

Reference Evapotranspiration (1948-2013) using 51-year Hydrological Reanalysis and North American Regional Reanalysis

By Clay Brown



South Florida Water Management District

Water Resources Division

Water Supply Bureau

Hydrologic and Environmental Systems Modeling Section

October 2013

Acknowledgments

This document and data were a product of detailed research and model development conducted by individuals and government agencies as noted in the literature cited.

Key climate investigations referenced in this document include studies performed by Michelle Irizarry. Significant contributions to understanding and implementing of the data were possible through the efforts of Paul Trimble.

Lastly, additional recognition goes to Jose Otero for providing project support, review, and technical contributions.

Table of Contents

Table of Contents	ii
List of Figures	iv
List of Tables	vi
Introduction	8
Equation.....	8
Interpolation Method	9
Dataset Development.....	10
NLDAS Data Processing.....	11
Step 1: Obtain Data	11
Step 2: Extract Data.....	14
Step 3: Aggregate Data Daily	14
Step 4: Create Reference ET	14
Step 5: Format Data for ArcMap TIN Utility.....	17
Step 6: Execute ArcMap TIN Utility.....	17
Step 7: Format Data.....	19
HYDRO51 Data Processing.....	20
Step 1: Obtain Data	20
Step 2: Aggregate Data Daily	22
Step 3: Create Reference ET	22
Step 4: Rescale Data	23
Step 5: Format Data for ArcMap TIN Utility.....	23
Step 6: Execute ArcMap TIN Utility.....	23
Step 7: Format Data.....	24
Combine Datasets	25
Step 1: Create GRIDIO File	25
Step 2: Extract NSM/WMM Data Extent	25
Results.....	26
Future Work	32
References.....	33
Appendix A Adjacent Cell Data Expansion of HYDRO51 and NLDAS Datasets	34
HYDRO51	35
NLDAS	37

Appendix B Comparison of Previous and New Reference ET (1965-2005)	39
Appendix C New Reference ET (2006-2012) and Climatic 30 Year Average (1981-2010)	83

List of Figures

Figure 1. District Full Extent grid (left) and HYDRO51/NLDAS 1/8 degree spatial resolution grid (right).	9
Figure 2. Process diagram for creating ET_o dataset (1965-2013).	10
Figure 3. Spatial resolution refinement in NLDAS dataset.	12
Figure 4. Spatial extent of NLDAS dataset.	13
Figure 5. USGS observation stations with NLDAS grid.	15
Figure 6. Monthly average of USGS observed and NLDAS solar radiation.	16
Figure 7. NLDAS grid with District Full Extent grid centers.	18
Figure 8. Spatial extent of HYDRO51 dataset.	21
Figure 9. HYDRO51 grid with District Full Extent grid centers.	24
Figure 10. Annual comparison of existing and new ET_o .	26
Figure 11. Seasonal comparison of existing and new ET_o .	27
Figure 12. Comparison of average of annual ET_o (1965-2005).	31
Figure A-1. HYDRO51 cells used to populate "No Data" cells.	36
Figure A-2. NLDAS cells used to populate "No Data" cells.	38
Figure B-1. Comparison of previous and new reference ET for 1965.	40
Figure B-2. Comparison of previous and new reference ET for 1966.	41
Figure B-3. Comparison of previous and new reference ET for 1967.	42
Figure B-4. Comparison of previous and new reference ET for 1968.	43
Figure B-5. Comparison of previous and new reference ET for 1969.	44
Figure B-6. Comparison of previous and new reference ET for 1970.	45
Figure B-7. Comparison of previous and new reference ET for 1971.	46
Figure B-8. Comparison of previous and new reference ET for 1972.	47
Figure B-9. Comparison of previous and new reference ET for 1973.	48
Figure B-10. Comparison of previous and new reference ET for 1974.	49
Figure B-11. Comparison of previous and new reference ET for 1975.	50
Figure B-12. Comparison of previous and new reference ET for 1976.	51
Figure B-13. Comparison of previous and new reference ET for 1977.	52
Figure B-14. Comparison of previous and new reference ET for 1978.	53
Figure B-15. Comparison of previous and new reference ET for 1979.	54
Figure B-16. Comparison of previous and new reference ET for 1980.	55
Figure B-17. Comparison of previous and new reference ET for 1981.	56
Figure B-18. Comparison of previous and new reference ET for 1982.	57
Figure B-19. Comparison of previous and new reference ET for 1983.	58

Figure B-20. Comparison of previous and new reference ET for 1984.	59
Figure B-21. Comparison of previous and new reference ET for 1985.	60
Figure B-22. Comparison of previous and new reference ET for 1986.	61
Figure B-23. Comparison of previous and new reference ET for 1987.	62
Figure B-24. Comparison of previous and new reference ET for 1988.	63
Figure B-25. Comparison of previous and new reference ET for 1989.	64
Figure B-26. Comparison of previous and new reference ET for 1990.	65
Figure B-27. Comparison of previous and new reference ET for 1991.	66
Figure B-28. Comparison of previous and new reference ET for 1992.	67
Figure B-29. Comparison of previous and new reference ET for 1993.	68
Figure B-30. Comparison of previous and new reference ET for 1994.	69
Figure B-31. Comparison of previous and new reference ET for 1995.	70
Figure B-32. Comparison of previous and new reference ET for 1996.	71
Figure B-33. Comparison of previous and new reference ET for 1997.	72
Figure B-34. Comparison of previous and new reference ET for 1998.	73
Figure B-35. Comparison of previous and new reference ET for 1999.	74
Figure B-36. Comparison of previous and new reference ET for 2000.	75
Figure B-37. Comparison of previous and new reference ET for 2001.	76
Figure B-38. Comparison of previous and new reference ET for 2002.	77
Figure B-39. Comparison of previous and new reference ET for 2003.	78
Figure B-40. Comparison of previous and new reference ET for 2004.	79
Figure B-41. Comparison of previous and new reference ET for 2005.	80
Figure B-42. Average annual (1965-2005) comparison of previous and new reference ET.	81
Figure B-43. Average annual (1965-2005) difference map of previous and new reference ET.	82
Figure C-1. Annual reference ET 2006.	84
Figure C-2. Annual reference ET 2007.	85
Figure C-3. Annual reference ET 2008.	86
Figure C-4. Annual reference ET 2009.	87
Figure C-5. Annual reference ET 2010.	88
Figure C-6. Annual reference ET 2011.	89
Figure C-7. Annual reference ET 2012.	90
Figure C-8. 30 year climatic average (1981-2010).	91

List of Tables

Table 1. Conversion factors, datums and acronyms.	vii
Table 2. NLDAS parameters for processing.	14
Table 3. Unit conversions for NLDAS.	14
Table 4. Monthly average, average error, and positive bias of USGS observed and NLDAS data.	16
Table 5. Monthly average, average error, and positive bias of USGS observed and NLDAS data.	16
Table 6. HYDRO51 parameters for processing.	22
Table 7. Unit conversions for HYDRO51.	22
Table 8. Monthly summary (inches) of new ET_o (1948-2013).	27
Table 9. Monthly difference (inches) between new and previous ET_o (1948-2013).	29
Table A-1. HYDRO51 cells used to populate "No Data" cells.	35
Table A-2. NLDAS cells used to populate "No Data" cells.	37

Table 1. Conversion factors, datums and acronyms.

Multiply	By	To Obtain
Length		
inch (in)	2.54	centimeter (cm)
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft ²)	0.0929	square meter (m ²)
square mile (mi ²)	2.590	square kilometer (km ²)
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	640.0	acre
Volume		
cubic foot (ft ³)	0.2832	cubic meter (m ³)
acre-foot	1233.48	cubic meter (m ³)
Flow rate		
acre-foot per year (acre-ft/yr)	1233.046	cubic meter per year (m ³ /yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per day (ft ³ /d)	0.2832	cubic meter per day (m ³ /d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)
Transmissivity		
foot squared per day (ft ² /d)	0.0929	meter squared per day (m ² /d)
Velocity		
inch per second (in/s)	25.4	millimeter per second (mm/s)
inch per day (in/d)	2.54	centimeter per day (cm/d)
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
Datums		
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).		
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) - High Accuracy Range Network (HARN).		

SFWMD

South Florida Water Management District

District Full Extent

A uniform grid with 119 rows x 70 columns, each cell is 2 mile by 2 mile, that covers the entire extent of the SFWMD

INTRODUCTION

Evapotranspiration (ET) is a major part of the hydrologic cycle in south Florida where the water table is near or above the land surface for much of the year. The calculation of ET by the model is based on reference evapotranspiration (ET_o), which is adjusted according to vegetation type, available soil moisture content, and location of the water table.

The objective of the ET_o dataset update was to expand the period of record from 2005 to 2010 using the same methodology prescribed for the ET_o as described in the South Florida Water Management Model Version 7.0. During the data download and subsequent processing, data was acquired through June 10, 2013 1200 hours; therefore, the final dataset in this document is referred to as a long term dataset from 1948 to 2013. The domain of this dataset occupies the area within the political boundary of the South Florida Water Management District (District) to ensure consistency between various District models as well as dataset economy.

Two datasets were used to create the ET_o dataset. The first dataset were a 51-year hydrological reanalysis (1948-1998) using the NOAA¹ land surface model (LSM) at 1/8th degree grid spacing completed at the Climate Prediction Center (CPC) of the National Center for Environmental Prediction, NOAA; referred to as HYDRO51. The second dataset were generated by the North American Land Data Assimilation System comprised of data from 1979 to present at 1/8th degree grid spacing; referred to as NLDAS. The input data includes all observations used in National Centers for Environmental Prediction–National Center For Atmospheric Research (NCEP–NCAR) Global Reanalysis project. NLDAS integrates data based on observation and reanalysis to guide offline land surface models. It is important to note that there was a refinement in grid spacing and temporal resolution in the NLDAS dataset. In addition, the surface downward shortwave radiation was bias-corrected. Although the same process was used to create the previous and new versions of ET_o , differences resulted when the datasets were compared. The differences represent improvements due to refinements in the NLDAS dataset.

EQUATION

The temporal expansion of the dataset was based on previous research and methods by the District (Irizarry-Ortiz et al., 2007). The reanalysis data used from HYDRO51 and NLDAS facilitates the use of the Penman-Montieth Method to estimate evapotranspiration. This methodology uses the recommended ASCE Penman-Montieth standardized reference equation (Irmak et al., 2005, Itenfisu et al., 2003) and calculates reference grass ET_o with specified physical characteristics (Smith et al. 1992). The Penman-Montieth Method requires the following meteorological parameters: solar radiation, relative humidity, wind speed and temperature. The equation is expressed as:

¹ The Environmental Modeling Center of NCEP created the name “NOAH” to recognize the LSM collaborators:

N - National Centers for Environmental Prediction (NCEP)

O - Oregon State University (Department of Atmospheric Sciences)

A – U.S. Air Force (both AFWA and AFRL - formerly AFGL, PL)

H - Hydrologic Research Lab - NWS (now Office of Hydrologic Development -- OHD).

$$ET_o = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 3.04u_2)}$$

where ET_o = standardized grass reference evapotranspiration (mm/day), Rn = calculated net radiation at the crop surface ($\text{MJ}/\text{m}^2\cdot\text{d}$), G is soil heat flux density at the soil surface ($\text{MJ}/\text{m}^2\cdot\text{d}$), T is the mean daily air temperature at 2 m height ($^{\circ}\text{C}$), u_2 is the wind speed at 2 m height (m/s), e_s is saturation vapor pressure (kPa), e_a is mean actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve ($\text{kPa}/^{\circ}\text{C}$), γ is psychrometric constant ($\text{kPa}/^{\circ}\text{C}$), and the units for 0.408 are $\text{m}^2\cdot\text{mm} / \text{MJ}$.

INTERPOLATION METHOD

A simple procedure was used to populate the District Full Extent grid (119 rows x 70 columns with 2 mile by 2 mile cells) with the ET_o dataset, Figure 1 left. Both datasets, HYDRO51 and NLDAS, use a 1/8 degree spatial resolution grid, shown in Figure 1 right. A triangulated irregular network (TIN) was created for each daily time step using the spatial locations of the 1/8 degree grid centers and Penman-Monteith ET_o . The grid centers of the District Full Extent grid were populated using data that was linearly interpolated from the TIN.

