Technical Memorandum

To: *South Carolina Department of Natural Resources (DNR)*
South Carolina Department of Health and Environmental Control (DHEC)

From: *CDM Smith*

Date: *May 4, 2015*

Subject: *Evaporation Data & Methodology (for Unimpairing Flows at Reservoirs)*

Evaporation Data

CDM Smith prepared daily pan evaporation records for eight South Carolina locations from 1925 through 2014 based on pan evaporation measurements at 11 sites supplemented with temperature-based estimates for missing dates or outside the period of record.

Data Sources

Pan evaporation measurements for 13 sites in South Carolina are available in the National Climatic Data Center's (NCDC) Global Historical Climatology Network (GHCN) database, as listed in **Table 1** and shown in **Figure 1** along with nearby sites in North Carolina and Georgia.

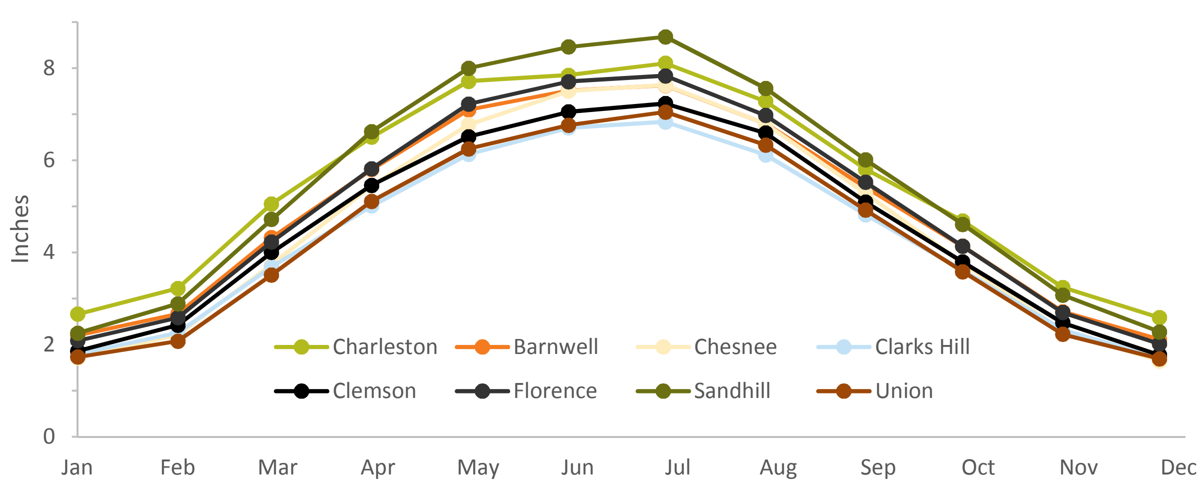
Long-term evaporation records were developed from these data through combining selected stations and through record extension and in-filling based on calibration of the Hargreaves (1985) reference evapotranspiration estimation method to pan evaporation measurements as discussed later in this section. Long-term records were developed from the following eight datasets:

- The Barnwell and Blackville (Clemson Edisto Research and Education Center) stations, which together have 46 years of record and are within nine miles of one another;
- Charleston International Airport, which has 44 years of record;
- The Chesnee, Rainbow Lake, and Simms WTP stations, which together have 49 years of record and are within one-half mile of one another;
- Clarks Hill, which has 46 years of record;
- Clemson University, which has 66 years of record;
- Florence, which has 30 years of record;

