ref. [2] among the earthquakes associated with the Monticello Reservoir, and was also identified in the SEUSSN Bulletin as RI. Recommendation is to identify the event as a RI earthquake.
TMP10104	1979/10/8	E[**M**] 3.16	Reexamination of the SEUSSN Bulletin indicates that this event is listed as associated with a reservoir. Recommendation is to identify the event as a RI earthquake.
TMP10109	1979/10/14	E[**M**] 3.08	Reexamination of the SEUSSN Bulletin indicates that this event is listed as associated with a reservoir. Recommendation is to identify the event as a RI earthquake.
TMP10506	1980/7/29	E[**M**] 3.31	This earthquake was not flagged in the SEUSSN Bulletin as associated with a reservoir and its location quality was listed as D. However, its location and shallow depth makes it a candidate as a RI earthquake. Recommendation is to identify the event as a probable RI earthquake.
TMP16282	1988/1/27	E[**M**] 2.32	Ref. [3] says activity is typical of reservoir induced sequences. SEUSSN Bulletin lists this event as "possible earthquake". Recommendation is to identify the event as a RI earthquake, although it is smaller than earthquakes used in recurrence calculations.

Table 4 contains a summary list of 15 earthquakes that, based on our review of references [1] through [13], should be classified as RI or probable RI and therefore not included in the CEUS SSC earthquake catalog used for recurrence parameter calculations. Once these events were identified, the Version 7 CEUS SSC earthquake catalog was examined for events with similar characteristics (namely: location, shallow depth, and temporal correlation). This analysis identified 18 additional earthquakes that should be classified as RI or probable RI earthquakes, also listed in Table 4.

TABLE 4

EARTHQUAKES THAT SHOULD BE CLASSIFIED AS RI OR PROBABLE RI.

TMPID	yr	mo	Dy	hr	mn	sec	Lat	lon	depth	E[M]	Comment
TMP07159	1971	7	13	11	42	26	34.8	-83	n/a	3.63	Probable RI
TMP08078	1975	11	25	15	17	34.8	34.93	-82.9	10*	3.21	RI
TMP08787	1977	9	7	14	41	32.7	34.982	-82.927	n/a	2.77	RI
TMP08971	1978	1	25	8	29	39	34.301	-81.234	5**	2.6	RI
TMP09354	1978	8	27	10	23	8	34.313	-81.337	2	2.93	RI
TMP08998	1978	2	10	20	23	38.7	34.343	-81.348	1	2.77	Probable RI
TMP08999	1978	2	11	0	19	0.7	34.343	-81.35	3	2.77	Probable RI
TMP09000	1978	2	11	5	19	0.2	34.346	-81.349	1	2.93	Probable RI
TMP09006	1978	2	14	12	45	7.2	34.342	-81.346	2	2.77	Probable RI
TMP09007	1978	2	14	13	9	59.5	34.351	-81.343	2	2.85	Probable RI
TMP09013	1978	2	15	21	14	34.2	34.349	-81.346	0	2.77	Probable RI
TMP09014	1978	2	16	2	14	33.4	34.332	-81.362	2	2.85	Probable RI
TMP09023	1978	2	22	7	13	25.1	34.327	-81.35	1	2.85	Probable RI
TMP09024	1978	2	22	12	13	24.3	34.339	-81.35	1	3.00	Probable RI
TMP09025	1978	2	22	13	4	59.2	34.356	-81.352	0	2.77	Probable RI
TMP09027	1978	2	24	7	34	10.5	34.334	-81.348	1	2.93	Probable RI
TMP09029	1978	2	25	4	2	42.7	34.345	-81.351	1	2.77	Probable RI
TMP09031	1978	2	26	6	52	35.4	34.315	-81.297	1	2.85	Probable RI
TMP09032	1978	2	26	11	52	33	34.391	-81.361	1	3.00	Probable RI
TMP09033	1978	2	26	18	17	48.8	34.321	-81.348	0	3.08	Probable RI
TMP09343	1978	8	24	10	23	7.6	34.311	-81.341	2	2.85	Probable RI
TMP09355	1978	8	27	10	23	8	34.313	-81.337	7	2.77	Probable RI
TMP09460	1978	10	27	16	27	18.1	34.302	-81.326	2	3.08	RI
TMP09518	1978	11	24	11	54	40.9	34.296	-81.347	1	2.85	Probable RI

TABLE 4

EARTHQUAKES THAT SHOULD BE CLASSIFIED AS RI OR PROBABLE RI.

TMPID	yr	mo	Dy	hr	mn	sec	Lat	lon	depth	E[M]	Comment
TMP10034	1979	8	26	1	31	45	34.916	-82.956	1	3.64	RI
TMP39374	1979	10	8	8	54	19.4	34.31	-81.33	2	2.85	RI
TMP10104	1979	10	8	23	20	11	34.306	-81.344	1	3.16	RI
TMP10109	1979	10	14	8	24	57.6	34.306	-81.338	2	3.08	RI
TMP10506	1980	7	29	1	10	22.7	34.351	-81.364	1	3.31	Probable RI
TMP16282	1988	1	27	22	5	42.9	34.189	-82.75	6.1	2.32	RI

* depth 17 km in Reinbold and Johnson [14]
** depth 1 km in Stover and Coffman [15]

Figure 1 shows the location of the earthquakes listed in Table 4 with respect to the NPPs that are located next to a lake or reservoir. The RI earthquakes are located near the Oconee and VC Summer NPP and their reservoirs (Monticello, Lake Keowee, Lake Jocassee) that are known areas of RIS.

In order to verify that there are no clusters of seismicity of non-tectonic origin in proximity of other NPPs in the Southeastern U.S., we analyzed the seismicity within 100 km of all the NPPs. The analyses are described in the following section.

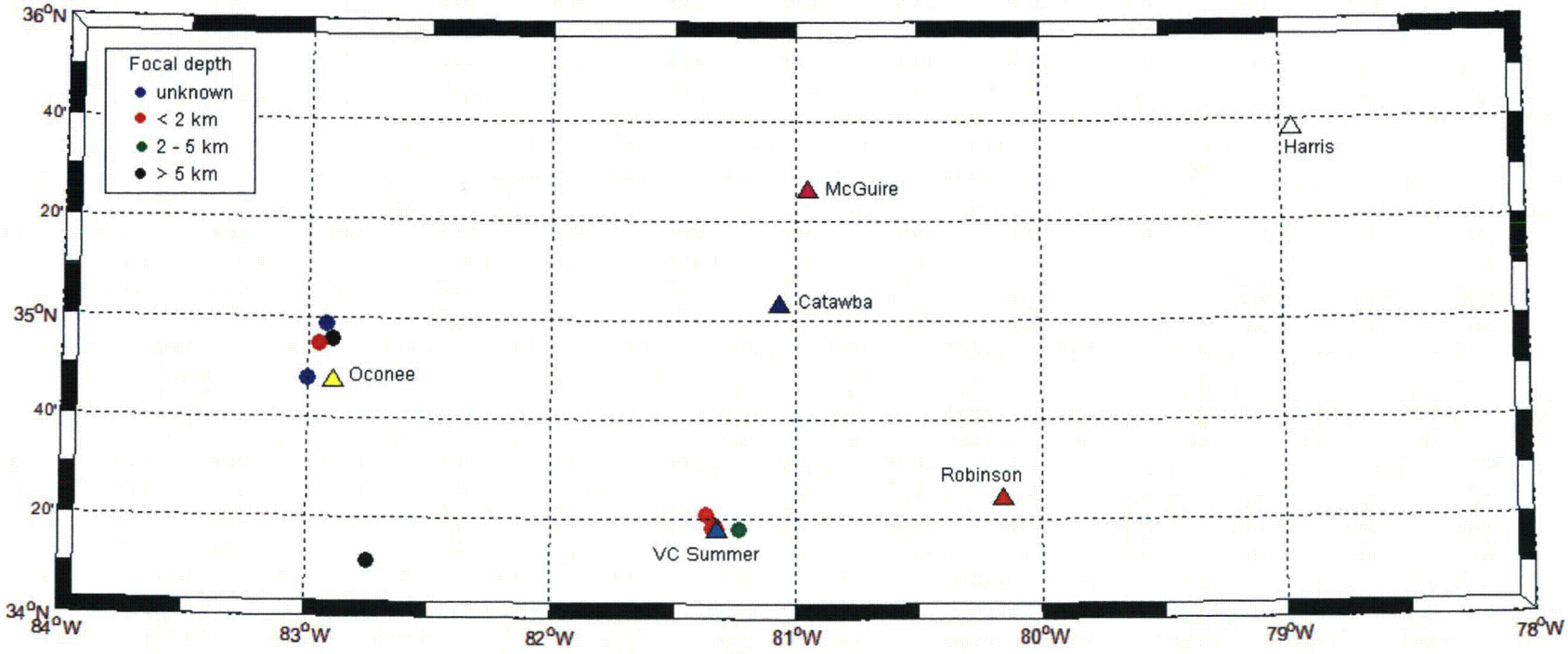


Figure 1: Location of the earthquakes listed in Table 4 (circles) with respect to NPPs in the southeastern US located in proximity of a lake or reservoir (triangles). Earthquakes are color-coded by focal depth.

1.3 SEISMICITY WITHIN 100 KM OF NPPS IN THE SOUTHEASTERN U.S.

The seismicity in the vicinity of NPPs in the southeast US that are near reservoirs was examined to look for potential clusters of earthquakes of non-tectonic origin. Table 5 lists the NPPs in the Southeastern U.S., highlighted in bold are the six plants located near a lake or reservoir, namely Oconee, Summer, Catawba, Robinson, McGuire and Harris.

TABLE 5

NPPS IN THE SOUTHEASTERN U.S.

No.	Nuclear site	Latitude (deg)	Longitude (deg)	State	Nearby Lake/River
1	Hatch	31.9342	-82.3444	GA	Altamaha River
2	Vogtle	33.1419	-81.7647	GA	Savannah River
3	**Oconee**	34.7917	-82.8986	SC	Lake Keowee
4	Lee Nuclear	35.0369	-81.5118	SC	Broad River
5	**Summer**	34.2958	-81.3203	SC	Monticello Reservoir
6	**Catawba**	35.0514	-81.0694	SC	Lake Wylie
7	**Robinson**	34.4053	-80.1586	SC	Lake Robinson
8	**McGuire**	35.4322	-80.9483	NC	Lake Norman
9	Harris	35.6333	-78.9561	NC	Shearon-Harris Reservoir
10	Brunswick	33.9583	-78.0106	NC	Coastal (Cape Fear River)
11	Surry	37.1656	-76.6983	VA	James River

The seismicity within 100 km of the six NPPs was extracted from the CEUS SSC earthquake catalog (rev 7) and plotted to see if there are any clusters of earthquakes showing a spatial correlation with the reservoirs. These data are shown in Figures 2 through 15. The purpose was to assess whether or not the seismicity pattern post-impoundment of the reservoirs is consistent with the distribution of earthquakes pre-impoundment. In addition, the depth of the earthquakes pre- and post-impoundment is used as an indicator of RIS.

In all figures:

- filled circles are earthquakes that occurred after the lake impoundment that are identified as mainshocks;
- filled squares are earthquakes that occurred prior to the lake impoundment that are identified as mainshocks;
- open circles and open squares are dependent events (post-and pre-impoundment respectively);
- unknown depths are plotted in blue;
- depths less than 2 km are plotted in red;
- depths between 2 and 5 km are in green;
- depths greater than 5 km are in black;
- the NPP site is shown by a yellow triangle.

1.3.1 NPPs Located on Lakes and Reservoirs

Oconee

There are 155 earthquakes within 100 km of the Oconee NPP. Most of the seismicity pre-1973 has unknown depth (fixed at 0). In Ref [5] the depth of the swarm is limited to the topmost 2 km.

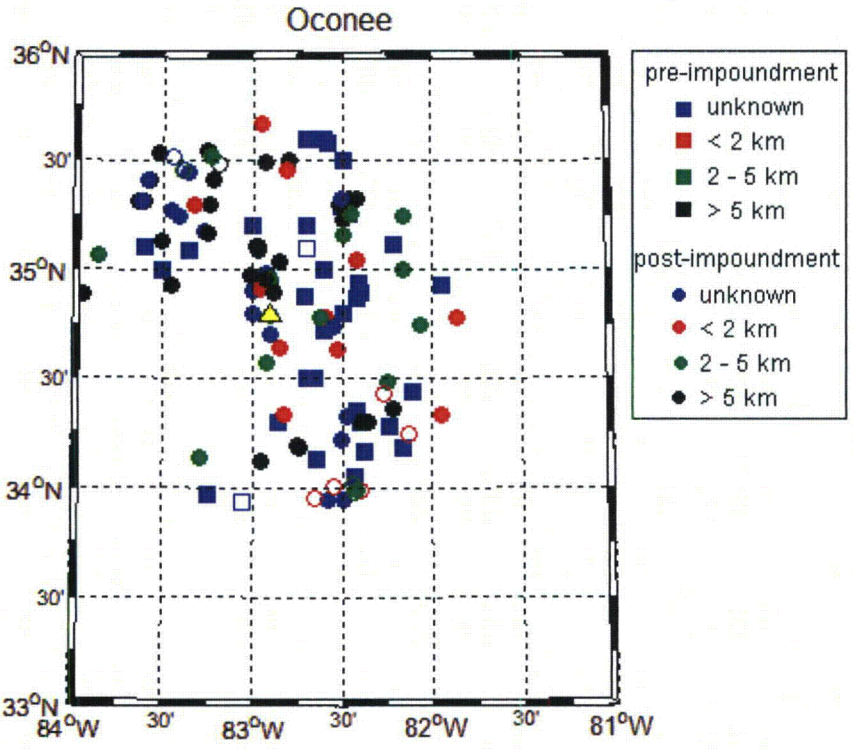
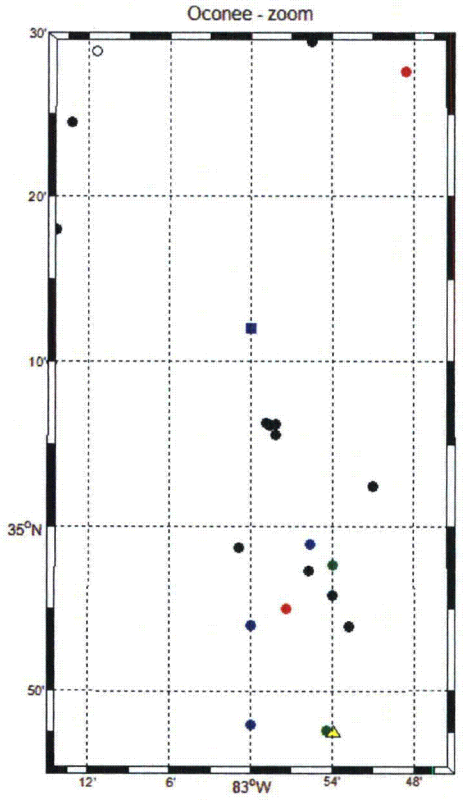
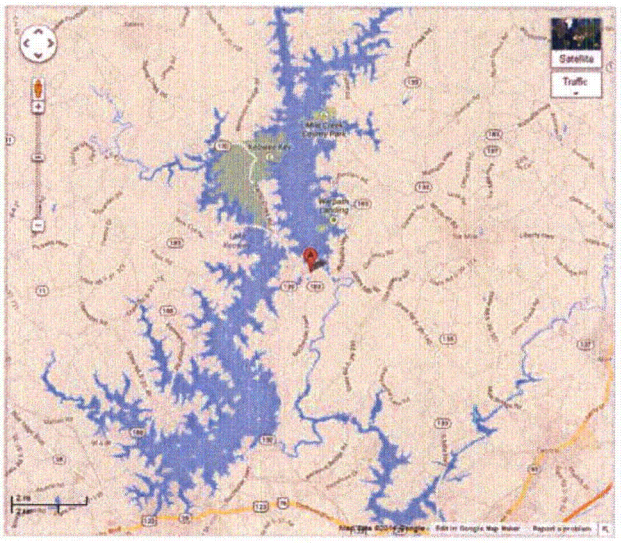


Figure 2: Seismicity within 100 km of the Oconee NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

The next figure shows a zoom of the seismicity cluster near the NPP (Figure 3a). These earthquakes are likely RI events from Lake Keowee (compare Figure 3a with 3b): they are typically shallow and occurred after the impoundment of the lake, in areas that have no prior seismicity.



(a)



(b)

Figure 3: (a) Close-up view of the cluster of seismicity near the Oconee NPP; (b) map showing the location of Oconee NPP (A) with respect to the lake.

VC Summer

There are 262 earthquakes within 100 km of the VC Summer NPP (Figure 4). The seismicity pre-1978 (time of the lake impoundment) has unknown depth (fixed at 0). The figure shows a cluster of seismicity very near the NPP, which is associated with the Monticello Reservoir.

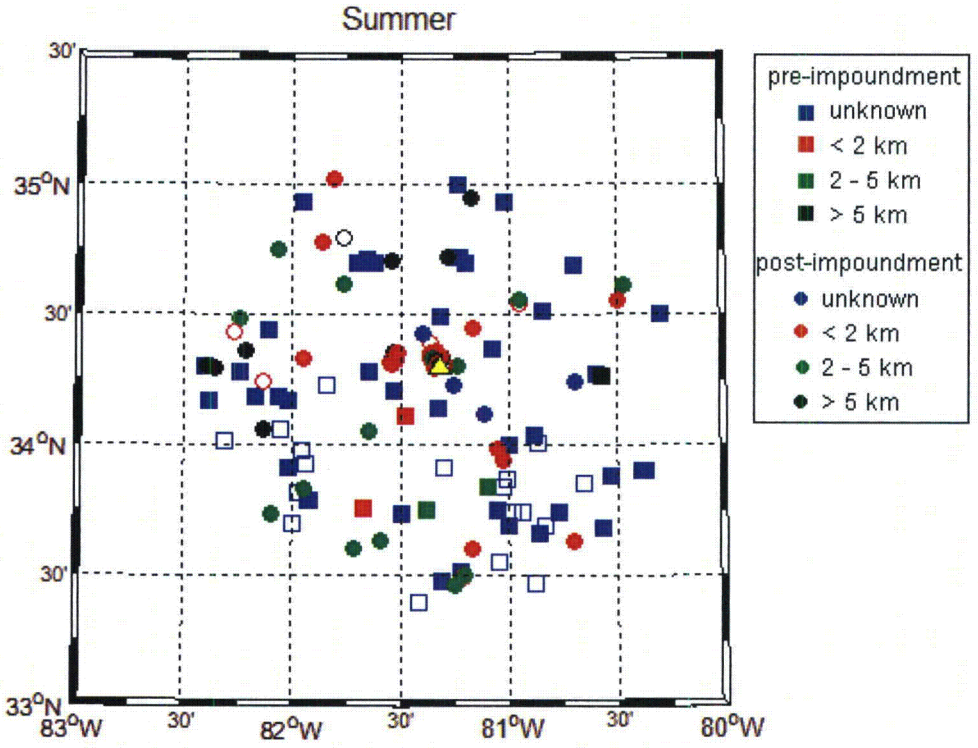


Figure 4: Seismicity within 100 km of the VC Summer NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

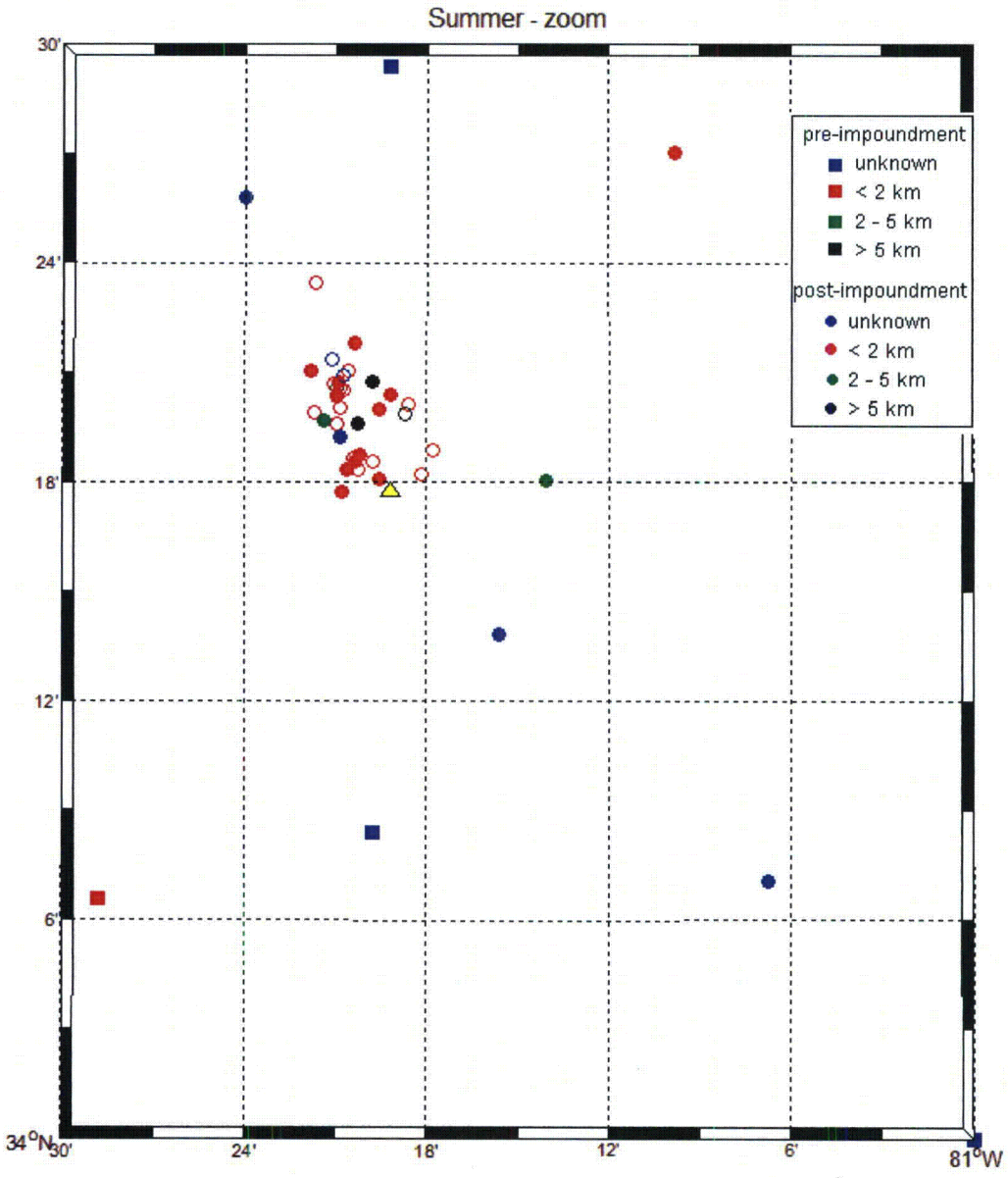


Figure 5: Close-up view of the seismicity cluster to the NW of the VC Summer NPP.

Figure 5 is a close-up view of the seismicity nearby the power plant. The earthquakes closer to the NPP have consistently depths of less than 2 km. The figure also shows that many of the earthquakes are removed in the declustering process (open circles indicate dependent earthquakes). Figure 6 compares the seismicity near the VC Summer NPP to Figure 2 of [12] (in the background) that shows the seismicity from 15 December 1996 to 31 December 1999 in the same region. Also shown in Figure 2 of [12] are two deep wells (W1 and W2) and the seismic

stations MR01, MR05, MR07, MR10 and JSC that have recorded the 1996-1999 earthquakes (black asterisks).

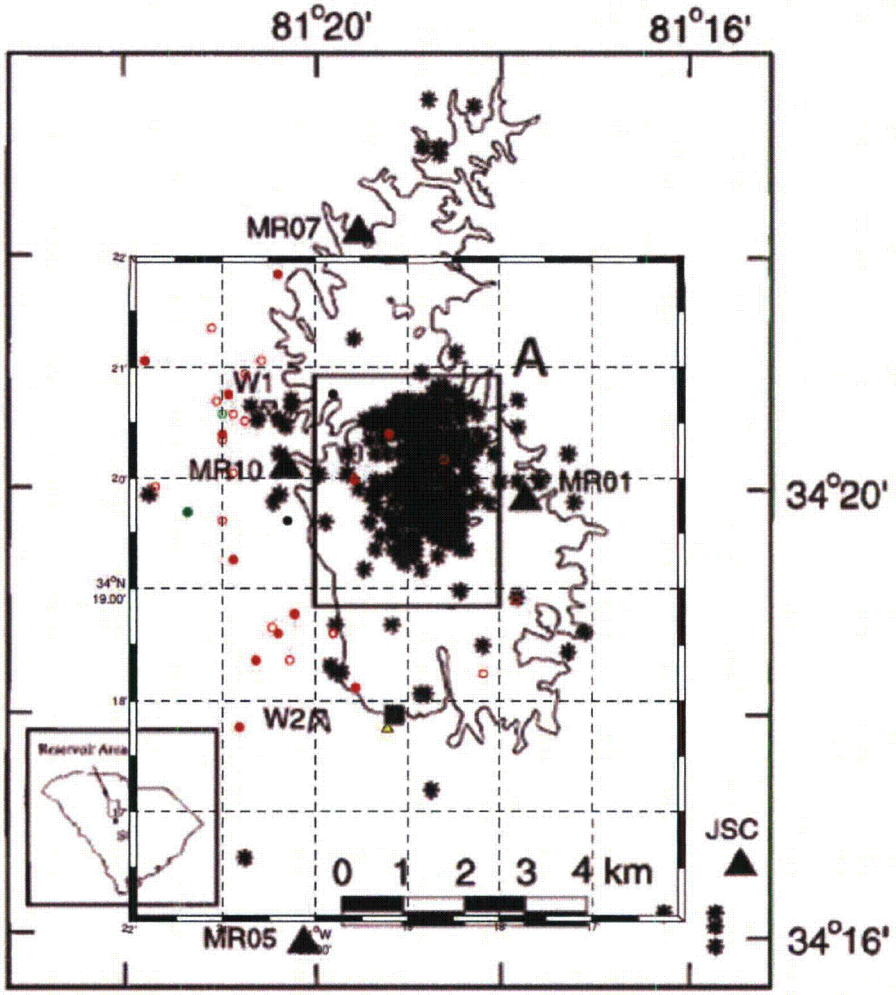
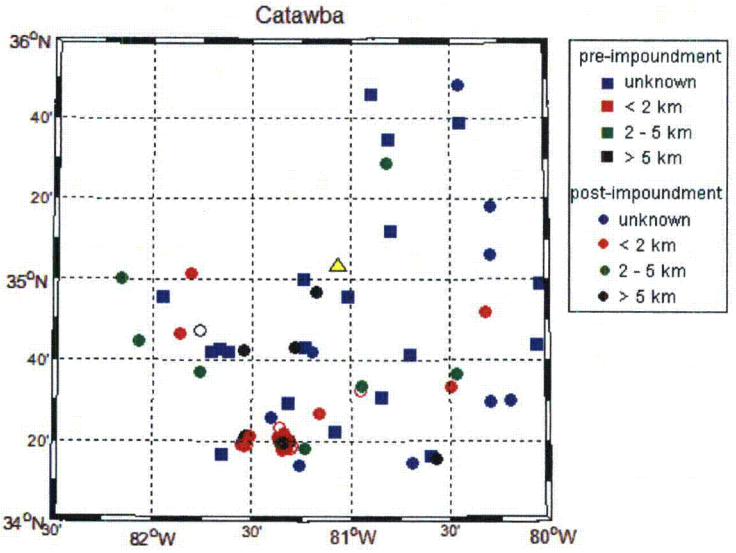


Figure 6: Comparison of the seismicity near VC Summer NPP from rev 7 of the CEUS-SSC catalog (red and green circles) with the seismicity recorded between 1996 and 1999 (black asterisks) as presented in Figure 2 of [12] (in the background). Earthquakes with unknown depth from Figure 5 are not shown.

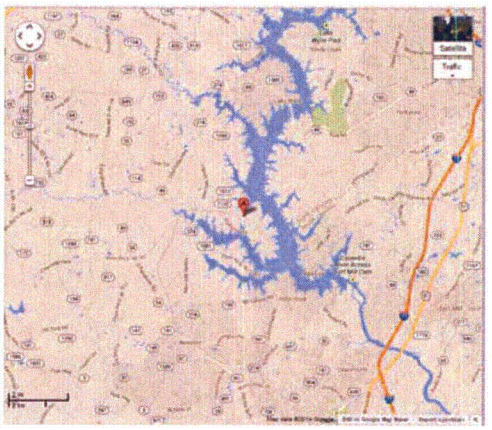
The northernmost cluster is probably in the area of the deep well W1; the three earthquakes that are lined up closer to the site have occurred in 1978, 1979 and 1982. The earthquakes shown in Figures 5 and 6 include the earthquakes identified in Table 4 as RI or potential RI (and therefore removed from Version 8 of the CEUS SSC catalog). The remaining earthquakes, if not removed by declustering, have magnitudes E[**M**]<2.9, which is the minimum magnitude used in recurrence analysis, therefore have no impact on the seismic hazard calculations.

Catawba

There are 136 earthquakes within 100 km of the Catawba NPP (Figure 7a). The seismicity pre-1975 has unknown focal depth. If these earthquakes are removed, the nearest earthquake has a depth of 23 km. The NPP is located on Lake Wylie (see Figure 7b from google maps): the earthquakes closer to the lake occurred prior to its impoundment. The cluster of earthquakes to the south is about 100 km of distance from the NPP. A search of literature (BSSA and SRL) did not return any specific study of the seismicity of Lake Wylie. Note that the cluster of seismicity located approximately 100 km south-southwest of Catawba is associated with the Monticello reservoir and is discussed previously.



(a)



(b)

Figure 7: (a) Seismicity within 100 km of the Catawba NPP (from Rev 7 of the CEUS-SSC earthquake catalog); (b) location of the Catawba NPP (A) with respect to Lake Wylie. The map is shown at a smaller scale than part (a)..

Robinson

There are 134 earthquakes within 100 km of the Robinson NPP (Figure 8), of which 17 (all post 1975) have an estimate of the focal depth. The nearest earthquake to the NPP has unknown depth. Figure 8 does not show clusters of seismicity associated with Lake Robinson. The two independent events closest to the NPP are the 1959 Chesterfield County earthquake and an earlier event in 1930 located about 5 km to the west of the 1959 event. The two earthquakes are located based on macroseismic intensities and felt area only, and SEUSSN gives to both earthquakes a location error of 83.4 km. We found no information in the literature on the 1959 earthquake that associates the event to the impoundment of Lake Robinson.

