Memo:

March 5, 2014

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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.

## *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.

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

**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.

**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.
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**

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
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
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.

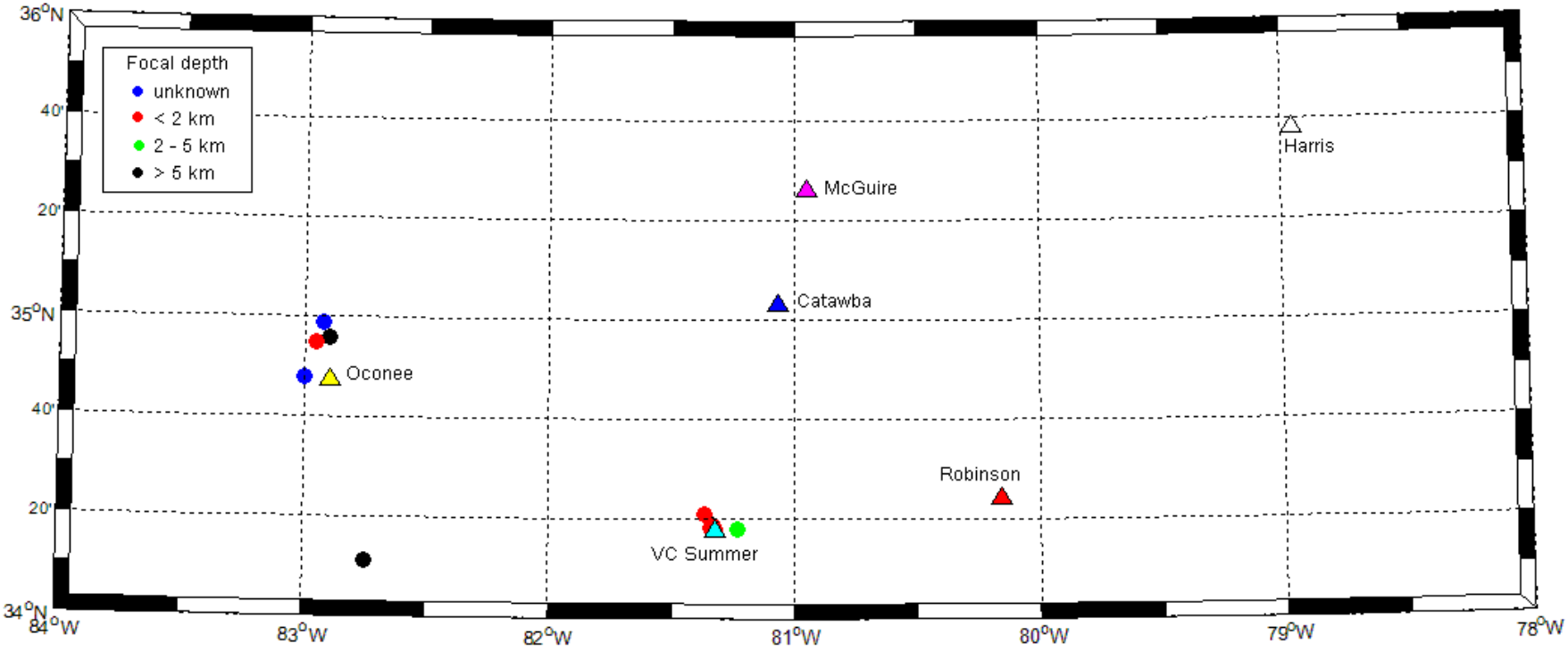
Based on the review of the references [1] through [5], a review of the SEUSSN Bulletins between 1979 and 1980, and examination of the catalog near other events flagged as RI, the following earthquakes are identified as possible RI.

| 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.



## *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.:

| 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.

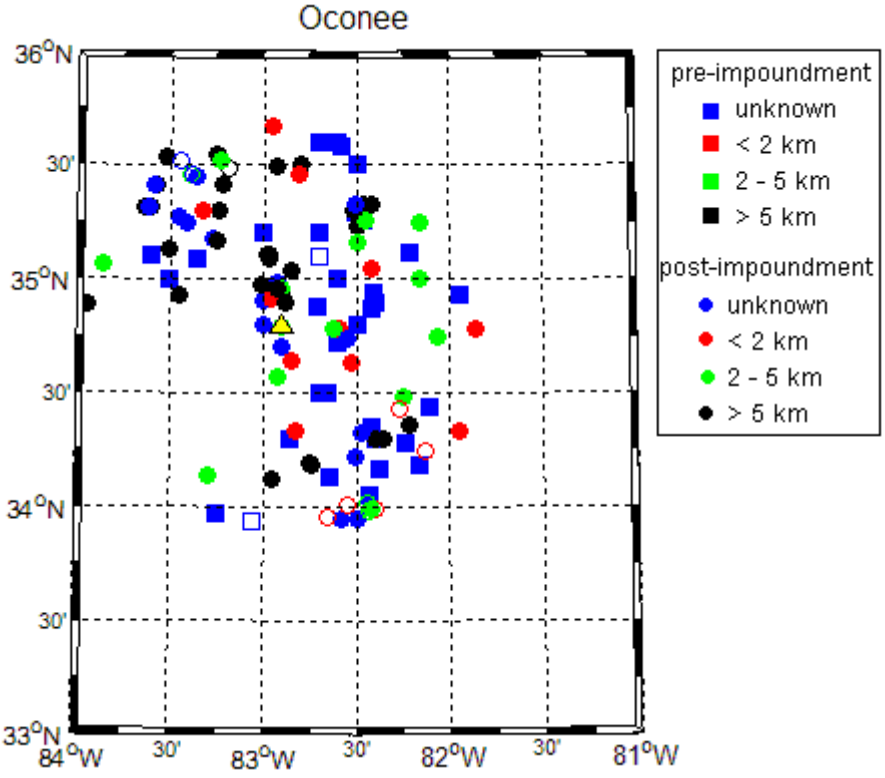
In all figures:

- 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.