Table 1. GHCN South Carolina Pan Evaporation Data

COOP ID	Location	° N	° W	Elev. (ft)	Start	End	Percent Complete	Years (July)	Years (Jan)
380490	BARNWELL 5 ENE	33.3	81.2	245	2007	2014	88%	7	4
380764	BLACKVILLE 3 W	33.4	81.3	324	1963	2002	90%	36	28
381544	CHARLESTON INTL AP	32.9	80.0	40	1959	2002	85%	41	27
381625	CHESNEE 7 WSW	35.1	82.0	748	1992	2014	51%	21	0
381726	CLARKS HILL 1 W	33.7	82.2	380	1952	1998	86%	42	20
381770	CLEMSON UNIV	34.7	82.8	824	1948	2014	91%	63	47
383111	FLORENCE 8 NE	34.3	79.7	120	1979	2009	88%	29	18
387113	RAINBOW LAKE	35.1	82.0	751	1965	1978	71%	14	2
387288	RIDGEVILLE	33.1	80.3	70	1996	2004	57%	7	0
387666	SANDHILL RSCH ELGIN	34.1	80.9	440	1963	2014	71%	39	19
387885	SIMMS WTP	35.1	82.0	751	1979	1991	59%	13	0
388786	UNION 8 S	34.6	81.7	480	1949	1964	81%	14	6
	WINTHROP UNIV	34.9	81.0	690	1967	1968	37%	1	0

Figure 1. South Carolina Evaporation



- Clemson's Sandhill Research and Education Center near Columbia, which has 51 years of record; and
- Union, which has 15 years of record.

The Ridgeville station was not used as its record mostly coincides with the nearby longer record at Charleston. The Winthrop University station was not used due to its record length of just one year. The only station outside South Carolina that is significantly closer to any part of the state than one of the in-state stations is Savannah. However, the Charleston station was considered adequately representative of South Carolina's coastal plain, so Savannah data were not considered in this assessment.

Record extension methodology

All the evaporation records needed extension and in-filling to obtain complete 90 year records. Daily potential evapotranspiration (PET) was estimated using the Hargreaves-Samani temperature-based method. PET (equivalent to open water evaporation) was converted to pan evaporation estimates through scaling according to a multiplier determined for each evaporation dataset based on minimization of least squares error for all dates with pan evaporation measurements. A single scale factor was adopted for each site; no attempt was made to distinguish monthly factors or factors specific to temperature data sources in cases where more than one climate station was used.

The Hargreaves method was chosen due to its ease of calculation via the USEPA SWMM model. This method is also incorporated into USDA's SWAT watershed model. While Lu et al. (2005) found that Hamon's method (Hamon, 1963) yielded better monthly PET estimates for the southeastern United States, that distinction was not considered relevant for this assessment, as the goal was estimation of daily pan evaporation rates, and modeled PET estimates were scaled based on calibration to observed pan rates.

Temperature data sources

Daily PET estimates using Hargreaves method require daily temperature data. To obtain complete 90-year temperature datasets, nearby GHCN meteorological stations were matched to each evaporation dataset. For each site, **Table 2** identifies a primary station that has at least 50 years of record through the present. **Table 3** identifies secondary stations with data beginning 1925 or earlier and extending until the beginning of the primary dataset. Table 3 also lists a supplemental station used to fill gaps of up to one year in the temperature records for most sites.

Table 2. Primary Temperature Stations

Evaporation Station	Temperature Station	NCDC ID	Distance (mi)	Elevation (ft)	Period	Coverage
Sandhill	Columbia	WBAN 13883	19 SW	231	1948-present	100%
Charleston	Charleston	WBAN 13880	0	40	1938-present	100%
Barnwell	Orangeburg	COOP 386527	27 NE	180	1953-present	99%
Chesnee	Greer	WBAN 03870	20 SW	940	1962-present	100%
Clarks Hill	Clarks Hill	COOP 381726	0	380	1952-present	97%
Clemson	Clemson	COOP 381770	0	824	1930-present	100%
Florence	Florence	COOP 383111	0	120	1942-March 2014	95%
Union	Union	COOP 388786	0	480	1949-present	96%

Table 3. Secondary Temperature Stations

Evap. Station	Temp. Station	NCDC ID	Distance (mi)	Elv. (ft)	Period	Coverage	Supplemental Data
Sandhill	Camden	COOP 381310	14 NE	140	1849-2001	78%	not needed
Charleston	Charleston City	WBAN 13782	10 SE	10	1893-present	100%	not needed
Barnwell	Aiken	COOP 380074	31 NW	492	1893-2008	91%	May 1947, Sep 1952: Augusta (WBAN 03820; 42 mi W)
Chesnee	Caroleen NC	COOP 311479	15 NE	810	1900-1974	99%	Nov 1926 - Jan 1927 and Oct 1940: Landrum (COOP 384936; 13 mi NW)