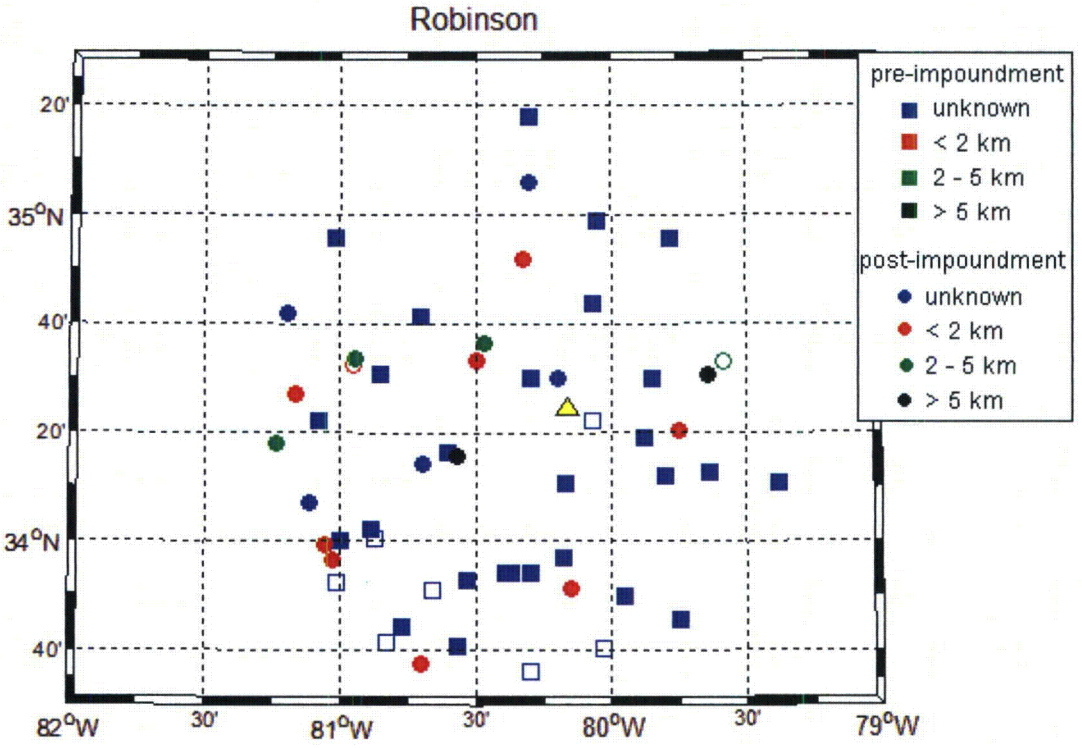


Figure 8: Seismicity within 100 km of the Robinson NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

McGuire

There are 46 earthquakes within 100 km of the McGuire NPP (Figure 9), of which 19 have an estimated focal depth (all post-1970). The seismicity doesn't show clusters in the area of Lake Norman.

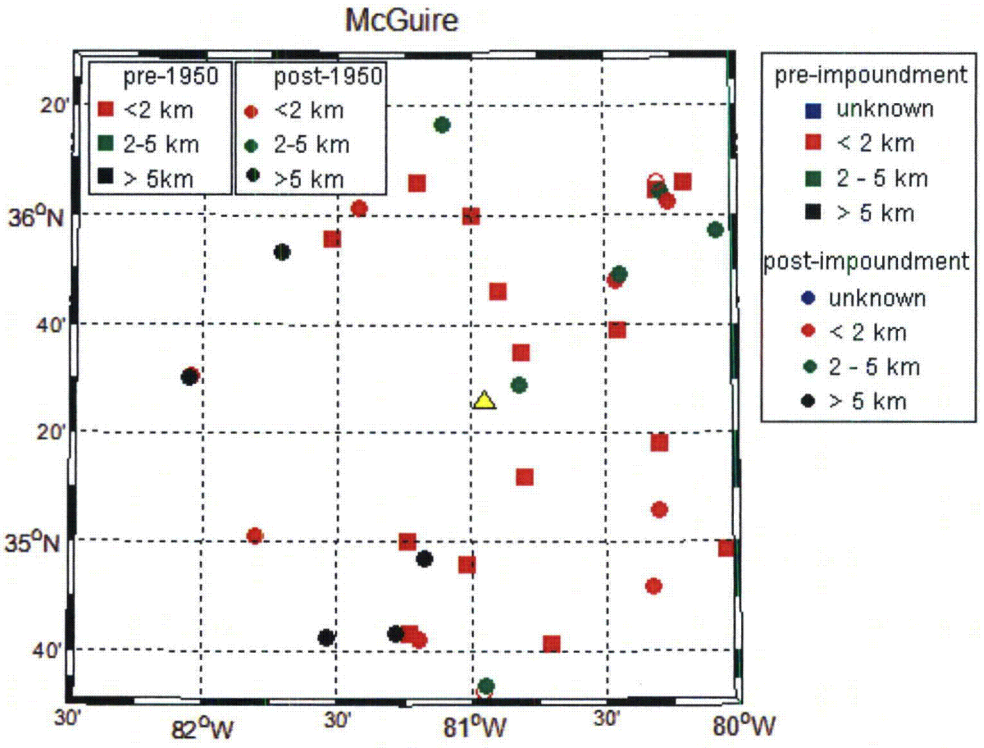


Figure 9: Seismicity within 100 km of the McGuire NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

Harris

There are 16 earthquakes within 100 km of the Harris NPP (Figure 10) of which only 2 have been instrumentally recorded: one in 1981 with a depth of 1km and one in 1993 with a depth of 5 km. Both are far from the Shearon-Harris Reservoir.

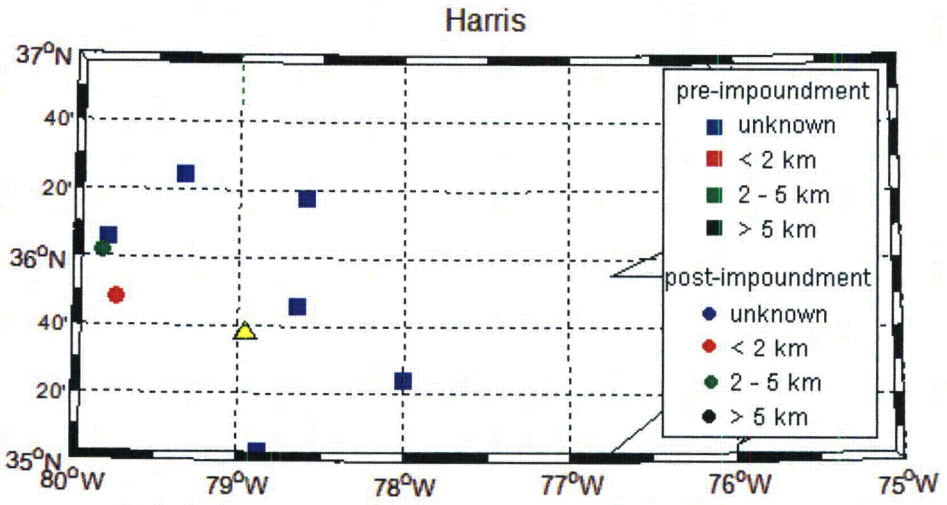


Figure 10: Seismicity within 100 km of the Harris NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

1.3.2 NPPs Located on Rivers

Hatch

There are 5 earthquakes within 100 km of the Hatch NPP (Figure 11). Note that the figure only shows four earthquakes because two are superimposed.

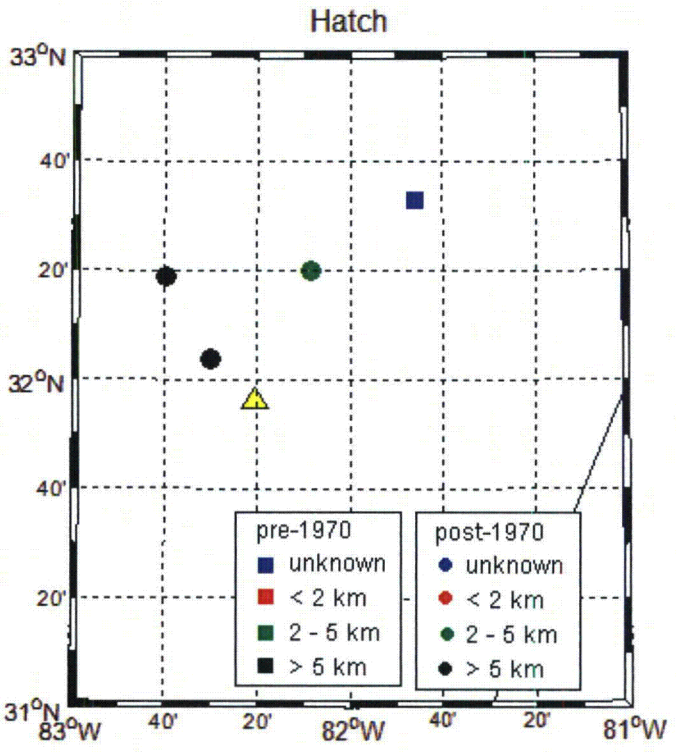


Figure 11: Seismicity within 100 km of the Hatch NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

Vogtle

There are 94 earthquakes within 100 km of the Vogtle NPP (Figure 12). The spatial distribution of locations of pre- and post-1950 earthquakes are similar, and the depths are consistent.

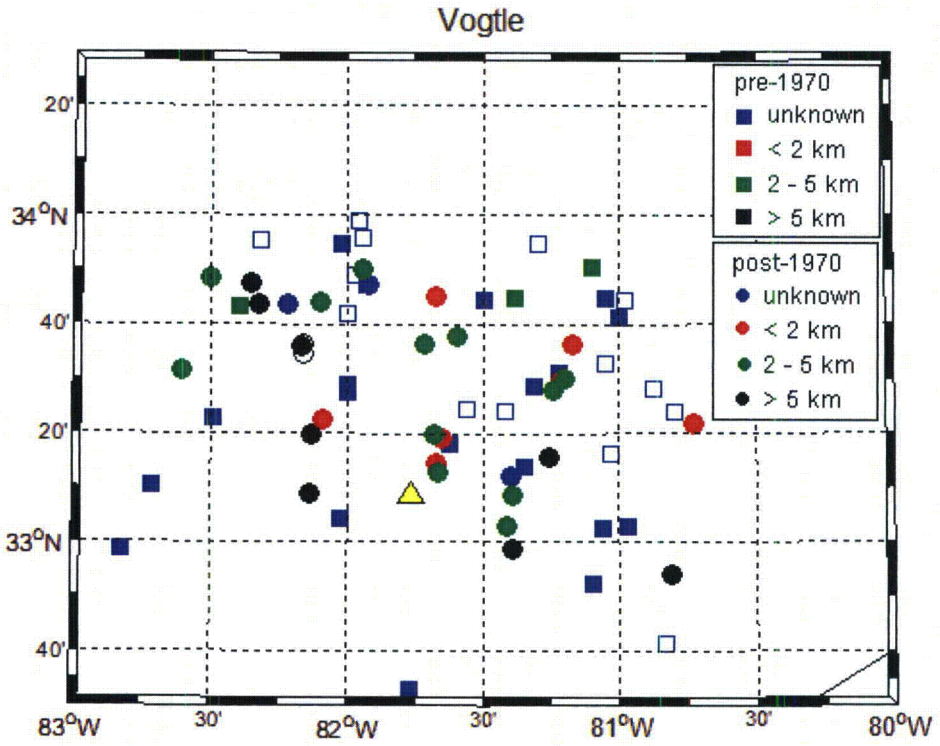


Figure 12: Seismicity within 100 km of the Vogtle NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

Lee

There are 164 earthquakes within 100 km of the Lee NPP (Figure 13). Most of the seismicity pre-1978 has unknown depth (fixed at 0).

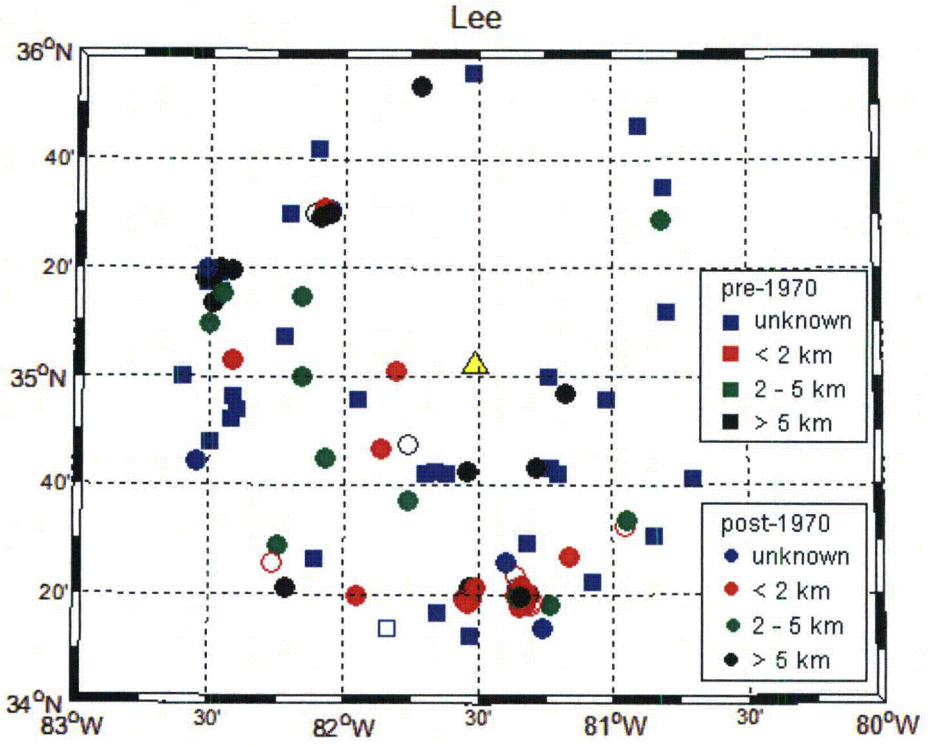


Figure 13: Seismicity within 100 km of the Lee NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

Brunswick

There are 45 earthquakes within 100 km of the Brunswick NPP (Figure 14); none of them has an estimate of the focal depth. The NPP is located near the coast.

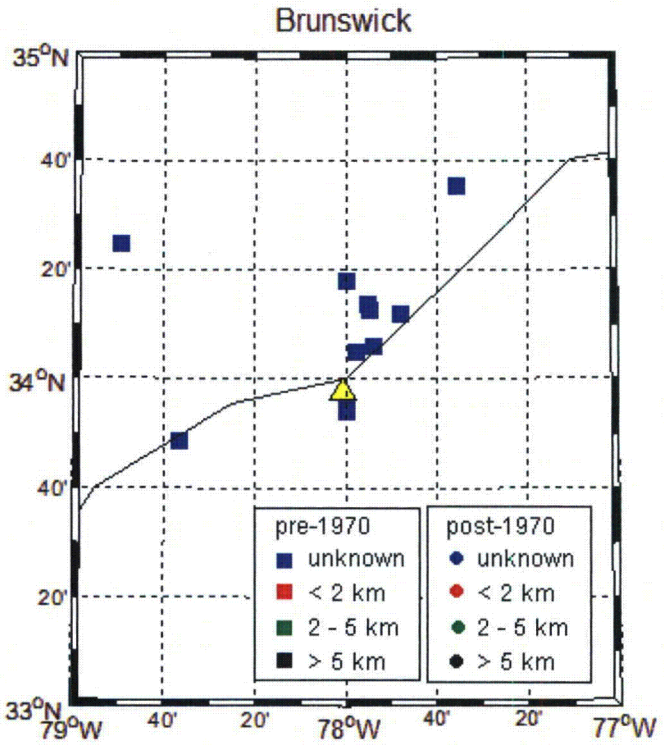


Figure 14: Seismicity within 100 km of the Brunswick NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

Surry

There are 31 earthquakes within 100 km of the Surry NPP (Figure 15) of which 8 (post-1978) have an estimate of focal depth. The plant is located on the James River.

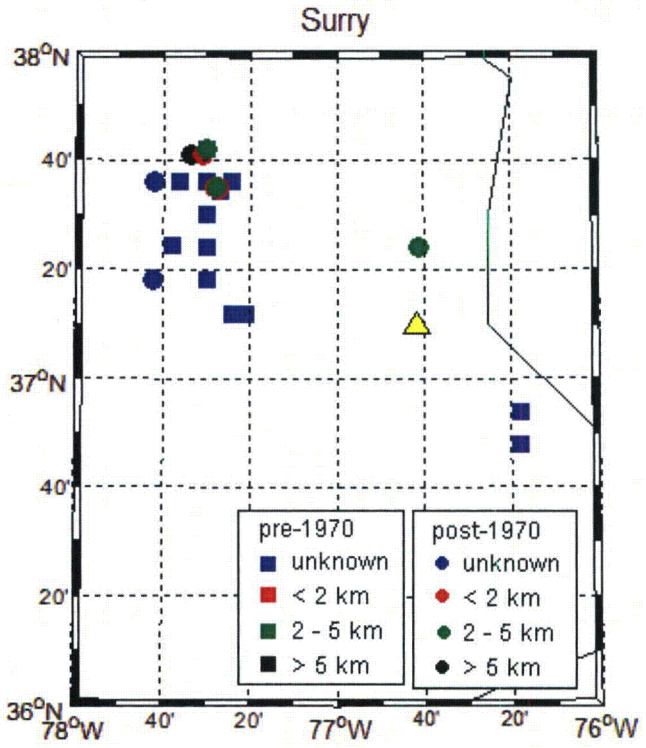


Figure 15: Seismicity within 100 km of the Surry NPP (from Rev 7 of the CEUS-SSC earthquake catalog).

1.4 SUMMARY OF ASSESSMENTS OF ADDITIONAL RIS

Thirty additional RI or probable RI earthquakes were identified in the Rev 7 CEUS-SSC catalog (Table 4). Of these, 21 were removed by declustering the catalog, while of the remaining 9 only 4 are large enough (E[**M**] ≥ 2.9) to have been included in earthquake recurrence calculations. The earthquakes identified in Table 4 were removed from the catalog and a new Rev 8 of the CEUS SSC catalog was prepared to be used for recurrence calculations.

Figure 1 shows that the events in Table 4 are located in proximity of two NPPs: Oconee and VC Summer. The earthquakes located within 100 km of each NPP were plotted and analyzed to identify any other cluster of seismicity of non-tectonic origin. Figure 16 compares the earthquakes with E[**M**] ≥ 2.9 that occurred from 1968 to December 2007, located within 100 km of the Oconee NPP, from Rev 7 of the CEUS SSC Catalog (Figure 16a) and from Rev 8 (Figure

16b). The comparison indicates that the analysis presented in this report has removed several earthquakes that had previously been used to calculate recurrence rates for PSHA.

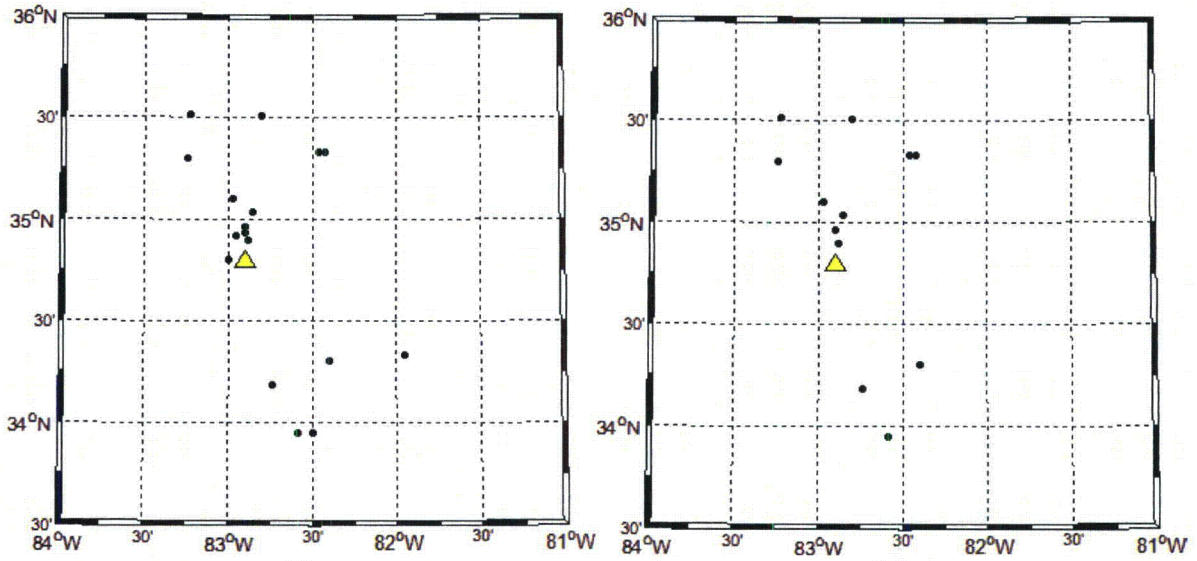
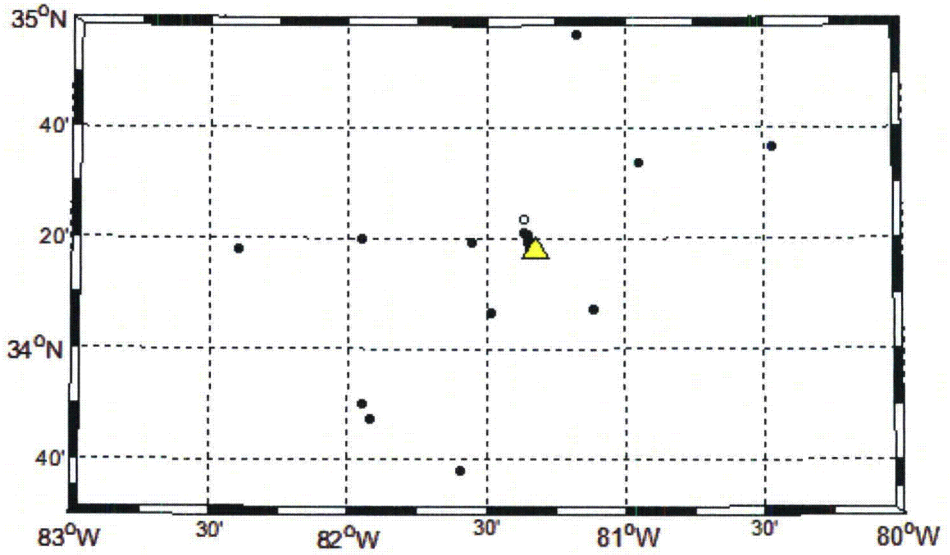
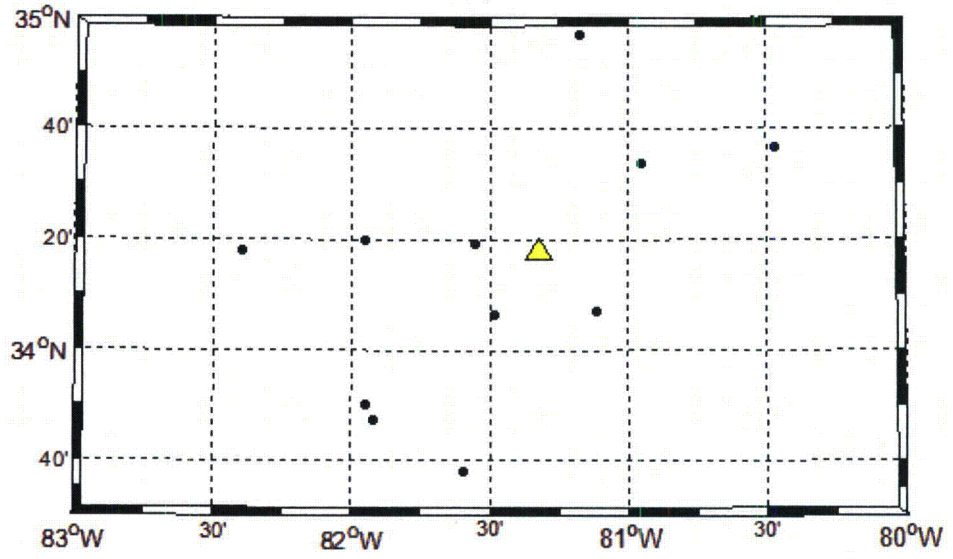


Figure 16: Seismicity with E[M] ≥ 2.9 occurred within 100 km of the Oconee NPP from 1968 through December 2007: a) from Rev 7 of the CEUS-SSC earthquake catalog; b) from Rev 8.

Figure 17 shows a similar comparison for the seismicity within 100 km of the VC Summer NPP: Figure 17a shows the earthquakes in Rev 7 of the catalog with E[**M**] ≥ 2.9 occurred from 1968 to December 2007; Figure 17b shows the earthquakes from Rev 8 of the catalog. The cluster of earthquakes associated with the Monticello Reservoir has been effectively removed from the earthquake catalog in Rev 8.



(a)



(b)

Figure 17: Seismicity with E[M] ≥ 2.9 occurred within 100 km of the VC Summer NPP from 1968 through December 2007: a) from Rev 7 of the CEUS-SSC earthquake catalog; b) from Rev 8.

The analysis shown above for Oconee and VC Summer NPPs was then extended to the other NPPs located in the southeastern U.S. nearby reservoirs or other bodies of water. No other clusters of seismicity of non-tectonic origin were identified by examination of the spatial correlation of the earthquakes or temporal correlation with the reservoir impoundment (if any).

Following the re-calculation of the seismicity rates in the Southeastern U.S. after removal of the RIS discussed above and the aftershocks of the Charleston earthquake discussed in the following, Dr. Martin Chapman has identified an additional six earthquakes that are considered by Virginia Tech to be RI. Of these, only one is large enough (E[**M**] 3.16) to have been included in the revised earthquake recurrence calculations. The event is located at 34.892 degrees N, 82.892 degrees W, near the Oconee NPP in the area of Lake Keowee. The event is listed in the SEUSSN Bulletins, however it is not explicitly identified as reservoir induced. Although it is agreed that the earthquake should be listed as RI in future releases of the earthquake catalog, it is expected that the impact on the earthquake recurrence analysis of removing one additional earthquake would be minor and does not warrant another update of the earthquake recurrence rates.

PART 2 EARTHQUAKES IN SOUTH CAROLINA NEAR THE TIME OF THE 1886 CHARLESTON, SC, EARTHQUAKE SEQUENCE

The table below lists 7 earthquakes from the Rev 7 CEUS SSC catalog from the time period 1799 to 1868 in South Carolina that were identified as being potentially mislocated to areas away from Charleston.

TABLE 6

QUESTIONED CHARLESTON SC AREA EARTHQUAKES FROM REV 7 OF CEUS SSC CATALOG

TMPID	yr	Mo	Dy	hr	mn	sec	Lat	lon	E[M]	Source of Catalog Location
TMP00331	1799	4	11	8	20	0	33.95	-80.18	4.68	USGSnd_000145 Revised by Jeff Munsey of TVA based on Bakun and Hopper Method
TMP01089	1860	1	19	23	0	0	33.68	-80.57	4.21	USGSnd_000427
TMP01731	1886	9	1	6	0	0	33.91	-82.02	4.54	SeebArm87_000014
TMP01739	1886	9	1	9	45	0	34.3	-82.86	4.17	USGSnd_000771
TMP02019	1886	10	22	5	0	0	34.71	-81.66	4.13	USGSnd_000805
TMP02025	1886	10	22	14	45	0	33.87	-81.01	4.5	USGSnd_000807
TMP02360	1888	1	12	9	55	0	34.18	-80.17	4.33	USGSnd_000860

The majority of these earthquakes have locations and times that come from the USGS's earthquake catalog used for seismic hazard mapping. The primary source of the USGS catalog is the NCEER-91 catalog. The events in question have alternative locations in the SUSN catalog that place them at the location of the 1886 Charleston, SC main shock. We have reviewed the identification of these earthquakes and assignment of these locations in the development of the Rev 7 CEUS SSC catalog in light of additional information in the paper by W.H. Bakun and M.G. Hopper (2004, "Magnitudes and Locations of the 1811-1812 New Madrid, Missouri, and the 1886 Charleston, South Carolina, Earthquakes," Bulletin of the Seismological Society of America, **94**, 64-75) and recent information provided by Donald Stevenson and Dr. Predeep Talwani (written communication, February 19, 2014). The individual earthquakes are discussed below.

TMP00331, 1799/4/11, E[**M**] 4.68.

This earthquake was originally located at the 1886 main shock site in the source catalogs. However, additional analysis of the reported intensity data by Jeff Munesy of TVA (written communication, 2010), which includes intensity VI at Statesburg, SC and intensity V at Wilmington, NC indicates a location north of Charleston. The location in the Rev 7 catalog was obtained by Jeff Munsey using the Bakun and Hopper method. There does not appear to be a

compelling reason to move this earthquake to Charleston and the recommendation is to use the location obtained by Jeff Munsey.

TMP01089, 1860/1/19, E[**M**] 4.21.

The location in the Rev 7 catalog is based on NCEER-91. Donald Stevenson and Dr. Predeep Talwani provided the isoseismal map shown below based on their interpretation of the available intensity data. This interpretation suggests a location near Charleston. The recommendation is to utilize the Charleston location given in the SUSN catalog.