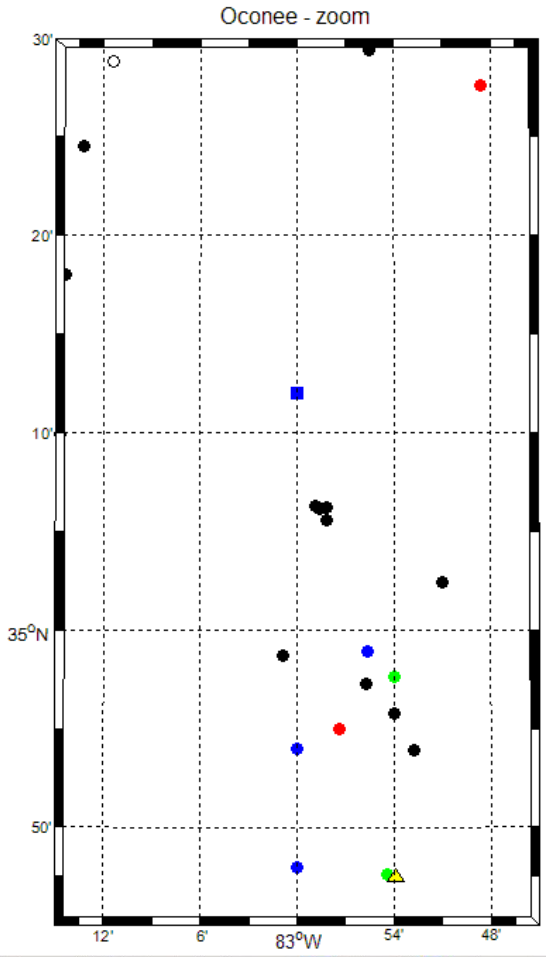
## NPPs Located on Lakes and Reservoirs

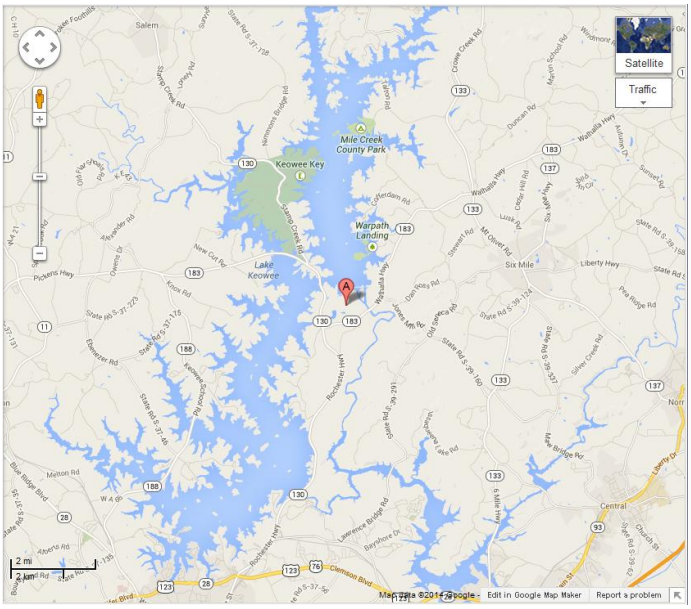
### Oconee

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.



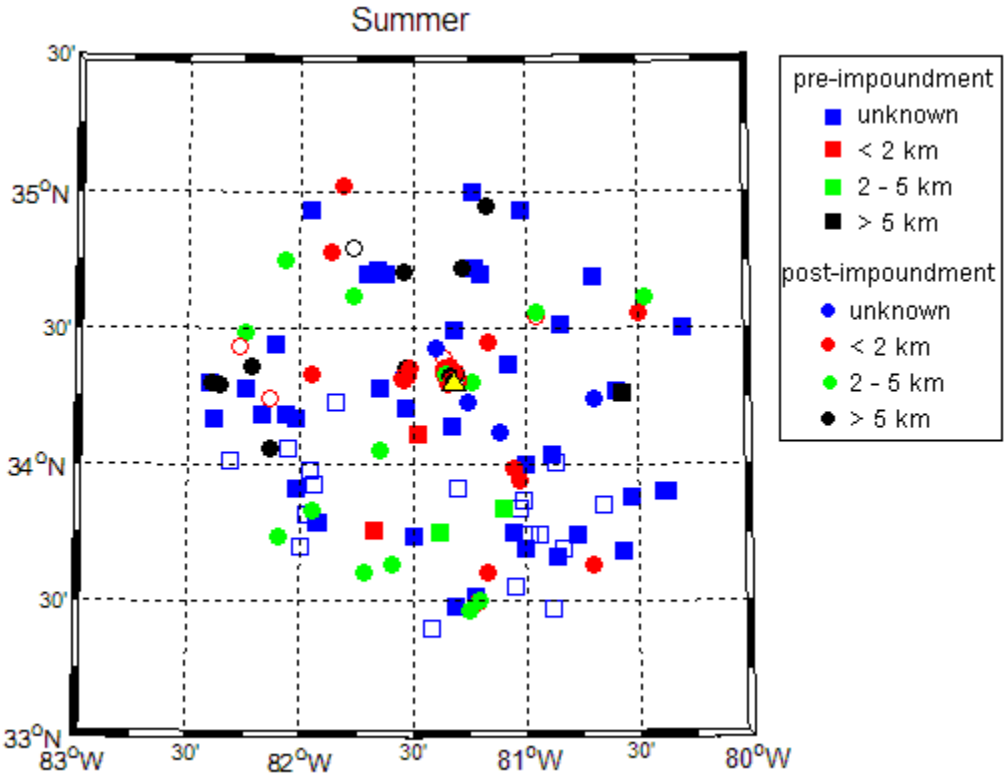

The next figure shows a zoom of the seismicity cluster near the NPP. These earthquakes are likely RIS events from Lake Keowee: they are typically shallow and occurred after the impoundment of the lake, in areas that have no prior seismicity.