Evap. Station	Temp. Station	NCDC ID	Distance (mi)	Elv. (ft)	Period	Coverage	Supplemental Data
Clarks Hill	Aiken	COOP 380074	31 SE	492	1893-2008	91%	May 1947: Augusta (WBAN 03820 24 mi SE)
Clemson	Anderson	COOP 380165	13 SE	800	1892-present	96%	not needed
Florence	Society Hill	COOP 388114	11 NW	141	1893-1959	96%	Sep 1931 and Apr-Dec 2014: Darlington (COOP 382260; 8 mi W)
Union	Santuck	COOP 387722	8 NE	520	1893-present	98%	Feb 1928 and Mar 1938: Laurens (COOP 385017; 22 mi SW)

Station Data Statistics and Quality Control

The eight evaporation stations collectively include 287 station-years of daily pan measurements. Quality control was conducted to screen out questionable data. Twenty measurements at Chesnee with negative evaporation were rejected. Among the rest of the data, 99.5% of measurements were less than 0.5 inches/day (in/d), 0.4% were between 0.5 and 1 in/d, and 0.1% were greater than 1 in/d. The 106 measurements 1 in/d and larger were excluded from the final database; most of these data were from Charleston (high readings throughout January 1963) and Blackville (high readings throughout August 1995).

Table 4 shows period-of-record average monthly pan evaporation for the 11 stations used in this assessment. Values in Table 4 are generally within 5 percent of those reported by the South Carolina State Climatology Office (Purvis, 2006). The Table 4 values differ from the Climatology Office statistics, as that analysis was limited to data through 2002, and included infilling with modeled values for dates with missing readings.

Table 4. Average Monthly Pan Evaporation

Inches	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	April-Oct
Charleston	2.91	3.52	5.55	6.89	7.85	7.79	8.06	7.14	5.73	4.83	3.38	2.79	66.44	48.28
Barnwell	3.72	3.65	5.54	6.61	7.81	8.53	8.69	7.34	6.22	4.80	3.25	2.90	69.05	49.99
Blackville	2.18	2.68	4.34	5.86	6.92	7.35	7.45	6.46	5.12	3.97	2.61	2.07	57.02	43.14
Chesnee				5.92	6.73	7.44	7.50	6.65	5.29	3.51				43.03
Clarks Hill	1.84	2.37	3.78	5.10	6.09	6.83	6.94	6.11	4.85	3.58	2.28	1.63	51.41	39.51
Clemson	1.92	2.53	4.12	5.51	6.38	6.87	7.13	6.56	4.94	3.73	2.48	1.79	53.97	41.12
Florence	2.41	2.84	4.71	6.13	7.33	7.72	7.85	6.78	5.08	3.84	2.68	2.25	59.61	44.72
Rainbow Lake	1.29	2.12	3.94	5.23	5.81	6.51	6.69	6.10	4.59	3.35	2.08	1.45	49.15	38.27
Sandhill	2.26	3.11	5.02	7.01	7.88	8.31	8.52	7.03	5.79	4.52	3.12	2.40	64.95	49.05
Simms				5.16	6.09	6.99	7.22	6.21	4.75	3.53				39.96
Union	3.07	2.07	3.70	6.17	6.23	6.62	6.92	6.33	4.83	3.47	2.20	2.56	54.17	40.57
Average	2.40	2.77	4.52	5.96	6.83	7.36	7.54	6.61	5.20	3.92	2.67	2.20	57.99	43.42

Extension/Infilling Methodology

The eight long-term datasets use pan data on all dates where pan data are available and were not censored due to quality control issues. For dates without pan data, pan evaporation was modeled from modified daily Hargreaves PET estimates (**Table 5**).