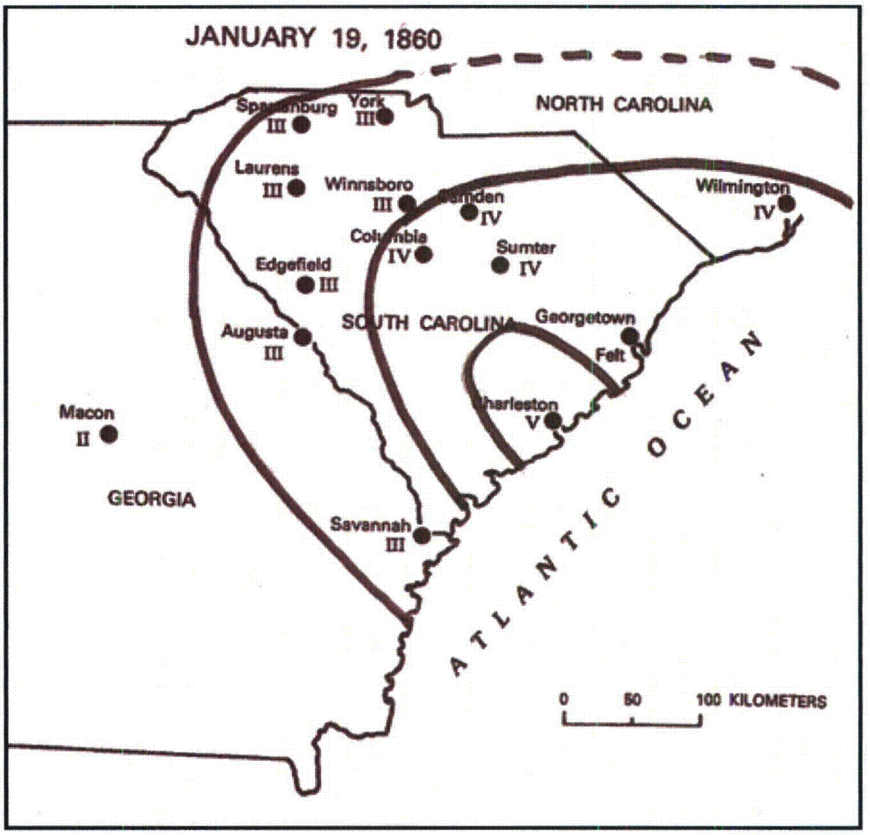


Figure 18: Isoseismal map for January 19, 1860 earthquake provided by Donald Stevenson and Dr. Predeep Talwani (written communication, February 19, 2014).

TMP01731, 1886/9/1, E[**M**] 4.54.

As indicated by Donald Stevenson and Dr. Predeep Talwani (written communication, February 19, 2014), TMP01731 appears to be a duplicate of TMP01732, which has a Charleston location based on their evaluation of archival data. The recommendation is to remove this earthquake from the catalog as a separate earthquake.

TMP01739, 1886/9/1, E[**M**] 4.17.

Donald Stevenson and Dr. Predeep Talwani (written communication, February 19, 2014) recommend that the location given in the SUSN catalog be used and the time changed to 14:45 UTC. The recommendation is based on examination of the two closest newspapers to the reported location (*Abbeville Press and Banner*, and *the Anderson Intelligencer*) that shows only references to the Charleston catastrophe, and no mention of any earthquake activity near Abbeyville or Anderson. Given this information, the record appears to be a duplicate of TMP01738, The recommendation is to remove the earthquake from the catalog as a separate earthquake.

TMP02019, 1886/10/22, E[**M**] 4.13.

Review of the data indicates that TMP02019 is likely a duplicate of TMP02024 and that the time for event TMP02024 should be changed to 10:25 UTC. Bakun and Hopper (2004) studied this event using the intensity data from Talwani and Sharma (1999) and obtained an offshore Charleston location. Recommendation is to remove TMP02019 from the catalog and use the Charleston location in SUSN and the estimated moment magnitude given in Bakun and Hopper (2004) for TMP02024.

TMP02025, 1886/10/22, E[**M**] 4.13.

Bakun and Hopper (2004) studied this event using the intensity data from Talwani and Sharma (1999) and obtained an offshore Charleston location. Recommendation is to use the Charleston location in SUSN and the estimated moment magnitude given in Bakun and Hopper (2004) for TMP02025.

TMP02360, 1888/1/12, E[**M**] 4.33.

The location for this event was taken from the USGS. Donald Stevenson and Predeep Talwani (written communication, February 19, 2014) indicate that there are no newspaper reports that support a location between Sumter and Darlington (34.18 -81.17) and that the correct time should be 14:55 UTC. The event may be a duplicate with TMP39326, with a reported time of 15:54 in SUSN and a Charleston location. Recommendation is to remove TMP02360 from the catalog.

Our review turned up another potential duplicate. Bakun and Hopper (2004) also studied the Charleston aftershock on 1886/11/5 17:20 and found a location near Charleston, but slightly inland from other locations. Talwani and Sharma (1999) also concluded that this earthquake occurred at a slightly different location than other Charleston aftershocks. This earthquake appears in the Rev 7 catalog as TMP02071. There is also an event TMP02072 that is listed in the USGS catalog with time 12:25 with a location to the northwest of Charleston. Both events were flagged as Charleston aftershocks in the declustering, but the timing suggests that they may be duplicates. The recommendation is to remove TMP02072 and use the magnitude and location given in Bakun and Hopper (2004) for TMP02071.

2.1 REFERENCES

Bakun, W.H. and M.G. Hopper, 2004, Magnitudes and Locations of the 1811-1812 New Madrid, Missouri, and the 1886 Charleston, South Carolina, Earthquakes, Bulletin of the Seismological Society of America, 94, 64-75.

Stevenson, D. and P. Talwani, 2014, written communication to Robert Youngs, February 19, 2014.

Munsey, J., 2010, Written communication to Robert Youngs, March 17, 2010.

Talwani, P. and N. Sharma, 1999, Reevaluation of the Magnitudes of Three Destructive Aftershocks of the 1886 Charleston Earthquake, Seismological Research Letters, 70(3), 360-367.

PART 3 DEVELOPMENT OF A REV 8 CATALOG

The assessments in Parts 1 and 2 were used to create a Rev 8 CEUS SSC catalog specifically for calculating earthquake recurrence rates in the southeastern US.

3.1 REVISED ASSIGNMENTS OF PARAMETERS FOR 1886 CHARLESTON ERA EARTHQUAKES

The above assessment that, six of the earthquakes listed in Table 6 should be either removed from the catalog as duplicates of other earthquakes or relocated to the vicinity of the1886 Charleston mainshock prompted a further review of the earthquake locations provided by Seeber and Armbruster (1987). The Seeber and Armbruster (1987) locations and size assessments were incorporated into the NCEER-91 catalog and then into the USGS catalog that was used as the primary source for the CEUS SSC Rev 7 catalog. The original Seeber and Armbruster (1987) listing was also incorporated into the CEUS SSC Rev 7 catalog, along with their listed values of felt area.

Seeber and Armbruster (1987) categorized the 1886 Charleston era earthquakes into 5 categories. Reexamination of Seeber and Armbruster (1987) indicated that the earthquakes in their Category 1 and Category 2 had nominal felt areas assigned to them (100 km^2). As these were not actual felt areas assessed from the distribution of felt reports, it was judged that they should not be used to assess magnitude using the models developed in NUREG-2115 based on actual felt areas, and the values of ln(FA) were removed from the Rev 8 catalog for the purpose of magnitude assessment.

The Seeber and Armbruster (1987) Category 3 earthquakes are defined as

> "...(3) events apparently reported from more than one town, but which are unreliable because large populated areas between these towns did not report feeling the event ..."

The interpreted mislocated events TMP01731 and TMP01739 are listed as Category 3 in Seeber and Armbruster (1987).

Seeber and Armbruster (1987) assigned felt areas as follows:

> "The felt areas assigned to events felt at less than 5 towns was the area of the circle with diameter equal to the distance between the most distant felt reports. The felt area assigned to events felt at 5 or more towns is the area of the ellipse with a major axis equal to the distance between the most distant felt reports and a minor axis twice the distance from the major axis to the furthest felt report."

The description of Category 3 events as "unreliable" and having large areas without felt reports between towns with felt reports indicates that the assigned felt areas for these events may also be unreliable. In many cases, the maximum intensity for Category 3 events is II or III. Figures 19, 20, and 21 compare the I_0 and ln(FA) values for Category 3, 4, and 5 earthquakes, respectively from Seeber and Armbruster (1987) with the data from other earthquakes in the

Rev 7 CEUS SSC catalog. The values of ln(FA) for Category 3 appear to be biased high for the assigned I_0 compared to the general population. Given the evident bias and the unreliability of the events, the Seeber and Armbruster Category 3 events that are duplicated by SUSN events are removed from the Rev 8 catalog and for those Category 3 events that are not duplicated, the values of ln(FA) are removed from the Rev 8 listing for use in magnitude assessment.

The comparisons for the Category 4 earthquakes on Figure 20 show general consistency in the I_0-ln(FA) data with the rest of the catalog. Many of the Category 4 earthquakes have locations near Charleston. These events are left in the catalog.

The remaining question is the large number (about 25) of the Category 5 earthquakes. A number of these have SUSN entries with the same time, but often significantly different locations. Category 5 is considered by Seeber and Armbruster (1987) as the best located. Five of the interpreted mislocated earthquakes discussed in Part 2 are Category 5 earthquakes, indicating that there are issues with some of these locations. In addition, the data shown on Figure 21 indicate that the assigned ln(FA) may be biased high for this category. These events were examined again in comparison to other events in the catalog from SUSN.

Where the Seeber and Armbruster (1987) error ellipses include the SUSN locations, the SUSN locations were used as the primary location. Clearly not all of these earthquakes occurred exactly in the same place. In many cases, the NCEER-91 locations differ from the Seeber and Armbruster (1987) locations and sometimes appear to be an average of the two. The bias in the I_0-ln(FA) data for these events and the location bias for the six large events initially identified further suggests that the SUSN locations be used in place of the Seeber and Armbruster (1987) / NCEER-91 locations. For those events that could not be associated with an SUSN event, have very large error ellipses, and I_0-ln(FA) assessments that appear biased, the ln(FA) data were removed from the catalog for magnitude assessment.

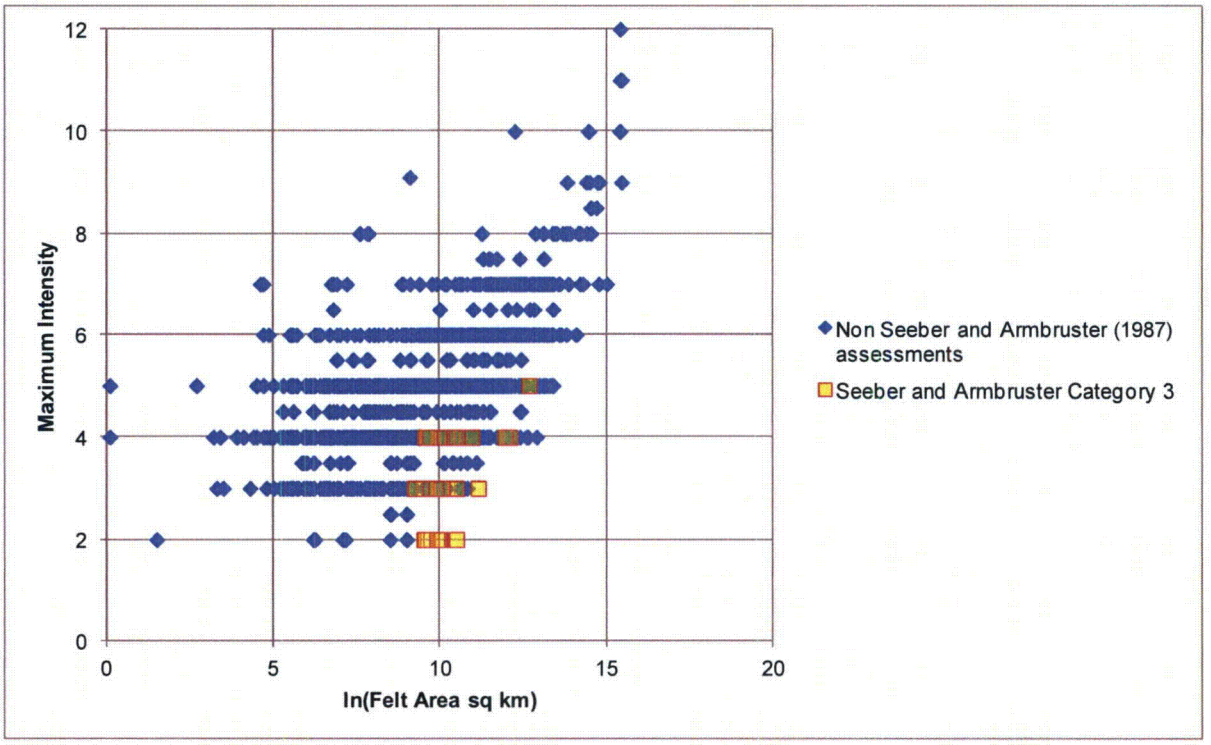


Figure 19: Comparison of ln(FA)-I_0 data for Category 3 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Rev 7 catalog.

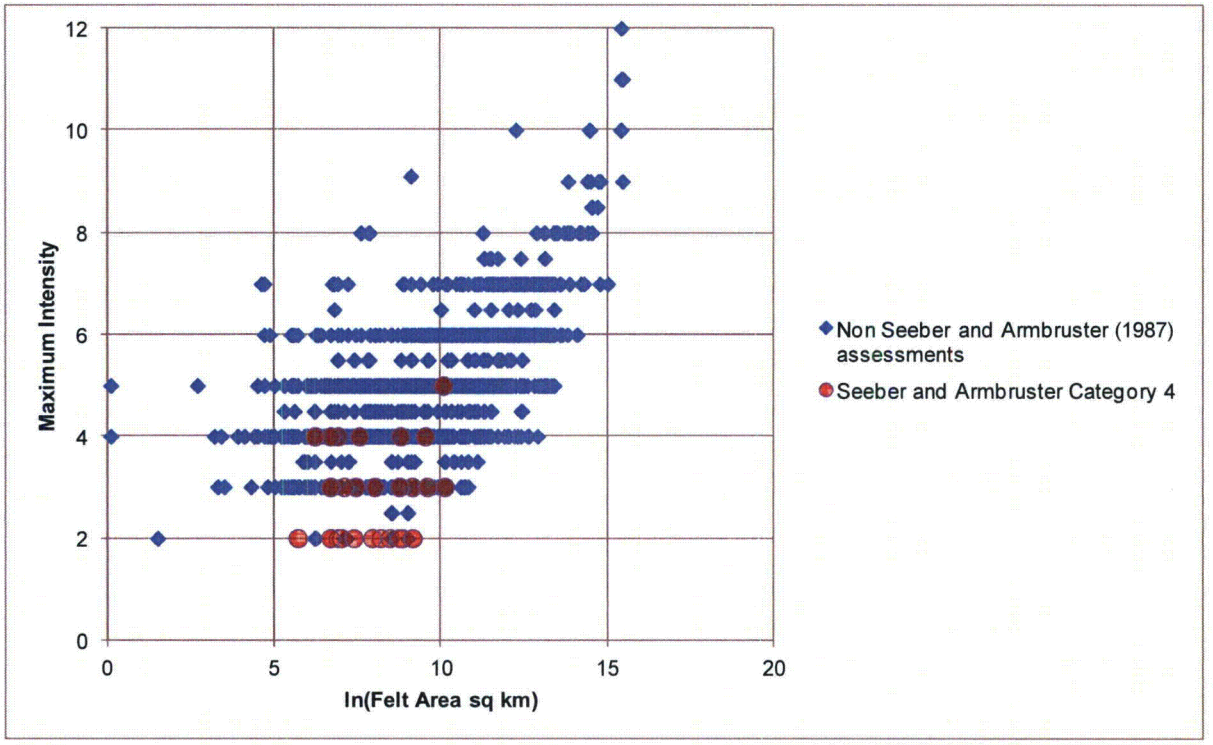


Figure 20: Comparison of ln(FA)-I0 data for Category 4 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Rev 7 catalog.

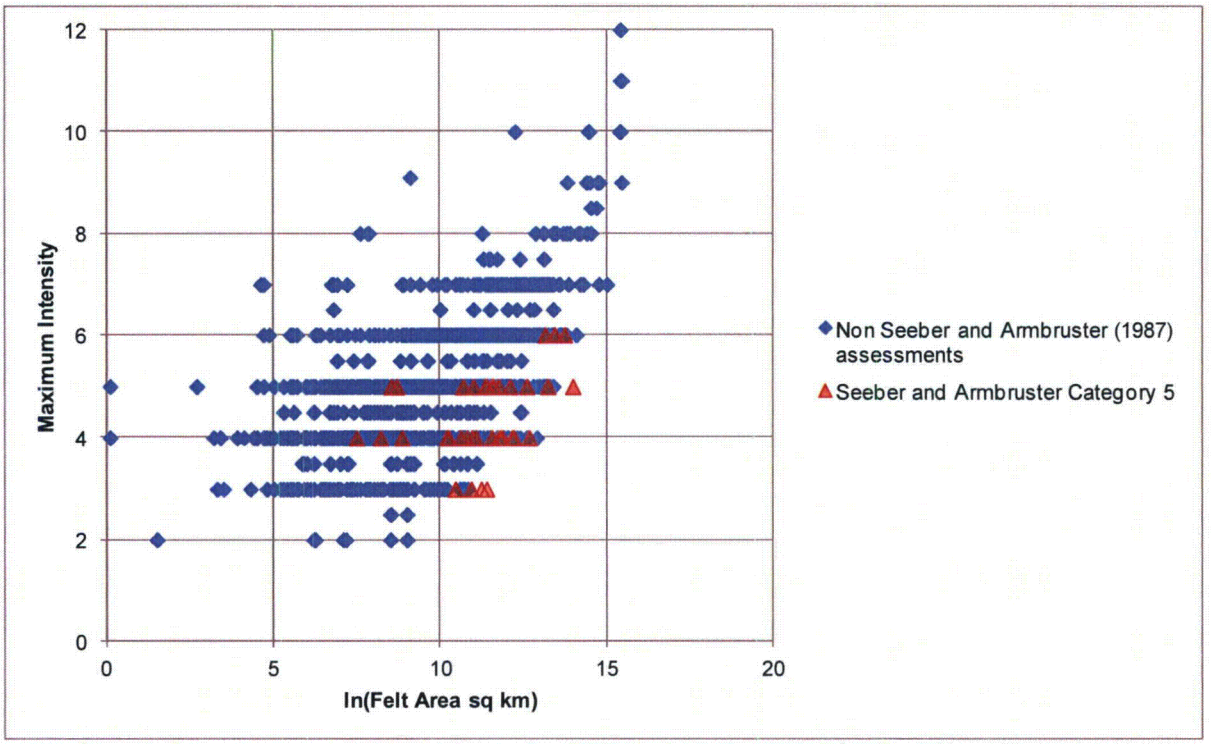


Figure 21: Comparison of ln(FA)-I_0 data for Category 5 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Rev 7 catalog.

After making the adjustments described above, catalog declustering was performed. As a result, the classification of nine additional earthquakes at locations distant from Charleston significant to hazard (E[**M**]≥2.9) were changed from dependent to independent. Previously, these earthquakes had been classified as dependent earthquakes in clusters associated with the earthquakes identified above. The information for each of these earthquakes was reviewed, including additional information provided by Stevenson and Talwani (written communication, Feb 26, 2014). These events are discussed below.

TMP01942, 1886/9/28, E[**M**] 3.10.

This is a Category 4 earthquake in Seeber and Armbruster (1987) and is listed in NCEER-91. Its I_0 (III) and ln[FA] (8.0) are consistent with the general population of CEUS SSC earthquakes (see Figure 20). However, Stevenson and Talwani (written communication, 2014) state:

> "This is one of the events listed by Seeber and Armbruster that we term to be phantom events. We can find no support or validation for the event or the location. The Union newspaper was not available for this date. However, a check of other papers in the region (The nearest at Greenville, SC approx. 40 miles away) showed no mention of an earthquake in Union, South Carolina on September 28. The Greenville

> paper contained articles related to the Charleston event but no mention of anything in the upstate. We do not believe this to be a genuine event."

Recommendation is to consider this a false event.

TMP02002, 1886/10/12, E[**M**] 3.04.

Although this event was listed as a category 4 earthquake in Seeber and Armbruster (1987), it was not carried forward into NCEER-91. Also the ln(FA) of 8.46 is anomalous compared to the I_0 of II (Figure 20). The recommendation is to not use the felt area reported by Seeber and Armbruster (1987), which will result in the event not being considered in estimation of earthquake recurrence.

TMP02068, 1886/11/04, E[**M**] 3.18.

Although this event was listed as a category 4 earthquake in Seeber and Armbruster (1987), it was not carried forward into NCEER-91. Also the ln(FA) of 8.92 is anomalous compared to the I_0 of II (Figure 20). The recommendation is to not use the felt area reported by Seeber and Armbruster (1987), which will result in the event not being considered in estimation of earthquake recurrence.

TMP02134, 1886/12/08, E[**M**] 2.82.

This event was listed as a category 2 earthquake in Seeber and Armbruster (1987) and was not carried forward into NCEER-91. Munsey (2006) also identified the event from archival data with a I_0 of IV/V similar to the I_0 of IV reported in Seeber and Armbruster (1987). Stevenson and Talwani (written communication, Feb 26, 2014) indicate:

> "...close review of the *Columbia Daily Record* for the time period of 12/08/1886 to 12/13/1886 showed no reports of felt earthquakes in Columbia. We do not believe this to be genuine."

Based on this assessment, and the fact that the earthquake only potentially affects recurrence calculations because of the I_0 assignment of IV/V, it is suggested that this earthquake be considered as either a false event or too small to include in recurrence calculations. The event was retained in Rev 8 of the CEUS SSC catalog with E[**M**] 2.82.

TMP02136, 1886/12/11, E[**M**] 3.25.

This is a Category 5 earthquake in Seeber and Armbruster (1987) and is listed in NCEER-91. Its I_0 (IV) and ln(FA) (8.22) are consistent with the general population of CEUS SSC earthquakes (see Figure 21). Stevenson and Talwani (written communication, Feb 26, 2014) indicate:

> "The listed location for this event plots just east of Abbeville, SC. This, may be a real event. In the December 13, 1886 edition of the *Abbeville Press and Banner* a short piece addressing a loud noise heard on the Saturday before (12/11) appeared.
> ""**The Noise on Saturday**: Many persons in the vicinity of Abbeville

> heard the noise, sound, explosion or whatever it may have been last Saturday afternoon. Mr. A.E. Lewis says it was in the air from him at an angle of 45 degrees a little south of west. Mr. T. L. Haddon says it sounded as if it was over and beyond his gin house."
> From this description it is unclear if this was an earthquake or not. Nothing is mentioned about people feeling the ground move, only about a loud sound. No mention of this event could be found in the *Columbia Daily Register, Edgefield Chronicle,* or *Laurens Advertiser.* We feel it doubtful that this is a real earthquake as all mentions above are to noises If this event were to be given the benefit of doubt and accepted as a genuine earthquake, the above, Abbeville, account would lend itself to an assigned intensity considerably less than IV and should probably not be considered. "

The above description indicates that the event may be real. Classification as Category 5 earthquakes in Seeber and Armbruster (1987) indicates that the earthquake was reported in multiple towns. As there is some evidence for the earthquake, there is no clear reason to discount it, and the recommendation is to retain it in the catalog.

TMP02173, 1887/01/12, E[**M**] 2.91.

This is a Category 4 earthquake in Seeber and Armbruster (1987) and is listed in NCEER-91. Its I_0 (III) and ln(FA) (7.09) are consistent with the general population of CEUS SSC earthquakes (see Figure 20). Stevenson and Talwani (written communication, Feb 26, 2014) indicate:

> "This event plots just outside Due West, SC. between Greenwood and Anderson. Checking issues of the *Anderson Intelligencer* and *Abbeville Press and Banner* through the remainder of January 1887 showed a report of a small earthquake near Due West, SC. However, it is reported to have occurred on 01/05/1887. This little event seems to have escaped all catalogers. There is nothing reported for 01/12/1887. From the *Abbeville Press an Banner*: CHICKASAW'S CHIT CHAT; from Due West, SC Jan. 10 1887: "A very perceptible shock of earthquake was felt here last Tuesday morning. Some persons have thought that shocks have been occurring quite frequently for several weeks, but not until last week have they had the bravery to speak positively as to their occurrence."

The above description indicates that this was likely a small earthquake. The assessment of felt area by Seeber and Armbruster (1987) is only approximate, and places this earthquake at the edge of being included in recurrence calculations (E[**M**] ≥ 2.91). The recommendation is to maintain this earthquake in the catalog without modification..

TMP02393, 1888/04/05, E[**M**] 4.3.

This event was identified by Munsey (2006). Its size was assessed on the basis of an assigned intensity of VI/VII, which were described by Munsey (2006) as being very localized effects. The fact that the event was not reported in Seeber and Armbruster (1987) indicates that the high local effects were not widespread. Stevenson and Talwani indicate:

> To our knowledge this event appears in no other catalog except the CEUS-SSC catalog. The location of the event plots just 5 miles south east from the center of Newberry, SC. In checking copies of the *Newberry Herold and News* for the month of April 1888 we could find no mention of an earthquake anywhere near Newberry. There was only a mention of an earthquake that apparently occurred in China. A check of the *Abbevillle Press and Banner, the Edgefield Advertiser,* and *the News and Herald* (Winnsboro,SC) for the month of April, 1888 showed no mention of any earthquakes other than the one in China also appearing in the Newberry paper."

Given that the effects identified by Munsey (2006) are very localized and other investigators did not identify effects on this date in surrounding areas indicates that if this was an earthquake, it was likely small. Therefore, the recommendation is to consider this potential event to be too small to affect recurrence calculations.

TMP02423, 1888/08/15, E[**M**] 3.12.

This is a Category 4 earthquake in Seeber and Armbruster (1987) and is listed in NCEER-91. Its I_0 (IV) and ln[(A) (7.55) are consistent with the general population of CEUS SSC earthquakes (see Figure 20). Stevenson and Talwani (written communication, Feb 26, 2014) indicate:

> "This is, in fact a real event although the listed intensity may be a bit on the high side. It is actually kind of an interesting little read. It apparently occurred in or near Winnsboro, South Carolina. Two mentions of it appeared in the *Augusta Chronicle* (Augusta Georgia). The first appeared in the August 17, 1888 issue: "NOT AN EARTHQUAKE: It was rumored on the streets Wednesday night that an earthquake had been felt at Winnsboro, SC, but it was too late to verify the report by telegraphic advises. It turns out that the report was started by the telegraph operator there who heard a terrific roar and rumbling, accompanied by a rattling of windows and shaking of houses. He told the operators over the wires that there was an earthquake going on and then left the office in haste. A coal burning locomotive of the R & D. road was at the station and the noise was caused by the engineer putting on the blowers."
>
> ...Three days later a letter appears in the August 20 issue of the *Augusta Chronicle* with the headline "KNOWS WHAT A QUAKE IS The Telegraph operator at Winnsboro Has Something to Say of a Shock". "In justice to myself I must ask space in your columns to correct this: I will briefly state the facts in the case: 1st. On August 15th (Wednesday) a very decided earthquake shock was here at 6:25 p. m., standard time, not only by myself but by the entire population of our town. The duration of the shock was about twenty seconds, accompanied by the usual roaring noise. All the inhabitants can make affidavits to the effect, if necessary. 2nd I asked only two operators by wire if they felt the shock, they being Ridgeway and Columbia. 3rd I did not leave my office during the tremor which was very perceptible and quietly remained and noted the time. 4th The passenger train, south had left Winnsboro about twenty minutes after the earthquake occurred, and there was no "coal burning locomotive" within 18 to 20

> miles of my office. 5th I have been in the railroad service about ten years and I think this is sufficiently log to enable me to distinguish the roaring sound which accompanies an earthquake from that of a "coal burning locomotive." 6th A special dispatch announcing the earthquake was sent to the Charleston World. Our county paper also announced the occurrence. 7th I am a man of veracity, if I do say it myself, and I am not a "nervous operator."
>
> J.H. Skinner; ticket agent and operator.
>
> Upon review of the *News and Herald* (Winnsboro, SC) only a very short mention was found in the August 22, 1888 issue: "An earthquake shock was felt by some people on Wednesday. The shock was not generally noticed." While this obviously is a genuine event it seems would seem the reported intensity might be a high.

Because the earthquake is clearly identified in the above reporting, the recommendation is to retain it in the catalog with the reported size measures given in Seeber and Armbruster (1987).

The following table summarizes the assessments of the larger events in the Rev 7 catalog that are located at sufficient distance from Charleston to not be identified as aftershocks of the 1886/09/01 main shock.

TABLE 7

REVISED LOCATIONS AND UNIFORM MAGNITUDES FOR SPECIFIC EARTHQUAKES NEAR CHARLESTON, SC

TMPID	yr	Mo	Dy	Hr	Mn	sec	lat	lon	Basis of Revised Magnitude
TMP01089	1860	1	19	23	0	0	33.68	-80.57	Move to Charleston and base E[**M**] on I_0
TMP01731	1886	9	1	6	0	0	33.91	-82.02	Event removed from catalog as a duplicate of TMP01732. Location and magnitude of TMP01732 do not require modification
TMP01739	1886	9	1	14*	45	0	34.04	-82.9	Event removed from catalog as a duplicate of TMP01738. Location and magnitude of TMP01738 do not require modification
TMP01942	1886	9	28	3	0	0	34.7	-81.62	Consider as a false event
TMP02002	1886	10	12	11	0	0	34.14	-81.33	Not use reported felt area, event becomes < E[**M**] 2.9
TMP02019	1886	10	22	5	0	0	34.71	-81.66	Event removed from catalog as a duplicate of TMP02023
TMP02023	1886	10	22	10	20		32.9	-80	Magnitude taken from Bakun and Hopper (2004)

TABLE 7

REVISED LOCATIONS AND UNIFORM MAGNITUDES FOR SPECIFIC EARTHQUAKES NEAR CHARLESTON, SC

TMPID	yr	Mo	Dy	Hr	Mn	sec	lat	lon	Basis of Revised Magnitude
TMP02024	1886	10	22	10*	25		33.69	-81	Event removed from catalog as a duplicate of TMP02023
TMP02025	1886	10	22	14	45	0	33.87	-81.01	Location moved to Charleston, magnitude taken from Bakun and Hopper (2004)
TMP02068	1886	11	5	5	0	0	33.38	-82.49	Not use reported felt area, event becomes < E[**M**] 2.9
TMP02071	1886	11	5	17	20	0	32.9	-80	Magnitude taken from Bakun and Hopper (2004)
TMP02072	1886	11	5	12	25		33.4	-80.42	Event removed from catalog as a duplicate of TMP02071.
TMP02134	1886	12	8	10	25	0	34.039	-80.886	Revise I_0 from 4.5 to 4
TMP02136	1886	12	11	21	0	0	34.18	-82.06	Retain as is
TMP02173	1887	1	12	11	0	0	34.35	-82.42	Retain as less than E[**M**] 2.9, remove felt area
TMP02210	1887	3	4	10	0	0	33.74	-81.5	Not use reported felt area, event becomes < E[**M**] 2.9
TMP02360	1888	1	12	9	55	0	34.18	-80.17	Event removed from catalog as a duplicate of TMP39326.
TMP02393	1888	4	5	0	0	0	34.21	-81.534	Retain, reduce to I_0 4, E[**M**] less than 2.9
TMP02423	1888	8	15	23	30	0	34.37	-81.08	Retain as is

* Change in hour

The review described above indicates that considerable uncertainty remains about the parameters of the 1886 Charleston earthquake aftershocks in the published literature. It is suggested that efforts be considered to support publishing the compilation of data on these earthquakes being developed by Don Stevenson and Dr. Pradeep Talwani to aid in further assessments of the earthquakes of this time period.