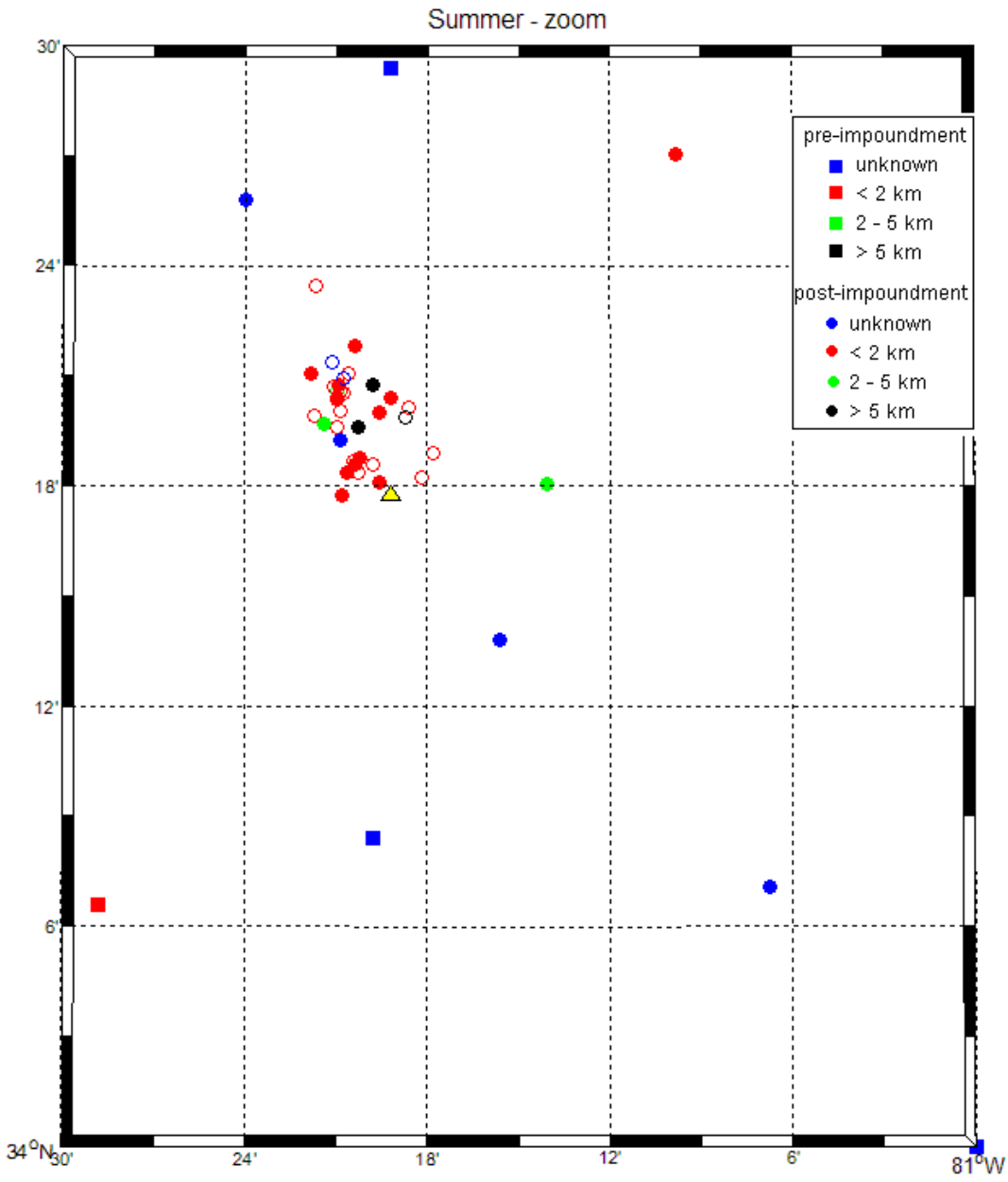

Oconee - zoom
30'
20'
10'
35°N
50'
12'
6'
83°W
54'
48'


Satellite
Traffic
Mile Creek County Park
Keowee Key
Warpath Landing
Lake Keowee
Six Mile
Central
2 mi
2 km
Map data ©2014 Google
Edit in Google Map Maker
Report a problem

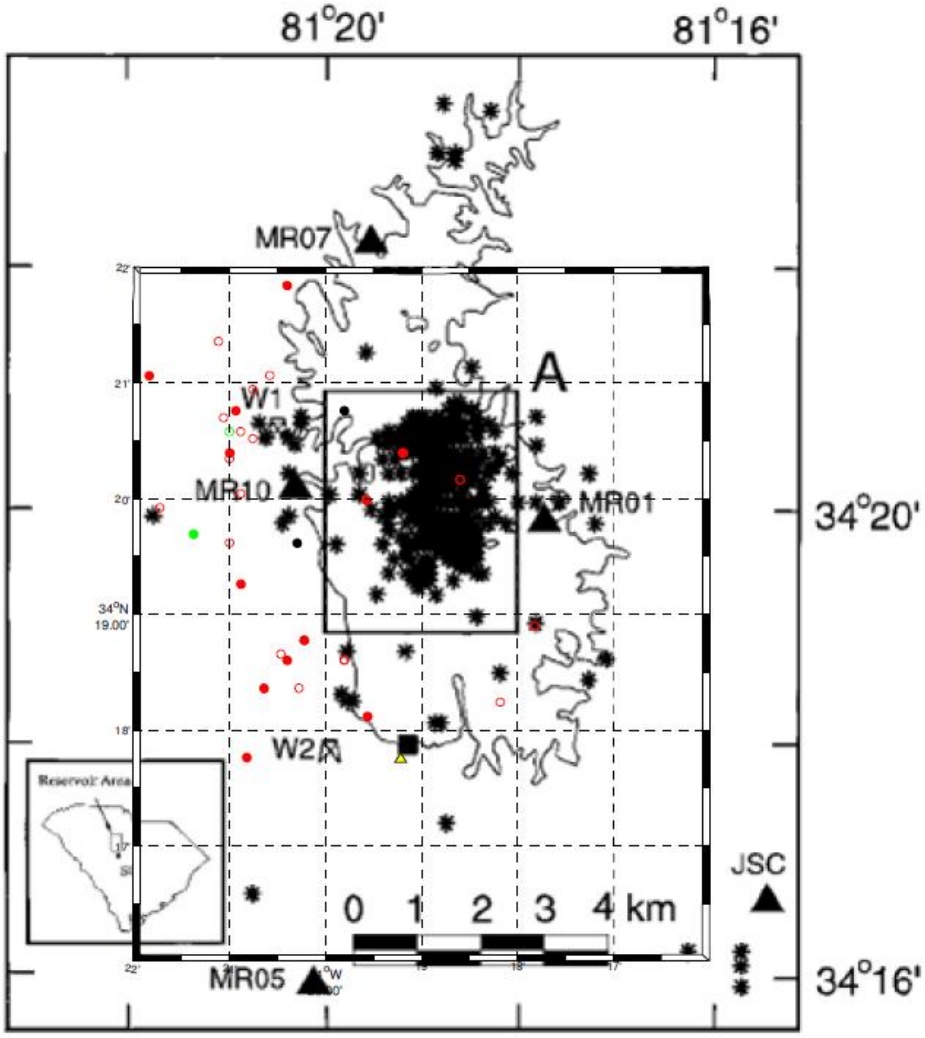
## VC Summer

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.