Hargreaves PET was computed using EPA SWMM (Rossman, 2010). SWMM input files were prepared with daily temperature data for each site along with site latitude. Output time series of PET computed by the software was transferred to a spreadsheet. A PET-to-pan evaporation coefficient was calculated for each site by minimizing least squares error for all dates with pan data

Table 5. Hargreaves PET to pan evaporation

Pan data source	Sandhill	Charleston	Barnwell	Chesnee	Clarks Hill	Clemson	Florence	Union
Temperature source	Columbia	Charleston	Orange-burg	Greenville-Spartanburg	Clarks Hill	Clemson	Florence	Union
Hargreaves -> pan coefficient	1.22	1.27	1.07	1.07	0.93	1.03	1.11	0.96
Pan average (in)	0.20	0.20	0.17	0.20	0.15	0.16	0.17	0.16
Adjusted Hargreaves matching dates (in)	0.19	0.19	0.16	0.19	0.15	0.15	0.17	0.15
Adjusted Hargreaves all dates (in)	0.18	0.18	0.16	0.15	0.14	0.15	0.16	0.14

Summary statistics

Resulting monthly average adjusted pan estimates are shown in **Table 6**. The composited estimates average 0.2 inches per month less than the actual pan data for November through April, and 0.1 inches per month greater than the pan data for May through October. These differences occur because of limitations of the estimation method, the reduced number of pan measurements during winter, and climatic variations among years with and without pan data . Thirty-eight percent of the composite dataset is comprised of actual pan measurements, ranging from 13% of total dates over 90 years at Union to 66% at Clemson.

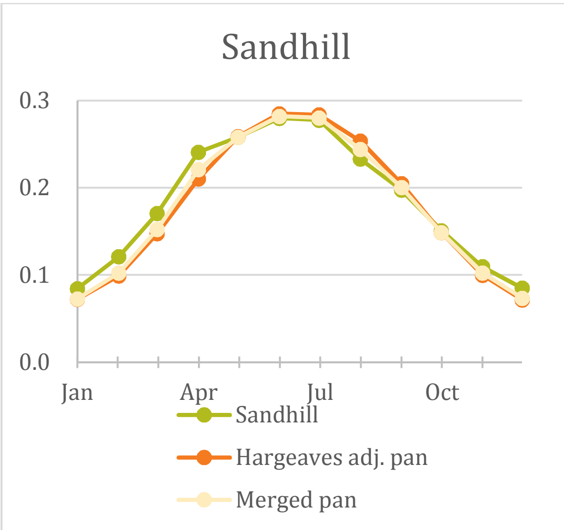
Table 6. Monthly composite pan evaporation estimates

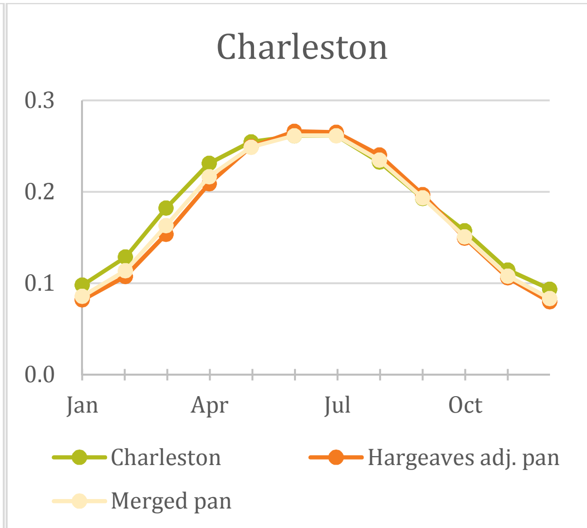
Inches	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Apr-Oct
Charleston	2.66	3.22	5.06	6.50	7.72	7.85	8.11	7.28	5.80	4.68	3.24	2.59	64.72	47.95
Barnwell	2.20	2.67	4.32	5.80	7.10	7.52	7.63	6.79	5.41	4.14	2.71	2.11	58.40	44.39
Chesnee	1.71	2.22	3.74	5.45	6.77	7.50	7.63	6.80	5.28	3.77	2.31	1.65	54.82	43.20
Clarks Hill	1.80	2.26	3.69	5.01	6.13	6.71	6.83	6.12	4.82	3.61	2.32	1.72	51.03	39.24
Clemson	1.86	2.42	4.01	5.46	6.52	7.05	7.24	6.59	5.10	3.79	2.47	1.78	54.29	41.75
Florence	2.09	2.59	4.23	5.82	7.22	7.71	7.83	6.98	5.52	4.14	2.70	2.02	58.84	45.22
Sandhill	2.25	2.89	4.72	6.63	8.00	8.46	8.68	7.56	6.01	4.61	3.08	2.28	65.17	49.96
Union	1.73	2.08	3.51	5.11	6.25	6.77	7.05	6.33	4.92	3.58	2.23	1.69	51.26	40.02
Average	2.04	2.54	4.16	5.72	6.96	7.45	7.63	6.81	5.36	4.04	2.63	1.98	57.32	43.96