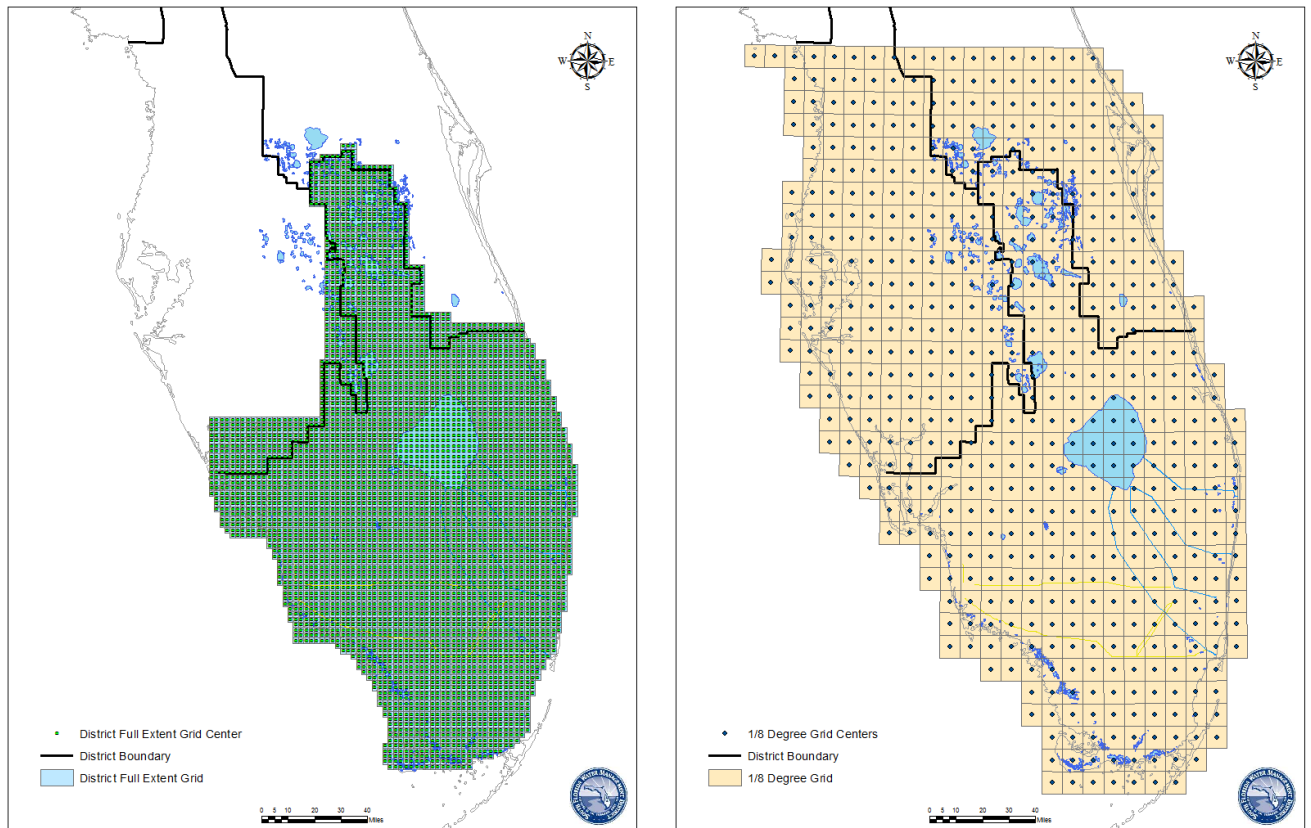


Figure 1. District Full Extent grid (left) and HYDRO51/NLDAS 1/8 degree spatial resolution grid (right).

DATASET DEVELOPMENT

Creation of the long term (1948-2013) ET_o dataset was performed incrementally. The process diagram is shown in Figure 2; each block corresponds to a folder on the network and is described below. The path to the ET_o folder listed in the process diagram is:

[\\ad.sfwmd.gov\dfsroot\data\hesm_san\data\et\PET_48_13](http://ad.sfwmd.gov/dfsroot/data/hesm_san/data/et/PET_48_13) (Windows) or
/nw/hesm_san/data/et/PET_48_13 (Linux)

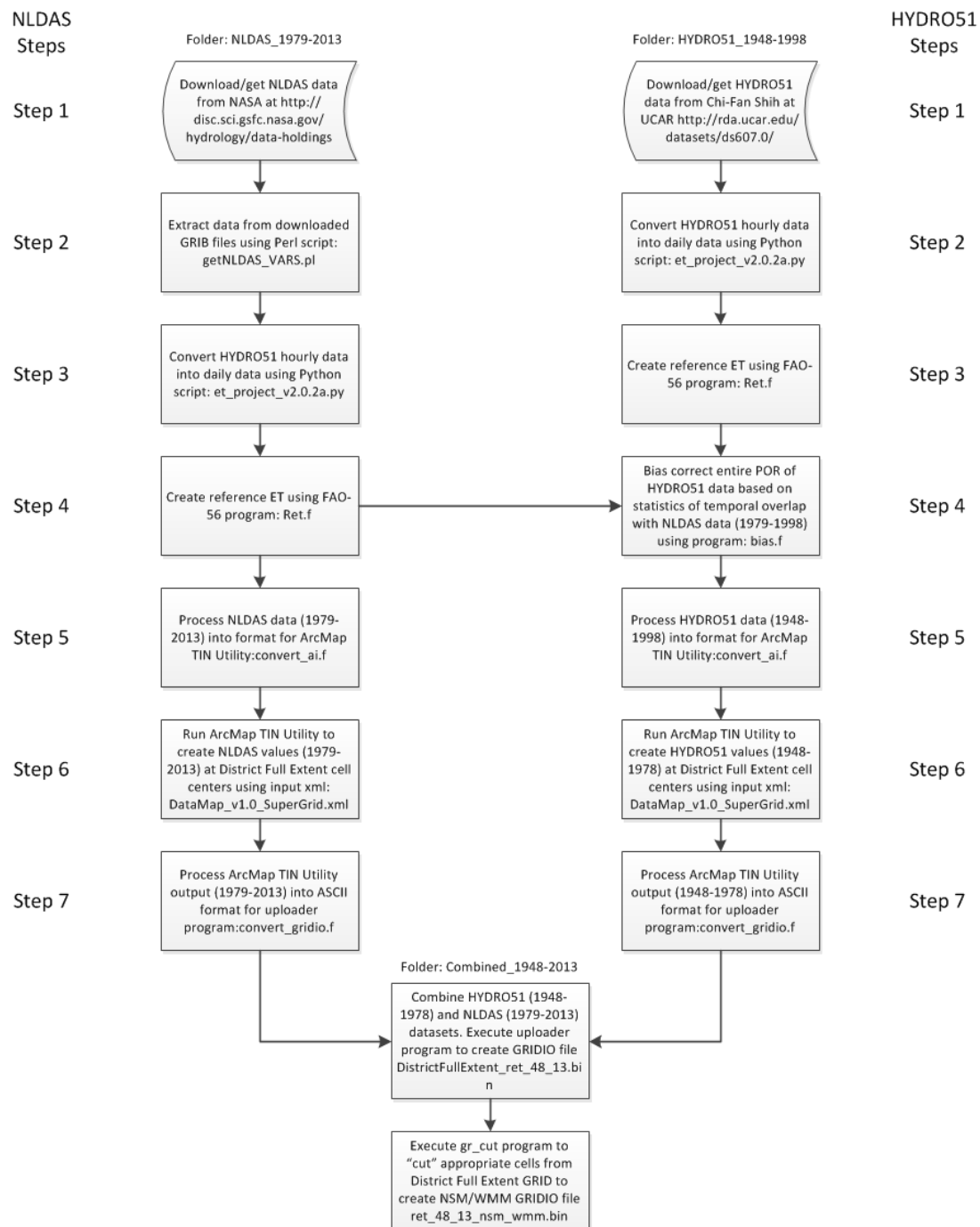


Figure 2. Process diagram for creating ET_o dataset (1965-2013).

NLDAS DATA PROCESSING

The NLDAS non-precipitation land-surface forcing fields were derived from the NCEP North American Regional Reanalysis (NARR). NARR consists of: 1) a dataset starting from Jan 1979, and 2) a daily update execution at NCEP. NARR is a long-term, high frequency, dynamically consistent meteorological and land surface hydrology dataset (Rui, 2013). NARR is a robust method for spatially estimating hydrologic and atmospheric parameters at a regional resolution. Estimation of the variables was accomplished by incorporating observational data with the underlying principles governing the system. This methodology facilitates a realistic estimation.

It is important to note that there was a refinement in grid spacing and temporal resolution in the NLDAS dataset. The NARR fields used to generate NLDAS forcing fields are spatially interpolated from the NARR 32 km grid to a finer resolution NLDAS 12 km (1/8th-degree) grid and then temporally disaggregated from NARR 3 hourly to the NLDAS hourly frequency, shown in Figure 3. Additionally, the fields of surface pressure, surface downward longwave radiation, near-surface air temperature and near-surface specific humidity were adjusted vertically to account for the vertical difference between the NARR and NLDAS fields of terrain height (Rui, 2013).

It is important to note that a bias-correction algorithm was applied to the NARR surface downward shortwave radiation using five years (1996-2000) of hourly 1/8th-degree GOES-based surface downward shortwave radiation data (Rui, 2013).

Step 1: Obtain Data

The data were obtained from Goddard Earth Sciences Data and Information Services Center (GES DISC). The data selected were NLDAS-2, 0.125 degree, North America, NLDAS_FORA0125_H.002 Primary forcing. Spatially, the data covers longitude (decimal degrees) from -84.0 to -80.0 and latitude (decimal degrees) from 24.0 to 30.0. Grid cells with data available for processing are shown in Figure 4.

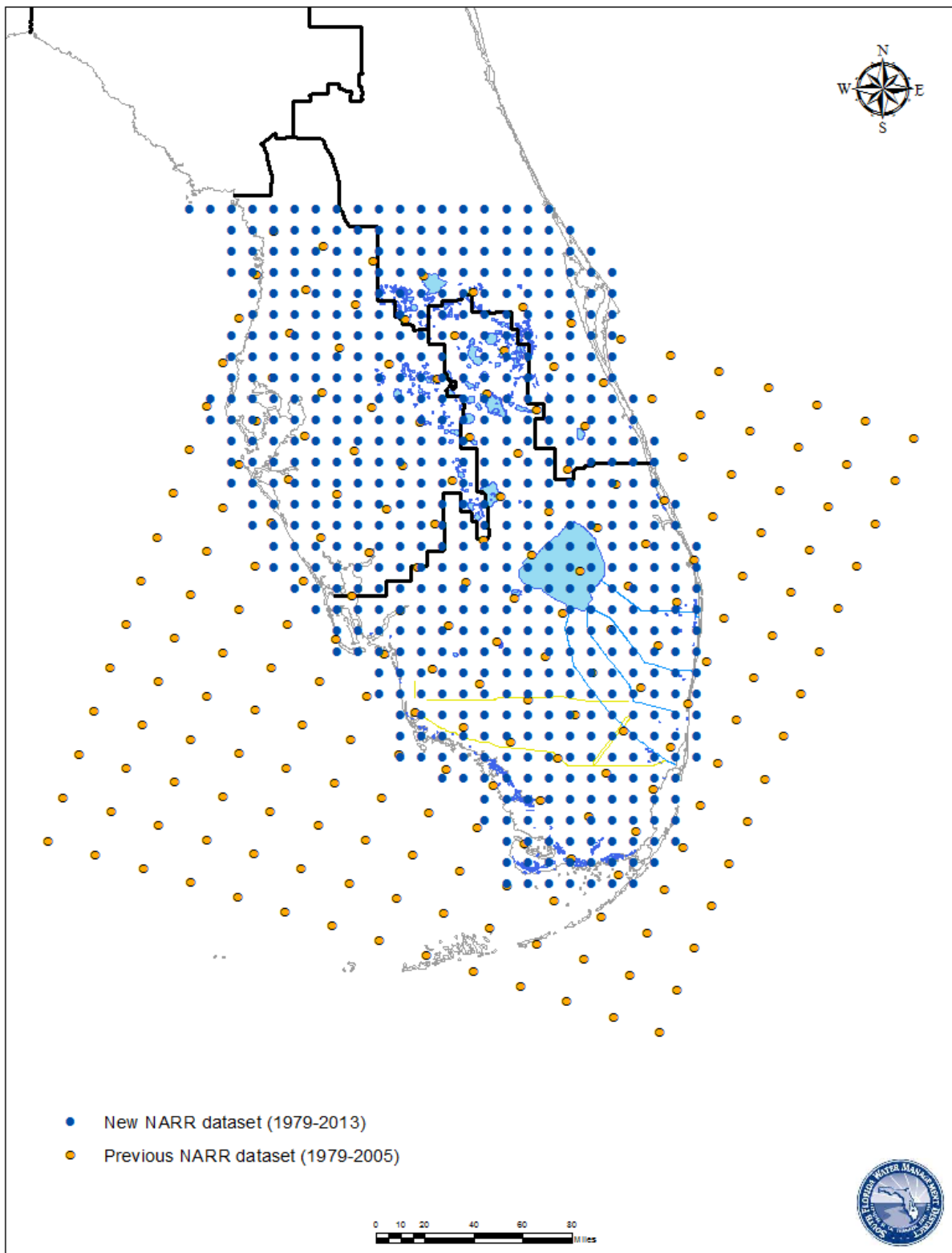


Figure 3. Spatial resolution refinement in NLDAS dataset.