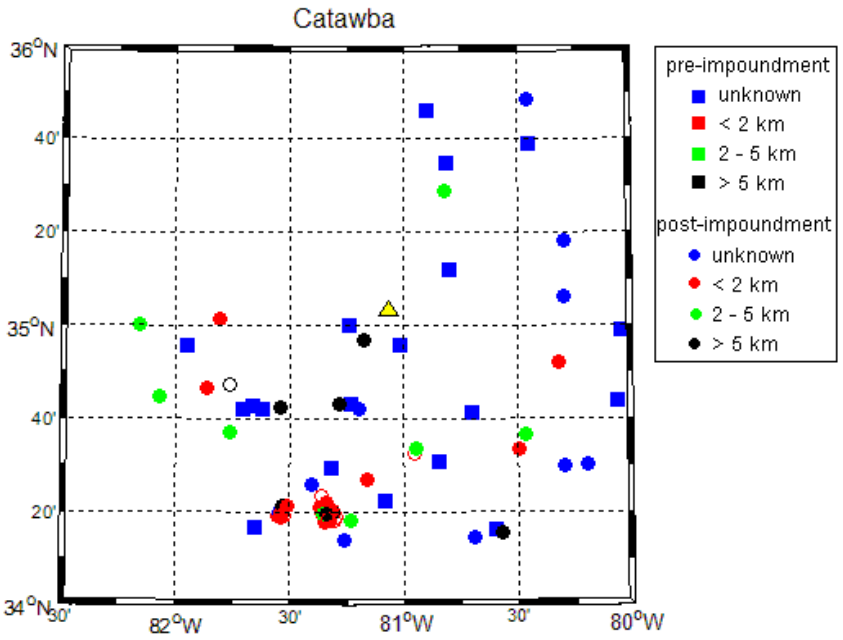

The enlarged figure above shows this cluster in detail: there are two clusters of earthquakes. One cluster is closer to the NPP (earthquakes have mostly depths of 1 km), and one cluster is further to the north where there are events in the 2-5 km depth range. The figure also shows that most of the earthquakes 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.

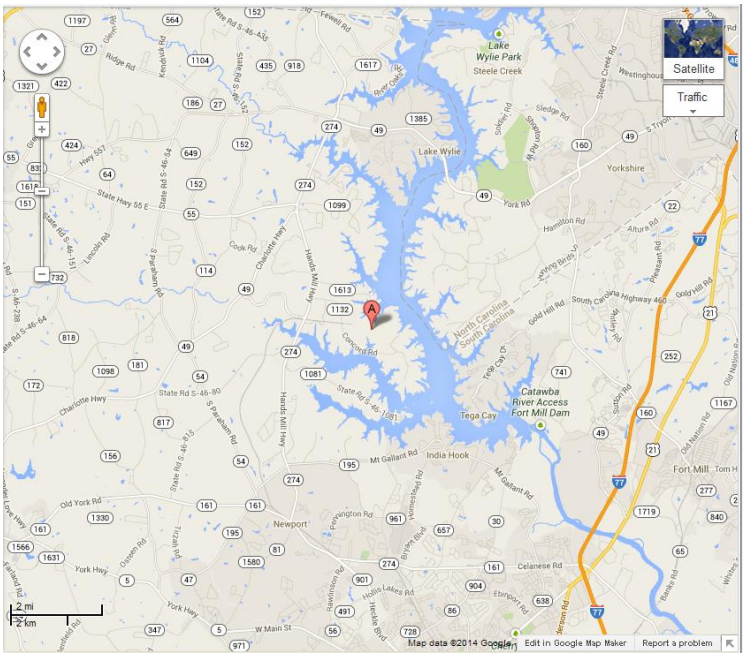



The northernmost cluster is probably in the area of W1; the three earthquakes that are lined up closer to the site have occurred in 1978, 1979 and 1982.

## Catawba

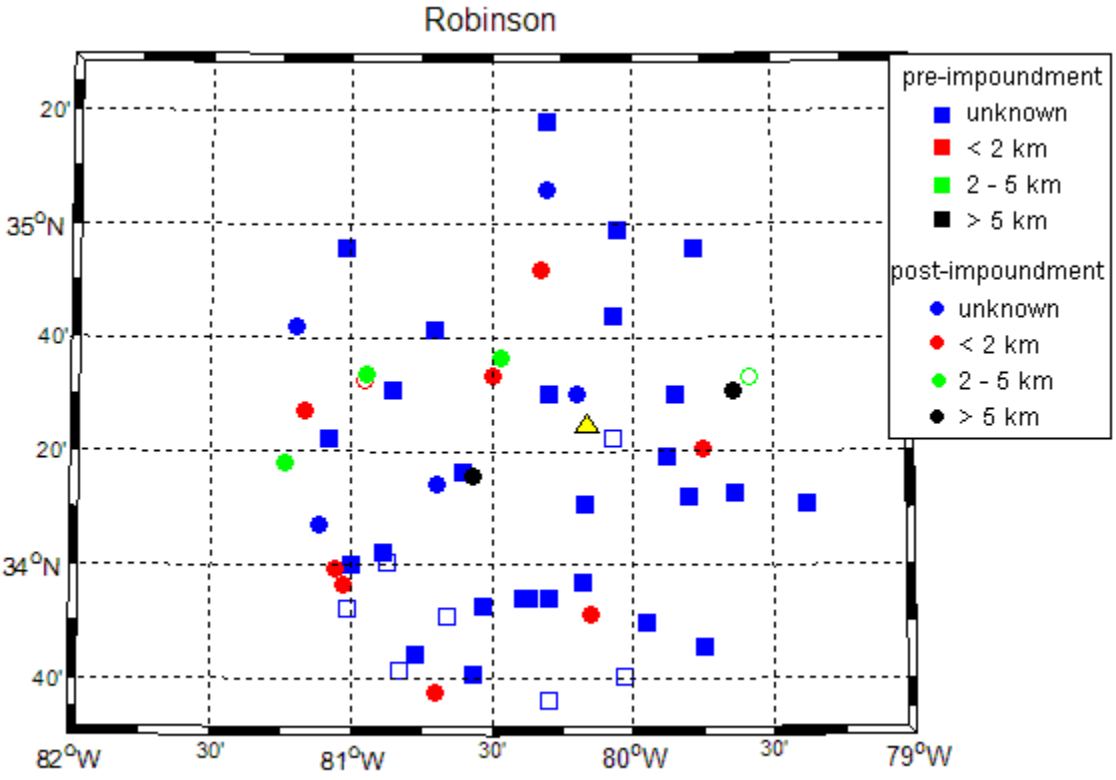
There are 136 earthquakes within 100 km of the Catawba NPP. The seismicity pre-1975 has unknown focal depth. If these earthquakes are removed the nearest earthquake has a depth of 23 km. The NPP is located on Lake Wylie (see figure from google maps): the earthquakes closer to the lake occurred prior 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.