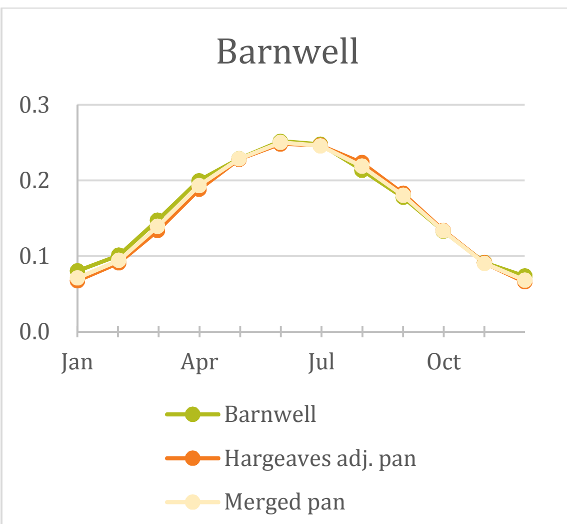
Figure 1 shows the values from Table 6. **Figures 2** through **9** show average daily pan evaporation by month for each station, with traces shown for the raw pan data, pan estimates derived from Hargreaves PET, and the final merged dataset. The figures show generally good agreement year-round at each site, with measured pan values somewhat higher than the Hargreaves estimates and final dataset averages in winter primarily at Sandhill, Charleston, and Florence. The Union figure shows inconsistent pan readings in the winter months due to the small size of its dataset.

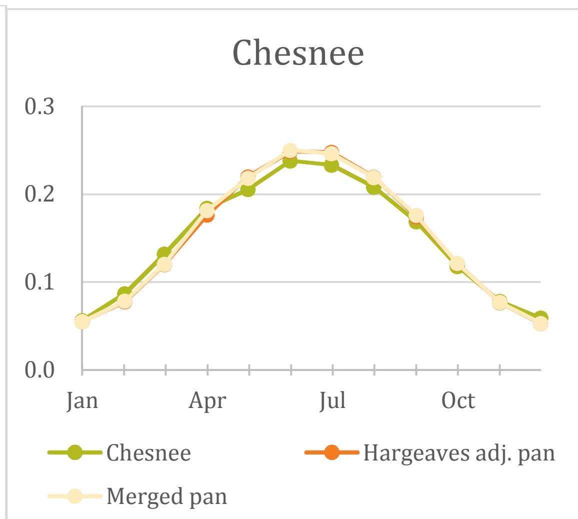
Overall, the method for obtaining daily evaporation estimates used here has the advantage of using available pan evaporation data in combination with modeled estimates calibrated to the measured datasets. The method was not rigorously checked to ensure consistency in variability between the measured and modeled values, and may also introduce variance due to the use of multiple temperature stations, and, in two cases, combination of data from different evaporation sites.