3.2 CATALOG PROCESSING

After revising the parameters of the Charleston aftershocks and removal of the RIS earthquakes, the updated catalog was processed in the same manner as the Rev 7 catalog. Magnitudes based on I_0 and ln(FA) of the Charleston aftershocks were recalculated using the updated metadata. These calculations were performed using the Rev 7 set of relationships and I_0-**M** and ln(FA)-**M** data in order to produce the same conversions as the Rev 7 catalog. This

was because some of the RIS earthquakes contributed to the conversions and their removal would produce slight differences in the calculated values.

After developing the updated E[**M**] catalog, it was declustered using the same procedure. The declustering program uses random number generation as part of the selection of which earthquakes to flag as dependent, therefore the updated declustered catalog was edited to utilize the same set of independent and dependent earthquakes as Rev 7 in areas not affected by the catalog updates in order to not introduce small differences in completeness due to this statistical fluctuation.

Completeness was then calculated for the entire region. The primary completeness regions affected were 5, 6, 7, and 12. The differences in completeness are generally less than 5 percent.

3.3 REFERENCES

Seeber, L. and J.G. Armbruster, 1987, The 1886-1889 Aftershocks of the Charleston, South Carolina, Earthquake: a Widespread Burst of Seismicity, Journal of Geophysical Research, 92(B3), 2663-2696.

Stevenson, D. and P. Talwani, 2014, written communication to Robert Youngs, February 26, 2014.

Munsey, J.W., 2006, Identification of "New" Historic Earthquakes in the Central and Eastern United States through Online Keyword Searches: Unpublished Report of River Operations, Tennessee Valley Authority, February.

amec
foster
wheeler

APPENDIX A

Donald Stevenson to Dr. Youngs Emails

a. Email dated 2/19/2014, 10:54 AM
b. Email dated 2/26/2014, 9:07 AM

Cox, Domonique C

From: donald.stevenson@srs.gov
Sent: Wednesday, February 19, 2014 10:54 AM
To: Youngs, Bob
Cc: pradeep@sc.edu
Subject: Re: South Carolina earthquakes
Attachments: Charleston_area_Eqs.xlsx

Bob,

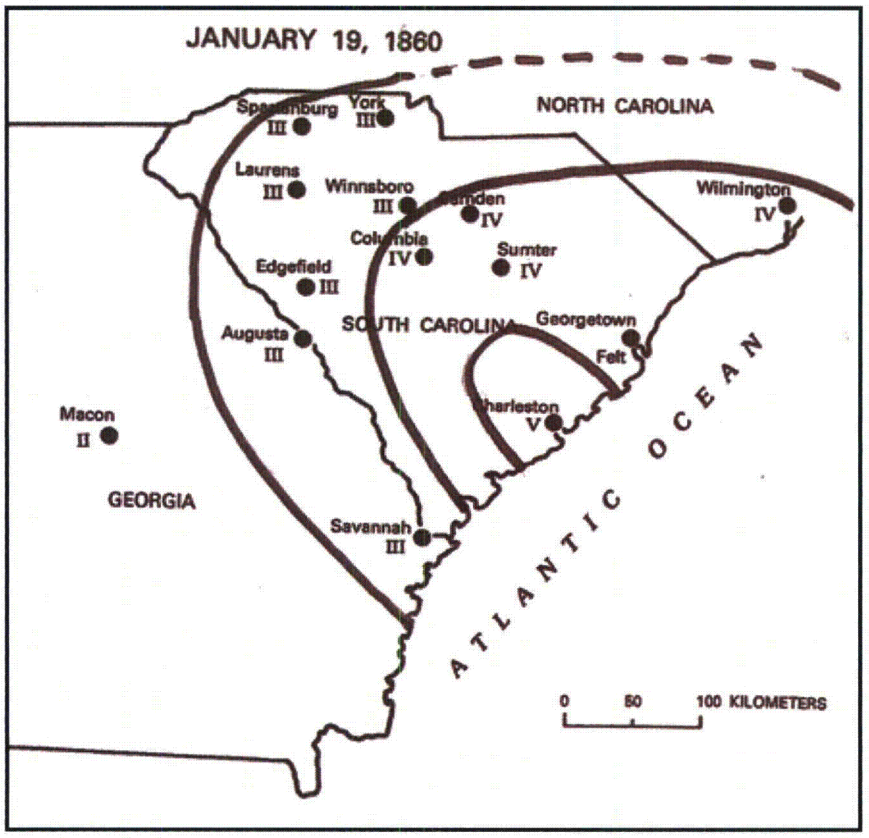
We have re-evaluated all of these events by doing an archival search of newspapers in the listed epicentral areas of each event. Our conclusion is that there should be only six earthquakes (one is a repetition), and that all of them occurred in the Charleston/Summerville region. Our revised locations are given in the attached table.

REVISED TABLE BASED ON AN EVALUATION OF CONTEMPORARY ARCHIVAL DATA, PLEASE SEE ATTACHED FILE

Some of our detailed information supporting table changes follow:

1. **TMP01089**: It is in fact a Charleston event, based on the macroseismal data listed by Bollinger and Visvanathan, and a review of newspaper accounts throughout the region. These data clearly point to a Charleston/Summerville source. Below is an Isoseismal map interpreted from Bollinger and Visvanathan (1977).

Bollinger, G.A., Visvanathan, T.R. (1977), The seismicity of South Carolina prior to 1886, *in* Rankin, D.W., ed., Studies related to the Charleston, South Carolina, earthquake of 1886 – preliminary report: U.S. Geological Survey Professional Paper 1028-C, p. 33 – 42.



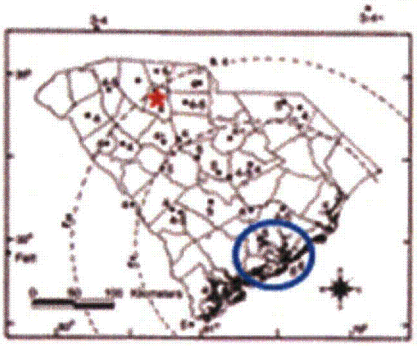
2. **TMP01731 and TMP01732:** These are two listings of the same event. The coordinates listed for TMP01732 are correct and supported by archival data, which do not support the mid-state location listed for TMP01731. TMP01731 has been removed from our corrected list. Based on the archival data this is a Charleston event.

3. **TMP01739**: Another Charleston event. This event actually occurred at 14:45 UTC. The 09:45 time originated from a list by Seeber and Armbruster (1987) where EST were used. Somewhere in its incorporation, the 9.45 time was listed as being UTC. It took place mere hours after the main Charleston event, and is listed as being just over the Georgia South Carolina border in a relatively remote area of Georgia (even today) 46 km northwest of Abbeyville, and 30 km southwest of Anderson over 300 km northwest of Charleston/Summerville area. Examination of the two closest newspapers to the reported location (*Abbeville Press and Banner*, and *the Anderson Intelligencer*) shows only references to the Charleston catastrophe, and no mention of any earthquake activity near Abbeyville or Anderson. The listed location is incorrect, and has been corrected in our revised table.

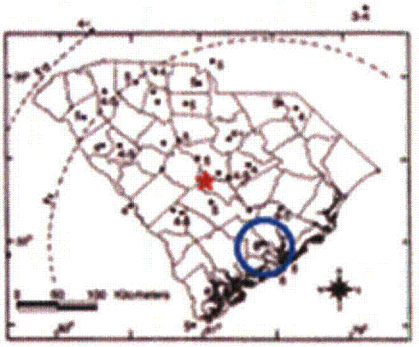
4. **TMP02019 and 02025**: These are two aftershocks of the Charleston earthquake. They were felt over a wide area. The macroseismal data were evaluated by Talwani and Sharma (1999), who located it in the Summerville area and revised the magnitude estimates.. Isoseimal data for these earthquakes and the revised locations by Talwani and Sharma are shown on the maps below taken from that paper, and compared with the WRONG locations (red stars) listed in the existing catalog.

Talwani, P., N. Sharma (1999), *Seismological Research Letters,* Volume 70, Number 3, 360-367. Red stars are erroneous CEUS SSC locations

October 22, 1886 10:20 UTC



October 22, 1886 19:45 UTC



5. **TMP02360**: This is another mis-located Charleston event. It is incorrectly listed as having occurred at **09:55 EST.** This event appears in regional newspaper reports as occurring at times varying from 09:52 to 10:05 EST. Converting to UTC the time becomes 14:52 or there about, a time coincides with a larger Charleston event. This earthquake actually occurred in the Charleston Summerville area and was widely reported throughout the region. However, there are no newspaper reports that support a location between Sumter and Darlington (34.18 -81.17). Its correct location near Summerville has been incorporated in our list above.

In summary, a careful perusal of contemporary newspaper accounts of the dates and times of earthquakes in your list, whose coordinates suggest that they occurred all over South Carolina, were all located in the Summerville Charleston area. The correct times and locations have been given in our revised list.

Original Table:

TID	yr	mo	dy	hr	mn	sec	lat	lon	dep	EM
TMP01089	1860	1	19	23	0	0	33.68	-80.57	0	4.21
TMP01731	1886	9	1	6	0	0	33.91	-82.02	0	4.54
TMP01732	1886	9	1	6	5	0	32.9	-80	0	3.93
TMP01739	1886	9	1	9	45	0	34.3	-82.86	0	4.17
TMP02019	1886	10	22	5	0	0	34.71	-81.66	0	4.13
TMP02025	1886	10	22	14	45	0	33.87	-81.01	0	4.5
TMP02360	1888	1	12	9	55	0	34.18	-80.17	0	4.33

Thank you

Don Stevenson and Pradeep Talwani

From: "Youngs, Bob" <Bob.Youngs@amec.com>
To: "donald.stevenson@srs.gov" <donald.stevenson@srs.gov>, "pradeep@sc.edu" <pradeep@sc.edu>,
Date: 02/14/2014 07:43 PM
Subject: South Carolina earthquakes

Dear Don:

We are looking into some of the South Carolina earthquakes that remain in the CEUS SSC catalog. When you and Pradeep performed your review of the preliminary catalog, you indicated that you were in the process of preparing a study of the earthquakes. I was wondering if you have results for specific earthquakes you could share with me. The specific earthquakes are listed in the attached Excel file with their CEUS SSC id numbers. Any additional information you could provide would be greatly appreciated.

Thank you.

Bob Youngs
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[attachment "Charleston_area_Eqs.xlsx" deleted by Donald Stevenson/SRNS/Srs]

Cox, Domonique C

From: donald.stevenson@srs.gov
Sent: Wednesday, February 26, 2014 9:07 AM
To: Youngs, Bob
Cc: pradeep@sc.edu
Subject: RE: South Carolina earthquakes
Attachments: Additional_Charleston_area_Eqs.xlsx

Bob,

These events were also included in our extensive archival search of newspapers in reviewing listed epicentral areas of each event. Our conclusion as is that there should be only two or maybe three earthquakes. We could find no mention of a Due West event on January 12, 1887. However, there was a small mention of a 'perceptible' earthquake in Due West on 01/05/1887. Not sure what you might want to do with that one as it looks to be pretty small.

REVISED TABLE BASED ON AN EVALUATION OF CONTEMPORARY ARCHIVAL DATA, PLEASE SEE ATTACHED FILE

Some of our detailed information supporting table changes follow:

TMP01942 : 1886/09/28
This is one of the events listed by Seeber and Arbruster that we term to be phantom events. We can find no support or validation for the event or the location. The Union newspaper was not available for this date. However, a check of other papers in the region (The nearest at Greenville, SC approx. 40 miles away) showed no mention of an earthquake in Union, South Carolina on September 28. The Greenville paper contained articles related to the Charleston event but no mention of any thing in the upstate. We do not believe this to be a genuine event.

TMP02134: 1886/12/08
This is another unverifiable event. While it does appear in Seeber and Armbruster (1987) it was not included in the original NCEER/EPRI (1991) catalog. We interpret this to us that it may have been judged a little too small to make the cut for 1991. However, Jeff Munsey seems to have picked it up, come up with a larger intensity and submitted it for consideration in the CEUS catalog. The plotted location is Columbia, SC. Whatever the case close review of the *Columbia Daily Record* for the time period of 12/08/1886 to 12/13/1886 showed **no** reports of felt earthquakes in Columbia. We do not believe this to be genuine.

TMP02136: 1886/12/11
The listed location for this event plots just east of Abbeville, SC. This, may be a real event . In the December 13, 1886 edition of the *Abbeville Press and Banner* a short piece addressing a loud noise heard on the Saturday before (12/11) appeared.

""**The Noise on Saturday**: Many persons in the vicinity of Abbeville heard the noise, sound, explosion or whatever it may have been last Saturday afternoon. Mr. A.E. Lewis says it was in the air from him at an angle of 45 degrees a little south of west. Mr. T. L. Haddon says it sounded as if it was over and beyond his gin house."
From this description it is unclear if this was an earthquake or not. Nothing is mentioned about people feeling the ground move, only about a loud sound. No mention of this event could be found in the *Columbia Daily Register, Edgefield Chronicle,* or *Laurens Advertiser*. We feel it doubtful that this is a real earthquake as all mentions above are to noises If this event were to be given the benefit of doubt and accepted as a genuine earthquake, the above, Abbeville, account would lend itself to an assigned intensity considerably less than IV and should probably not be considered.

TMP02173:1887/01/12
This event plots just outside Due West, SC. between Greenwood and Anderson. Checking issues of the *Anderson Intelligencer* and *Abbeville Press and Banner* through the remainder of January 1887 showed a report of a small earthquake near Due West, SC. However, it is reported to have occurred on 01/05/1887. This little event seems to have escaped all catalogers. There is nothing reported for 01/12/1887.
From the *Abbeville Press an Banner*: CHICKASAW'S CHIT CHAT; from Due West, SC Jan. 10 1887: " A very perceptible shock of earthquake was felt here last Tuesday morning. Some persons have thought that shocks have been occurring quite frequently for several weeks, but not until last week have they had the bravery to speak positively as to their occurrence." Not really sure what you may want to do about this one.

TMP02393:1888/04/05
To our knowlege this event appears in no other catalog except the CEUS-SSC catalog. The location of the event plots just 5 miles south east from the center of Newberry, SC. In checking copies of the *Newberry Herold and News* for the month of April 1888 we could find no mention of an earthquake anywhere near Newberry. There was only a mention of an earthquake that apparently occurred in China. A check of the *Abbevillle Press and Banner, the Edgefield Advertiser,* and *the News and Herald* (Winnsboro,SC) for the month of April, 1888 showed no mention of any earthquakes other than the one in China also appearing in the Newberry paper. We would be interested to know where Jeff Munsey got his information on this event as there is nothing in that location to suggest an earthquake let alone something as large as a VI/VII.

TMP02423:188/08/15
This is, in fact a real event although the listed intensity may be a bit on the high side. It is actually kind of an interesting little read. It apparently occurred in or near Winnsboro, South Carolina Two mentions of it appeared in the *Augusta Chronicle* (Augusta Georgia). The first appeared in the August 17, 1888 issue:
"NOT AN EARTHQUAKE: It was rumored on the streets Wednesday night that an earthquake had been felt at Winnsboro, SC, but it was too late to verify the report by telegraphic advises. It turns out that the report was started by the telegraph operator there who heard a terrific roar and rumbling, accompanied by a rattling of windows and shaking of houses. He told the operators over the wires that there was an earthquake going on and then left the office in haste. A coal burning locomotive of the R & D. road was at the station and the noise was caused by the engineer putting on the blowers."

But wait, three days later a letter appears in the August 20 issue of the *Augusta Chronicle* with the headline "KNOWS WHAT A QUAKE IS The Telegraph operator at Winnsboro Has Something to Say of a Shock".
"In justice to myself I must ask space in your columns to correct this: I will briefly state the facts in the case:
1st. On August 15th (Wednesday) a very decided earthquake shock was here at 6:25 p. m., standard

time, not only by myself but by the entire population of our town. The duration of the shock was about twenty seconds, accompanied by the usual roaring noise. All the inhabitants can make affidavits to the effect, if necessary.
2nd I asked only two operators by wire if they felt the shock, they being Ridgeway and Columbia.
3rd I did not leave my office during the tremor which was very perceptible and quietly remained and noted the time.
4th The passenger train, south had left Winnsboro about twenty minutes after the earthquake occurred, and there was no "coal burning locomotive" within 18 to 20 miles of my office.
5th I have been in the railroad service about ten years and I think this is sufficiently log to enable me to distinguish the roaring sound which accompanies an earthquake from that of a "coal burning locomotive."
6th A special dispatch announcing the earthquake was sent to the Charleston World. Our county paper also announced the occurrence.
7th I am a man of veracity, if I do say it myself, and I am not a "nervous operator."

J.H. Skinner; ticket agent and operator

Upon review of the *News and Herald* (Winnsboro, SC) only a very short mention was found in the August 22, 1888 issue: "An earthquake shock was felt by some people on Wednesday. The shock was not generally noticed." While this obviously is a genuine event it seems would seem the reported intensity might be a high.

Hope that this helps.

don and Pradeep

Don Stevenson
donald.stevenson@srs.gov
(803) 725-3568

From: "Youngs, Bob" <Bob.Youngs@amec.com>
To: "donald.stevenson@srs.gov" <donald.stevenson@srs.gov>,
Cc: "pradeep@sc.edu" <pradeep@sc.edu>
Date: 02/24/2014 03:06 PM
Subject: RE: South Carolina earthquakes

Dear Don and Pradeep:

I very much appreciate your help last week. Moving the identified events back to the Charleston area has resulted in the emergence of six additional earthquakes that may be questioned. These earthquakes are listed in the attached Excel file. I would greatly appreciate it if you have any information on these specific events as their locations are too far from Charleston for the declustering approach to identify them as aftershocks of 1886.

Thank you again for any help you can provide.

Bob Youngs
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510-663-4231
510-381-5567 (cell)
bob.youngs@amec.com

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From: donald.stevenson@srs.gov [mailto:donald.stevenson@srs.gov]
Sent: Wednesday, February 19, 2014 10:54 AM
To: Youngs, Bob
Cc: pradeep@sc.edu
Subject: Re: South Carolina earthquakes

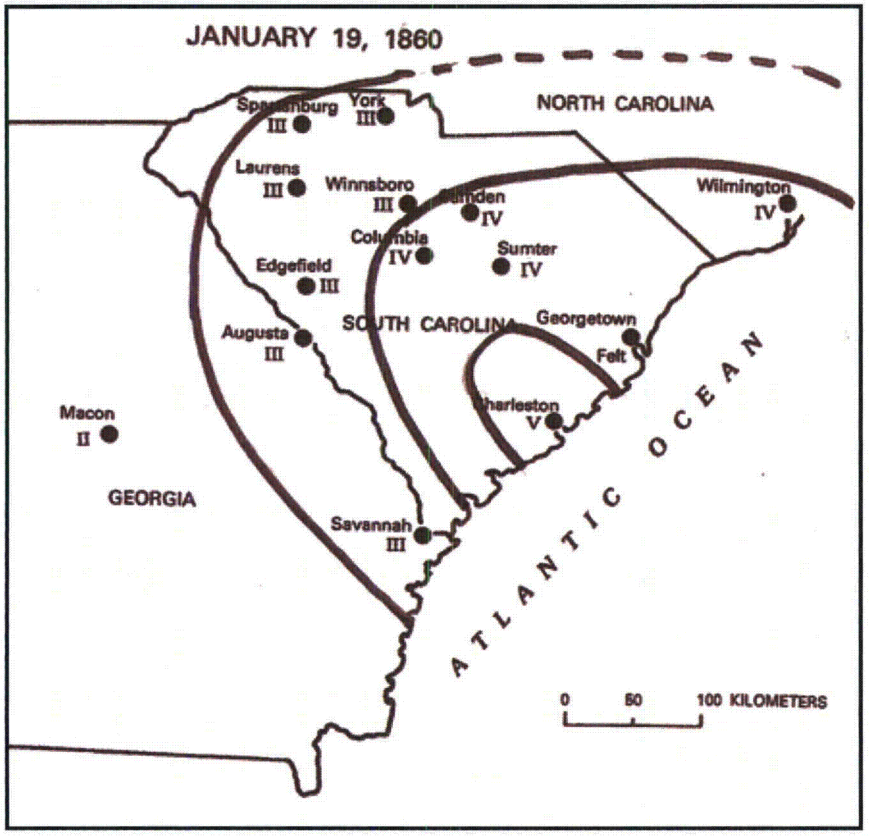
Bob,

We have re-evaluated all of these events by doing an archival search of newspapers in the listed epicentral areas of each event. Our conclusion is that there should be only six earthquakes (one is a repetition), and that all of them occurred in the Charleston/Summerville region. Our revised locations are given in the attached table.

REVISED TABLE BASED ON AN EVALUATION OF CONTEMPORARY ARCHIVAL DATA, PLEASE SEE ATTACHED FILE

Some of our detailed information supporting table changes follow:

1. **TMP01089**: It is in fact a Charleston event, based on the macroseismal data listed by Bollinger and Visvanathan, and a review of newspaper accounts throughout the region. These data clearly point to a Charleston/Summerville source. Below is an Isoseismal map interpreted from Bollinger and Visvanathan (1977).
Bollinger, G.A., Visvanathan, T.R. (1977), The seismicity of South Carolina prior to 1886, *in* Rankin, D.W., ed., Studies related to the Charleston, South Carolina, earthquake of 1886 – preliminary report: U.S. Geological Survey Professional Paper 1028-C, p. 33 – 42.



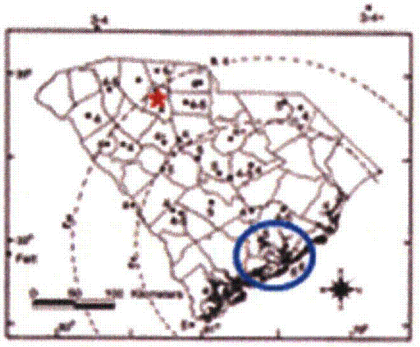
2. **TMP01731 and TMP01732:** These are two listings of the same event. The coordinates listed for TMP01732 are correct and supported by archival data, which do not support the mid-state location listed for TMP01731. TMP01731 has been removed from our corrected list. Based on the archival data this is a Charleston event.

3. **TMP01739**: Another Charleston event. This event actually occurred at 14:45 UTC. The 09:45 time originated from a list by Seeber and Armbruster (1987) where EST were used. Somewhere in its incorporation, the 9.45 time was listed as being UTC. It took place mere hours after the main Charleston event, and is listed as being just over the Georgia South Carolina border in a relatively remote area of Georgia (even today) 46 km northwest of Abbeyville, and 30 km southwest of Anderson over 300 km northwest of Charleston/Summerville area. Examination of the two closest newspapers to the reported location (*Abbeville Press and Banner*, and *the Anderson Intelligencer*) shows only references to the Charleston catastrophe, and no mention of any earthquake activity near Abbeyville or Anderson. The listed location is incorrect, and has been corrected in our revised table.

4. **TMP02019 and 02025**: These are two aftershocks of the Charleston earthquake. They were felt over a wide area. The macroseismal data were evaluated by Talwani and Sharma (1999), who located it in the Summerville area and revised the magnitude estimates.. Isoseimal data for these earthquakes and the revised locations by Talwani and Sharma are shown on the maps below taken from that paper, and compared with the WRONG locations (red stars) listed in the existing catalog.

Talwani, P., N. Sharma (1999), *Seismological Research Letters,* Volume 70, Number 3, 360-367. Red stars are erroneous CEUS SSC locations

October 22, 1886 10:20 UTC



October 22, 1886 19:45 UTC

5. **TMP02360**: This is another mis-located Charleston event. It is incorrectly listed as having occurred at **09:55 EST.** This event appears in regional newspaper reports as occurring at times varying from 09:52 to 10:05 EST. Converting to UTC the time becomes 14:52 or there about, a time coincides with a larger Charleston event. This earthquake actually occurred in the Charleston Summerville area and was widely reported throughout the region. However, there are no newspaper reports that support a location between Sumter and Darlington (34.18 -81.17). Its correct location near Summerville has been incorporated in our list above.

In summary, a careful perusal of contemporary newspaper accounts of the dates and times of earthquakes in your list, whose coordinates suggest that they occurred all over South Carolina, were all located in the Summerville Charleston area. The correct times and locations have been given in our revised list.

Original Table:

TID	yr	mo	dy	hr	mn	sec	lat	lon	dep	EM
TMP01089	1860	1	19	23	0	0	33.68	-80.57	0	4.21
TMP01731	1886	9	1	6	0	0	33.91	-82.02	0	4.54
TMP01732	1886	9	1	6	5	0	32.9	-80	0	3.93
TMP01739	1886	9	1	9	45	0	34.3	-82.86	0	4.17
TMP02019	1886	10	22	5	0	0	34.71	-81.66	0	4.13
TMP02025	1886	10	22	14	45	0	33.87	-81.01	0	4.5
TMP02360	1888	1	12	9	55	0	34.18	-80.17	0	4.33

Thank you

Don Stevenson and Pradeep Talwani

From: "Youngs, Bob" <Bob.Youngs@amec.com>
To: "donald.stevenson@srs.gov" <donald.stevenson@srs.gov>, "pradeep@sc.edu" <pradeep@sc.edu>,
Date: 02/14/2014 07:43 PM
Subject: South Carolina earthquakes

Dear Don:

We are looking into some of the South Carolina earthquakes that remain in the CEUS SSC catalog. When you and Pradeep performed your review of the preliminary catalog, you indicated that you were in the process of preparing a study of the earthquakes. I was wondering if you have results for specific earthquakes you could share with me. The specific earthquakes are listed in the attached Excel file with their CEUS SSC id numbers. Any additional information you could provide would be greatly appreciated.

Thank you.

Bob Youngs
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[attachment "Charleston_area_Eqs.xlsx" deleted by Donald Stevenson/SRNS/Srs]
[attachment "Additional_Charleston_area_Eqs.xlsx" deleted by Donald Stevenson/SRNS/Srs]

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amec
foster
wheeler

ATTACHMENT 2

Reviews by Dr. Martin Chapman and Dr. Richard Quittmeyer

Memo:

March 5, 2014

John Richards
Electric Power Research Institute
1300 West WT Harris Blvd | Charlotte, NC 28262

Subject: Review of NUREG-2115 Earthquake catalog with regard to identification of additional Reservoir Induced Seismicity (RIS) earthquakes in the southeastern United States and locations of earthquakes in South Carolina near the time of the 1886 Charleston, SC earthquake sequence.

Dear John:

We have completed our review of the CEUS SSC catalog published in NUREG-2115 with regard to two issues: (1) identification of additional reservoir induced seismicity (RIS) earthquakes in the southeastern US and (2): locations of earthquakes in South Carolina near the time of the 1886 Charleston, SC earthquake sequence. The results of that review are described below.

Robert Youngs
AMEC Environment & Infrastructure

Additional RIS Earthquakes

In developing the CEUS SSC catalog, earthquakes identified as RIS were removed from the final earthquake listing. The source for this identification in the southeastern US was the set of available Southeast US Seismic Network (SEUSSN) Bulletins. The master list contained 120 earthquakes. Sixteen of these were large enough to be in CEUS SSC catalog. These earthquakes occurred primarily near Monticello Reservoir and Lake Keowee. These earthquakes were removed from the final (Version 7) CEUS SSC catalog published in NUREG-2115.

At the request of EPRI, we have performed additional reviews of available information to identify potential additional RIS earthquakes that are in the CEUS SSC catalog.

References

The following list contains the additional reference material consulted to identify potential RIS earthquakes in the CEUS SSC catalog.

[1] Acree, S.D., Acree, J.R., and P. Talwani, 1988, The Lake Keowee, South Carolina earthquakes of February through July 1986, Seismological Research Letters, 59 (2), 63-70.

[2] Talwani, P.,1981, Earthquake Prediction Studies in South Carolina, in "Earthquake Prediction: An International Review". American Geophysical Union.

[3] Talwani, P., 1990, Appendix D in Krinitzsky, E.L. and J.B. Dunbar (1990): "Geological Seismological Evaluation of Earthquake Hazards at Hartwell and Clemson Upper and Lower Dams, South Carolina". Final Report prepared for US Army Engineer District Savannah, Savannah, Georgia.

[4] Talwani, P., 1997, On the Nature of Reservoir-induced Seismicity, Pure and Applied Geophysics, 150, 473-492.

[5] Talwani, P., Stevenson, D., Amick, D., and J. Chiang, 1979, An Earthquake Swarm at Lake Keowee, South Carolina, Bulletin of the Seismological Society of America, 69 (2), 825-841.

[6] Long, L.T., Kocaoglu, A., Hawman, R., and P.J.W. Gore, The Norris Lake earthquake swarm of June through September, 1993; Preliminary Findings. Seismological Reserarch Letters, 65 (2), 167-171.

[7] Fletcher, J.B., Boatwright, J., and W.B. Joyner, 1983, Depth dependence of source parameters at Monticello, South Carolina, Bulletin of the Seismological Society of America, 73 (6), 1735-1751.

[8] Chen L., and P. Talwani, 2001, Mechanism of Initial Seismicity Following Impoundment of the Monticello Reservoir, South Carolina, Bulletin of the Seismological Society of America, 91 (6), 1582-1594.

[9] Rajendran, K., and P. Talwani, 1992, The role of elastic, undrained, and drained responses in triggering earthquakes at Monticello Reservoir, South Carolina, Bulletin of the Seismological Society of America, 82 (4), 1867-1888.

[10] Shedlock, K.M., 1988, Seismicity in South Carolina, Seismological Research Letters, 59 (4), 165-171.