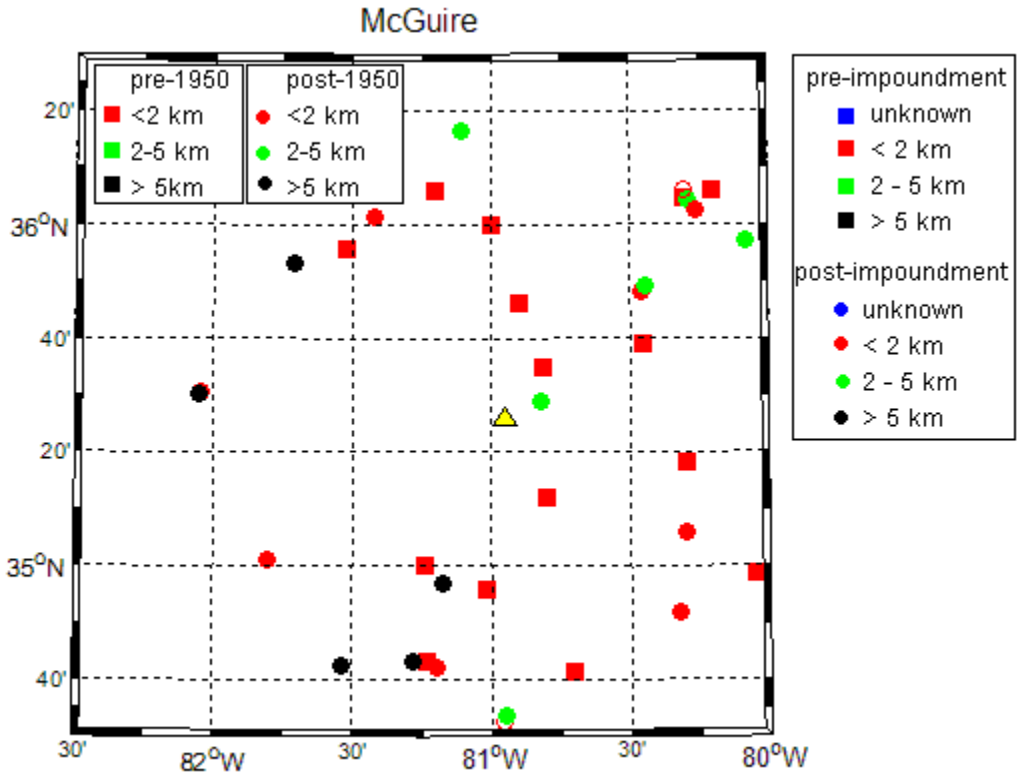
## Robinson

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.



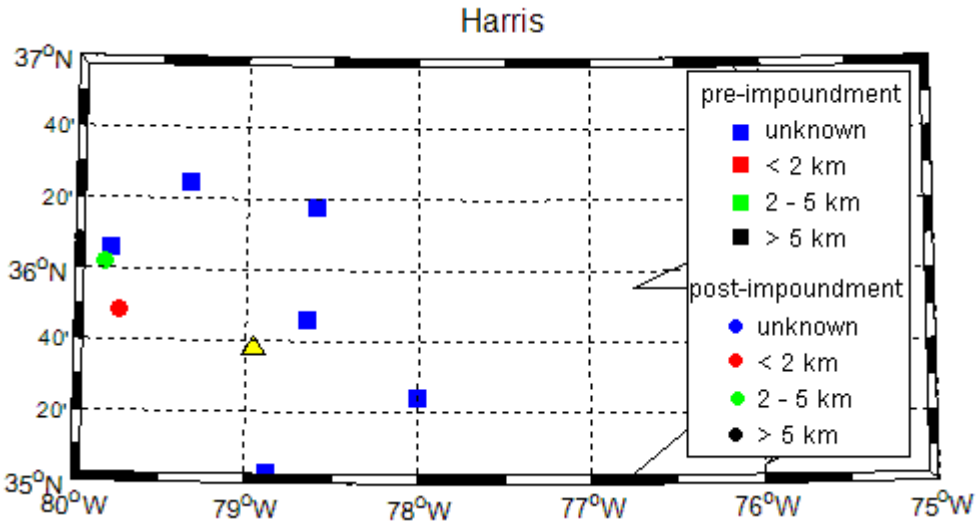
## McGuire

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

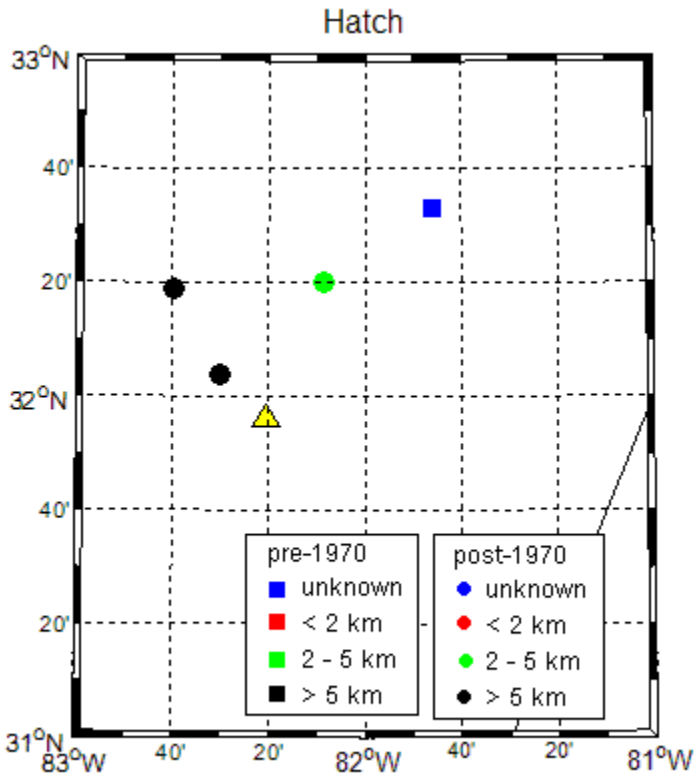
There are 16 earthquakes within 100 km of the Harris NPP of which only 2 have been instrumentally recorded: one in 1981 with a depth of 1km and one in 1993 with a depth of 5 km. Both are far from the Shearon-Harris Reservoir.