Figures 2, 3, 4, and 5 - Average Daily Pan Evaporation by Month

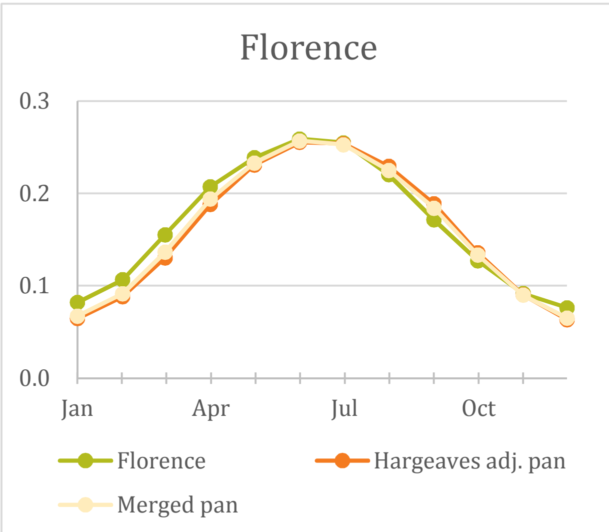


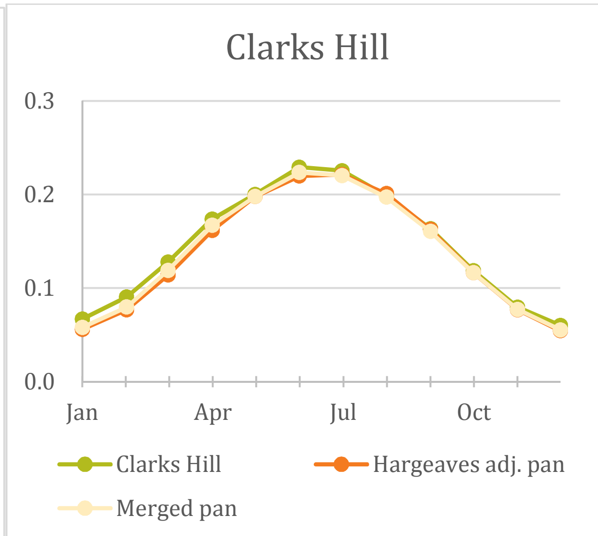


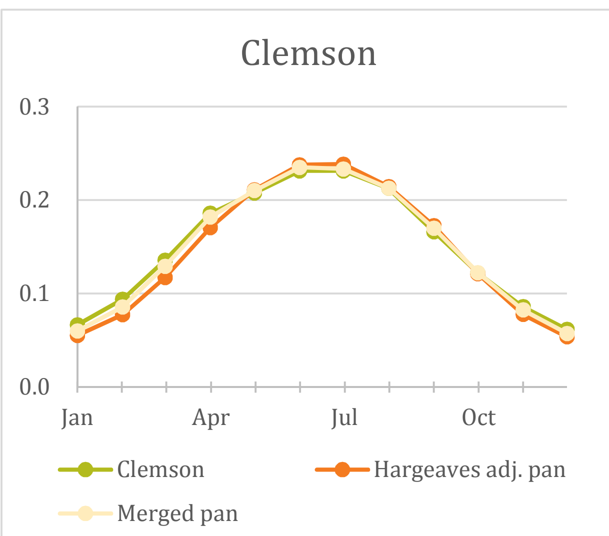


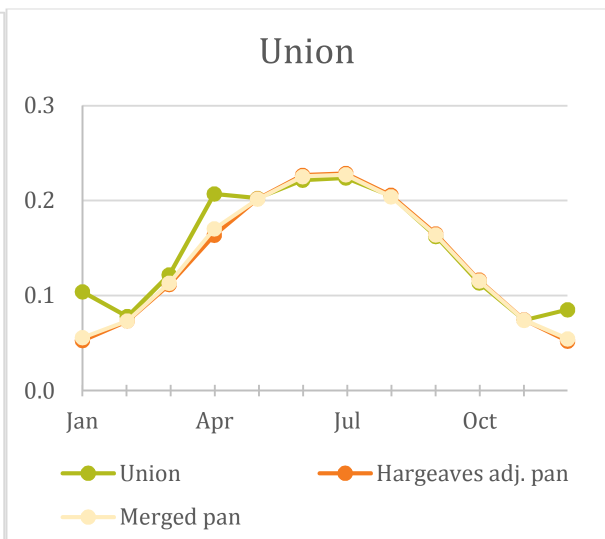


Figures 6, 7, 8, and 9 - Average Daily Pan Evaporation by Month









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