[11] Tarr, A.C., Talwani, P., Rhea, S., Carver, D., and D. Amick, 1981, Results of recent South Carolina seismological studies, Bulletin of the Seismological Society of America, 71 (6), 1883-1902.

[12] Chen L., and P. Talwani, 2001, Renewed seismicity near Monticello Reservoir, South Carolina, 1996-1999, Bulletin of the Seismological Society of America, 91 (1), 94-101.
[13] Marion, G.E., and L.T. Long, 1980, Microearthquake spectra in the Southeastern United States, Bulletin of the Seismological Society of America, 70 (4), 1037-1054.

1

Review Results

The documents listed above were reviewed to identify specific RIS events. Often the earthquakes are vaguely listed by month and year, without a precise date, or magnitude. Coordinates usually not listed. As an example: [4], [9], [10], [12] do not list a single individual earthquake. Also, most of the RIS is low magnitude (less than 2), which was typically not included in the CEUS-SSC catalog.

The following sets of lists show all the earthquakes that are reported with a date and occasionally magnitude in the references above.

2

The first list contains earthquakes identified as RIS that were too small to be included in the CEUS SSC Version 7 catalog.

3

Earthquakes Identified as RIS that are not in the CEUS-SSC catalog

Eq date	Ref
1978/10/27	[7]
1979/1/19	[1]
1976/1/14	[2]
1977/2/23	[2]
1987/12/24	[3]
1988/1/26	[3]
1993/9/23	[6]

Events 1 through 40 and 42 through 53 of Table 1 in [8].
Events in Table 1 of [13].

The second list contains three earthquakes mentioned in the above literature that we consider to have been correctly classified in the Version 7 CEUS SSC catalog.

4

Earthquakes Correctly Classified

TMP10113, 1979/10/16 M 3.0

Ref. [7] analyzed four well recorded reservoir induced earthquakes near the Monticello reservoir to determine stress drop. The events are taken from Fletcher (1982). This earthquake was identified as RIS in the Version 7 CEUS-SSC catalog.

TMP14740, 1986/2/13 E[M] 3.32. 5
Ref [1] states there is no correlation between reservoir level and the onset of seismicity (this event), while rapid fluctuations in the water levels were observed before the subsequent events in June (see below) and July. This earthquake was included in the Version 7 CEUS-SSC catalog as a non RIS earthquake.

TMP14964, 1986/6/11 Md 2.8
This event was identified as RIS in the Version 7 CEUS-SSC catalog from the SEUSSN Bulletins.

The third list contains additional earthquakes described in the above references that were evaluated as potential RIS earthquakes

Potential Additional RIS earthquakes in CEUS-SSC Version 7 Catalog 6

TMP07012, 1969/12/13, E[M] 3.46
Ref. [5] argues that location of this event is based on "meager macroseismic data" and the earthquake could possibly be a RI event at Lake Keowee. This earthquake is too old to be listed in the SEUSSN Bulletins. Because the event is not clearly identified as RIS in the reference, our recommendation is that it should remain in the catalog as a non RI earthquake.

TMP07159, 1971/7/13, E[M] 3.63
Ref. [5] suggests that the location of the Seneca earthquake by Bollinger (1972) is less accurate than the location by Sowers and Fogle (1978), which is based on detailed macroseismic studies. The Sowers and Fogle (1978) location coincides with observed RIS. This earthquake is too old for the SEUSSN Bulltins. The earthquake appears in a number of catalogs: EPRI, NCEER91, USGS, SEUSSN, South Carolina seismic network, Reagor, Stover and Coffman, and Hopper. Conclusion is that the more precise location suggests that it may be an RI earthquake and the recommendation is to identify as a potential RI earthquake.

TMP07565, 1974/8/2 E[M] 3.91
Ref. [3] says there is excellent correlation between water fluctuations and earthquakes, however admits that "The observation that the seismicity occurred 43 km upstream of the Clarks Hill dam and 22 years after its impoundment led to the questioning of the suggestion that the activity was induced". The earthquake is also mentioned in [11]. This earthquake is too old for the SEUSSN Bulletin. Because Ref [3] questions the categorization of this earthquake as RIS, recommendation is to retain as a non RI earthquake in the catalog.

TMP08078, 1975/11/25 E[M] 3.21
Ref. [11] says that following this earthquake a monitoring program was carried out in the vicinity of Lakes Jocassee and Keowee. This earthquake is too old for the SEUSSN Bulletin and is not in our list of non-tectonic earthquakes. Recommendation is to identify as an RIS earthquake.

TMP08787, 1977/9/7 E[M] 2.77
Ref. [2] says this event was found to be associated with the larger related changes in water levels at a well. This earthquake was not listed in the SEUSSN Bulletin. Recommendation is to identify as an RIS earthquake, although it is smaller that earthquakes used in recurrence calculations.

TMP08971, 1978/1/25 E[M] 2.6
This earthquake is #41 in Table 1 of [8]. SEUSSN Bulletin lists the earthquake as 25 January 1978 Jenkinsville, South Carolina, ML 2.8 (USC), Lat 34.3 N, Long 81.3W at 3:29:38.7 and depth of 2 km. A note in parenthesis reads: "Same event as the 8/29/38.9 shock in the microearthquakes in South Carolina listing?" Recommendation is to identify as an RIS earthquake, although it is smaller that earthquakes used in recurrence calculations.

TMP09000, 1978/1/25 E[M] 2.93
This earthquake is not flagged in the SEUSSN Bulletins, but location and shallow depth suggests in may be RIS. Recommendation is to identify as a possible RI earthquake.

TMP09354, 1978/8/27 E[M] 2.93
Not listed in SEUSSN Bulletin. This earthquake is one of the four events studied in [7]. Location is obtained from Fletcher (1982). Recommendation is to identify as an RI earthquake.

TMP09355, 1978/8/27 E[M] 2.77
7
Not listed in SEUSSN Bulletin. This earthquake occurred immediately after TMP09354 in nearly the same location and was flagged as a dependent even. It has an assigned depth of 7 km, which is much deeper than typical RIS. Recommendation is to identify as a possible RI earthquake, although it is smaller than earthquakes used in recurrence calculations.

TMP09460, 1978/10/27 E[M] 3.08
Not listed in SEUSSN Bulletin. This earthquake is one of the four events studied in [7]. Location is obtained from Fletcher (1982). Recommendation is to identify as a RI earthquake.

TMP10034, 1979/8/26 E[M] 3.64
This is listed in Ref. [2] and was also flagged in the SEUSSN Bulletin. Recommendation is to identify as a RI earthquake.

TMP10104, 1979/10/8 E[M] 3.16
Reexamination of the SEUSSN Bulletin indicates that this event is listed. Recommendation is to identify as a RI earthquake.

TMP10109, 1979/10/14 E[M] 3.08
Reexamination of the SEUSSN Bulletin indicates that this event is listed. Recommendation is to identify as a RI earthquake.

TMP10506, 1980/7/29 E[M] 3.31
8
This earthquake was not flagged in the SEUSSN Bulletin and its location quality was listed as D. However, its location and shallow depth makes it a candidate as an RI earthquake. Recommendation is to consider the event as a possible RI earthquake.

TMP16282 1988/1/27 E[M] 2.32
Ref. [3] says activity is typical of reservoir induced sequences. SEUSSN Bulletin lists this event as "possible earthquake". Recommendation is to identify as an RIS earthquake, although it is smaller that earthquakes used in recurrence calculations.

Based on the review of the references [1] through [5], a review of the SEUSSN Bulletins between 1979 and 1980, and examination of the catalog near other events flagged as RI, the following earthquakes are identified as possible RI.

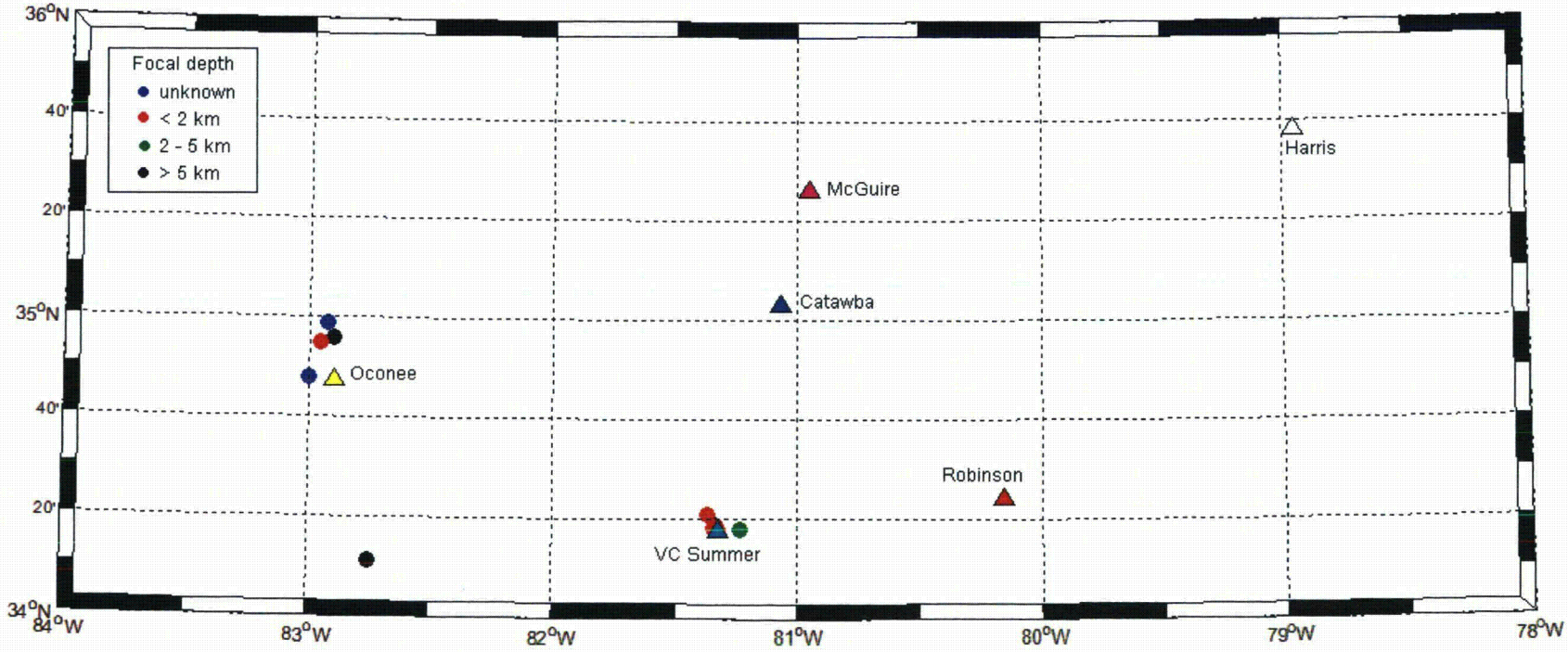
9

TMPID	yr	mo	Dy	hr	mn	sec	lat	lon	depth	E[M]	Comment
TMP07012	1969	12	13	10	19	29.7	35.04	-82.85	6	3.46	Speculative, retain as non RIS
TMP07159	1971	7	13	11	42	26	34.8	-83	n/a	3.63	Possible RIS
TMP07565	1974	8	2	8	52	11.1	33.91	-82.53	4	3.91	Speculative, retain as non RIS
TMP08078	1975	11	25	15	17	34.8	34.93	-82.9	10*	3.21	RIS
TMP08787	1977	9	7	14	41	32.7	34.982	-82.927	n/a	2.77	RIS
TMP08971	1978	1	25	8	29	39	34.301	-81.234	5**	2.6	RIS
TMP09354	1978	8	27	10	23	8	34.313	-81.337	2	2.93	RIS
TMP08998	1978	2	10	20	23	38.7	34.343	-81.348	1	2.77	Possible RIS
TMP08999	1978	2	11	0	19	0.7	34.343	-81.35	3	2.77	Possible RIS
TMP09000	1978	2	11	5	19	0.2	34.346	-81.349	1	2.93	Possible RIS
TMP09006	1978	2	14	12	45	7.2	34.342	-81.346	2	2.77	Possible RIS
TMP09007	1978	2	14	13	9	59.5	34.351	-81.343	2	2.85	Possible RIS
TMP09013	1978	2	15	21	14	34.2	34.349	-81.346	0	2.77	Possible RIS
TMP09014	1978	2	16	2	14	33.4	34.332	-81.362	2	2.85	Possible RIS
TMP09023	1978	2	22	7	13	25.1	34.327	-81.35	1	2.85	Possible RIS
TMP09024	1978	2	22	12	13	24.3	34.339	-81.35	1	3.00	Possible RIS
TMP09025	1978	2	22	13	4	59.2	34.356	-81.352	0	2.77	Possible RIS
TMP09027	1978	2	24	7	34	10.5	34.334	-81.348	1	2.93	Possible RIS
TMP09029	1978	2	25	4	2	42.7	34.345	-81.351	1	2.77	Possible RIS
TMP09031	1978	2	26	6	52	35.4	34.315	-81.297	1	2.85	Possible RIS
TMP09032	1978	2	26	11	52	33	34.391	-81.361	1	3.00	Possible RIS
TMP09033	1978	2	26	18	17	48.8	34.321	-81.348	0	3.08	Possible RIS
TMP09343	1978	8	24	10	23	7.6	34.311	-81.341	2	2.85	Possible RIS
TMP09355	1978	8	27	10	23	8	34.313	-81.337	7	2.77	Possible RIS
TMP09460	1978	10	27	16	27	18.1	34.302	-81.326	2	3.08	RIS
TMP09518	1978	11	24	11	54	40.9	34.296	-81.347	1	2.85	Possible RIS
TMP10034	1979	8	26	1	31	45	34.916	-82.956	1	3.64	RIS
TMP39374	1979	10	8	8	54	19.4	34.31	-81.33	2	2.85	RIS
TMP10104	1979	10	8	23	20	11	34.306	-81.344	1	3.16	RIS
TMP10109	1979	10	14	8	24	57.6	34.306	-81.338	2	3.08	RIS
TMP10506	1980	7	29	1	10	22.7	34.351	-81.364	1	3.31	Possible RIS
TMP16282	1988	1	27	22	5	42.9	34.189	-82.75	6.1	2.32	RIS

* depth 17 km in RANDJ

** depth 1 km in Stover & Coffman

The figure below shows the location of the earthquakes listed above with respect to the NPPs that are located next to a lake or reservoir. The only two NPPs that are affected by these RIS earthquakes are Oconee and VC Summer.



10

Seismicity within 100 km of NPPs in the Southeastern U.S.

An additional step was to examine seismicity in the vicinity of NPPs in the southeast US that are near reservoirs to look for potential clusters of earthquakes not presently identified as RIS. The following is a list of NPPs in the Southeastern U.S.: 11

No.	Nuclear site	Latitude (deg)	Longitude (deg)	State	Nearby Lake/River
1	Hatch	31.9342	-82.3444	GA	Altamaha River
2	Vogtle	33.1419	-81.7647	GA	Savannah River
3	Oconee	34.7917	-82.8986	SC	Lake Keowee
4	Lee Nuclear	35.0369	-81.5118	SC	Broad River
5	Summer	34.2958	-81.3203	SC	Monticello Reservoir
6	Catawba	35.0514	-81.0694	SC	Lake Wylie
7	Robinson	34.4053	-80.1586	SC	Lake Robinson
8	McGuire	35.4322	-80.9483	NC	Lake Norman
9	Harris	35.6333	-78.9561	NC	Shearon-Harris Reservoir
10	Brunswick	33.9583	-78.0106	NC	Coastal (Cape Fear River)
11	Surry	37.1656	-76.6983	VA	James River

The seismicity within 100 km of these NPPs was pulled from the CEUS SSC earthquake catalog (rev 7) and plotted to identify clusters that might be associated with the reservoirs.

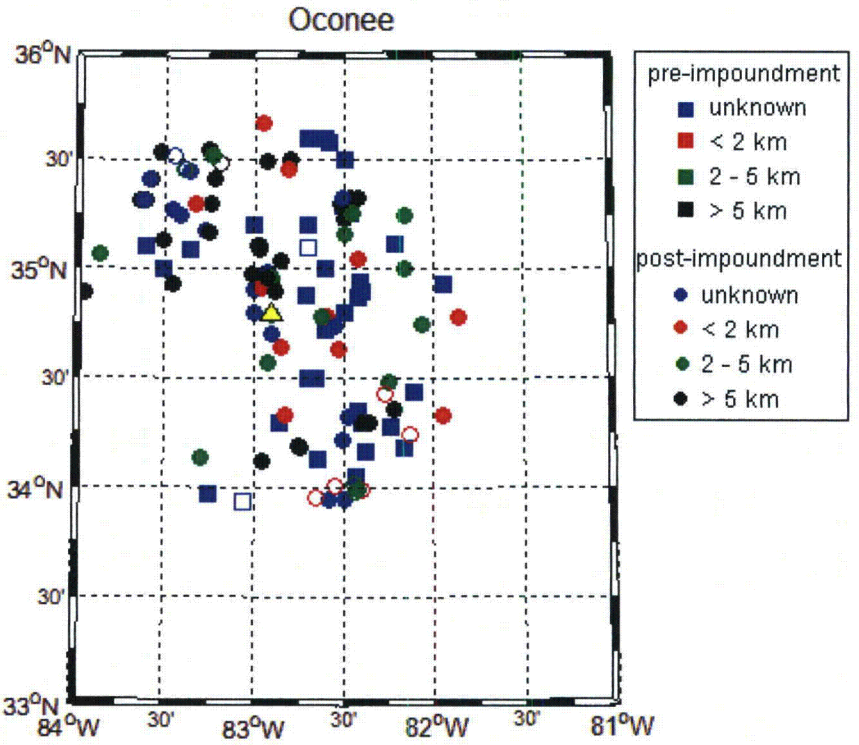
In all figures:

- filled circles are earthquakes occurred after the lake impoundment that are identified as mainshocks;
- filled squares are earthquakes occurred prior to the lake impoundment that are identified as mainshocks;
- open circles and open squares are dependent events (post-and pre-impoundment respectively);
- unknown depths are plotted in blue;
- depths less than 2 km are plotted in red;
- depths between 2 and 5 km are in green;
- depths greater than 5 km are in black;
- the NPP site is shown by a yellow triangle.

NPPs Located on Lakes and Reservoirs

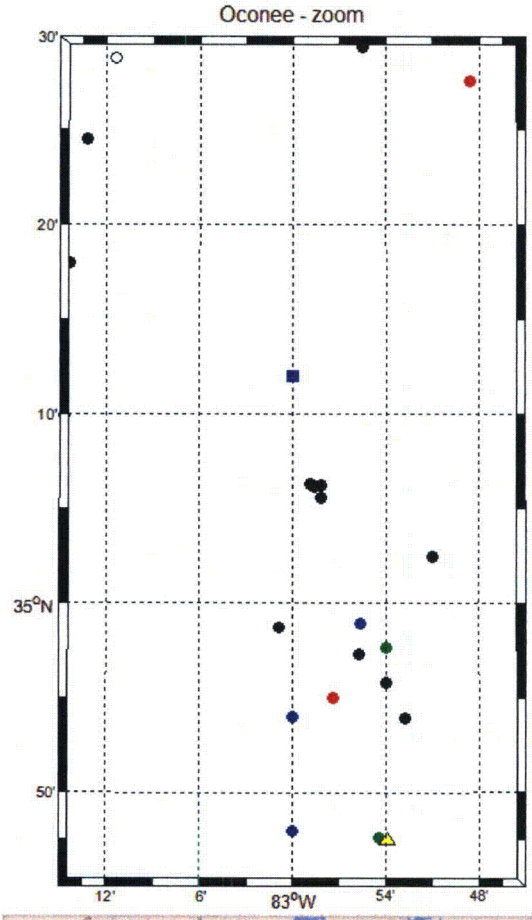
Oconee

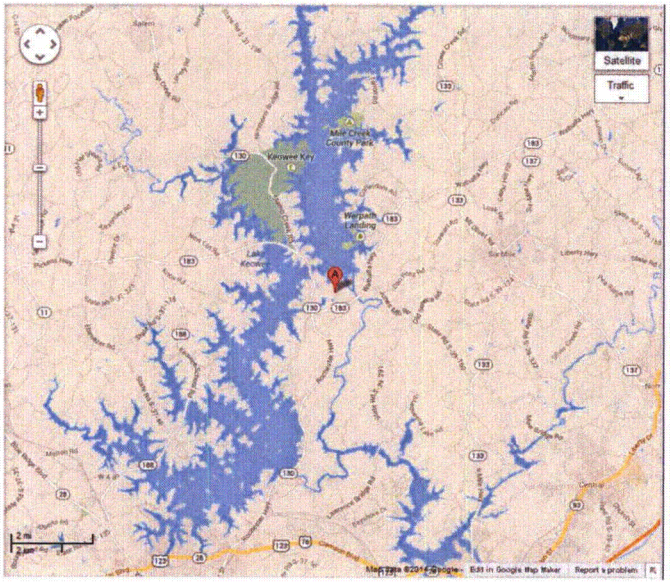
There are 155 earthquakes within 100 km of the Oconee NPP. Most of the seismicity pre-1973 has unknown depth (fixed at 0). In Ref [5] the depth of the swarm is limited to the topmost 2 km.



The next figure shows a zoom of the seismicity cluster near the NPP. These earthquakes are likely RIS events from Lake Keowee: they are typically shallow and occurred after the impoundment of the lake, in areas that have no prior seismicity.

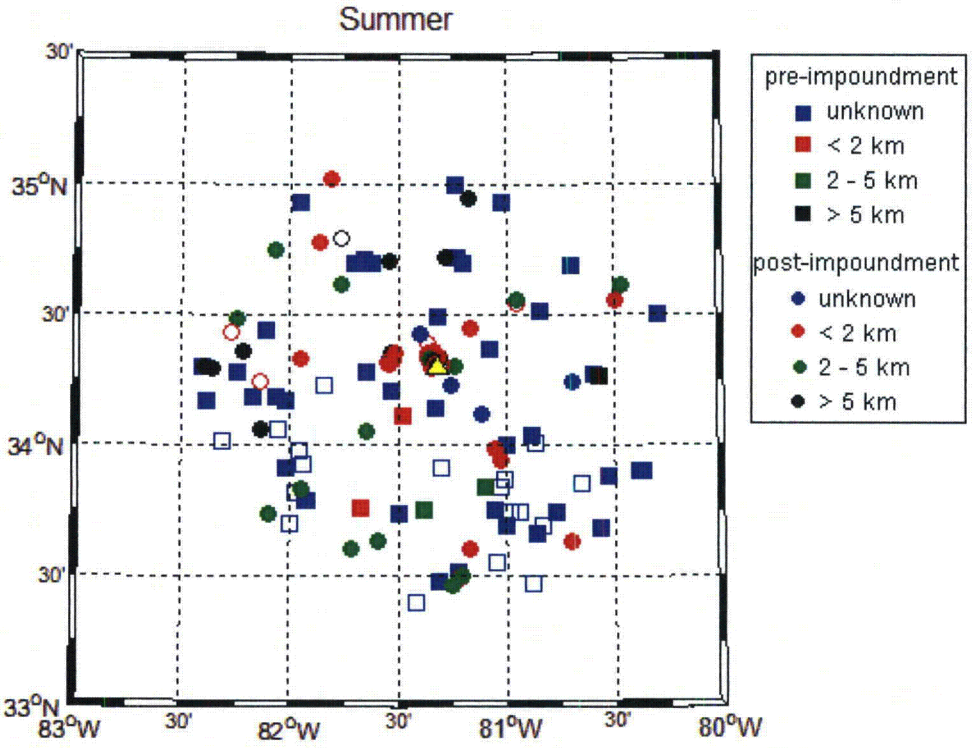
12

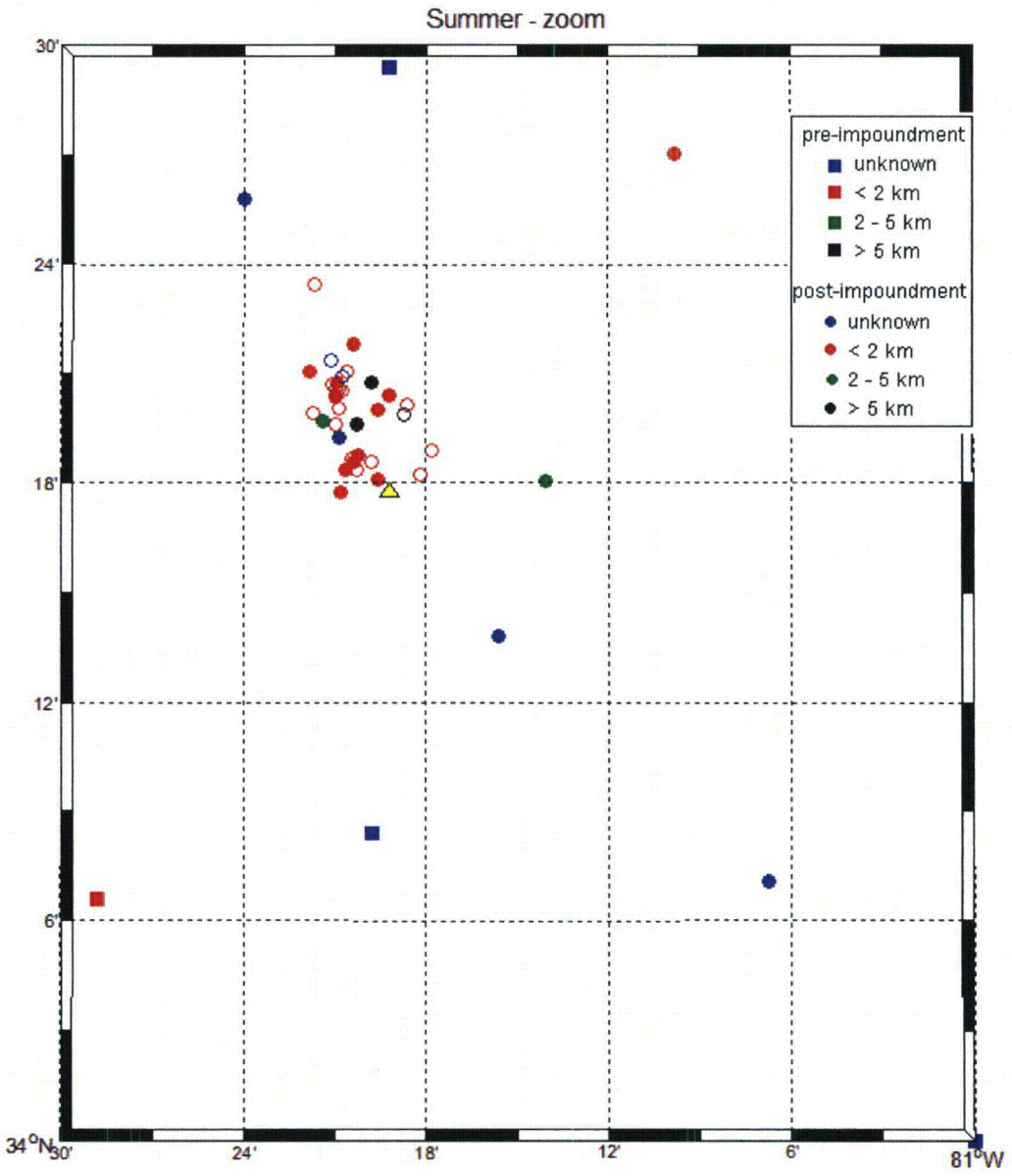

Oconee - zoom
30'
20'
10'
35°N
50'
12'
6'
83°W
54'
48'


Satellite
Traffic
Mile Creek County Park
Keowee Key
Map data ©2014 Google
Edit in Google Map Maker
Report a problem

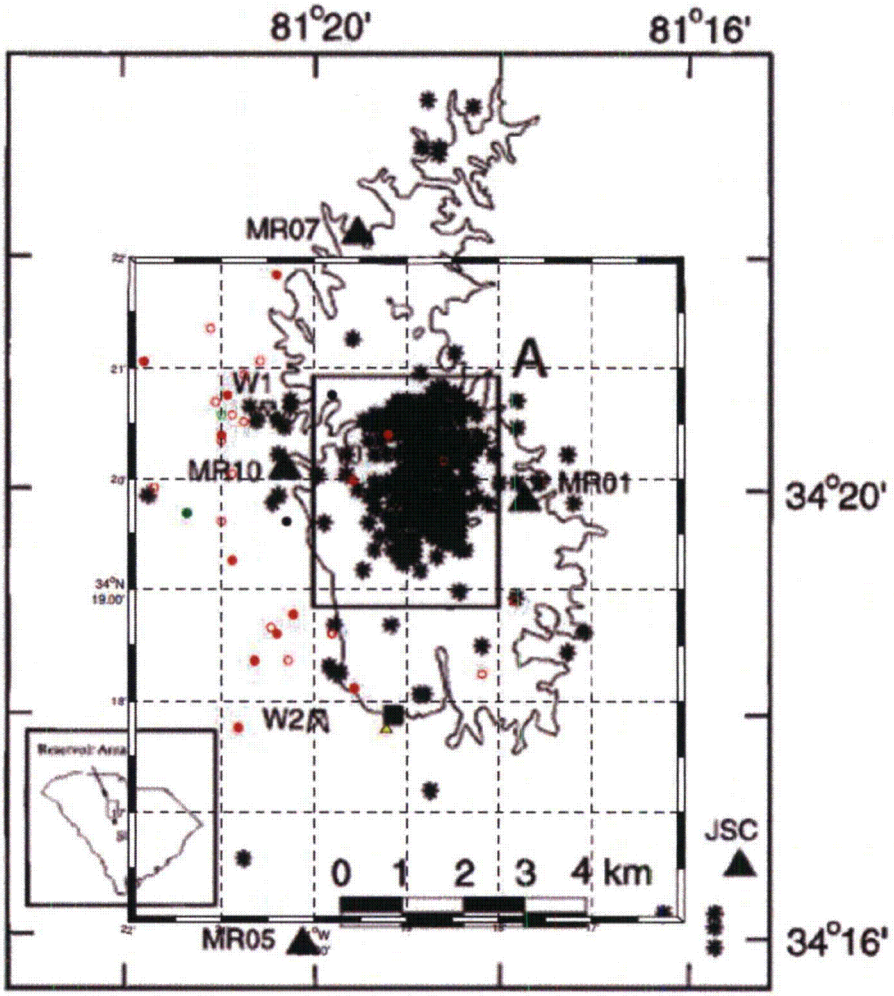
VC Summer

There are 262 earthquakes within 100 km of the VC Summer NPP. The seismicity pre-1968 has unknown depth (fixed at 0). There is a cluster of seismicity very near the NPP, which is associated with the Monticello Reservoir.