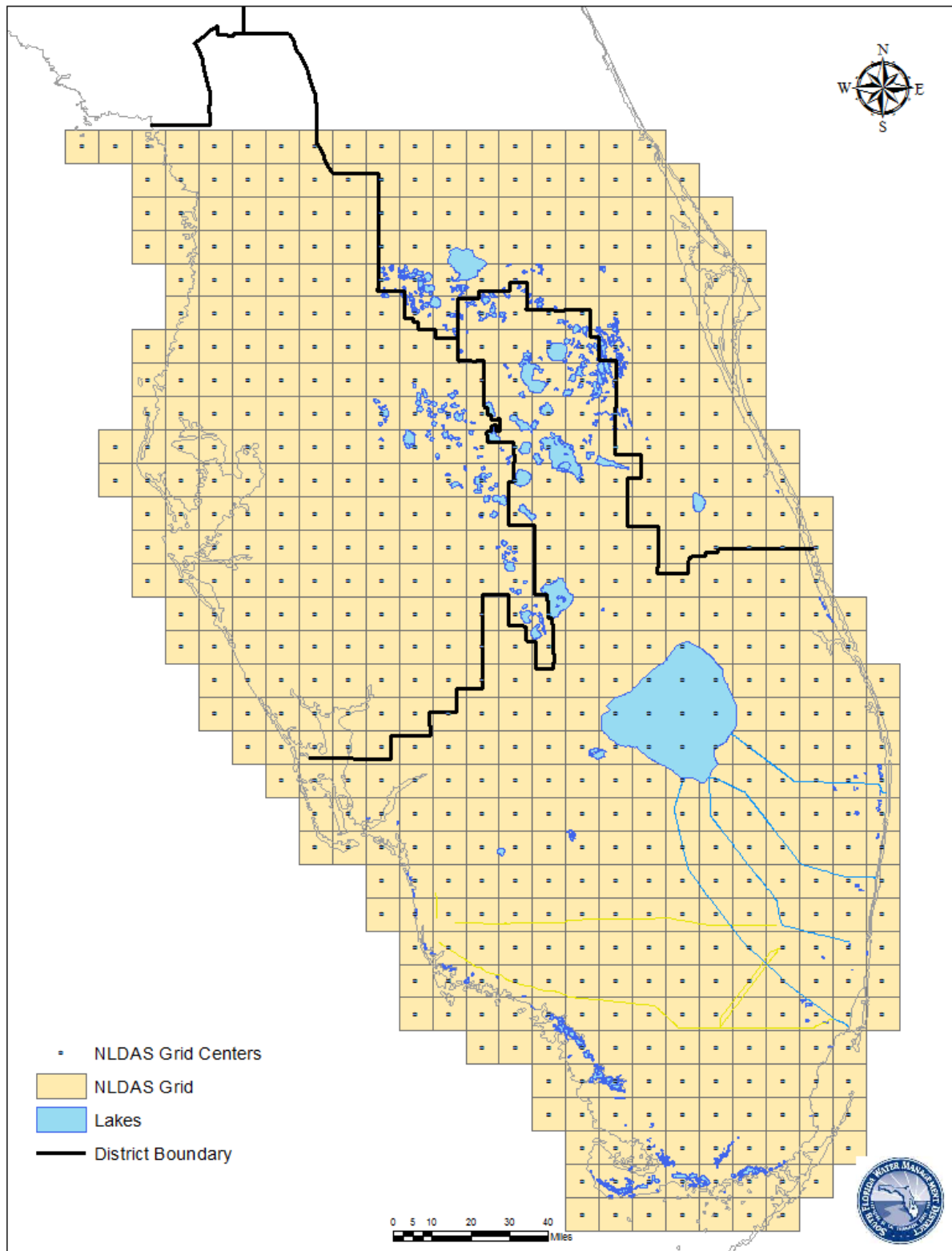


Figure 4. Spatial extent of NLDAS dataset.

Temporally, the data covers hourly data from January 1, 1979 to June 10, 2013. The data were downloaded using the linux “wget” command with the appropriate download input file and is currently located in its respective ET_o folder. Each downloaded file, in GRIB format, is representative of a unique date/time stamp and contains seven parameters listed in Table 2.

Table 2. NLDAS parameters for processing.

Parameters and units	Short name	Level
Temperature [K]	TMP	2m above ground
Pressure [Pa]	PRES	Ground or water surface
Downward long wave rad. flux [W/m ²]	DLWRF	Ground or water surface
Specific humidity [kg/kg]	SPFH	2m above ground
u-component of wind [m/s]	UGRD	10m above ground
v-component of wind [m/s]	VGRD	10m above ground
Downward short wave rad. flux [W/m ²]	DSWRF	Ground or water surface

Step 2: Extract Data

A “Perl” script was used to extract parameters from each GRIB file and store in ASCII format. The script getNLDAS_VAR.pl is located in its respective ET_o folder.

Step 3: Aggregate Data Daily

The hourly data was aggregated into daily values using the “Python” script et_project_v2.0.2a.py located in its respective ET_o folder. The script converts the data into the units listed in Table 3.

Table 3. Unit conversions for NLDAS.

Parameters and units	Short name	Unit conversion
Temperature [K]	TMP	Celsius
Pressure [Pa]	PRES	KPa
Downward long wave rad. flux [W/m ²]	DLWRF	MJ/m ² /d
Specific humidity [kg/kg]	SPFH	No conversion
u-component of wind [m/s]	UGRD	No conversion
v-component of wind [m/s]	VGRD	No conversion
Downward short wave rad. flux [W/m ²]	DSWRF	MJ/m ² /d

Step 4: Create Reference ET

Although the surface downward shortwave radiation was a bias-corrected field, observed differences are present when compared to USGS observation stations (German, 2000). A significant regional positive bias was observed in the solar radiation component. The bias has been determined to be overestimated by 10 to 20% (Betts et al., 1997). In order to rescale the NLDAS data, a comparison was performed with USGS observation sites. The observed solar radiation data from 9 USGS observation stations were compared with the nearest NLDAS grid cell, shown in Figure 5. The monthly average for observed and NLDAS data were computed using daily data from 1996 to 1999, shown in Figure 6 and Table 4.

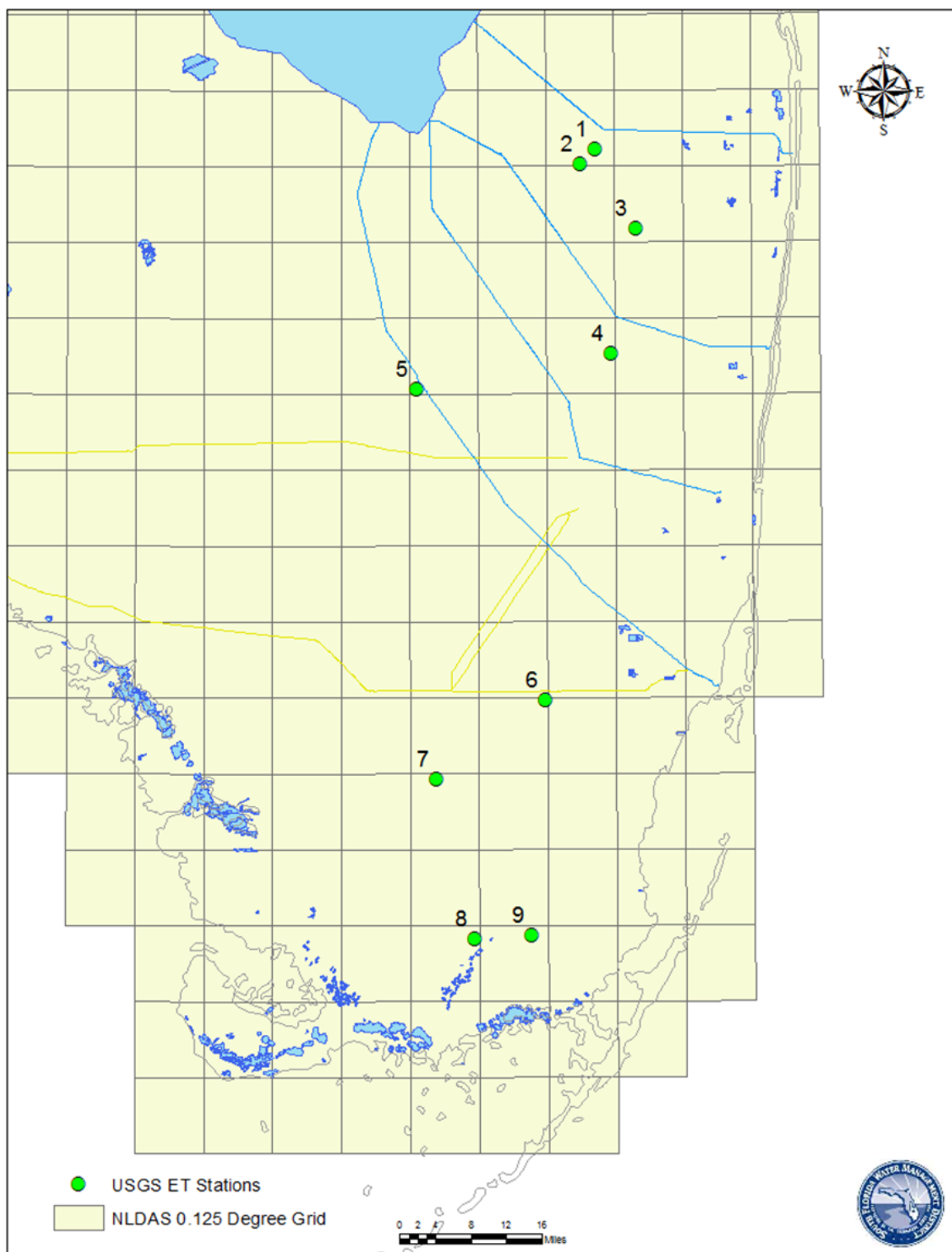


Figure 5. USGS observation stations with NLDAS grid.