## *NPPs Located on Rivers*

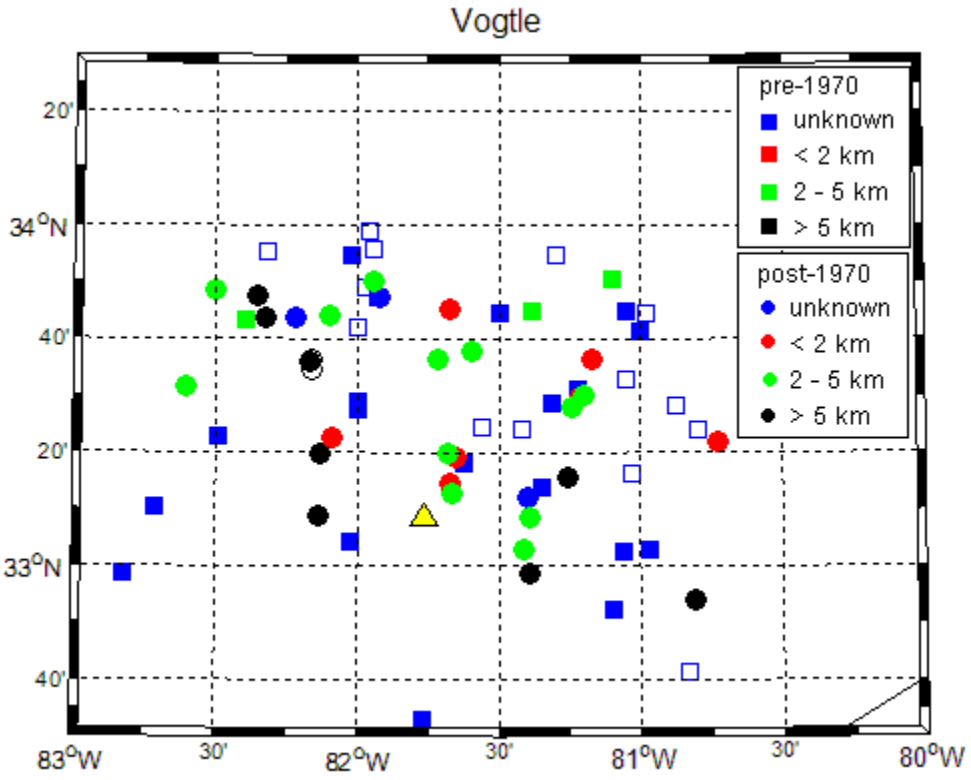
### Hatch

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



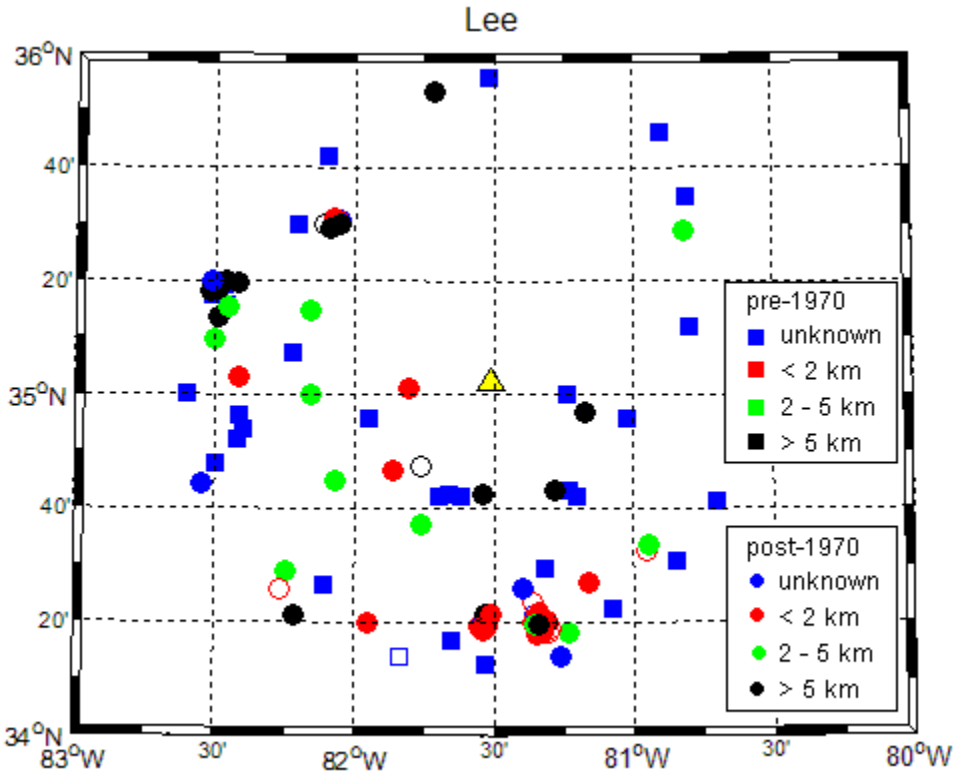
## Vogtle

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



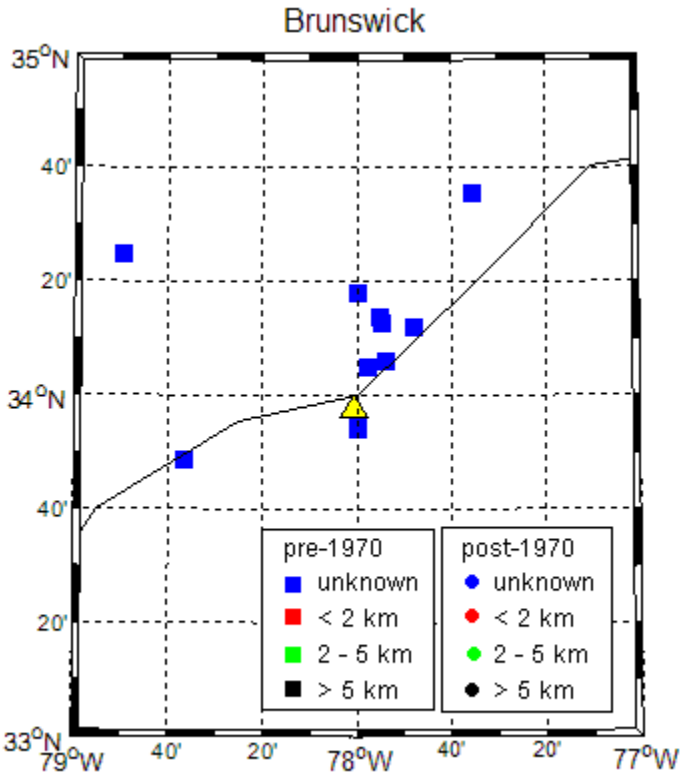
## Lee

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



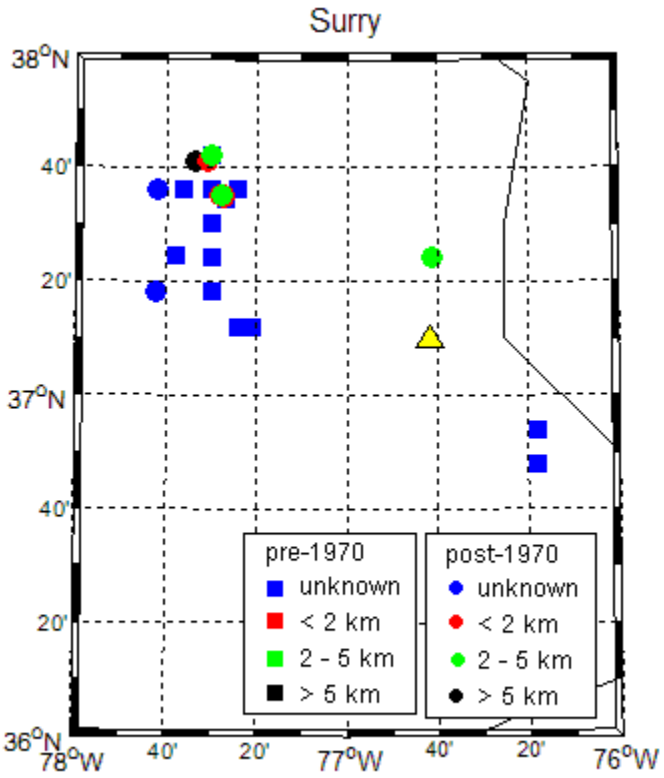
## Brunswick

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

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

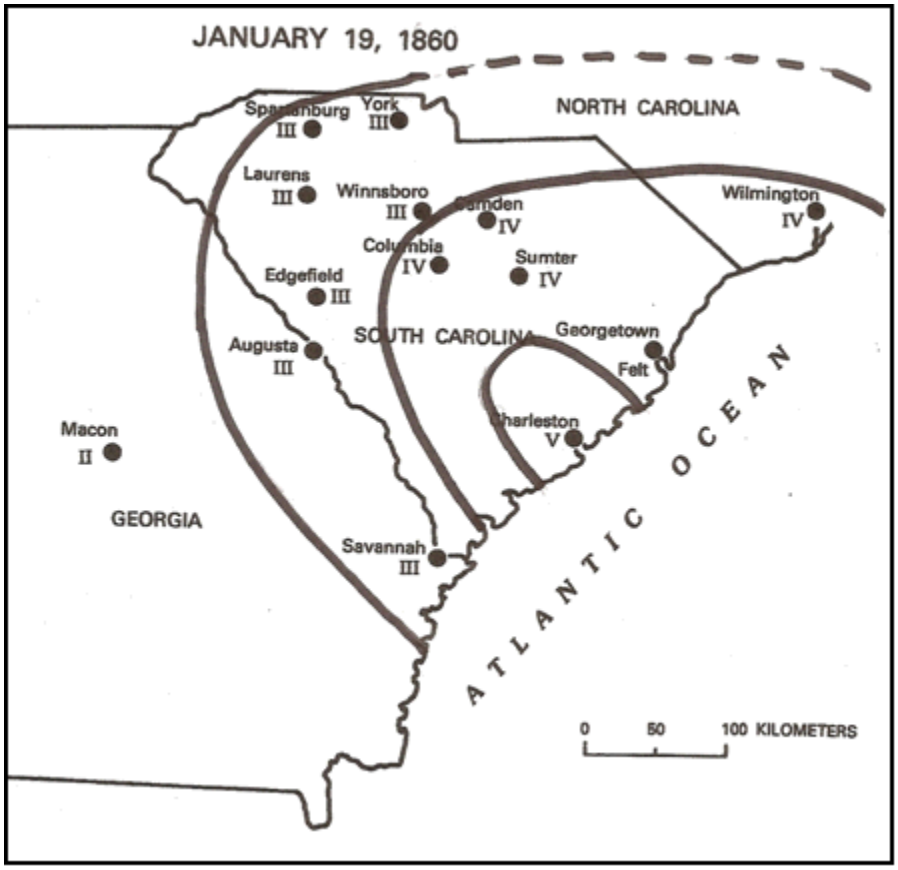
| TMPID | yr | Mo | Dy | hr | mn | sec | Lat | lon | E[M] | Source of Catalog Location |
|---|---|---|---|---|---|---|---|---|---|---|