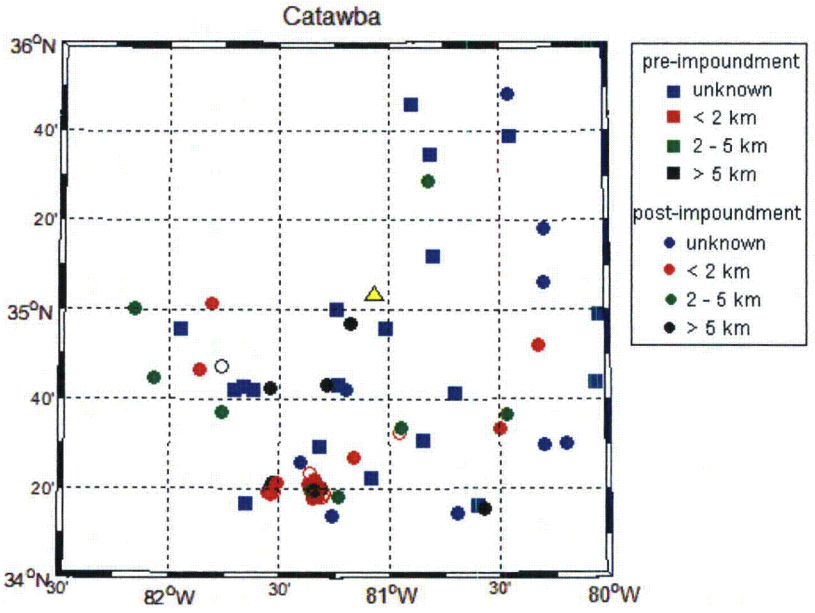
The enlarged figure above shows this cluster in detail: there are two clusters of earthquakes. One cluster is closer to the NPP (earthquakes have mostly depths of 1 km), and one cluster is further to the north where there are events in the 2-5 km depth range. The figure also shows that most of the earthquakes are removed in the declustering process. The next figure compares the seismicity near the VC Summer NPP to figure 2 of [12] that shows the seismicity in from 15 December 1996 to 31 December 1999. 13

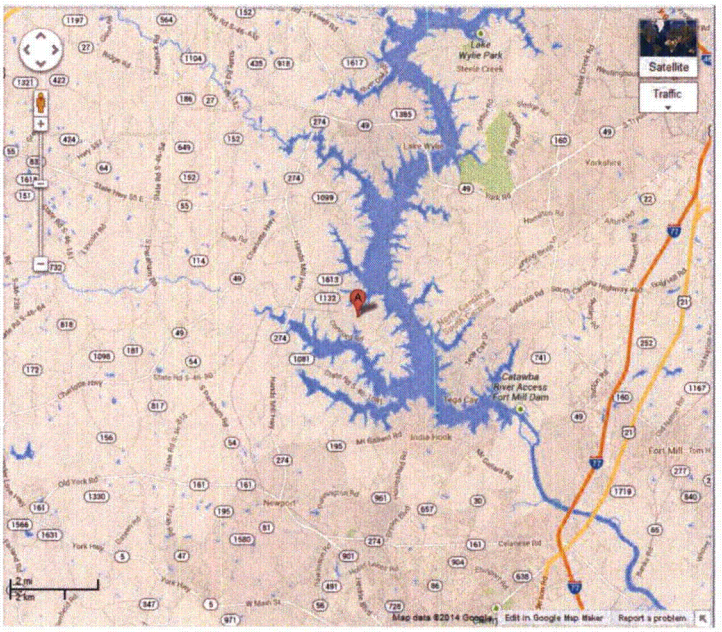


The northernmost cluster is probably in the area of W1; the three earthquakes that are lined up closer to the site have occurred in 1978, 1979 and 1982.

Catawba

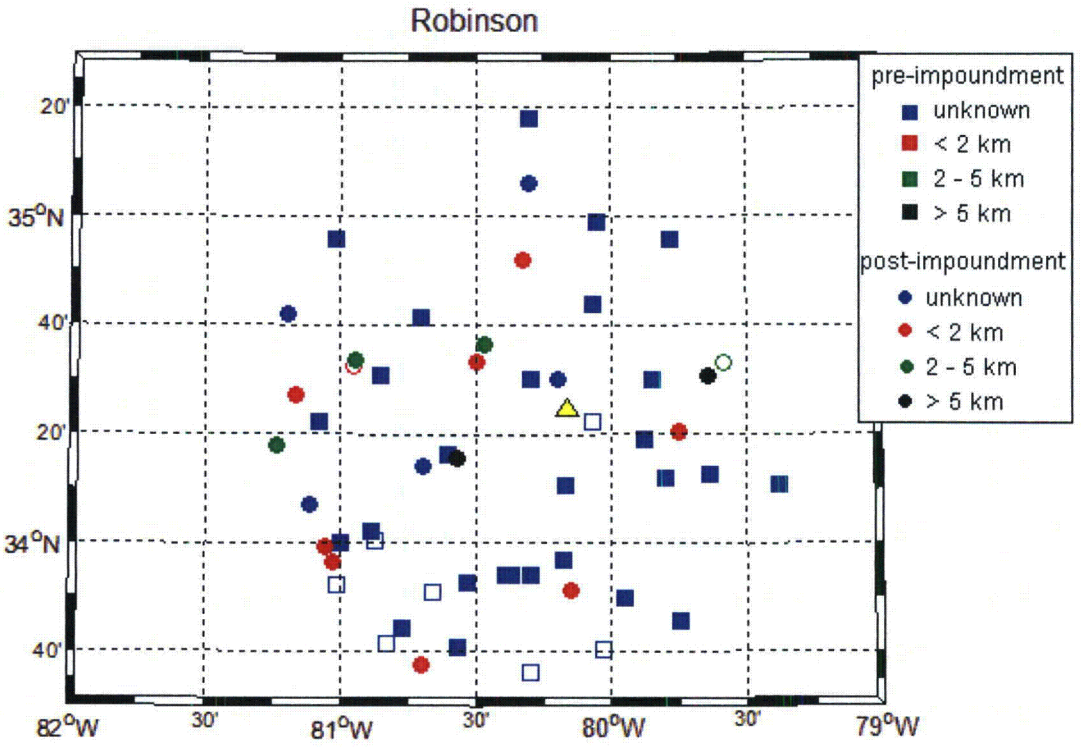
There are 136 earthquakes within 100 km of the Catawba NPP. The seismicity pre-1975 has unknown focal depth. If these earthquakes are removed the nearest earthquake has a depth of 23 km. The NPP is located on Lake Wylie (see figure from google maps): the earthquakes closer to the lake occurred prior to its impoundment. The cluster of earthquakes to the south is about 100 km of distance from the NPP. A search of literature (BSSA and SRL) did not return any specific study of the seismicity of Lake Wylie.





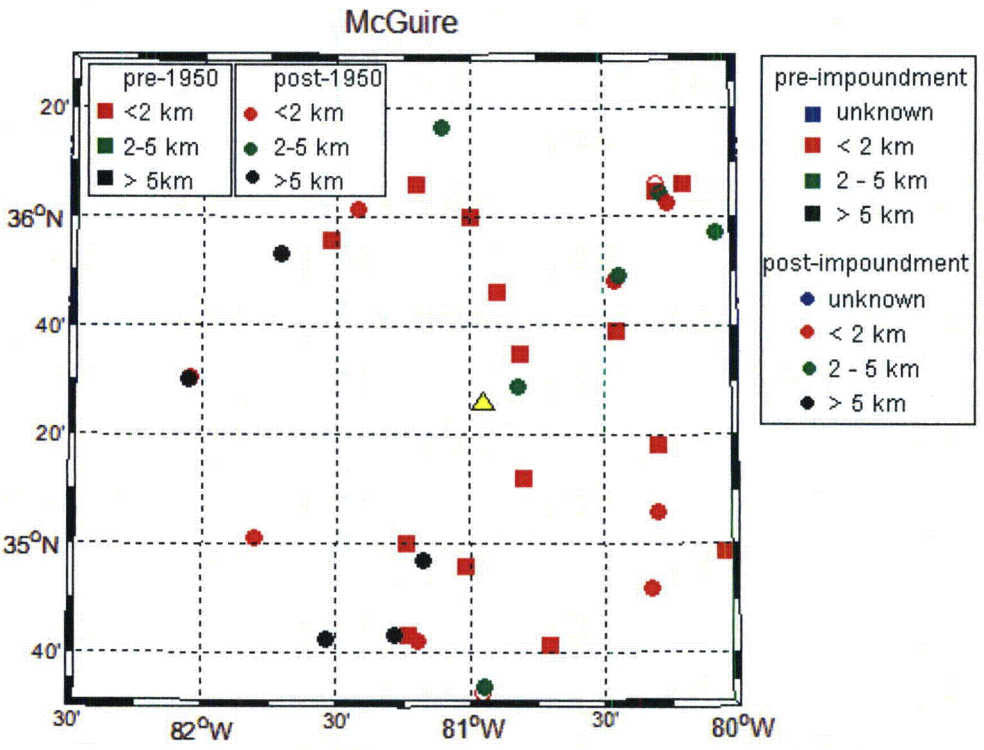
Robinson

There are 134 earthquakes within 100 km of the Robinson NPP, of which 17 (all post 1975) have an estimate of the focal depth. The nearest earthquake to the NPP has unknown depth. The figure does not show clusters of seismicity associated with Lake Robinson. The two events closest to the NPP are the 1959 Chesterfield County earthquake and an earlier event in 1930 located about 5 km to the west of the 1959 event. The two earthquakes are located based on macroseismic intensities and felt area only, and SEUSSN gives to both earthquakes a location error of 83.4 km. We found no information in the literature on the 1959 earthquake that associates the event to the impoundment of Lake Robinson.



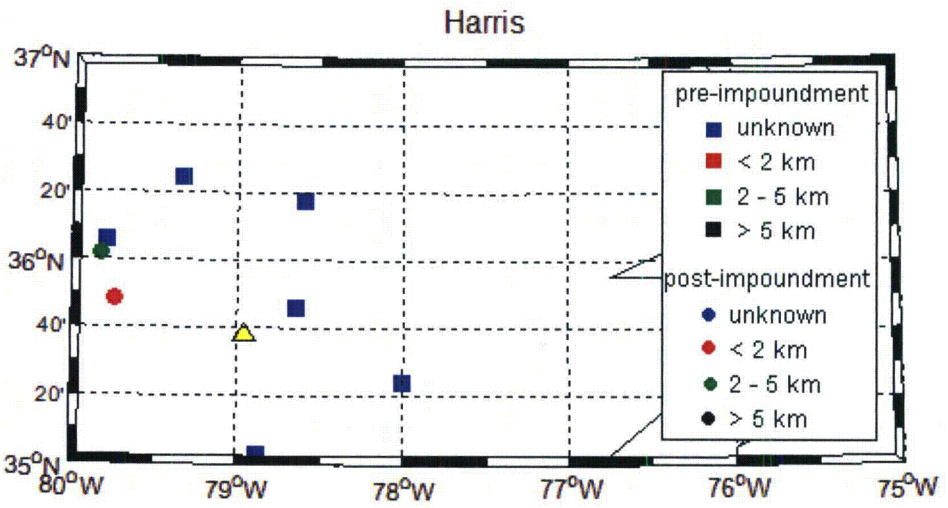
McGuire

There are 46 earthquakes within 100 km of the McGuire NPP, of which 19 have an estimated focal depth (all post-1970). The seismicity doesn't show clusters in the area of Lake Norman.



Harris

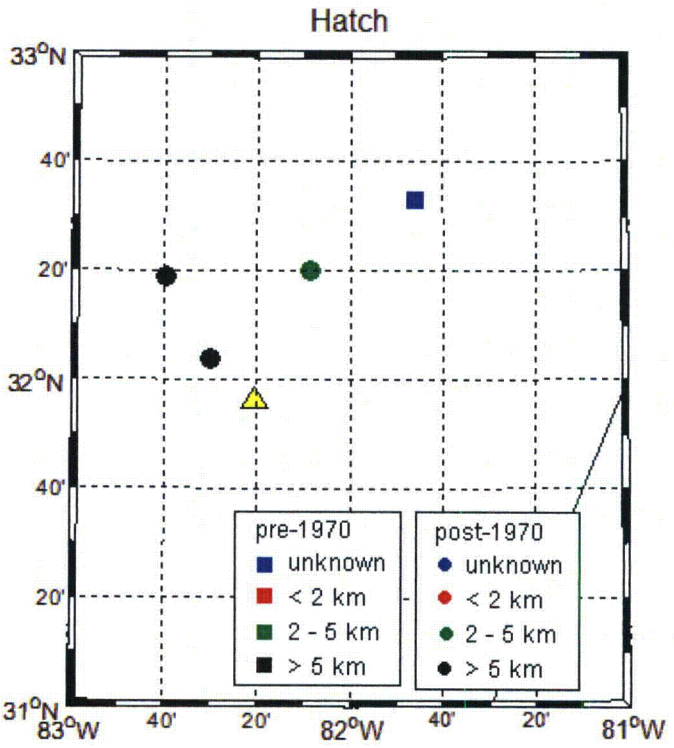
There are 16 earthquakes within 100 km of the Harris NPP of which only 2 have been instrumentally recorded: one in 1981 with a depth of 1km and one in 1993 with a depth of 5 km. Both are far from the Shearon-Harris Reservoir.



NPPs Located on Rivers

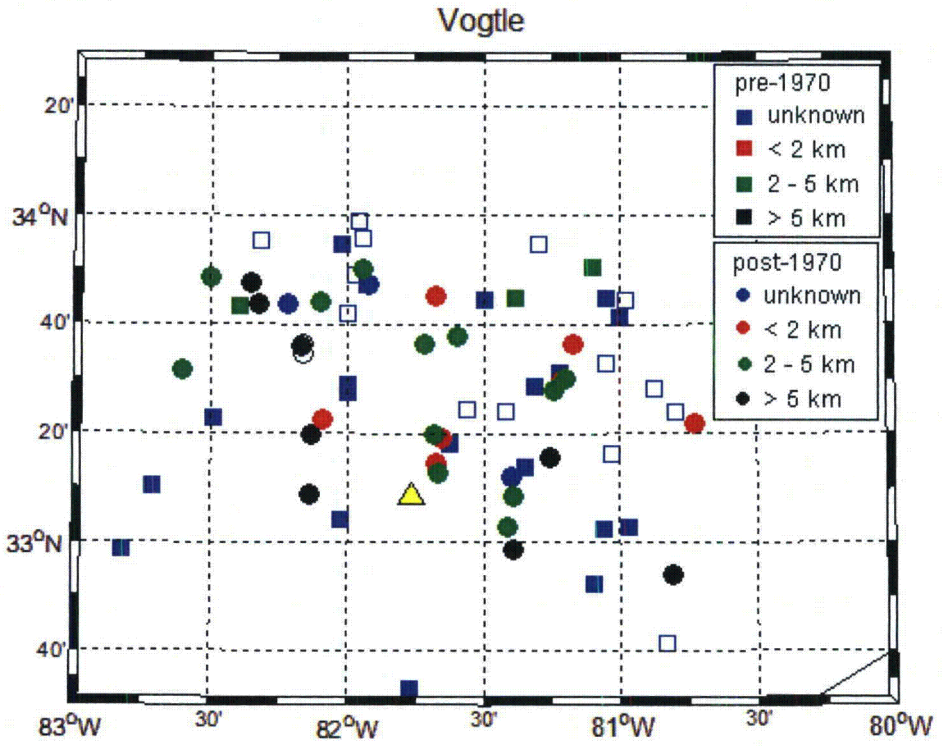
Hatch

There are 5 earthquakes within 100 km of the Hatch NPP (earthquakes are superimposed in the figure).



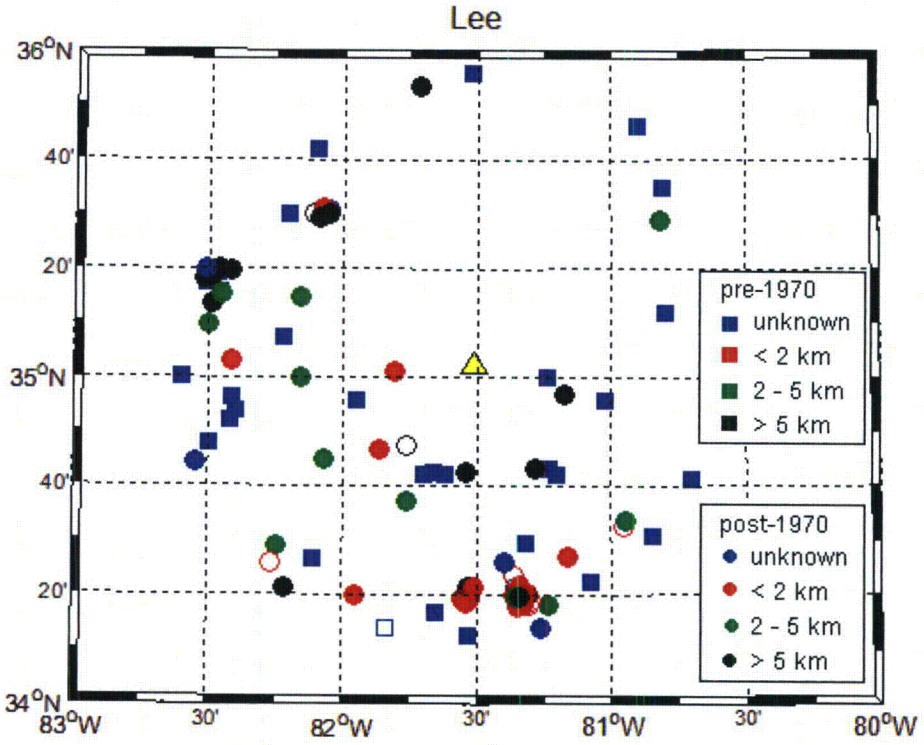
Vogtle

There are 94 earthquakes within 100 km of the Vogtle NPP. Location of pre and post 1950 earthquakes are the same, depths are consistent.



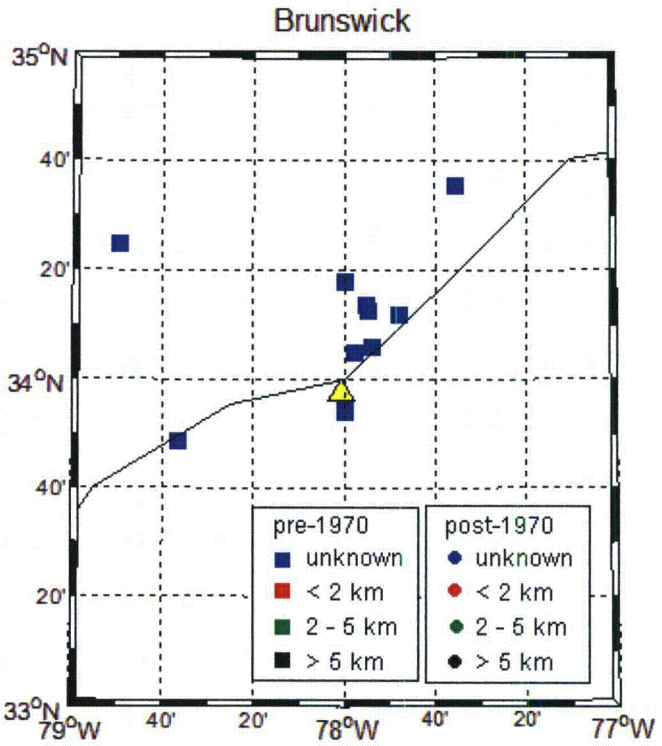
Lee

There are 164 earthquakes within 100 km of the Lee NPP. Most of the seismicity pre-1978 has unknown depth (fixed at 0).



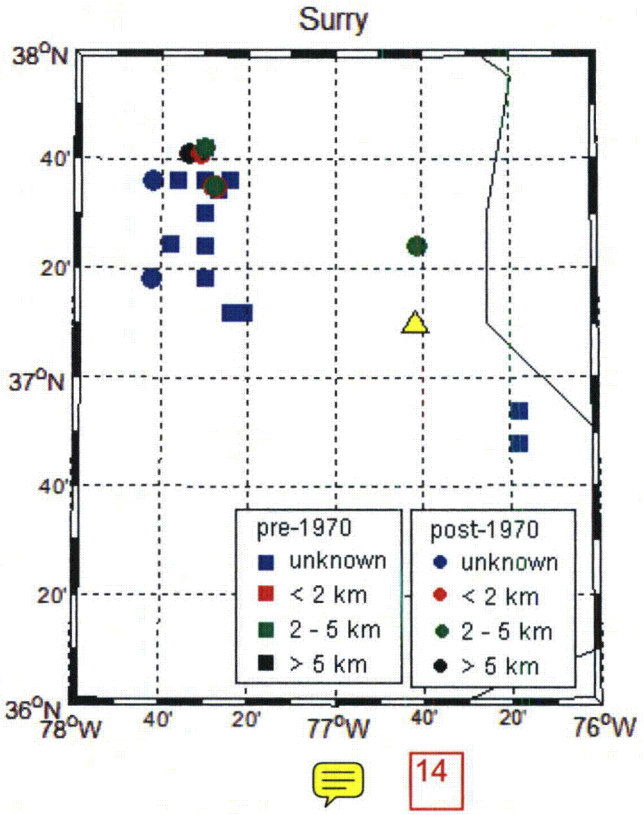
Brunswick

There are 45 earthquakes within 100 km of the Brunswick NPP, none of them has an estimate of the focal depth. The NPP is located near the coast.



Surry

There are 31 earthquakes within 100 km of the Surry NPP of which 8 (post-1978) have an estimate of focal depth. The plant is located on the James River.



Summary of Assessments of Additional RI Earthquakes

Thirty additional RI or potentially RI earthquakes were identified in the Version 7 CEUS SSC catalog. Of these, thirteen are large enough (E[M] ≥ 2.9) to potentially affect recurrence calculations. Some of these were identified as dependent events of other earthquakes in the Version 7 catalog. The thirty earthquakes will be removed from an updated catalog prior to updated completeness and recurrence calculations.

Charleston, SC Earthquakes Near the Time of the 1886 Earthquake Sequence

15

The table below lists 7 earthquakes from the Version 7 CEUS SSC catalog from the time period 1799 to 1868 in South Carolina that were identified as being potentially mislocated to areas away from Charleston.

Questioned Charleston SC Area Earthquakes from Version 7 of CEUS SSC Catalog

TMPID	yr	Mo	Dy	hr	mn	sec	Lat	lon	E[M]	Source of Catalog Location
TMP00331	1799	4	11	8	20	0	33.95	-80.18	4.68	USGSnd_000145 Revised by Jeff Munsey of TVA based on Bakun and Hopper Method
TMP01089	1860	1	19	23	0	0	33.68	-80.57	4.21	USGSnd_000427
TMP01731	1886	9	1	6	0	0	33.91	-82.02	4.54	SeebArm87_000014
TMP01739	1886	9	1	9	45	0	34.3	-82.86	4.17	USGSnd_000771
TMP02019	1886	10	22	5	0	0	34.71	-81.66	4.13	USGSnd_000805
TMP02025	1886	10	22	14	45	0	33.87	-81.01	4.5	USGSnd_000807
TMP02360	1888	1	12	9	55	0	34.18	-80.17	4.33	USGSnd_000860

The majority of these earthquakes have locations and times that come from the USGS's earthquake catalog used for seismic hazard mapping. The primary source of the USGS catalog is the NCEER-91 catalog. The events in question have alternative locations in the SUSN catalog that place them at the location of the 1886 Charleston, SC main shock. We have reviewed the identification of these earthquakes and assignment of these locations in the development of the Version 7 CEUS SSC catalog in light of additional information in the paper by W.H. Bakun and M.G. Hopper (2004, "Magnitudes and Locations of the 1811-1812 New Madrid, Missouri, and the 1886 Charleston, South Carolina, Earthquakes," Bulletin of the Seismological Society of America, **94**, 64-75) and recent information provided by Donald Stevenson and Dr. Predeep Talwani (written communication, February 19, 2014). The individual earthquakes are discussed below.

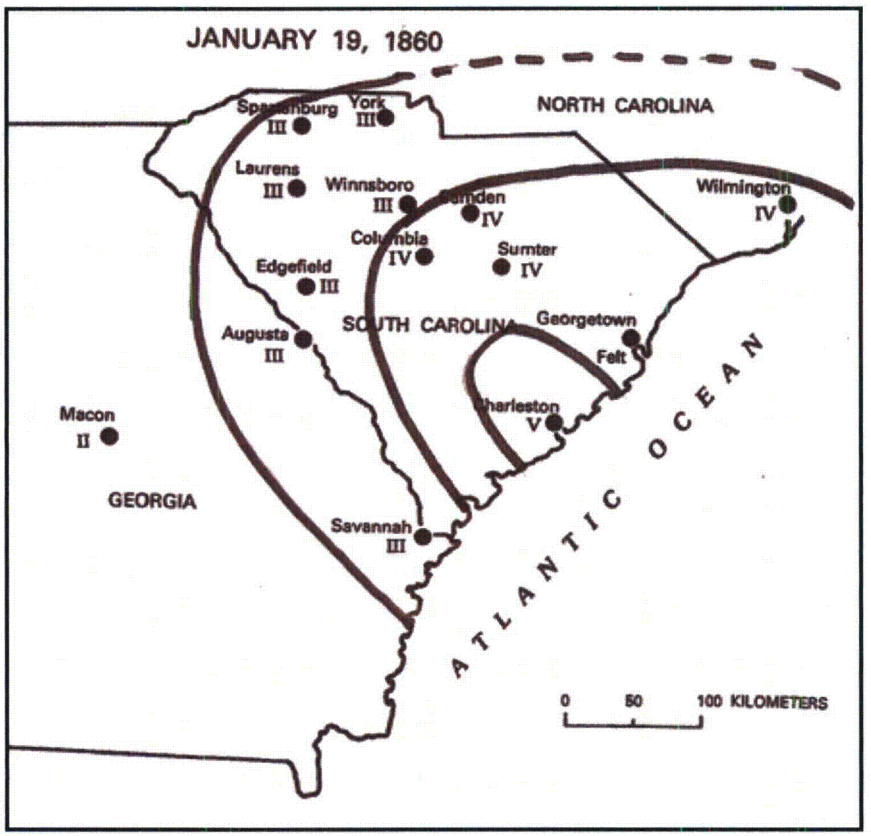
<u>TMP00331, 1799/4/11, E[M] 4.68.</u>

This earthquake was originally located at the 1886 main shock site in the source catalogs. However, additional analysis of the reported intensity data by Jeff Munesy of TVA, which includes intensity VI at Statesburg, SC and intensity V at Wilmington, NC indicates a location north of Charleston. The location in the Version 7 catalog was obtained by Jeff Munsey using the Bakun and Hopper method. There does not appear to be a compelling reason to move this earthquake to Charleston and the recommendation is to use the location obtained by Jeff Munsey.

16

TMP01089, 1860/1/19, E[M] 4.21.

The location in the Version 7 catalog is based on NCEER-91. Donald Stevenson and Dr. Predeep Talwani provided the Isoseismal map shown below based on their interpretation of the available intensity data. These data clearly suggest a location near Charleson. The recommendation is to utilize the Charleston location given in the SUSN catalog.



Isoseismal map for January 19, 1860 earthquake provided by Donald Stevenson and Predeep Talwani (written communication, February 19, 2014).

TMP01731, 1886/9/1, E[M] 4.54.

As indicated by Donald Stevenson and Predeep Talwani (written communication, February 19, 2014), TMP01731 appears to be a duplicate of TMP01732, which has a Charleston location based on their evaluation of archival data. The recommendation is to remove this earthquake from the catalog as a separate earthquake.

TMP01739, 1886/9/1, E[M] 4.17.

Donald Stevenson and Predeep Talwani (written communication, February 19, 2014) recommends that the location given in the SUSN catalog be used and the time changed to 14:45 UTC. The recommendation is based on examination of the two closest newspapers to the reported location (*Abbeville Press and Banner*, and *the Anderson Intelligencer*) that shows only references to the Charleston catastrophe, and no mention of any earthquake activity near Abbeyville or Anderson. Given this information, the record appears to be a duplicate of TMP01738, The recommendation is to remove the earthquake from the catalog as a separate earthquake.

TMP02019, 1886/10/22, E[M] 4.13.
Review of the data indicates that TMP02019 is likely a duplicate of TMP02024 and that the time for event TMP02024 should be changed to 10:25 UTC. Bakun and Hopper (2004) studied this event using the intensity data from Talwani and Sharma (1999) and obtained an offshore Charleston location. Recommendation is to remove TMP02019 from the catalog and use the Charleston location in SUSN and the estimated moment magnitude given in Bakun and Hopper (2004) for TMP02024.

TMP02025, 1886/10/22, E[M] 4.13.
Bakun and Hopper (2004) studied this event using the intensity data from Talwani and Sharma (1999) and obtained an offshore Charleston location. Recommendation is to use the Charleston location in SUSN and the estimated moment magnitude given in Bakun and Hopper (2004) for TMP02025.

TMP02360, 1888/1/12, E[M] 4.33.
The location for this event was taken from the USGS. Donald Stevenson and Predeep Talwani (written communication, February 19, 2014) indicate that there are no newspaper reports that support a location between Sumter and Darlington (34.18 -81.17) and that the correct time should be 14:55 UTC. The event may be a duplicate with TMP39326, with a reported time of 15:54 in SUSN and a Charleston location. Recommendation is to remove TMP02360 from the catalog.

Our review turned up another potential duplicate. Bakun and Hopper (2004) also studied the Charleston aftershock on 1886/11/5 17:20 and found a location near Charleston, but slightly inland from other locations. Talwani and Sharma (1999) also concluded that this earthquake occurred at a slightly different location than other Charleston aftershocks. This earthquake appears in the Version 7 catalog as TMP02071. There is also an event TMP02072 that is listed in the USGS catalog with time 12:25 with a location to the northwest of Charleston. Both events were flagged as Charleston aftershocks in the declustering, but the timing suggests that they may be duplicates. The recommendation is to remove TMP02072 and use the magnitude and location given in Bakun and Hopper for TMP02071.