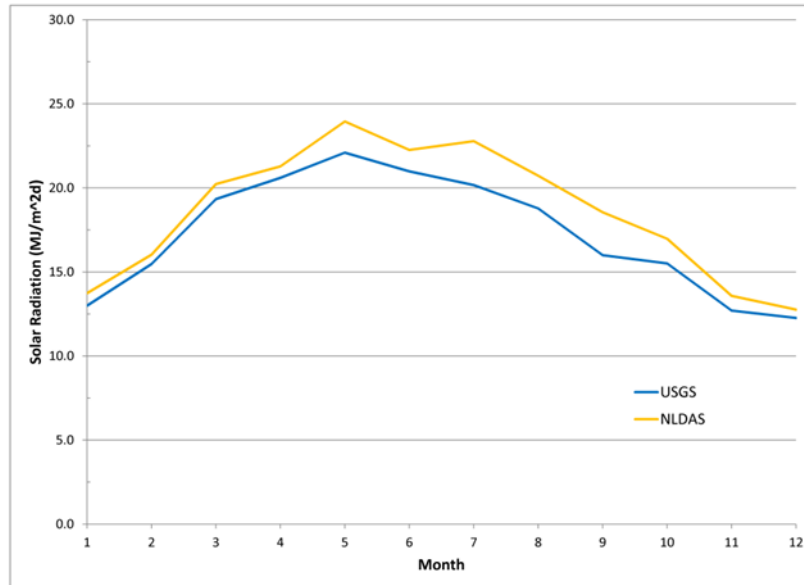


Figure 6. Monthly average of USGS observed and NLDAS solar radiation.

Table 4. Monthly average, average error, and positive bias of USGS observed and NLDAS data.

Month	USGS Observed	NLDAS	Average Error	Positive Bias
1	13.00	13.75	0.74	5.7%
2	15.48	16.03	0.56	3.6%
3	19.33	20.23	0.89	4.6%
4	20.60	21.28	0.68	3.3%
5	22.10	23.95	1.86	8.4%
6	20.99	22.27	1.27	6.1%
7	20.17	22.78	2.61	12.9%
8	18.78	20.73	1.95	10.4%
9	16.00	18.55	2.55	16.0%
10	15.51	16.97	1.47	9.4%
11	12.70	13.58	0.88	6.9%
12	12.27	12.77	0.50	4.1%

Using the monthly positive bias, a quarterly bias based was used and applied to the NLDAS dataset. The quarterly bias is listed in Table 5.

Table 5. Monthly average, average error, and positive bias of USGS observed and NLDAS data.

Quarter (months)	Positive Bias	Multiplier in Program Ret.f
Feb-Mar-Apr	3.8%	0.9615
May-Jun-Jul	9.1%	0.9093
Aug-Sep-Oct	11.9%	0.8813
Nov-Dec-Jan	5.6%	0.9441

Using the daily files computed in Step 3 and the positive bias in Table 5, ET_o was created using a FORTRAN program. The program was based on the Food and Agricultural Organization of the

United Nations (FAO) Irrigation and Drainage Paper No. 56 (FAO-56). The methodology improves daily simulation of crop ET by considering a separate contribution of evaporation from soil (Smith et al., 1992). The program provides ET_o (units inches/day) using the Penman-Monteith, Priestley-Taylor, and Simple methods. It is important to note that the method for computing actual vapor pressure was based on relative humidity minimum/maximum and temperature minimum/maximum; relative humidity was limited to 100%; the method for computing ground heat flux was neglected. The program Ret.f is located in its respective ET_o folder.

Once complete, the ET_o dataset becomes the primary model for comparison since the (satellite based) NLDAS data were considered to be the best available. The HYDRO51 data (1948-1998), discussed in the next section, uses a model without considering satellite based data; satellite data became available in 1979. The overlap period (1979-1998) between NLDAS and HYDRO51 data was used to compute bias in the HYDRO51 Penman-Monteith ET_o dataset.

Step 5: Format Data for ArcMap TIN Utility

The NLDAS Penman-Monteith ET_o dataset was converted into a format compatible with the ArcMap TIN Utility for the period from 1/1/1979 to 6/10/2013. The program convert_ai.f is located in its respective ET_o folder. It is important to note that “No Data” cells were present along the boundary of the NLDAS dataset; this prevented the model domain of the District Full Extent from being populated. This was resolved by applying values of adjacent cell to the “No Data” cells, as detailed in Appendix A.

Step 6: Execute ArcMap TIN Utility

The ArcMap TIN Utility was executed using DataMap_v1.0_DistrictFullExtent.xml. The utility created a triangulated irregular network (TIN) for each daily time step using the spatial locations of the NLDAS cell centers and Penman-Monteith ET_o . The grid cell centers of the District Full Extent grid (119 rows x 70 columns) were linearly interpolated with the TIN created using the NLDAS data, shown in Figure 7. When referring to Figure 7, it is important to note that the cell centers of the NLDAS grid are not depicted; the 1/8 degree grid cells were shown for simplicity. The output was a file containing the ET_o at each District Full Extent grid center. This utility replaces the “gr_thsn” utility.

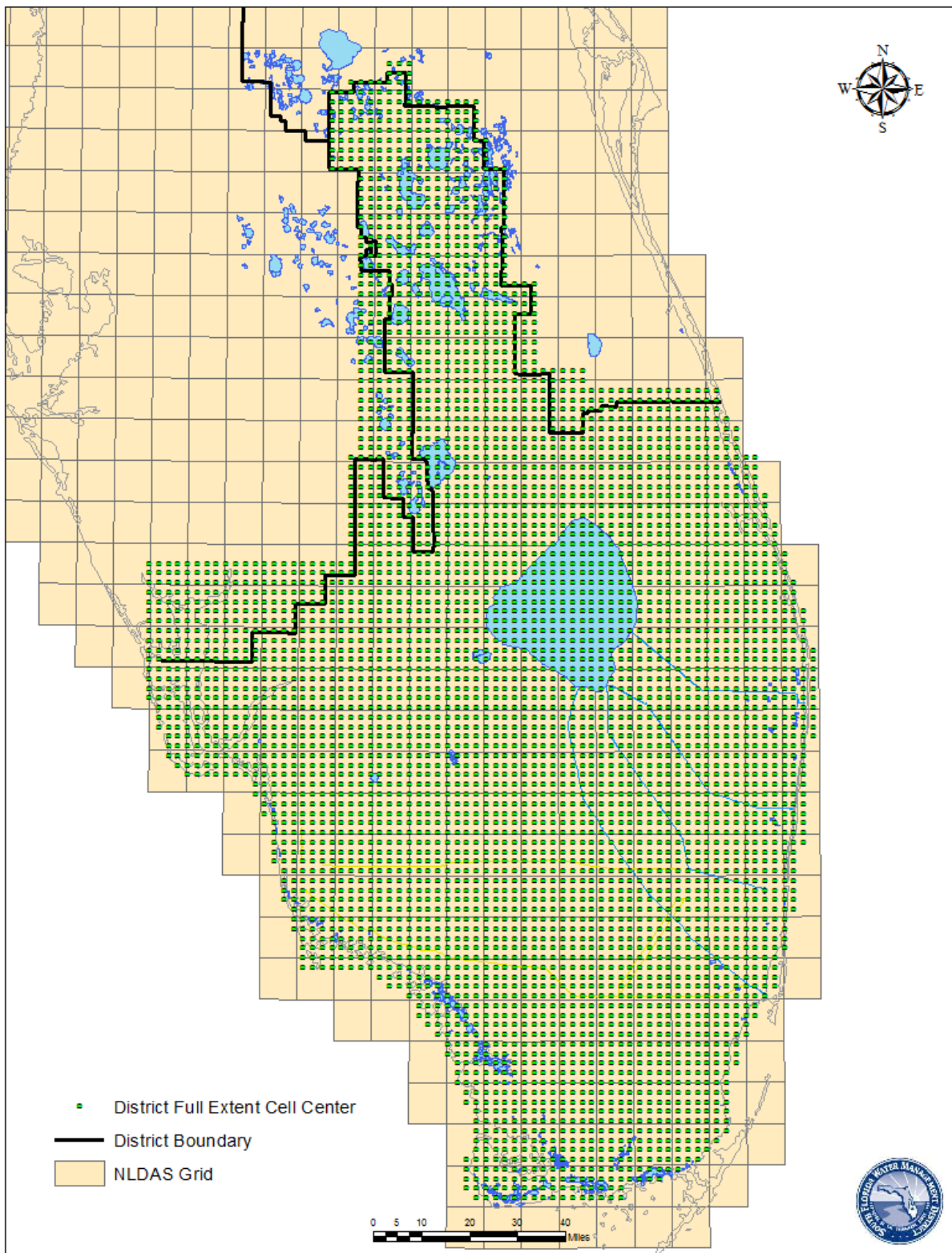


Figure 7. NLDAS grid with District Full Extent grid centers.

Step 7: Format Data

The output from the ArcMap TIN Utility was converted into a format compatible with the “uploader” program; “uploader” is a program that converts a formatted ASCII file into a GRIDIO formatted file. At this step, the file is the bias corrected NLDAS Penman-Monteith ET_o at the District Full Extent grid centers for the period of record 1/1/1979 to 6/10/2013. The program `convert_gridio.f` is located in its respective ET_o folder.

HYDRO51 DATA PROCESSING

The 51-year hydrological reanalysis hourly land surface meteorological forcing dataset was produced and used to execute the NOAH land surface model on the same $1/8^\circ$ grid as NLDAS. The surface forcing datasets includes air temperature, air humidity, surface pressure, wind speed, and surface downward shortwave and longwave radiation derived from NCEP-NCAR Global Reanalysis. The NCEP-NCAR Global Reanalysis was used to generate hourly forcing dataset on the $1/8^\circ$ NLDAS grid for 2-m air temperature and humidity, surface pressure, 10-m wind speed, surface downward shortwave radiation, and surface downward longwave radiation (Fan et al., 2006).

Step 1: Obtain Data

The data were obtained from Dr. Chi-Fan Shih of University Corporation of Atmospheric Research (UCAR). The data is currently located in its respective ET_o folder. Spatially, the data covers longitude (decimal degrees) from -83.1255 to -79.7505 and latitude (decimal degrees) from 25.0 to 29.3755. Grid cells with data available for processing are shown in Figure 8.

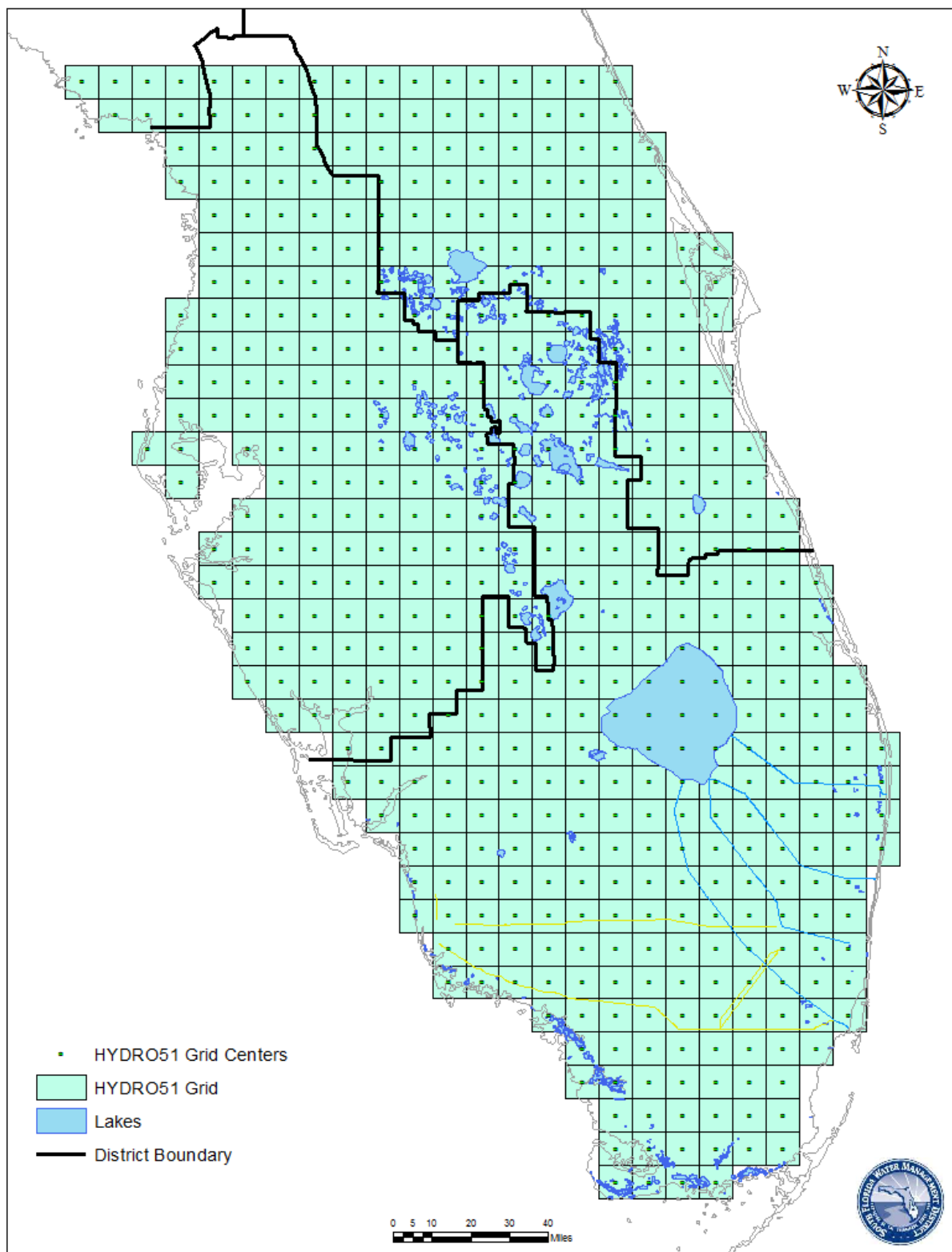


Figure 8. Spatial extent of HYDRO51 dataset.