| TMP00331 | 1799 | 4 | 11 | 8 | 20 | 0 | 33.95 | -80.18 | 4.68 | USGSnd_000145 Revised by Jeff Munsey of TVA based on Bakun and Hopper Method |
| TMP01089 | 1860 | 1 | 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.

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.

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 Version 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 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.

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

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.

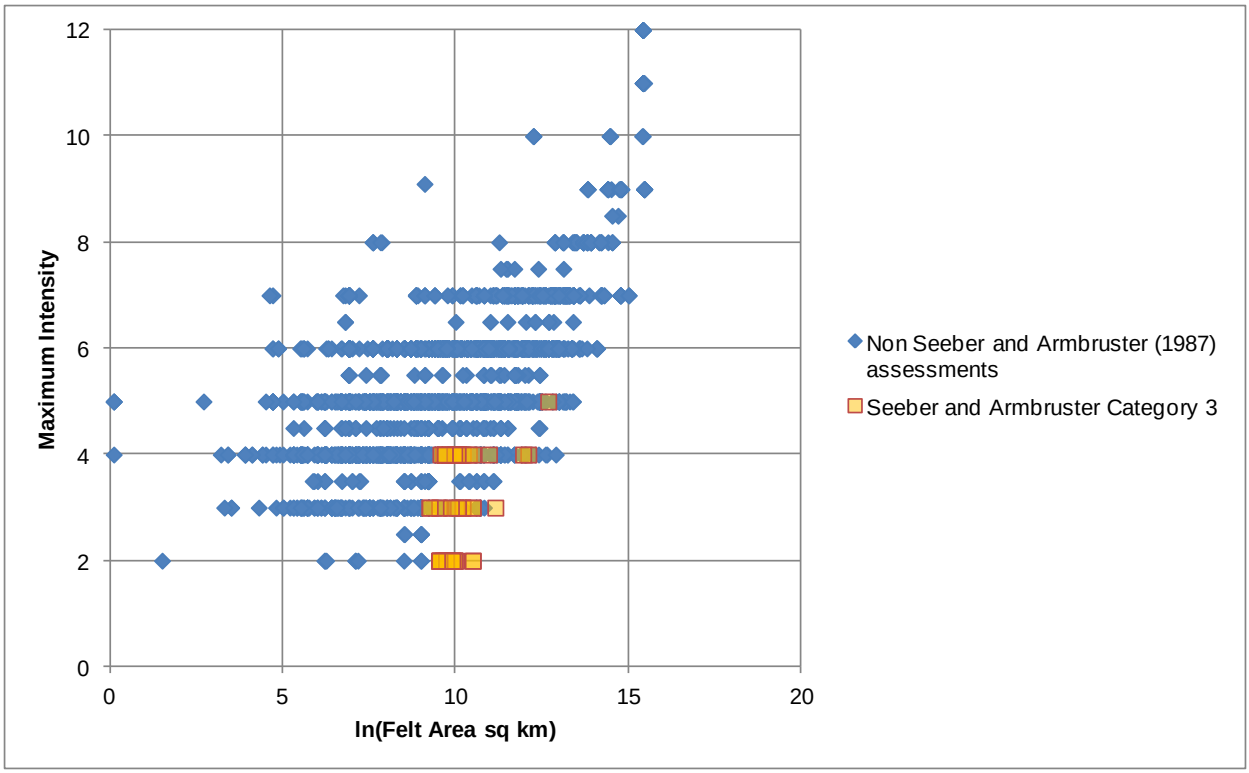


Figure A1 comparison of ln(FA)-I0 data for Category 3 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Version 7 catalog.