Development of a Version 8 Catalog

The above assessments were used to create a Version 8 CEUS SSC catalog specifically for calculating earthquake recurrence rates in the southeastern US.

Revised Assignments of Parameters for 1886 Charleston Era Earthquakes

The assessments of the six Charleston 1886 era earthquakes described above further call into question the earthquake locations provided by Seeber and Armbruster (1987). These locations and size assessments were incorporated into the NCEER-91 catalog and then into the USGS catalog that was used as the primary source for the CEUS SSC Version 7 catalog. The original Seeber and Armbruster (1987) listing was also incorporated into the CEUS SSC Version 7 catalog, along with their listed values of felt area.

18

Seeber and Armbruster (1987) categorized the 1886 Charleston era earthquakes into 5 categories. Reexamination of Seeber and Armbruster (1987) indicated that the earthquakes in their Category 1 and Category 2 had nominal felt areas assigned to them (100 km² As these were not actual felt areas assessed from the distribution of felt reports, it was judged that they should not be used to assess magnitude using the models developed in NUREG-2115 based on actual felt areas, and the values of ln(FA) were removed from the Version 8 catalog for the purpose of magnitude assessment.

19

The Seeber and Armbruster (1987) Category 3 earthquakes are defined as

> "...(3) events apparently reported from more than one town, but which are unreliable because large populated areas between these towns did not report feeling the event ..."

The interpreted mislocated events TMP01731 and TMP01739 are listed as Category 3 in Seeber and Armbruster (1987).

Seeber and Armbruster (1987) assigned felt areas as follows:

> "The felt areas assigned to events felt at less than 5 towns was the area of the circle with diameter equal to the distance between the most distant felt reports. The felt area assigned to events felt at 5 or more towns is the area of the ellipse with a major axis equal to the distance between the most distant felt reports and a minor axis twice the distance from the major axis to the furthest felt report."

The description of Category 3 events as "unreliable" and having large areas without felt reports between towns with felt reports indicates that the assigned felt areas for these events may also be unreliable. In many cases, the maximum intensity for Category 3 events is II or III. Figures A1, A2, A2, and A3 compare the I0 and ln(FA) values for Category 3, 4, and 5 earthquakes, respectively from Seeber and Armbruster (1987) with the data from other earthquakes in the Version 3 CEUS SSC catalog. The values of ln(FA) for Category 3 appear to be biased high for the assigned I0 compared to the general population. Given the evident bias and the unreliability of the events, the Seeber and Armbruster Category 3 events that are duplicated by SUSN

events are removed from the Version 8 catalog and for those Category 3 events that are not duplicated, the values of ln(FA) are removed from the Version 8 listing for use in magnitude assessment. 20

The comparisons for the Category 4 earthquakes on Figure A2 show general consistency in the I0-ln(FA) data with the rest of the catalog. Many of the Category 4 earthquakes have locations near Charleston. These events are left in the catalog.

The remaining question is the large number (about 25) of the Category 5 earthquakes. A number of these have SUSN entries with the same time, but often significantly different locations. Category 5 is considered by Seeber and Armbruster as the best located. Five of the interpreted mislocated earthquakes in the above list are Category 5 earthquakes, indicating that there are issues with some of these locations. In addition, the data shown of Figure A3 indicate that the assigned ln(FA) may be biased high for this category. These events were examined again in comparison to other events in the catalog from SUSN. The NCEER-91 location for 21

Where the Seeber and Armbruster error ellipses include the SUSN locations, the SUSN locations were used as the primary location. Clearly not all of these earthquakes occurred exactly in the same place, In many cases, the NCEER locations differ from the Seeber and Armbruster locations and sometimes appear to be an average of the two. The bias in the I0-ln(FA) data for these events and location bias for the 6 large events initially identified further suggests that the SUSN locations be used in place of the Seeber and Armbruster / NCEER locations. For those events that could not be associated with SUSN and have very large error ellipses and I0-ln(FA) assessments that appear biased, the ln(FA) data were removed from the catalog for magnitude assessment.

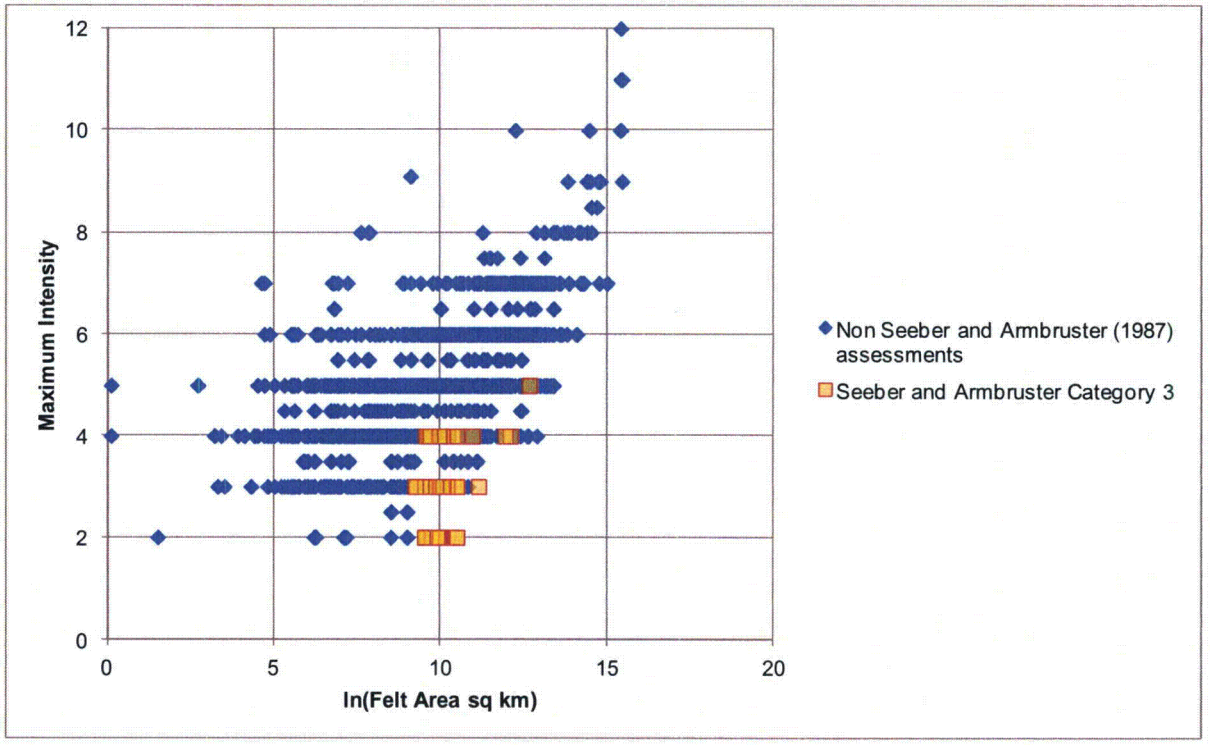


Figure A1 comparison of ln(FA)-I0 data for Category 3 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Version 7 catalog.

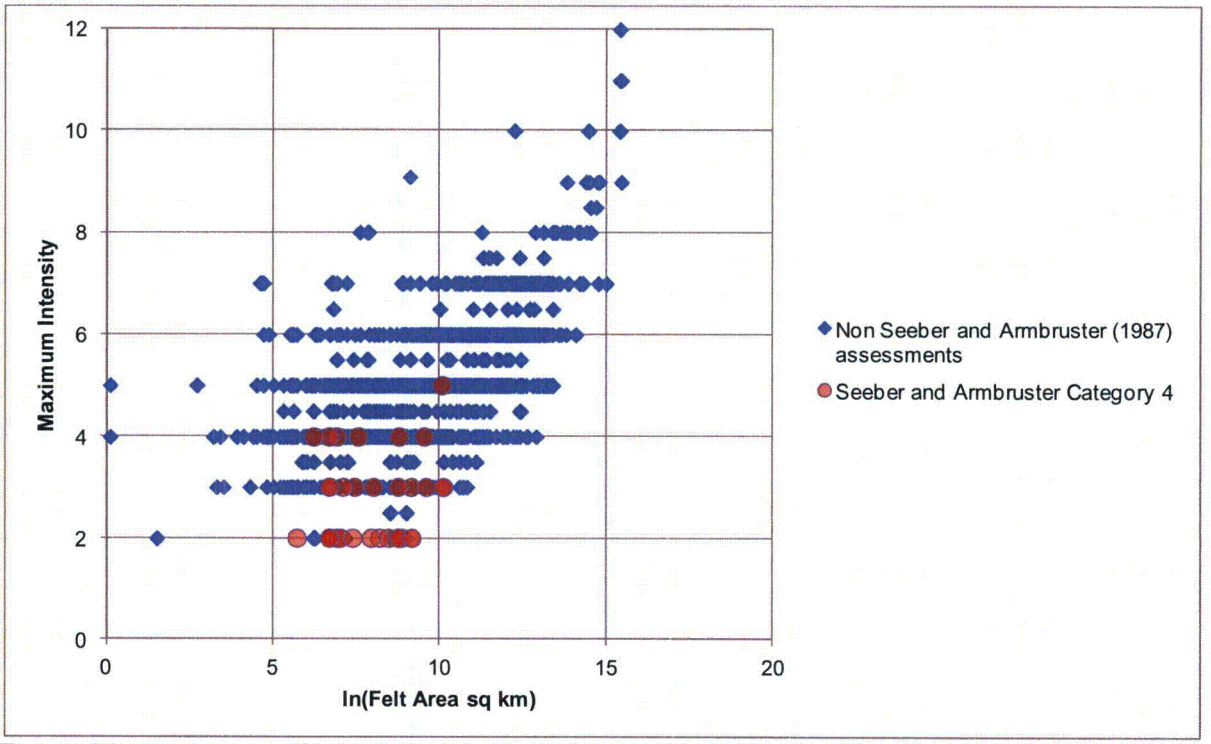


Figure A2 comparison of ln(FA)-I0 data for Category 4 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Version 7 catalog.

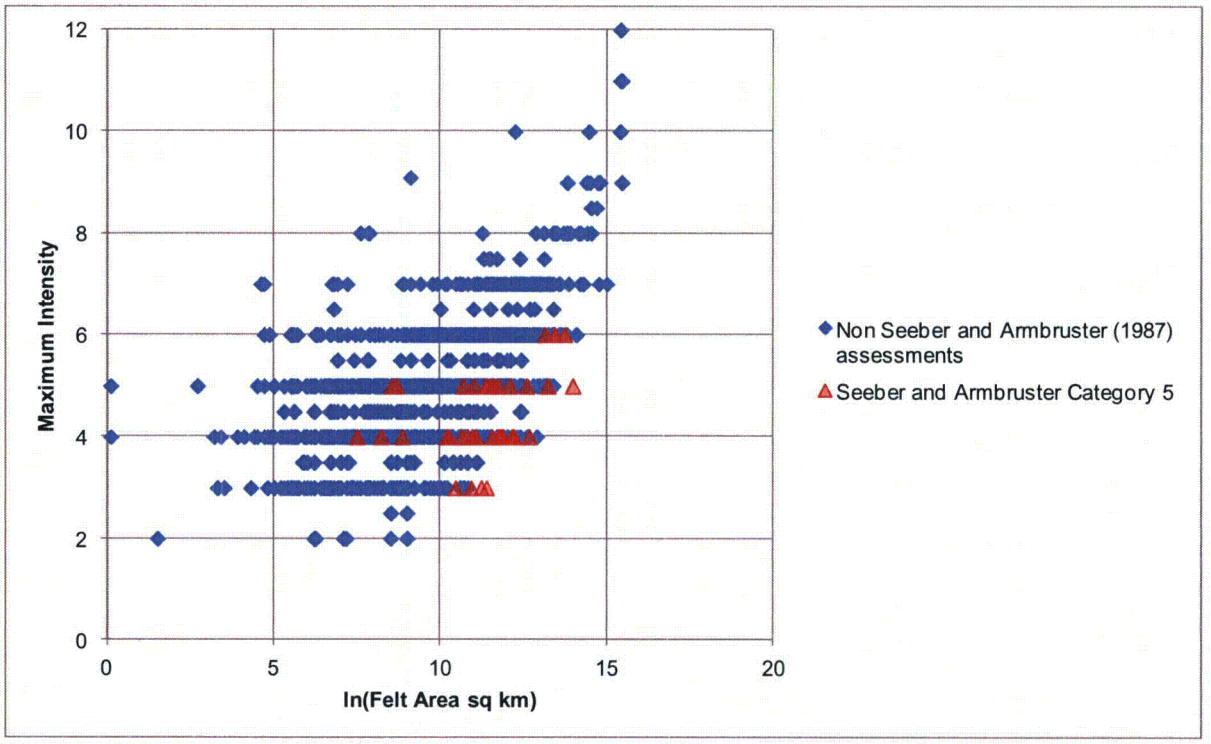


Figure A3 comparison of ln(FA)-I0 data for Category 5 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Version 7 catalog.

After making the adjustments described above, catalog declustering was performed. As a result, the classification of nine additional earthquakes at locations distance from Charleston significant to hazard (E[M]≥2.9) were changed from dependent to independent. Previously, these earthquakes had been classified as dependent earthquakes in clusters associated with the earthquakes identified above. The information for each of these earthquakes was reviewed, including additional information provided by Stevenson and Talwani (written communication, Feb 26, 2014). These events are discussed below.

22

TMP01942, 1886/9/28, E[M] 3.10.

This is a Category 4 earthquake in Seeber and Armbruster (1987) and is listed in NCEER-91. Its I0 (3) and ln[FA] (8.0) are consistent with the general population of CEUS SSC earthquakes (see Figure A2). However, Stevenson and Talwani (written communication, 2014) state:

> "This is one of the events listed by Seeber and Armbruster that we term to be phantom events. We can find no support or validation for the event or the location. The Union newspaper was not available for this date. However, a check of other papers in the region (The nearest at Greenville, SC approx. 40 miles away) showed no mention of an earthquake in Union, South Carolina on September 28. The Greenville paper contained articles related to the Charleston event but no mention of anything in the upstate. We do not believe this to be a genuine event."

Recommendation, consider this to be a false event.

TMP02002, 1886/10/12, E[M] 3.04.
Although this event was listed as a category 4 earthquake in Seeber and Armbruster (1987), it was not carried forward into NCEER-91. Also the ln(FA) of 8.46 is anomalous compared to the I0 of II (Figure A2). The recommendation is to not use the felt area reported by Seeber and Armbruster (1987), which will result in the event not being considered in estimation of earthquake recurrence.

TMP02068, 1886/11/04, E[M] 3.18.
Although this event was listed as a category 4 earthquake in Seeber and Armbruster (1987), it was not carried forward into NCEER-91. Also the ln(FA) of 8.92 is anomalous compared to the I0 of II (Figure A2). The recommendation is to not use the felt area reported by Seeber and Armbruster (1987), which will result in the event not being considered in estimation of earthquake recurrence.

TMP02134, 1886/12/08, E[M] 3.11.
This event was listed as a category 2 earthquake in Seeber and Armbruster (1987) and was not carried forward into NCEER-91. Jeff Munsey also identified the event from archival data with a similar I0 of IV/V to the I0 of IV reported in Seeber and Armbruster (1987). Stevenson and Talwani (written communication, Feb 26, 2014) indicate:

> "...close review of the *Columbia Daily Record* for the time period of 12/08/1886 to 12/13/1886 showed no reports of felt earthquakes in Columbia. We do not believe this to be genuine."

Based on this assessment, and the fact that the earthquake only potentially affects recurrence calculations because of the I0 assignment of 4.5 Munsey (2006) suggests that this earthquake be considered as either a false event or too small to include in recurrence calculations.

TMP02136, 1886/12/11, E[M] 3.25.
This is a Category 5 earthquake in Seeber and Armbruster (1987) and is listed in NCEER-91. Its I0 (4) and ln[FA] (8.22) are consistent with the general population of CEUS SSC earthquakes (see Figure A3). Stevenson and Talwani (written communication, Feb 26, 2014) indicate:

> "The listed location for this event plots just east of Abbeville, SC. This, may be a real event . In the December 13, 1886 edition of the *Abbeville Press and Banner* a short piece addressing a loud noise heard on the Saturday before (12/11) appeared.
> ""**The Noise on Saturday**: Many persons in the vicinity of Abbeville heard the noise, sound, explosion or whatever it may have been last Saturday afternoon. Mr. A.E. Lewis says it was in the air from him at an angle of 45 degrees a little south of west. Mr. T. L. Haddon says it sounded as if it was over and beyond his gin house."
> From this description it is unclear if this was an earthquake or not. Nothing is mentioned about people feeling the ground move, only about a loud sound. No mention of this event could be found in the *Columbia Daily Register, Edgefield Chronicle,* or *Laurens Advertiser*. We feel it doubtful that this is a real earthquake as all mentions above are to noises If this event were to be given the benefit of doubt and accepted as a genuine earthquake, the above, Abbeville, account would lend itself to an

assigned intensity considerably less than IV and should probably not be considered. "

The above description indicates that the event may be real. Classification as Category 5 earthquakes in Seeber and Armbruster (1987) indicates that the earthquake was reported in multiple towns. As there is some evidence for the earthquake, there is no clear reason to discount it, and the recommendation is to retain it in the catalog.

TMP02173, 1887/01/12, E[M] 2.91.

This is a Category 4 earthquake in Seeber and Armbruster (1987) and is listed in NCEER-91. Its I0 (3) and ln[FA] (7.09) are consistent with the general population of CEUS SSC earthquakes (see Figure A2). Stevenson and Talwani (written communication, Feb 26, 2014) indicate:

> "This event plots just outside Due West, SC. between Greenwood and Anderson. Checking issues of the *Anderson Intelligencer* and *Abbeville Press and Banner* through the remainder of January 1887 showed a report of a small earthquake near Due West, SC. However, it is reported to have occurred on 01/05/1887. This little event seems to have escaped all catalogers. There is nothing reported for 01/12/1887. From the *Abbeville Press an Banner*: CHICKASAW'S CHIT CHAT; from Due West, SC Jan. 10 1887: "A very perceptible shock of earthquake was felt here last Tuesday morning. Some persons have thought that shocks have been occurring quite frequently for several weeks, but not until last week have they had the bravery to speak positively as to their occurrence."

The above description indicates that this was likely a small earthquake. However, the assessment of felt area by Seeber and Armbruster (1987) is only approximate, and places this earthquake at the edge of being included in recurrence calculations (E[M] ≥ 2.9). The recommendation is to include this earthquake in the catalog, but consider its size to be likely smaller than E[M] 2.9.

TMP02393, 1888/04/05, E[M] 4.3. 23

This event was identified by Munsey (2006). Its size was assessed on the basis of an assigned intensity of VI/VII, which were described by Munsey (2006) as being very localized effects. The fact that the event was not reported in Seeber and Armbruster (1987) indicates that the high local effects were not widespread. Stevenson and Talwani indicate:

> To our knowlege this event appears in no other catalog except the CEUS-SSC catalog. The location of the event plots just 5 miles south east from the center of Newberry, SC. In checking copies of the *Newberry Herold and News* for the month of April 1888 we could find no mention of an earthquake anywhere near Newberry. There was only a mention of an earthquake that apparently occurred in China. A check of the *Abbevillle Press and Banner, the Edgefield Advertiser,* and *the News and Herald* (Winnsboro,SC) for the month of April, 1888 showed no mention of any earthquakes other than the one in China also appearing in the Newberry paper."

Given that the effects identified by Munsey (2006) are very localized and other investigators did not identify effects on this date in surrounding areas indicates that if this was an earthquake, it

was likely small. Therefore, the recommendation is to consider this potential event to be too small to affect recurrence calculations.

TMP02423, 1888/08/15, E[M] 3.12.

This is a Category 4 earthquake in Seeber and Armbruster (1987) and is listed in NCEER-91. Its I0 (4) and ln[FA] (7.55) are consistent with the general population of CEUS SSC earthquakes (see Figure A2). Stevenson and Talwani (written communication, Feb 26, 2014) indicate:

> "This is, in fact a real event although the listed intensity may be a bit on the high side. It is actually kind of an interesting little read. It apparently occurred in or near Winnsboro, South Carolina Two mentions of it appeared in the *Augusta Chronicle* (Augusta Georgia). The first appeared in the August 17, 1888 issue: "NOT AN EARTHQUAKE: It was rumored on the streets Wednesday night that an earthquake had been felt at Winnsboro, SC, but it was too late to verify the report by telegraphic advises. It turns out that the report was started by the telegraph operator there who heard a terrific roar and rumbling, accompanied by a rattling of windows and shaking of houses. He told the operators over the wires that there was an earthquake going on and then left the office in haste. A coal burning locomotive of the R & D. road was at the station and the noise was caused by the engineer putting on the blowers."
>
> ...Three days later a letter appears in the August 20 issue of the *Augusta Chronicle* with the headline "KNOWS WHAT A QUAKE IS The Telegraph operator at Winnsboro Has Something to Say of a Shock". "In justice to myself I must ask space in your columns to correct this: I will briefly state the facts in the case: 1st. On August 15th (Wednesday) a very decided earthquake shock was here at 6:25 p. m., standard time, not only by myself but by the entire population of our town. The duration of the shock was about twenty seconds, accompanied by the usual roaring noise. All the inhabitants can make affidavits to the effect, if necessary. 2nd I asked only two operators by wire if they felt the shock, they being Ridgeway and Columbia. 3rd I did not leave my office during the tremor which was very perceptible and quietly remained and noted the time. 4th The passenger train, south had left Winnsboro about twenty minutes after the earthquake occurred, and there was no "coal burning locomotive" within 18 to 20 miles of my office. 5th I have been in the railroad service about ten years and I think this is sufficiently log to enable me to distinguish the roaring sound which accompanies an earthquake from that of a "coal burning locomotive." 6th A special dispatch announcing the earthquake was sent to the Charleston World. Our county paper also announced the occurrence. 7th I am a man of veracity, if I do say it myself, and I am not a "nervous operator."
>
> J.H. Skinner; ticket agent and operator
>
> Upon review of the *News and Herald* (Winnsboro, SC) only a very short mention was found in the August 22, 1888 issue: "An earthquake shock was felt by some people on Wednesday. The shock was not generally

noticed." While this obviously is a genuine event it seems would seem the reported intensity might be a high.

Because the earthquake is clearly identified in the above reporting, the recommendation is to retain it in the catalog with the reported size measures given in Seeber and Armbruster (1987).

The following table summarizes the assessments of the larger events in the Version 7 catalog that are located at sufficient distance from Charleston to not be identified as aftershocks of the 1886/09/01 main shock.

Revised Locations and Uniform Magnitudes for Specific Earthquakes Near Charleston, SC

TMPID	yr	Mo	Dy	Hr	Mn	sec	lat	lon	Basis of Revised Magnitude
TMP01089	1860	1	19	23	0	0	33.68	-80.57	Move to Charleston and base E[M] on I0
TMP01731	1886	9	1	6	0	0	33.91	-82.02	Event removed from catalog as a duplicate of TMP01732. Location and magnitude of TMP01732 do not require modification
TMP01739	1886	9	1	14*	45	0	34.04	-82.9	Event removed from catalog as a duplicate of TMP01738. Location and magnitude of TMP01738 do not require modification
TMP01942	1886	9	28	3	0	0	34.7	-81.62	Consider as a false event
TMP02002	1886	10	12	11	0	0	34.14	-81.33	Not use reported felt area, event becomes < E[M] 2.9
TMP02019	1886	10	22	5	0	0	34.71	-81.66	Event removed from catalog as a duplicate of TMP02023
TMP02023	1886	10	22	10	20		32.9	-80	Magnitude taken from Bakun and Hopper (2004)
TMP02024	1886	10	22	10*	25		33.69	-81	Event removed from catalog as a duplicate of TMP02023
TMP02025	1886	10	22	14	45	0	33.87	-81.01	Location moved to Charleston, magnitude taken from Bakun and Hopper (2004)
TMP02068	1886	11	5	5	0	0	33.38	-82.49	Not use reported felt area, event becomes < E[M] 2.9
TMP02071	1886	11	5	17	20	0	32.9	-80	Magnitude taken from Bakun and Hopper (2004)
TMP02072	1886	11	5	12	25		33.4	-80.42	Event removed from catalog as a duplicate of TMP02071.
TMP02134	1886	12	8	10	25	0	34.039	-80.886	Revise I0 from 4.5 to 4
TMP02136	1886	12	11	21	0	0	34.18	-82.06	Retain as is
TMP02173	1887	1	12	11	0	0	34.35	-82.42	Retain as less than E[M] 2.9, remove felt area

TMPID	yr	Mo	Dy	Hr	Mn	sec	lat	lon	Basis of Revised Magnitude
TMP02210	1887	3	4	10	0	0	33.74	-81.5	Not use reported felt area, event becomes < E[M] 2.9
TMP02360	1888	1	12	9	55	0	34.18	-80.17	Event removed from catalog as a duplicate of TMP39326.
TMP02393	1888	4	5	0	0	0	34.21	-81.534	Retain, reduce to I0 4, E[M] less than 2.9
TMP02423	1888	8	15	23	30	0	34.37	-81.08	Retain as is

* Change in hour

The review described above indicates that their remains considerable uncertainty about the parameters of the 1886 Charleston earthquake aftershocks in the published literature. It is suggested that efforts be considered to support publishing the compilation of data on these earthquakes being developed by Don Stevenson and Dr. Pradeep Talwani to aid in further assessments of the earthquakes of this time period.

Catalog Processing

After revising the parameters of the Charleston aftershocks and removal of the RIS earthquakes, the updated catalog was processed in the same manner as the Version 7 catalog. Magnitudes based on I0 and ln(FA) of the Charleston aftershocks were recalculated using the updated metadata. These calculations were performed using the Version 7 set of relationships and I0-**M** and ln(FA)-**M** data in order to produce the same conversions as the Version 7 catalog. This was because some of the RIS earthquakes contributed to the conversions and their removal would produce slight differences in the calculated values.

After developing the updated E[**M**] catalog, it was declustered using the same procedure. Because the declustering program uses random number generation as part of the selection of which earthquakes to flag as dependent, the updated declustered catalog was edited to utilize the same set of independent and dependent earthquakes as Version 7 in areas not affected by the catalog updates in order to not introduce small differences in completeness due to this statistical fluctuation.

Completeness was then calculated for the entire region. The primary completeness regions affected were 5 and 12. The differences in completeness are generally less than 5 percent.

COMMENTS OF NUREG-2115 EARTHQUAKE CATALOG

Comment Number	Page Number	Comment
1	3	insert space here between references.
2	3	I suggest that you refer to specific tables here. e.g., Tables X though Y show all the earthquakes that are reported with a date and occasionally magnitude in the references above. Table x contains earthquakes identified as RIS that are too small to be included in the CEUS SSC version 7 catalog
3	3	TABLE 1
4	3	TABLE 2
5	4	This event made is in my master file of RIS events. It is 2 miles west of the Oconee NPP. If you feel the reference is compelling, I wont argue, but the epicenter is right at the shoreline of Lake Keowee.
6	4	Maybe a TABLE 3 to include the Potential Additional RIS events.
7	5	This one is in my master file of RIS events. Somehow it never made it into the SEUSSN Bulletins.
8	5	This one is also in my master file of RIS. It should have been in the SEUSSN Bulletin.
9	6	TABLE 4 ?
10	7	figure numbers with captions below figure would seem useful here.
11	8	TABLE ?
12	9	Figure numbers, captions would help, here and in the following.
13	12	The text is not clear here about what is being discussed. What is W1 MR10 W2, etc.?
14	22	You dont include North Anna in this group. Lake Anna does not appear to have generated much if any RIS seismicity, which is curious given the proximity to the CVSZ. Since 2011, there have been a few events near the Lake, but the filling of the reservoir did not seem to generate much if anything.
15	23	This section needs bibliography for the citations.
16	23	reference for Munsey?
17	25	reference for Bakun and Hopper, Talwani and Sharma (1999)
18	26	Reference for Seeber and Armbruster (1987).
19	26	This is an important point. The Seeber and Armbruster/NCEER work and catalog has some serious issues, and I am in complete agreement with what you are doing here to try and straighten these problems out.
20	27	good.

COMMENTS OF NUREG-2115 EARTHQUAKE CATALOG

Comment Number	Page Number	Comment
21	27	Something is missing here. Paragraph should be re-written.
21	29	Not clear. distant from Charleston?
23	31	Need to have bibliography with this in it.
24	33	TABLE XX

Abbreviation

#	= Number to reference on spreadsheet to reveal the comment

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April 16, 2015
Project No.: 15-5403

Dr. Robert Youngs
AMEC Foster Wheeler
Environment & Infrastructure
Oakland, California

via email: Bob.Youngs@amecfw.com

REVIEW OF REVISED EARTHQUAKE CATALOG FOR THE CENTRAL AND EASTERN UNITED STATES

Dear Dr. Youngs:

In accordance with Amec Foster Wheeler (AMEC) Work Order and Purchase Order (PO) No. C012206224, I have reviewed the Memo from Robert Youngs (AMEC) to John Richards (EPRI) on the subject "Review of NUREG-2115 Earthquake catalog with regard to identification of additional Reservoir Induced Seismicity (RIS) earthquakes in the southeastern United States and locations of earthquakes in South Carolina near the time of the 1886 Charleston, SC earthquake sequence." The results of my review are attached.

If you have any questions regarding the review, please contact me at Richard.Quittmeyer@rizzoassoc.com or 1-412-825-2117.

Respectfully submitted,
RIZZO Associates

R.C. Quittmeyer

Richard C. Quittmeyer, Vice President-Seismology, RIZZO Associates

Richard C. Quittmeyer, Ph.D.
Vice President – Seismology

RCQ/sdr

Attachment

L01 155403/15

ATTACHMENT

REVIEW OF REVISED EARTHQUAKE CATALOG FOR THE CENTRAL AND EASTERN UNITED STATES

REVIEW OF REVISED EARTHQUAKE CATALOG FOR THE CENTRAL AND EASTERN UNITED STATES

INTRODUCTION

This review addresses revisions made to Version 7 of the Central and Eastern United States (CEUS) earthquake catalog published in "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities" (Electric Power Research Institute [EPRI]/ U.S. Department of Energy [DOE]/U.S. Nuclear Regulatory Commission [NRC], 2012). Revisions were made to address two issues:

- Identification of additional reservoir induced seismicity (RIS) earthquakes in the southeastern US.
- Locations of earthquakes in South Carolina near the time of the 1886 Charleston earthquake.