Temporally, the data covers hourly data from January 1, 1948 to December 31, 1998. Parameters available for processing are listed in Table 6.

Table 6. HYDRO51 parameters for processing.

Parameters and units	Short name	Level
Temperature [K]	TMP	2m above ground
Pressure [Pa]	PRES	Ground or water surface
Downward long wave rad. flux [W/m ²]	DLWRF	Ground or water surface
Specific humidity [kg/kg]	SPFH	2m above ground
u-component of wind [m/s]	UGRD	10m above ground
v-component of wind [m/s]	VGRD	10m above ground
Downward short wave rad. flux [W/m ²]	DSWRF	Ground or water surface
Total precipitation [kg/m ²]	APCP	Ground or water surface

Step 2: Aggregate Data Daily

The hourly data was aggregated into daily values using the Python script `et_project_v2.0.2a.py` located in its respective ET_o folder. The Python script converts the data into the units listed in Table 7.

Table 7. Unit conversions for HYDRO51.

Parameters and units	Short name	Unit conversion
Temperature [K]	TMP	Celsius
Pressure [Pa]	PRES	KPa
Downward long wave rad. flux [W/m ²]	DLWRF	MJ/m ² /d
Specific humidity [kg/kg]	SPFH	No conversion
u-component of wind [m/s]	UGRD	No conversion
v-component of wind [m/s]	VGRD	No conversion
Downward short wave rad. flux [W/m ²]	DSWRF	MJ/m ² /d
Total precipitation [kg/m ²]	APCP	No conversion

Step 3: Create Reference ET

Using the daily files, ET_o was created using a FORTRAN program. The program was based on the Food and Agricultural Organization of the United Nations (FAO) Irrigation and Drainage Paper No. 56 (FAO-56) that improves daily simulation of crop ET by considering the separate contribution of evaporation from soil (Smith et al., 1992). The program provides ET_o (units inches/day) using the Penman-Monteith, Priestley-Taylor, and Simple methods. It is important to note that the method for computing actual vapor pressure was based on relative humidity minimum/maximum and temperature minimum/maximum; relative humidity was limited to 100%; the method for computing ground heat flux was neglected. The program `Ret.f` is located in its respective ET_o folder.

Step 4: Bias Correct Data

The HYDRO51 ET_o data was bias corrected in order to align with the NLDAS ET_o data which is considered more accurate. To accomplish this, a FORTRAN program was written that computes an average monthly value for 20 years, for the overlap period from 1979 to 1998, at each cell between the HYDRO51 and NLDAS datasets. For each cell:

$$\text{Average monthly value}_{j=1 \text{ to } 12} = \frac{\sum_{k=1979}^{1998} NLDAS_{j,k} - HYDRO51_{j,k}}{20_{\text{years}}}$$

The HYDRO51 dataset was bias corrected daily, for the entire period of record from 1948 to 1998, at each cell by adding the average daily difference computed from the 20 year monthly average. At each cell for day i in month j from 1948 to 1998:

$$HYDRO51 \text{ bias corrected}_{i,j} = HYDRO51_{i,j} + \frac{\text{Average monthly value}_j}{\text{ndays in month } j}$$

The program bias.f is located in its respective ET_o folder. It is important to note that the Penman-Monteith ET_o dataset for the NLDAS dataset was computed before the bias correction was introduced into the HYDRO51 ET_o Penman-Monteith dataset.

Step 5: Format Data for ArcMap TIN Utility

The biased ET_o Penman-Monteith dataset was converted into a format compatible with the ArcMap TIN Utility for the period from 1/1/1948 to 12/31/1978. The program convert_ai.f is located in its respective ET_o folder. It is important to note that “No Data” cells were present along the boundary of the HYDRO51 dataset; this prevented the model domain of the District Full Extent grid from being populated. This was resolved by applying values of adjacent cell to the “No Data” cells, as detailed in Appendix A.

Step 6: Execute ArcMap TIN Utility

The ArcMap TIN Utility was executed using DataMap_v1.0_DistrictFullExtent.xml. The utility created a triangulated irregular network (TIN) for each daily time step using the spatial locations of the HYDRO51 cell centers and Penman-Monteith ET_o. The grid cell centers of the District Full Extent grid (119 rows x 70 columns) were linearly interpolated with the TIN created using the HYDRO51 data, shown in Figure 9. Although Figure 7 and Figure 9 look similar, data availability varies along the shoreline. When referring to Figure 9, it is important to note that the cell centers of the HYDRO51 grid are not depicted; the 1/8 degree grid cells were shown for simplicity. The output was a file containing the ET_o at each District Full Extent grid center. This utility replaces the “gr_thsn” utility.

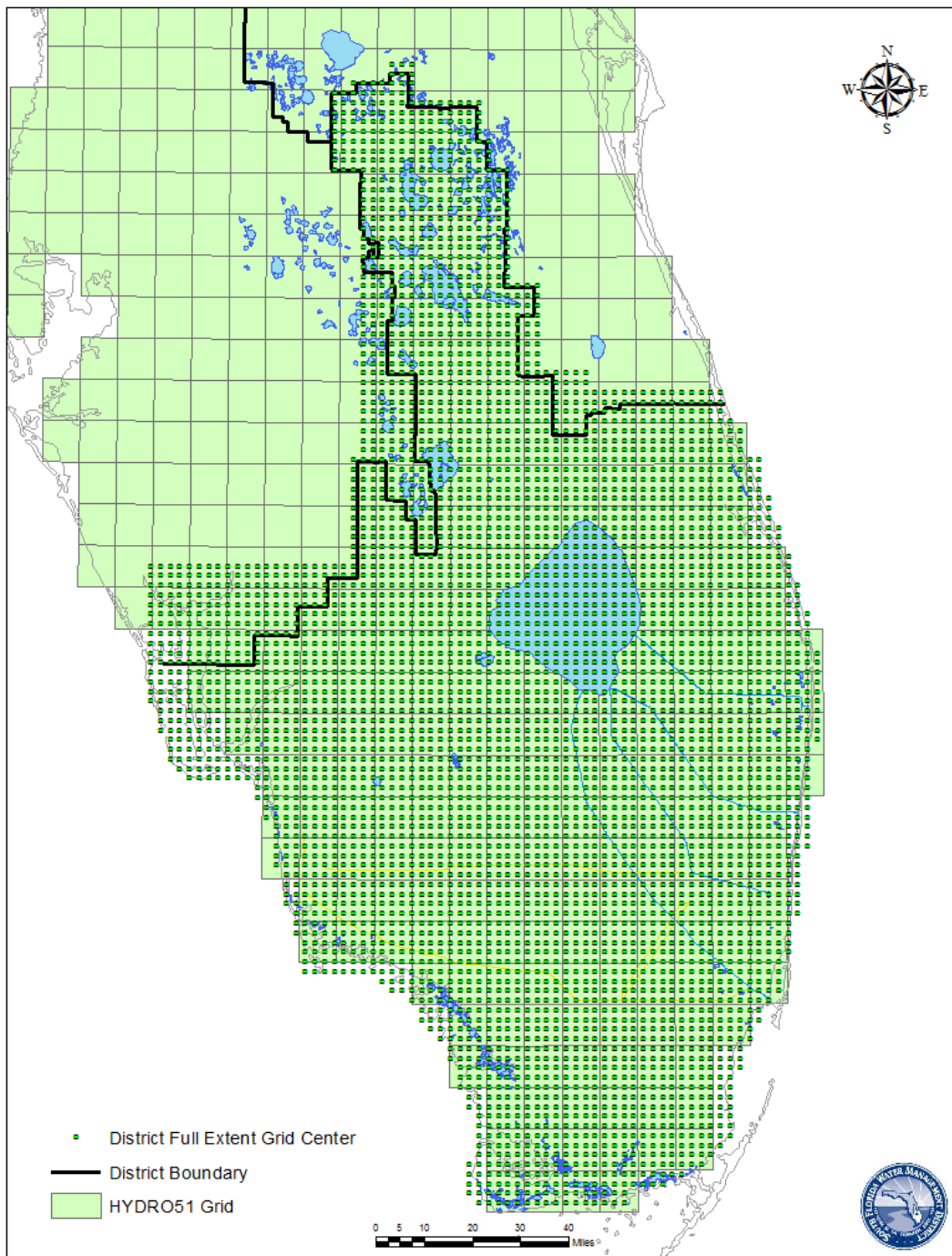


Figure 9. HYDRO51 grid with District Full Extent grid centers.

Step 7: Format Data

The output from the ArcMap TIN Utility was converted into a format compatible with the uploader program. At this step, the file is the bias corrected Penman-Monteith ET_o at the District Full Extent grid centers for the period of record 1/1/1948 to 12/31/1978. The program `convert_gridio.f` is located in its respective ET_o folder.

COMBINE DATASETS

Step 1: Create GRIDIO File

The Penman-Monteith ET_o data files from HYDRO51 (1/1/1948 to 12/31/1978) and NLDAS (1/1/1979 to 6/10/2013) were combined to create complete uploader input data file (1/1/1948 to 6/10/2013). The uploader program was executed with the Penman-Monteith ET_o file of District Full Extent grid (1/1/1948 to 6/10/2013) to create the GRIDIO file `ret_48_13.bin`. The file is located in its respective ET_o folder.

Step 2: Extract NSM/WMM Data Extent

The program “`gr_cut`” was used to create the GRIDIO file with column and row dimensions of the NSM/WMM; it was called `ret_48_13_nsm_wmm.bin`. The file is located in its respective ET_o folder.

RESULTS

A comparison of the new ET_o (1948-2013) and previous ET_o (1948-2005) for the entire District was performed and shown below. When compared annually (Figure 10) and seasonally (Figure 11), the new ET_o was slightly lower than the previous version by an average of 1.2 in/yr. For the period of record (1948-2005), the new ET_o was lower by 68.3 in. The monthly summary for the new ET_o are shown in Table 8. The differences between the new and previous (new – previous) ET_o are shown in Table 9.

Since the downloaded data had bias corrected shortwave downward radiation data, refined spatial and temporal resolution (Rui, 2013), this may result in a spatial variation or overall decrease when compared to the previous version of ET_o . To illustrate the differences, a spatial comparison of the average of annual ET_o for the common period of record (1965-2005) is shown in Figure 12. Appendix B contains the spatial comparison of the previous and new ET_o datasets for each year for the period of record (1965-2005). Appendix C contains the spatial view of the new annual average ET_o for 2006-2012 and a climatic 30 average of annual ET_o (1981-2010). The annual average ET_o for 2013 cannot be computed since the data available extends to June 10, 2013.