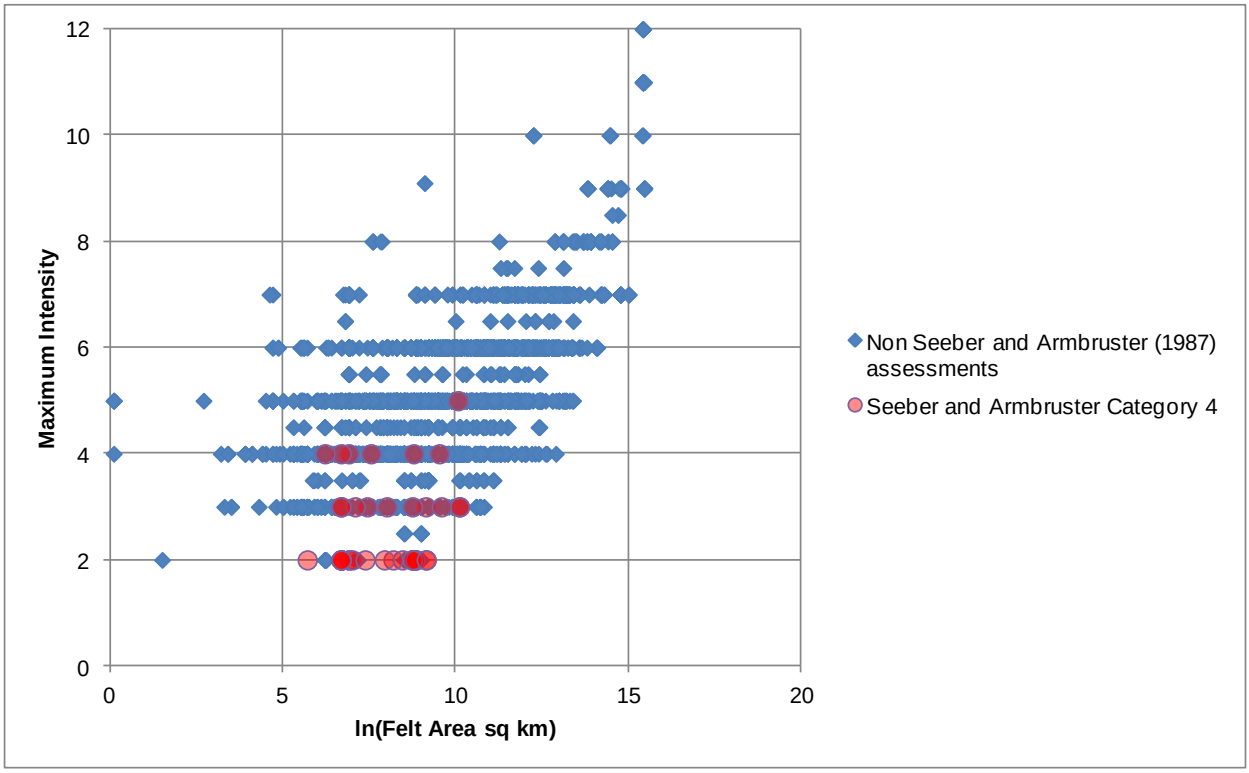



Figure A2 comparison of ln(FA)-I0 data for Category 4 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Version 7 catalog.

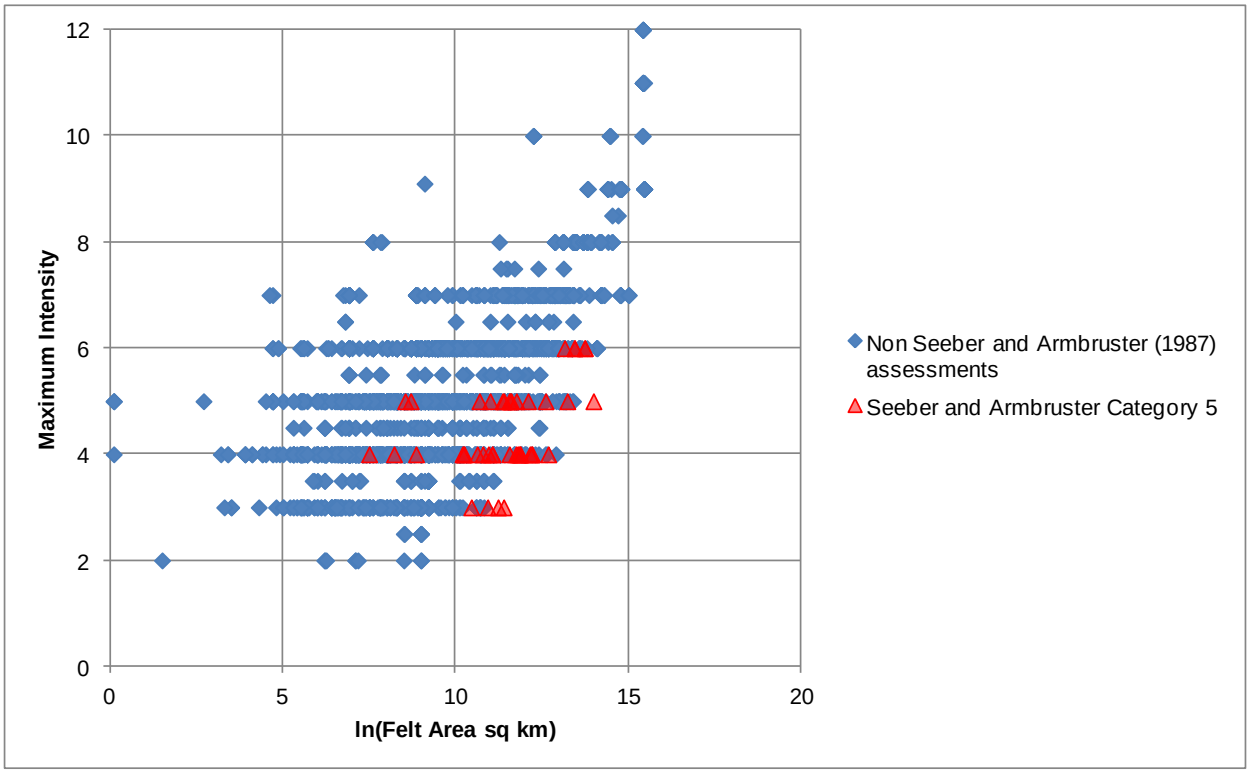



Figure A3 comparison of ln(FA)-I0 data for Category 5 Earthquakes from Seeber and Armbruster (1987) with data from other earthquakes from the CEUS SSC Version 7 catalog.

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.

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.

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.