Materials provided to review consist of:

- A memorandum from Robert Youngs (AMEC) to John Richards (EPRI) that describes the changes to the catalog and their basis (Youngs, 2015).
- Two emails from Donald Stevenson (Savannah River Site) to Robert Youngs (AMEC) regarding evaluation of earthquake locations in South Carolina near the time of the 1886 Charleston, South Carolina earthquake (Stevenson, 2015a, 2015b).

BACKGROUND

The CEUS earthquake catalog (Version 7) was developed as part of a Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 study to carry out an updated seismic source characterization (SSC) for the CEUS (EPRI/DOE/NRC, 2012). Three goals were identified for the catalog development:

1. Completeness – Include earthquakes relevant to seismic source characterization from available sources. The compilation process was based on previous compilations and seismic network bulletins and attempted to trace back information to the original source.

The compilation also included special studies of individual earthquakes, earthquake sequences, and regional or topical assessments. Duplicate earthquakes and nontectonic earthquakes were flagged and not included in the final catalog used for SSC.

2. Uniformity of Earthquake Size Measure – Various estimates of size (intensity, magnitude using different scales) were compiled for each earthquake based on available information and used to determine a moment magnitude (**M**) value, taking into account uncertainty in magnitude estimation.

3. Catalog Review – To increase confidence in the developed catalog, it was submitted to an extensive review process by seismologists with knowledge and experience in catalog compilation. The reviewers recommended that original sources should be used, that magnitude determinations be scrutinized to discriminate use of different approaches and different manners of implementing the same approach, and that identified nontectonic events be compiled in a separate catalog. In addition the reviewers in some cases provided additional information on specific earthquakes.

Of relevance to the current revision and review, regional catalogs from the South Carolina Seismic Network (SCSN) and Southeastern United States Seismic Network (SEUSSN) were included in the compilation. Also, Dr. Pradeep Talwani from the University of South Carolina and Dr. Donald Stevenson from Savannah River Nuclear Solutions both participated in the catalog review that ultimately led to Version 7 of the CEUS catalog.

As the product of a SSHAC Level 3 process, it is expected that the CEUS earthquake catalog (Version 7, EPRI/DOE/NRC, 2012) is of high quality. As new information becomes available, however, it is necessary to evaluate the impacts and make revisions as necessary. In keeping with the SSHAC process, changes in the catalog should be based on technically defensible information, be justified, and be well documented, including their basis. This review of the current revisions focuses on those criteria.

REVIEW

REVIEW OF ADDITIONAL RIS EARTHQUAKES

In the CEUS SSC (EPRI/DOE/NRC, 2012) earthquake catalog, nontectonic events, including reservoir induced seismicity (RIS) earthquakes, are flagged and not included in analyses supporting SSC. Youngs (2015) indicates that, for the southeastern US, bulletins of the SEUSSN were the primary source to identify RIS events. For the current catalog revision,

Youngs (2015) identifies 13 additional references that were evaluated to identify additional RIS or possible RIS earthquakes. This evaluation identified:

- RIS earthquakes not compiled in the raw published CEUS SSC catalog (EPRI/DOE/NRC, 2012)
- RIS earthquakes in the published CEUS SSC catalog and already flagged as RIS events
- RIS and possible RIS earthquakes in the published CEUS SSC catalog, but not flagged as RIS events

In addition, seismicity within 100 km of nuclear power plants (NPPs) in the southeastern US located near water bodies (e.g., lakes, reservoirs, rivers), was plotted and examined.

Comments on the evaluation of RIS earthquakes are listed in ***Table 1***.

TABLE 1
COMMENTS ON THE EVAULATION OF RIS EARTHQUAKES

COMMENT NUMBER	REFERENCE	DESCRIPTION
1	Section "Additional RIS Earthquakes"	In general, the conclusions regarding RIS status need to be better justified and documented. As a first step, criteria should be defined for determining if an earthquake is reservoir induced or not. Criteria might include: • Determined to be RIS by an investigator with a reasonable, documented technical basis • Spatial proximity to a reservoir and shallow focal depth • Temporal relation to reservoir filling or variations in level
2	Section "Additional RIS Earthquakes"	Clarify the use of the terms "non-RIS," "possible RIS," "potential RIS," and "RIS" with respect to the use of "probable nontectonic" and "nontectonic" in the CEUS SSC report (EPRI/DOE/NRC, 2012). It is noted, however, that the list of nontectonic types in the CEUS SSC master catalog does not include "probable reservoir-induced." Does this need to be added?

TABLE 1
COMMENTS ON THE EVAULATION OF RIS EARTHQUAKES
(CONTINUED)

COMMENT NUMBER	REFERENCE	DESCRIPTION
3	Section "Additional RIS Earthquakes/ References"	While it states at the beginning of this section that the 13 references contain the additional material used to identify potential RIS events, at the bottom of page 5 it is noted that the review also included SEUSSN Bulletins for 1979 and 1980, and other events in the catalog near (spatially and temporally?) RIS events. The complete scope of the review should be clarified at the beginning of the discussion.
4	Section "Additional RIS Earthquakes/ References"	For Reference [3], the report number (Technical Report GL-90-11) could be added for better traceability.
5	Section "Additional RIS Earthquakes/ References"	For Reference [5], the correct Issue is 3, not 2.
6	Section "Additional RIS Earthquakes/ Review Results"	For earthquakes identified as RIS that are not in the CEUS SSC catalog, clarify if they will be added to the CEUS SSC catalog of nontectonic events.
7	Section "Additional RIS Earthquakes/ Review Results"	Use consistent criteria to evaluate earthquakes. For example, TMP14740 is judged to be a non-RIS earthquake because Reference [1] noted there was no correlation between the onset of seismicity and reservoir level; but TMP07159 is judged to be a potential RIS earthquake because its preferred location coincides with the location of other earthquakes judged to be RIS. TMP14740 also coincides with the location of other events judged to be RIS, but a different criterion is used (correlation to reservoir water level) in assessing that event.
8	Section "Additional RIS Earthquakes / Review Results"	TMP07012: The discussion notes that the earthquake could possibly be a RI event, but the conclusion is to retain it as a non-RIS earthquake. Elsewhere (e.g., TMP09000) events of uncertain RIS origin are identified as a "possible RI earthquake." Clarify the basis and implications for the "possible" classification.
9	Section "Additional RIS Earthquakes/ Review Results"	TMP07159: Correct the spelling of "Bulltins."

TABLE 1
COMMENTS ON THE EVAULATION OF RIS EARTHQUAKES
(CONTINUED)

COMMENT NUMBER	REFERENCE	DESCRIPTION
10	Section "Additional RIS Earthquakes/ Review Results"	TMP07565: Clarify what criteria are used to reach the conclusion (excellent correlation with water fluctuations, but poor spatial and temporal proximity). Also, the discussion notes that the earthquake is mentioned in Reference [11], which cites Talwani (1976, "Earthquakes associated with the Clark Hill Reservoir, South Carolina--A case of induced seismicity"), the title of which suggests the event is induced.
11	Section "Additional RIS Earthquakes/ Review Results"	TMP08078: Document the basis for the RIS conclusion. Current discussion suggests it is because a monitoring program was established after it occurred. Also, note that this event and TMP07565 are discussed in the same section of Reference [11], but different RIS conclusions are reached for the two events.
12	Section "Additional RIS Earthquakes/ Review Results"	TMP08787: If possible, clarify what water level is being measured in the well. It appears this earthquake is located at Lake Jocassee; how does the lake level correspond to the water level in the well? Also, in the last sentence of the discussion, "smaller that earthquakes" should be "smaller than earthquakes."
13	Section "Additional RIS Earthquakes/ Review Results"	TMP08971: It is not clear how the information presented leads to the conclusion that the earthquake is reservoir-induced. Location and depth?
14	Section "Additional RIS Earthquakes/ Review Results"	TMP09000: Note that the date given for this event appears to be incorrect. In the CEUS SSC report, TMP09000 has a date of 2/11/1978. This evaluation implies that classification of "possible RIS event" derives from a "location and depth" criterion.
16	Section "Additional RIS Earthquakes/ Review Results"	TMP09355: In the first sentence "dependent even" should be "dependent event."
17	Section "Additional RIS Earthquakes/ Review Results"	TMP10034: Clarify if Reference [2] identifies the event as reservoir-induced or simply lists it.
18	Section "Additional RIS Earthquakes/ Review Results"	TMP10034 and TMP10104: Clarify if there is a difference between being "flagged" and "listed" in the SEUSSN Bulletin. For example, does "flagged" imply identification as a RIS event? Does "listed" simply mean "included" or does it also carry the meaning of being identified as a RIS event?
19	Section "Additional RIS Earthquakes/ Review Results"	Bottom of Page 5: Should "references [1] through [5]" be "[1] through [13]"? If not, explain how the following list differs from the review discussed above.

TABLE 1
COMMENTS ON THE EVAULATION OF RIS EARTHQUAKES
(CONTINUED)

COMMENT NUMBER	REFERENCE	DESCRIPTION
20	Section "Additional RIS Earthquakes/ Review Results"	Page 6, Table: For many earthquakes in this table there has been no specific or general discussion of the criteria and basis for determining they are "RIS" or "possible RIS." Because this review is modifying a product developed as part of a SSHAC Level 3 SSC study, the basis for making changes to the catalog should be clearly and completely documented.
21	Section "Additional RIS Earthquakes/ Review Results"	Page 7, Figure: Clarify what is meant by "affected by these RIS earthquakes." Is the focus on recurrence parameters? Are all earthquakes in the list shown, or only those that would be included in recurrence calculation? At what distance from a site does the impact of changes to the catalog on calculation of recurrence parameters become negligible?
22	Section "Additional RIS Earthquakes/ Seismicity within 100 km of NPPs"	While plots of earthquakes are shown relative to NPP locations and lakes/rivers, there is no summary for each NPP, or in general, whether this comparison identified any additional RIS or possible RIS earthquakes. Consider providing at least a general summary of the conclusions of this comparison.
23	Section "Additional RIS Earthquakes/ Summary"	Consider providing a summary figure that shows the seismicity from the CEUS SSC catalog Version 7 for the SEUS and identifies (e.g., filled versus open symbols) the 30 events now being moved to the nontectonic events catalog. It would also be useful to discriminate those newly classified RIS events that have E[M] of 2.9 or greater and thus would impact recurrence calculations. Multiple figures might be needed to show the information at a useful scale.

REVIEW OF CHARLESTON, SC EARTHQUAKES NEAR THE TIME OF THE 1886 EARTHQUAKE SEQUENCE

Youngs (2015) reviews available data relevant to evaluation of the catalog parameters for seven earthquakes in the South Carolina region that are suspected of being mislocated. Two of the earthquakes occurred prior to the 1886 mainshock (in 1799 and 1860), four occurred in 1886, and one in 1888. Reevaluations are based largely on ongoing, unpublished evaluations by Dr. Donald Stevenson and Dr. Pradeep Talwani (Stevenson, 2015a, 2015b) of archival material from newspapers in South Carolina and adjacent regions. These evaluations update those made based on more limited archival data by Seeber and Armbruster in the 1980s (e.g., Seeber and Armbruster, 1981, 1987) and those incorporated in the EPRI-SOG and NCEER-91 catalogs that evolved into the USGS catalog.

Although the technical bases for the locations in the CEUS SSC Version 7 catalog are not compared to those of Stevenson and Talwani (and may not be readily available), the data described and reasoning used by Stevenson and Talwani support the conclusions Stevenson and Talwani reach. The updates in location and the identifications of duplicate or false events are supported by the available information.

REVIEW OF DEVELOPMENT OF VERSION 8 CATALOG

In preparing Version 8 of the CEUS SSC catalog to incorporate identified revisions, the overall results of Seeber and Armbruster (1987) were reconsidered, especially with respect to the appropriateness of their estimates of felt area used for E[**M**] estimation. Reexamination of the felt areas determined by Seeber and Armbruster (1987) clarified that the basis for some was a nominal assumption of 100 km^2; for others comparison to larger datasets relating felt area and maximum intensity suggest the methodology used by Seeber and Armbruster (1987) can be biased. Based on the information and analyses documented in Youngs (2015), the elimination of some Seeber and Armbruster (1987) felt areas from the Version 8 CEUS SSC catalog is reasonable and justified.

The recommendation that support be provided for the publication of the assessments of Stevenson and Talwani is endorsed. Publication would make these assessments more transparent and readily available to the seismological community. Pending such publication, it is recommended that the emails from Dr. Stevenson be included as attachments to Youngs (2015) to enhance the traceability and transparency of the assessments.

Processing of the catalog following reevaluation of RIS events and events related to the 1886 Charleston sequence is reasonable and straightforward.

Specific comments on this section of Youngs (2015) are contained in ***Table 2***.

TABLE 2
COMMENTS ON DEVELOPMENT OF VERSION 8 CATALOG

COMMENT NUMBER	REFERENCE	DESCRIPTION
24	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	First sentence: The previous section states that seven earthquakes are identified as possibly mislocated. Here the assessments of six earthquakes are mentioned. Seven were assessed, but one was not changed. This apparent difference (seven versus six) should be clarified to avoid confusion.
25	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	First sentence: The sentence indicates that the reevaluation of six Charleston 1886 era earthquakes "further calls into question the earthquake locations provided by Seeber and Armbruster (1987)." Why "further?" This appears to assume knowledge of other assessments not documented in the current memo.
26	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	Page 27, end of the 2nd full paragraph: A sentence fragment appears at the end of the paragraph. Provide the missing portion of the sentence or delete, as appropriate.
27	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	The SUSN catalog locations are often preferred over the Seeber and Armbruster (1987) locations. If available, consider providing some discussion of the basis for the SUSN locations for pre-instrumental locations.
28	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	TMP02134: For this event the conclusion mentions two options: false event or too small to include in recurrence relations. Clarify how the event was treated in the Version 8 catalog. That is, was it deleted from the earthquake catalog and added to the nontectonic list as a false event, or was it included with a E[**M**] less than 2.9. The following table suggests it was retained. Also, can it be clarified if Stevenson and Talwani considered the archival data that Munsey used to identify the event?

TABLE 2
COMMENTS ON DEVELOPMENT OF VERSION 8 CATALOG
(CONTINUED)

COMMENT NUMBER	REFERENCE	DESCRIPTION
29	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	TMP02173: For this earthquake the conclusion indicates that it is likely smaller than E[**M**] 2.9. Clarify how this conclusion is implemented in the catalog. What E[**M**] is assigned in the Version 8 catalog for this earthquake (e.g., 2.8, something else)?

SUMMARY

As new information becomes available, it is appropriate to revise the evaluation of seismic events included in CEUS SSC earthquake catalog (Version 7). Because the Version 7 catalog represents a product developed as part of a SSHAC Level 3 study, it is important that revisions to the catalog have an appropriate technical basis, be justified, and be well documented. The comments provided here on the Youngs (2015) memo are provided with that goal in mind and to enhance the confidence in the Version 8 catalog.

REFERENCES

Electric Power Research Institute/U.S. Department of Energy/U.S. Nuclear Regulatory Commission (EPRI/DOE/NRC), 2012, "Central and Eastern United States Seismic Source Characterization of Nuclear Facilities," EPRI Report #1021097, DOE Report # DOE/NE-0140, NRC NUREG-2115,Palo Alto, CA (EPRI), Washington, D.C. (DOE, NRC), 2012.

Seeber, L., and J. G. Armbruster, 1981, "The 1886 Charleston, South Carolina Earthquake and the Appalachian Detachment," Journal of Geophysical Research, Vol. 86, No. B9, pages 7874-7894, 1981.

Seeber, L., and J.G. Armbruster, 1987, "The 1886-1889 Aftershocks of the Charleston, South Carolina Earthquake: A Widespread Burst of Seismicity," Journal of Geophysical Research, Vol. 92, No. B3, pages 2663-2696, 1987.

Stevenson, D., 2015a, Email from Donald Stevenson (SRS) to Robert Youngs (AMEC) with the Subject: "Re: South Carolina earthquakes," February 19, 2014 (with attached Microsoft ® Excel ® file Charleston_area_Eqs.xlsx), 2015.

Stevenson, D., 2015b, Email from Donald Stevenson (SRS) to Robert Youngs (AMEC) with the Subject: "Re: South Carolina earthquakes," February 26, 2014 (with attached Microsoft ® Excel ® file Additional_Charleston_area_Eqs.xlsx), 2015.

Youngs, R., 2015, Memorandum from Robert Youngs (AMEC) to John Richards (EPRI) with the Subject: "Review of NUREG-2115 Earthquake catalog with regard to identification of additional Reservoir Induced Seismicity (RIS) earthquakes in the southeastern United States and locations of earthquakes in South Carolina near the time of the 1886 Charleston, SC earthquake sequence," March 5, 2014.

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ATTACHMENT 3

Amec Foster Wheeler's Responses to Review Comments

April 23, 2015

Subject: RESPONSE TO COMMENTS BY DR. MARTIN CHAPMAN

amec foster wheeler

All editorial comments have been accepted, and the suggested modifications have been made to the text. A revised version of the document is attached to this letter.

Discussion of the North Anna NPP is not included because the revision is limited to plants in the Southeastern U.S. As noted, Lake Anna has not produced RIS, so its exclusion has no impact on our analysis.

Of the potential 6 discrepancies noted in the review letter, only one (event dated 12/11/1986) has E[**M**] large enough (3.16) to be included in the recurrence calculation. Although we agree that all six earthquakes should be marked as RIS in future releases of the catalog, we conclude that the exclusion of that one earthquake from the recurrence calculation will have negligible impact on the recurrence rates, and a re-analysis is not necessary at this time.

As a general comment, we note that it would be helpful for future efforts to have a publicly available list of RIS. Currently, the SEUSSN Bulletins are not consistent in the identification of RIS: in some cases the earthquakes are clearly labeled as "reservoir induced" in other cases they are not. For example the event discussed above (12/11/1986) is only listed by its location "Lake Keowee", but it is not called out as reservoir induced.

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RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
1	Section "Additional RIS Earthquakes"	In general, the conclusions regarding RIS status need to be better justified and documented. As a first step, criteria should be defined for determining if an earthquake is reservoir induced or not. Criteria might include: Determined to be RIS by an investigator with a reasonable, documented technical basis Spatial proximity to a reservoir and shallow focal depth Temporal relation to reservoir filling or variations in level	Revised text.
2	Section "Additional RIS Earthquakes"	Clarify the use of the terms "non-RIS," "possible RIS," "potential RIS," and "RIS" with respect to the use of "probable nontectonic" and "nontectonic" in the CEUS SSC report (EPRI/DOE/NRC, 2012). It is noted, however, that the list of nontectonic types in the CEUS SSC master catalog does not include "probable reservoir-induced." Does this need to be added?	Corrected nomenclature for consistency.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
3	Section "Additional RIS Earthquakes/ References"	While it states at the beginning of this section that the 13 references contain the additional material used to identify potential RIS events, at the bottom of page 5 it is noted that the review also included SEUSSN Bulletins for 1979 and 1980, and other events in the catalog near (spatially and temporally?) RIS events. The complete scope of the review should be clarified at the beginning of the discussion.	Text revised to clarify that the SEUSSN Bulletin were the sole source of RIS in the southeastern US used in Rev 7 of the catalog.
4	Section "Additional RIS Earthquakes/ References"	For Reference [3], the report number (Technical Report GL-90-11) could be added for better traceability.	Added.
5	Section "Additional RIS Earthquakes/ References"	For Reference [5], the correct Issue is 3, not 2.	Corrected.
6	Section "Additional RIS Earthquakes/ Review Results"	For earthquakes identified as RIS that are not in the CEUS SSC catalog, clarify if they will be added to the CEUS SSC catalog of nontectonic events.	They should in future releases of the Catalog. A new issue of the non-tectonic events list is beyond the scopes of this project.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
7	Section "Additional RIS Earthquakes/ Review Results"	Use consistent criteria to evaluate earthquakes. For example, TMP14740 is judged to be a non-RIS earthquake because Reference [1] noted there was no correlation between the onset of seismicity and reservoir level; but TMP07159 is judged to be a potential RIS earthquake because its preferred location coincides with the location of other earthquakes judged to be RIS. TMP14740 also coincides with the location of other events judged to be RIS, but a different criterion is used (correlation to reservoir water level) in assessing that event.	Ref [1] does not consider TMP14740 as RI, and the SEUSSN Bulletin does not flag this event as RI either. Dr Martin Chapman considers this event to be RI, see discussion at the end of Part 1.
8	Section "Additional RIS Earthquakes / Review Results"	For TMP07012, the discussion notes that the earthquake could possibly be a RI event, but the conclusion is to retain it as a non-RIS earthquake. Elsewhere (e.g., TMP09000) events of uncertain RIS origin are identified as a "possible RI earthquake." Clarify the basis and implications for the "possible" classification.	The difference is that the location of TMP07012 is based on "meager" data (Ref. [5]). Since the event is poorly located it could have happened somewhere else and not be RI.
9	Section "Additional RIS Earthquakes/ Review Results"	In the discussion for TMP07159, correct the spelling of "Bulltins."	Corrected.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
10	Section "Additional RIS Earthquakes/ Review Results"	For TMP07565, clarify what criteria are used to reach conclusion (excellent correlation with water fluctuations, but poor spatial and temporal proximity). Also, the discussion notes that the earthquake is mentioned in Reference [11], which cites Talwani (1976, "Earthquakes associated with the Clark Hill Reservoir, South Carolina--A case of induced seismicity"), the title of which suggests the event is induced.	Revised text for clarity. The same author (Talwani) first seems to believe that the event is RI (as referenced in [11]), then in a subsequent paper (Ref [3]) determines that the induced nature of the earthquake is questionable.
11	Section "Additional RIS Earthquakes/ Review Results"	For TMP08078, document the basis for the RIS conclusion. Current discussion suggests it is because a monitoring program was established after it occurred. Also, note that this event and TMP07565 are discussed in the same section of Reference [11], but different RIS conclusions are reached for the two events.	Revised text. See also response to comment 10.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
12	Section "Additional RIS Earthquakes/ Review Results"	For TMP08787, clarify what water level is being measured in the well. It appears this earthquake is located at Lake Jocassee; how does the lake level correspond to the water level in the well? Also, in the last sentence of the discussion, "smaller that earthquakes" should be "smaller than earthquakes."	Revised text based on information available in Ref [2]. No information given in Ref [2]. Corrected.
13	Section "Additional RIS Earthquakes/ Review Results"	TMP08971: It is not clear how the information presented leads to the conclusion that the earthquake is reservoir-induced. Location and depth?	Revised text.
14	Section "Additional RIS Earthquakes/ Review Results"	TMP09000: Note that the date given for this event appears to be incorrect. In the CEUS SSC report, RMP09000 has a date of 2/11/1978. This evaluation implies that classification of "possible RIS event" derives from a "location and depth" criterion.	Corrected.
16	Section "Additional RIS Earthquakes/ Review Results"	TMP09355: In the first sentence "dependent even" should be "dependent event."	Corrected.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
17	Section "Additional RIS Earthquakes/ Review Results"	TMP10034: Clarify if Reference [2] identifies the event as reservoir-induced or simply lists it.	Clarified.
18	Section "Additional RIS Earthquakes/ Review Results"	TMP10034 and TMP10104: Clarify if there is a difference between being "flagged" and "listed" in the SEUSSN Bulletin. For example, does "flagged" imply identification as a RIS event? Does "listed" simply mean "included" or does it also carry the meaning of being identified as a RIS event?	Clarified.
19	Section "Additional RIS Earthquakes/ Review Results"	Bottom of Page 5: Should "references [1] through [5]" be "[1] through [13]"? If not, explain how the following list differs from the review discussed above.	Corrected.
20	Section "Additional RIS Earthquakes/ Review Results"	Page 6, Table: For many earthquakes in this table there has been no specific or general discussion of the criteria and basis for determining they are "RIS" or "possible RIS." Because this review is modifying a product developed as part of a SSHAC Level 3 SSC study, the basis for making changes to the catalog should be clearly and completely documented.	Revised text.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
21	Section "Additional RIS Earthquakes/ Review Results"	Page 7, Figure: Clarify what is meant by "affected by these RIS earthquakes."	Revised text.
		Is the focus on recurrence parameters? Are all earthquakes in the list shown, or only those that would be included in recurrence calculation?	All earthquakes in Table 4, at the scale of the figure many are superimposed.
		At what distance from a site does the impact of changes to the catalog on calculation of recurrence parameters become negligible?	This is beyond the scope of the project.
22	Section "Additional RIS Earthquakes/ Seismicity within 100 km of NPPs"	While plots of earthquakes are shown relative to NPP locations and lakes/rivers, there is no summary for each NPP, or in general, whether this comparison identified any additional RIS or possible RIS earthquakes. Consider providing at least a general summary of the conclusions of this comparison.	Revised summary section.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
23	Section "Additional RIS Earthquakes/ Summary"	Consider providing a summary figure that shows the seismicity from the CEUS SSC catalog Version 7 for the SEUS and identifies (e.g., filled versus open symbols) the 30 events now being moved to the nontectonic events catalog. It would also be useful to discriminate those newly classified RIS events that have E[M] of 2.9 or greater and thus would impact recurrence calculations. Multiple figures might be needed to show the information at a useful scale.	Added figures 16 and 17.
24	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	First sentence: The previous section states that seven earthquakes are identified as possibly mis-located. Here the assessments of six earthquakes are mentioned. Seven were assessed, but one was not changed. This apparent difference (seven versus six) should be clarified to avoid confusion.	Text revised for clarity.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
25	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	First sentence: The sentence indicates that the reevaluation of six Charleston 1886 era earthquakes "further calls into question the earthquake locations provided by Seeber and Armbruster (1987)." Why "further?" This appears to assume knowledge of other assessments not documented in the current memo.	Removed word "further".
26	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	Page 27, end of the 2nd full paragraph: A sentence fragment appears at the end of the paragraph. Provide the missing portion of the sentence or delete, as appropriate.	Revised.
27	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	The SUSN catalog locations are often preferred over the Seeber and Armbruster (1987) locations. If available, consider providing some discussion of the basis for the SUSN locations for pre-instrumental locations.	Information on the SUSN catalog can be found at: http://www.magma.geos.vt.edu/vtso/anonftp/catalog/catalog_readme.txt The catalog is a synthesis of the U.S. Geological Survey State Seismicity Map Series (C. W., B. G. Reagor, and S. T. Algermissen, 1984, 'United States Earthquake Data File', U. S. Geological Survey Open-File Report 84-225, 123 pp.), and the Southeastern U. S. Seismic Network catalog for events after July 1977.

RESPONSE TO COMMENTS BY DR. RICHARD QUITTMEYER

Comment Number	Reference	Description	Response
28	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	TMP02134: For this event the conclusion mentions two options: false event or too small to include in recurrence relations. Clarify how the event was treated in the Version 8 catalog. That is, was it deleted from the earthquake catalog and added to the nontectonic list as a false event, or was it included with a E[**M**] less than 2.9. The following table suggests it was retained.	The event was retained in Rev 8 of the catalog. The list of non-tectonic events is not being updated at this time.
		Also, can it be clarified if Stevenson and Talwani considered the archival data that Munsey used to identify the event?	We do not have that information.
29	Section "Development of a Version 8 Catalog"/ "Revised Assignments of Parameters"	TMP02173: For this earthquake the conclusion indicates that it is likely smaller than E[**M**] 2.9. Clarify how this conclusion is implemented in the catalog. What E[**M**] is assigned in the Version 8 catalog for this earthquake (e.g., 2.8, something else)?	The statement was incorrect. The earthquake was maintained unmodified in Rev 8 of the catalog.

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ATTACHMENT 4

Concurrence letters from Dr. Martin Chapman and Dr. Richard Quittmeyer

April 17, 2015

Martin Chapman
[redacted]

RE: Review of NUREG-2115 earthquake catalog

Dear Bob:

I have examined your responses to my comments on the work concerning the review of the NUREG-2115 earthquake catalog with regard to identification of additional reservoir induced sesimicity (RIS) earthquakes in the southeastern United States and the locations of earthquakes in South Carolina near the time of the 1886 Charleston, SC earthquake sequence.

Your responses fully address my comments.

Sincerely,

Martin Chapman

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April 23, 2015
Project No.: 15-5403

Dr. Robert Youngs
Amec Foster Wheeler
Environment & Infrastructure
Oakland, California

via email: Bob.Youngs@amecfw.com

CONCURRENCE ON UPDATED REVISED EARTHQUAKE CATALOG FOR THE CENTRAL AND EASTERN UNITED STATES

Dear Dr. Youngs:

In accordance with Amec Foster Wheeler (AMEC) Work Order and Purchase Order (PO) No. C012206224, I reviewed the Memo from Robert Youngs (AMEC) to John Richards (EPRI) on the subject "Review of NUREG-2115 Earthquake catalog with regard to identification of additional Reservoir Induced Seismicity (RIS) earthquakes in the southeastern United States and locations of earthquakes in South Carolina near the time of the 1886 Charleston, SC earthquake sequence." Comments were provided as an attachment to a letter, addressed to you, dated April 15, 2015.

In response to my comments and those of Dr. Martin Chapman, you provided me with a revised document on April 21, 2015. I reviewed the revised document and made additional comments that were transmitted to you by email on April 22, 2015. In response to these additional comments, you provided an updated revised document for my consideration on April 23, 2015. Following review of this latest document, I find that all of my comments are satisfactorily addressed and I have no further comments.

The current document describes, and supports with sufficient technical basis and justification, revisions to the Central and Eastern United States (CEUS) Seismic Source Characterization (SSC) earthquake catalog (Revision 7). The revisions focus on the southeastern United States and reflect evaluation of additional information. The additional information pertains to reservoir-induced seismicity and the location and size of earthquakes in South Carolina that occurred generally near the time of the large 1886 Charleston earthquake. The revised CEUS SSC catalog (Revision 8) is appropriate for updated calculation of recurrence parameters for the southeastern United States.

If you have any questions regarding my review or my concurrence with the comment resolutions, please contact me at Richard.Quittmeyer@rizzoassoc.com or 1-412-825-2117.

Respectfully submitted,
RIZZO Associates

Richard C. Quittmeyer, Vice President-Seismology, RIZZO Associates

Richard C. Quittmeyer, Ph.D.
Vice President – Seismology

RCQ/sdr

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