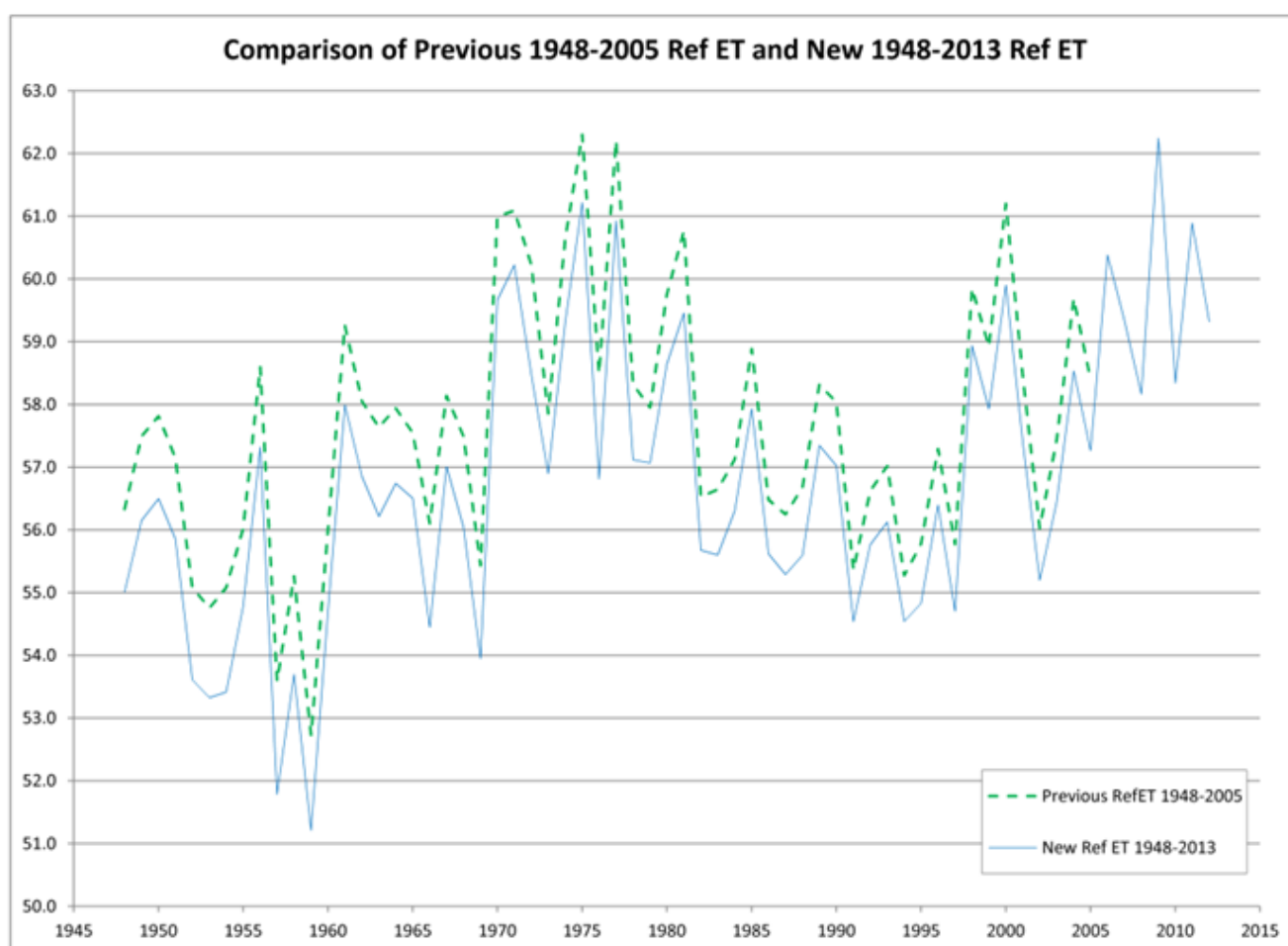


Figure 10. Annual comparison of existing and new ET_o .

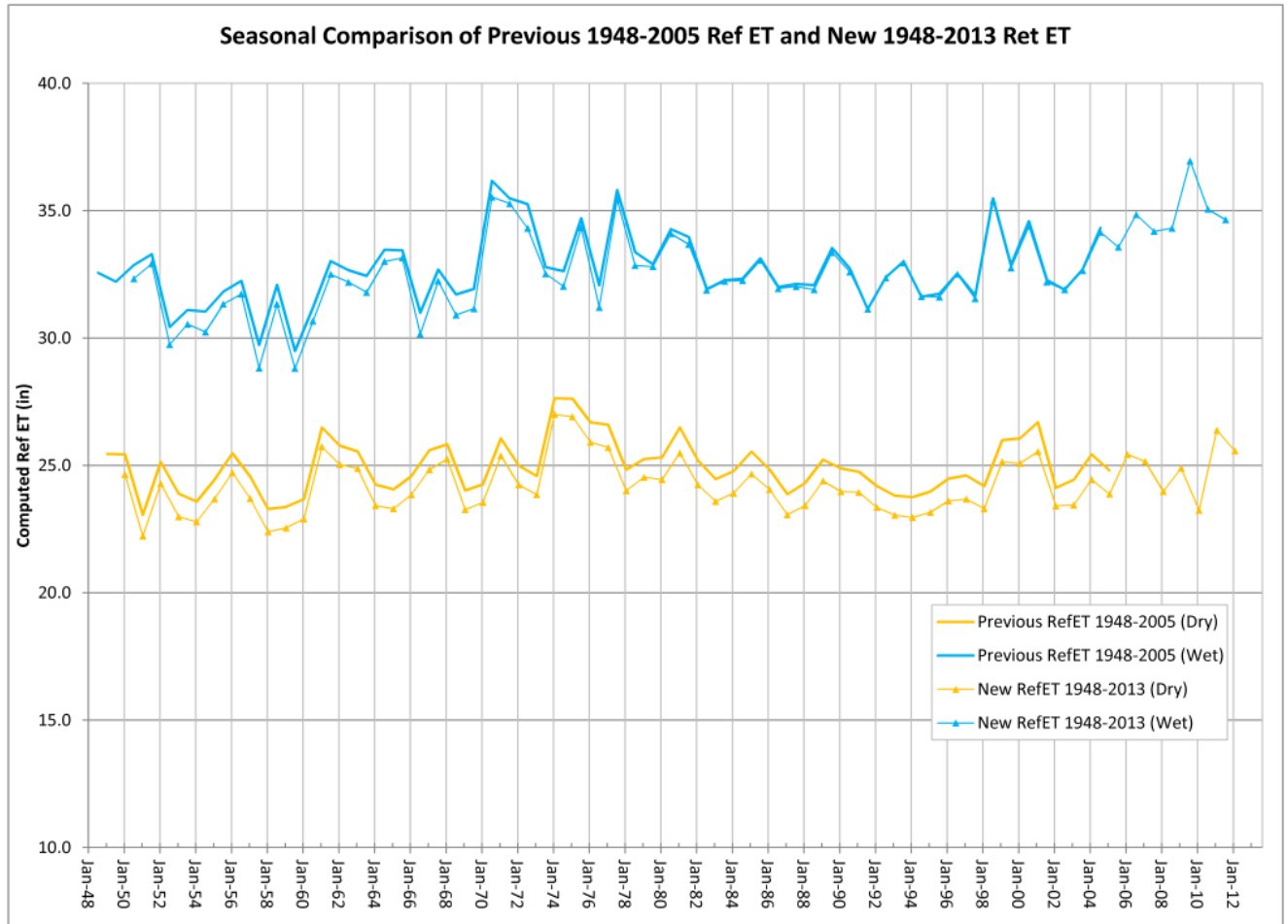


Figure 11. Seasonal comparison of existing and new ET_o.

Table 8. Monthly summary (inches) of new ET_o (1948-2013).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1948	2.69	3.65	4.69	5.32	5.94	6.35	5.86	5.40	4.35	4.17	3.56	3.03	55.01
1949	3.54	3.84	5.44	5.19	6.65	5.56	5.69	5.33	4.60	3.88	3.32	3.12	56.15
1950	3.75	3.93	4.66	5.88	6.14	6.40	6.25	5.37	4.56	3.61	3.14	2.80	56.50
1951	3.27	3.57	4.92	4.52	6.59	6.64	5.62	5.36	4.81	3.90	3.44	3.21	55.86
1952	3.25	3.48	5.01	5.90	5.40	5.79	5.65	5.28	4.27	3.36	3.33	2.90	53.61
1953	3.01	3.45	4.98	5.32	6.74	4.90	5.62	5.11	4.28	3.90	3.04	2.97	53.32
1954	3.33	3.80	4.99	4.66	5.38	5.13	5.75	5.49	4.43	4.07	3.36	3.04	53.42
1955	3.13	3.55	4.97	5.64	6.30	5.91	5.53	5.09	4.44	4.07	3.46	2.70	54.78
1956	3.33	4.04	5.51	5.68	6.03	6.13	5.96	5.61	4.31	3.70	3.72	3.31	57.32
1957	3.33	3.61	4.58	5.15	4.62	4.95	5.57	5.25	4.36	4.09	3.25	3.04	51.79
1958	2.75	3.50	4.09	5.76	5.49	5.97	5.64	5.35	4.79	4.09	3.57	2.68	53.70
1959	2.95	3.62	4.28	5.44	5.33	5.22	5.41	5.05	4.14	3.67	3.02	3.08	51.21
1960	3.41	3.50	4.85	5.03	6.29	5.28	5.56	5.37	4.09	4.08	3.94	3.32	54.73
1961	3.19	3.84	5.42	6.03	6.50	5.64	5.96	5.26	4.76	4.39	3.58	3.43	57.99
1962	3.34	3.77	5.09	5.84	7.02	4.94	6.02	5.13	4.61	4.48	3.59	3.05	56.86

1963	3.28	3.24	5.41	6.31	5.87	5.49	5.92	5.62	4.50	4.39	3.42	2.76	56.22
1964	2.82	3.45	5.05	5.92	6.28	6.31	6.49	5.32	4.53	4.08	3.39	3.09	56.74
1965	3.35	3.39	4.38	5.69	7.53	5.74	5.84	5.47	4.32	4.25	3.29	3.25	56.51
1966	3.04	3.46	4.86	5.95	5.53	4.83	5.75	5.36	4.65	4.03	3.85	3.13	54.45
1967	3.08	3.40	5.05	6.33	7.08	4.97	6.01	5.18	4.69	4.31	3.76	3.16	57.01
1968	3.45	3.52	5.28	6.09	5.62	5.07	5.99	5.57	4.77	3.88	3.58	3.21	56.04
1969	3.22	3.45	4.36	5.45	5.64	5.49	6.05	5.56	4.45	3.96	3.30	3.02	53.95
1970	2.90	3.48	4.72	6.13	6.63	6.70	6.83	6.39	5.04	3.96	3.54	3.36	59.67
1971	3.51	3.71	5.21	6.06	7.23	6.60	7.14	5.51	4.79	4.02	3.28	3.17	60.22
1972	3.35	3.44	5.07	5.93	5.55	5.50	6.90	5.79	5.47	5.10	3.17	3.20	58.47
1973	3.08	3.21	5.30	5.89	6.87	6.15	5.72	5.12	4.55	4.12	3.88	3.01	56.90
1974	3.69	4.00	5.68	6.75	6.44	4.97	5.62	5.43	4.72	4.84	3.99	3.17	59.31
1975	3.73	3.91	5.70	6.42	6.67	6.47	5.75	5.78	4.89	4.78	3.82	3.30	61.22
1976	3.28	3.73	5.65	6.12	5.52	4.98	6.18	5.33	4.69	4.51	3.56	3.25	56.81
1977	3.12	3.63	5.53	6.61	6.52	6.82	7.13	5.40	4.71	4.85	3.69	2.91	60.93
1978	3.27	3.01	4.87	6.26	6.70	6.14	5.99	5.46	4.70	3.87	3.70	3.16	57.12
1979	3.17	3.56	5.04	5.91	5.74	6.11	6.38	5.57	4.66	4.35	3.49	3.09	57.07
1980	3.28	3.55	5.35	5.68	6.11	6.40	6.34	5.76	4.81	4.68	3.50	3.18	58.65
1981	3.35	3.78	5.21	6.47	7.07	6.06	6.22	5.19	4.62	4.53	3.72	3.25	59.46
1982	3.39	3.65	4.88	5.36	5.78	6.00	5.74	5.67	4.68	4.01	3.23	3.28	55.68
1983	3.11	3.29	4.92	5.75	6.41	5.56	6.18	5.19	4.81	4.09	3.36	2.92	55.60
1984	3.13	3.59	5.18	5.72	6.14	5.79	5.64	5.49	4.73	4.49	3.20	3.21	56.30
1985	3.32	3.78	5.39	5.77	6.59	6.46	5.69	5.45	4.76	4.10	3.56	3.07	57.93
1986	2.96	3.68	4.62	6.18	6.62	5.15	6.03	5.40	4.57	4.19	3.33	2.91	55.62
1987	3.27	3.38	4.53	5.66	5.77	5.81	6.00	5.82	4.26	4.37	3.21	3.21	55.29
1988	2.93	3.38	4.66	6.03	6.35	5.74	5.61	5.11	4.81	4.29	3.63	3.07	55.60
1989	3.27	3.84	4.89	5.71	6.93	6.33	5.96	5.49	4.47	4.19	3.53	2.76	57.35
1990	3.27	3.67	5.15	5.59	6.43	5.91	5.99	5.35	4.78	4.14	3.56	3.18	57.02
1991	3.12	3.59	5.07	5.44	5.88	5.36	5.64	5.53	4.62	4.13	3.17	3.01	54.54
1992	3.24	3.72	5.01	5.19	6.28	5.25	6.72	5.39	4.47	4.26	3.14	3.09	55.76
1993	2.95	3.48	4.65	5.75	6.07	5.93	6.21	5.90	4.75	4.10	3.30	3.04	56.12
1994	2.97	3.35	4.99	5.31	6.07	5.72	6.02	5.42	4.37	4.03	3.37	2.92	54.54
1995	3.10	3.32	4.92	5.53	6.39	5.69	5.90	5.31	4.47	3.85	3.47	2.86	54.83
1996	3.12	3.78	4.79	5.59	5.58	5.72	6.62	5.61	4.86	4.12	3.58	3.04	56.40
1997	3.28	3.48	5.11	5.19	5.86	5.63	5.77	5.31	4.62	4.36	3.26	2.83	54.71
1998	3.14	3.52	4.80	5.76	6.79	7.16	6.42	5.81	4.96	4.27	3.26	3.06	58.94
1999	3.27	3.64	5.42	6.49	6.33	5.39	6.22	5.70	4.92	4.21	3.44	2.90	57.93
2000	3.29	3.79	5.34	6.31	7.18	6.16	6.08	5.82	4.75	4.40	3.77	3.01	59.90
2001	3.40	4.00	5.42	5.94	6.38	5.96	5.73	5.65	4.36	4.12	3.44	2.98	57.38
2002	3.18	3.23	5.06	5.53	6.46	5.40	5.78	5.40	4.61	4.25	3.47	2.84	55.20
2003	2.99	3.72	5.16	5.28	6.26	5.62	6.15	5.36	4.78	4.47	3.60	3.05	56.45
2004	3.20	3.51	5.17	5.91	6.82	6.26	6.25	5.57	5.03	4.23	3.55	3.03	58.53
2005	3.08	3.50	4.96	5.76	6.17	5.48	6.68	6.03	5.15	4.07	3.44	2.96	57.27
2006	3.50	3.57	5.51	6.45	7.08	6.20	6.09	5.96	4.82	4.71	3.44	3.06	60.38

2007	3.30	3.54	5.69	6.15	6.60	6.14	6.20	6.09	4.88	4.27	3.49	2.99	59.33
2008	3.17	3.91	4.94	5.49	6.92	6.23	6.07	5.81	5.05	4.23	3.31	3.03	58.17
2009	3.24	3.62	5.07	6.62	6.33	6.90	7.24	6.38	5.31	4.80	3.84	2.89	62.24
2010	2.97	3.26	4.71	5.57	6.68	6.41	6.55	5.59	4.94	4.88	3.59	3.19	58.34
2011	3.21	4.07	5.73	6.59	7.12	6.98	6.14	5.71	4.71	3.98	3.48	3.15	60.89
2012	3.61	3.77	5.32	6.23	6.46	6.02	6.52	5.95	4.67	4.27	3.35	3.14	59.32
2013	3.33	3.95	5.69	5.94	6.49	1.53	-	-	-	-	-	-	26.93

Table 9. Monthly difference (inches) between new and previous ET_o (1948-2013).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1948	-0.17	-0.13	-0.16	-0.17	-0.31	0.07	0.09	-0.01	-0.14	-0.18	-0.13	-0.08	-1.32
1949	-0.13	-0.14	-0.13	-0.26	-0.09	-0.11	0.12	-0.04	-0.19	-0.19	-0.10	-0.07	-1.34
1950	-0.08	-0.20	-0.20	-0.14	-0.30	0.10	0.10	-0.07	-0.17	-0.21	-0.09	-0.08	-1.32
1951	-0.15	-0.17	-0.13	-0.23	-0.15	0.11	0.12	-0.03	-0.22	-0.20	-0.13	-0.11	-1.29
1952	-0.15	-0.17	-0.14	-0.16	-0.42	-0.02	0.10	0.00	-0.12	-0.22	-0.09	-0.08	-1.47
1953	-0.22	-0.15	-0.09	-0.27	-0.09	-0.24	0.07	0.01	-0.10	-0.21	-0.06	-0.08	-1.43
1954	-0.18	-0.18	-0.06	-0.23	-0.41	-0.15	0.11	-0.05	-0.13	-0.18	-0.11	-0.09	-1.66
1955	-0.15	-0.17	-0.11	-0.13	-0.25	-0.05	0.12	0.03	-0.14	-0.20	-0.11	-0.09	-1.24
1956	-0.14	-0.18	-0.06	-0.19	-0.27	-0.04	0.15	-0.05	-0.12	-0.19	-0.13	-0.06	-1.28
1957	-0.14	-0.15	-0.14	-0.24	-0.53	-0.18	0.10	-0.02	-0.11	-0.17	-0.13	-0.11	-1.80
1958	-0.21	-0.16	-0.15	-0.14	-0.43	-0.04	0.14	-0.01	-0.21	-0.21	-0.07	-0.09	-1.57
1959	-0.17	-0.16	-0.17	-0.16	-0.41	-0.15	0.12	0.02	-0.06	-0.21	-0.09	-0.08	-1.51
1960	-0.12	-0.19	-0.16	-0.14	-0.22	-0.17	0.09	0.00	-0.07	-0.16	-0.09	-0.07	-1.30
1961	-0.14	-0.15	-0.11	-0.19	-0.18	-0.12	0.15	-0.01	-0.20	-0.16	-0.09	-0.07	-1.26
1962	-0.16	-0.12	-0.14	-0.17	-0.09	-0.21	0.12	0.02	-0.15	-0.16	-0.12	-0.03	-1.20
1963	-0.12	-0.17	-0.10	-0.14	-0.32	-0.08	0.12	-0.02	-0.15	-0.20	-0.15	-0.09	-1.42
1964	-0.15	-0.15	-0.15	-0.13	-0.21	0.04	0.12	-0.02	-0.18	-0.22	-0.08	-0.07	-1.20
1965	-0.17	-0.14	-0.20	-0.10	0.05	-0.07	0.09	-0.05	-0.12	-0.19	-0.04	-0.09	-1.04
1966	-0.18	-0.14	-0.11	-0.17	-0.37	-0.26	0.15	-0.01	-0.17	-0.19	-0.13	-0.09	-1.66
1967	-0.18	-0.13	-0.12	-0.11	-0.04	-0.23	0.13	0.02	-0.16	-0.17	-0.08	-0.06	-1.13
1968	-0.12	-0.12	-0.08	-0.11	-0.37	-0.21	0.16	-0.01	-0.19	-0.19	-0.09	-0.11	-1.45
1969	-0.15	-0.10	-0.16	-0.15	-0.37	-0.11	0.09	-0.04	-0.14	-0.19	-0.07	-0.08	-1.48
1970	-0.14	-0.17	-0.13	-0.10	-0.21	0.09	0.14	-0.16	-0.31	-0.19	-0.08	-0.06	-1.33
1971	-0.13	-0.17	-0.13	-0.11	-0.02	0.09	0.18	-0.06	-0.18	-0.22	-0.07	-0.06	-0.87
1972	-0.15	-0.12	-0.18	-0.17	-0.34	-0.14	0.12	-0.12	-0.31	-0.16	-0.12	-0.06	-1.75
1973	-0.15	-0.13	-0.11	-0.15	-0.08	0.01	0.11	0.01	-0.10	-0.19	-0.10	-0.06	-0.96
1974	-0.09	-0.20	-0.05	-0.14	-0.17	-0.21	0.11	0.03	-0.22	-0.13	-0.18	-0.07	-1.33
1975	-0.13	-0.18	-0.06	-0.08	-0.15	0.07	0.11	-0.05	-0.22	-0.14	-0.12	-0.15	-1.09
1976	-0.16	-0.18	-0.05	-0.12	-0.40	-0.22	0.12	-0.01	-0.19	-0.17	-0.17	-0.13	-1.68
1977	-0.19	-0.20	-0.07	-0.13	-0.23	0.21	0.05	-0.07	-0.13	-0.21	-0.14	-0.16	-1.27
1978	-0.13	-0.16	-0.10	-0.13	-0.17	-0.01	0.08	-0.03	-0.17	-0.24	-0.05	-0.10	-1.20
1979	-0.17	-0.13	-0.07	-0.20	-0.10	0.01	0.18	0.06	-0.11	-0.13	-0.10	-0.12	-0.88
1980	-0.19	-0.19	-0.13	-0.14	-0.13	-0.02	0.17	0.03	-0.08	-0.14	-0.17	-0.13	-1.11

1981	-0.22	-0.16	-0.15	-0.19	-0.20	0.00	0.14	0.02	-0.10	-0.14	-0.13	-0.19	-1.31
1982	-0.21	-0.15	-0.09	-0.19	-0.10	0.04	0.19	0.05	-0.09	-0.13	-0.09	-0.09	-0.85
1983	-0.17	-0.20	-0.14	-0.18	-0.16	0.01	0.19	0.07	-0.07	-0.09	-0.17	-0.14	-1.04
1984	-0.17	-0.19	-0.04	-0.15	-0.12	0.02	0.18	0.04	-0.10	-0.09	-0.13	-0.07	-0.82
1985	-0.20	-0.16	-0.13	-0.18	-0.16	0.01	0.17	0.06	-0.07	-0.09	-0.08	-0.13	-0.96
1986	-0.20	-0.16	-0.06	-0.17	-0.17	0.01	0.19	0.08	-0.09	-0.08	-0.09	-0.12	-0.86
1987	-0.18	-0.17	-0.12	-0.12	-0.11	0.01	0.18	0.05	-0.09	-0.14	-0.12	-0.16	-0.96
1988	-0.19	-0.15	-0.08	-0.19	-0.14	-0.03	0.17	0.06	-0.11	-0.13	-0.15	-0.14	-1.09
1989	-0.22	-0.14	-0.03	-0.15	-0.18	-0.02	0.19	0.04	-0.10	-0.11	-0.16	-0.10	-0.97
1990	-0.21	-0.18	-0.08	-0.17	-0.19	0.01	0.19	0.04	-0.08	-0.11	-0.14	-0.09	-1.01
1991	-0.19	-0.20	-0.08	-0.11	-0.12	0.04	0.20	0.07	-0.08	-0.12	-0.13	-0.11	-0.82
1992	-0.20	-0.14	-0.08	-0.18	-0.13	0.03	0.21	0.08	-0.07	-0.13	-0.13	-0.11	-0.86
1993	-0.13	-0.17	-0.04	-0.20	-0.15	0.04	0.20	0.05	-0.07	-0.12	-0.16	-0.15	-0.90
1994	-0.17	-0.11	-0.10	-0.10	-0.13	0.04	0.18	0.09	-0.07	-0.11	-0.14	-0.11	-0.73
1995	-0.20	-0.16	-0.06	-0.15	-0.14	0.00	0.18	0.04	-0.07	-0.14	-0.15	-0.11	-0.95
1996	-0.21	-0.16	-0.08	-0.17	-0.12	0.04	0.18	0.07	-0.08	-0.13	-0.13	-0.13	-0.89
1997	-0.21	-0.14	-0.11	-0.22	-0.15	0.00	0.20	0.07	-0.10	-0.14	-0.14	-0.12	-1.06
1998	-0.19	-0.16	-0.08	-0.19	-0.11	0.02	0.18	0.05	-0.10	-0.12	-0.11	-0.10	-0.91
1999	-0.16	-0.11	-0.15	-0.21	-0.14	0.03	0.21	0.04	-0.10	-0.14	-0.12	-0.13	-1.00
2000	-0.25	-0.13	-0.13	-0.24	-0.19	-0.02	0.15	0.07	-0.09	-0.12	-0.20	-0.17	-1.30
2001	-0.24	-0.17	-0.15	-0.23	-0.13	0.03	0.15	0.06	-0.07	-0.12	-0.09	-0.10	-1.06
2002	-0.16	-0.18	-0.06	-0.12	-0.16	0.05	0.19	0.07	-0.04	-0.10	-0.14	-0.17	-0.83
2003	-0.20	-0.18	-0.11	-0.18	-0.09	0.04	0.17	0.07	-0.10	-0.15	-0.12	-0.16	-1.00
2004	-0.26	-0.16	-0.09	-0.20	-0.14	-0.01	0.20	0.06	-0.14	-0.13	-0.12	-0.16	-1.15
2005	-0.17	-0.17	-0.12	-0.20	-0.17	0.01	0.21	0.07	-0.08	-0.14	-0.14	-0.26	-1.14

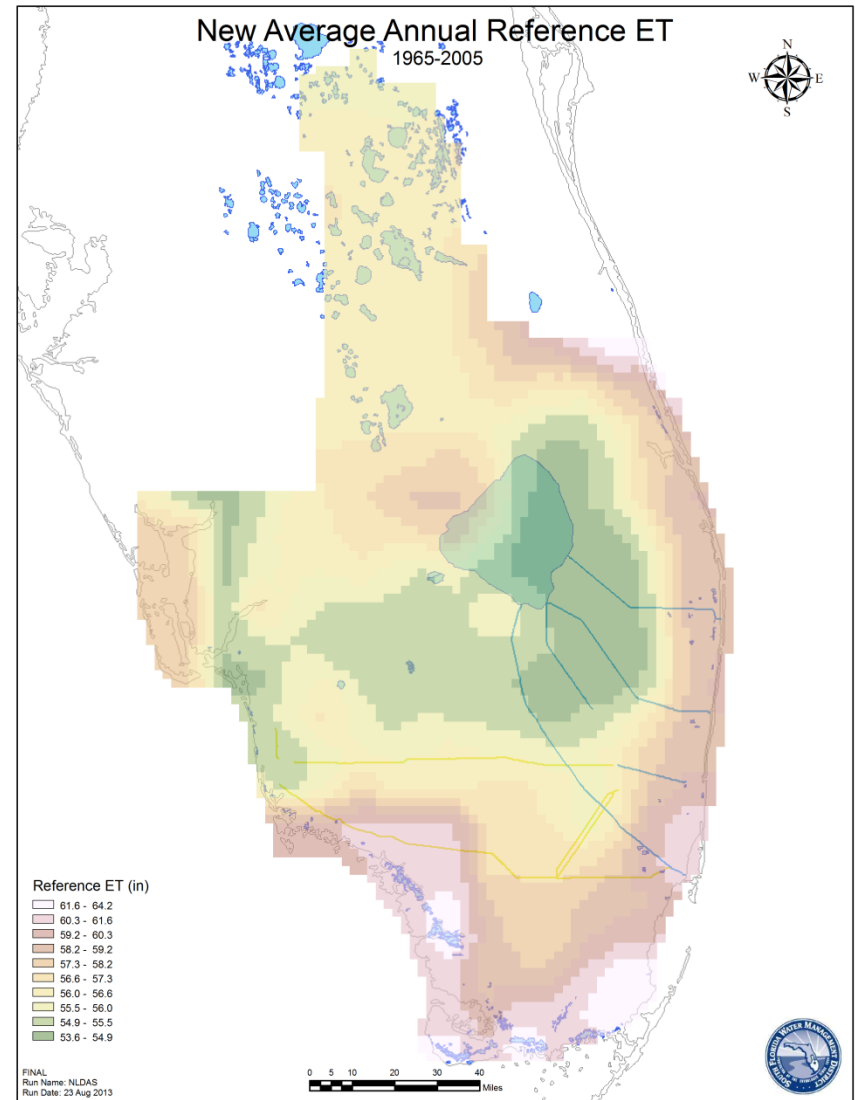
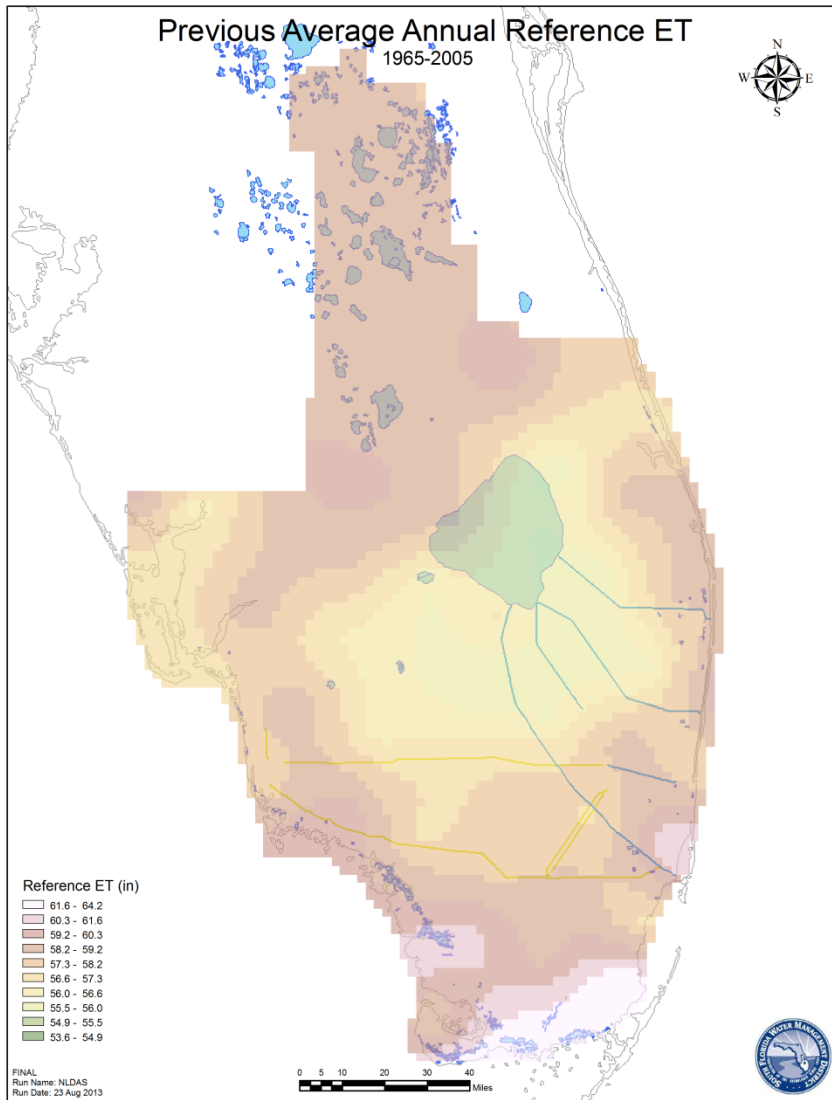


Figure 12. Comparison of average of annual ET_0 (1965-2005).

FUTURE WORK

The current version of ET_o accounts for a quarterly bias of shortwave downward radiation based on 9 USGS observation stations. The quarterly bias was assumed to be spatially uniform. Future work should involve determining a spatial bias between the shortwave radiation component of the NLDAS dataset and observed value (Jacobs et al., 2008). Since other organizations may already be investigating a spatial bias and/or other improvements, it is recommended to wait until the next ET_o update in order to determine the progress made by other organizations and if new improvements are needed.

REFERENCES

- Betts, Alan K., Fei Chen, Kenneth E. Mitchell, and Zaviša I. Janjic. "Assessment of the land surface and boundary layer models in two operational versions of the NCEP Eta model using FIFE data." *Monthly Weather Review* 125, no. 11 (1997): 2896-2916.
- Fan, Y., H. van den Dool, D. Lohmann, and K. Mitchell. "1948-1998 US hydrological reanalysis of the Noah Land Data Assimilation System". *Journal of Climate*, Vol. 19 (2006): 1214-1237.
- German, Edward R. "Regional Evaluation of Evapotranspiration in the Everglades." US Department of the Interior, U.S. Geological Survey Water-Resources Investigations Report 00-4217, 2000.
- "Hydro51 Data" University Corporation of Atmospheric Research, accessed March 26, 2008, <https://dss.ucar.edu/datazone/dsszone/HYDRO51>.
- "Hydrology Data Holdings" Goddard Earth Sciences Data and Information Services Center, accessed June 10, 2013, <http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings>.
- Irizarry-Ortiz, Michelle M., Winifred Said, Paul Trimble, Beheen Trimble, Michael Brown, Alaa Ali, Jayantha Obeysekera, Ken Tarboton, and Timothy Newton. "Estimation of long-term reference evapotranspiration from regional climate model datasets." In *Proceedings of the world environmental and water resources congress*, pp. 15-19. 2007.
- Irmak, S., T. A. Howell, R. G. Allen, J. O. Payero, and D. L. Martin. "Standardized ASCE Penman-Monteith: Impact of sum-of-hourly vs. 24-hour timestep computations at reference weather station sites." *TRANSACTIONS-AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS* 48, no. 3 (2005): 1063.
- Itenfisu, Daniel, Ronald L. Elliott, Richard G. Allen, and Ivan A. Walter. "Comparison of reference evapotranspiration calculations as part of the ASCE standardization effort." *Journal of irrigation and drainage engineering* 129, no. 6 (2003): 440-448.
- Jacobs, Jennifer, John Mecikalski, and Simon Paech. "Satellite-based solar radiation, net radiation, and potential and reference evapotranspiration estimates over Florida." Report prepared for the South Florida Water Management District 138 (2008).
- Rui, Hualan. "README Document for North America Land Data Assimilation System Phase 2 (NLDAS-2) Products." Goddard Earth Sciences, Data and Information Services Center. 2013.
- Smith, Martin, R. Allen, J. L. Monteith, A. Perrier, L. Santos Pereira, and A. Segeren. "Expert consultation on revision of FAO methodologies for crop water requirements." Land and Water Development Division, Food and Agriculture Organisation, Rome (1992).

Appendix A

Adjacent Cell Data Expansion of HYDRO51 and NLDAS Datasets

HYDRO51

Data from the HYDRO51 1/8th degree grid needed to be expanded in order to provide coverage for the entire domain of the ET_o grid. Table A-1 below identifies the cells used to populate the “No Data” cells and shown in Figure A-1. It is important to note that centers of the HYDRO51 grid are not depicted; boundaries of the 1/8 degree grid were shown for simplicity.

Table A-1. HYDRO51 cells used to populate “No Data” cells.

No.	(Row,Column) of Cells Populating “No Data” Cells	(Row,Column) of “No Data” Cells
1	(3,21)	(2,21)
2	(3,22)	(2,22)
3	(3,22)	(3,23)
4	(4,22)	(4,23)
5	(5,22)	(5,23)
6	(6,23)	(6,24)
7	(7,24)	(7,25)
8	(8,24)	(8,25)
9	(9,24)	(9,25)
10	(10,24)	(10,25)
11	(11,24)	(11,25)
12	(16,24)	(16,25)
13	(17,24)	(17,25)
14	(11,25)	(11,26)
15	(12,25)	(12,26)
16	(13,25)	(13,26)
17	(14,25)	(14,26)
18	(15,25)	(15,26)
19	(16,25)	(16,26)
20	(15,9)	(15,7)
21	(15,9)	(15,8)
22	(14,9)	(15,7)
23	(14,9)	(15,8)
24	(13,10)	(13,7)
25	(13,10)	(13,8)
26	(13,10)	(13,9)
27	(2,17)	(2,16)
28	(3,17)	(3,16)
29	(4,17)	(4,16)
30	(2,17)	(2,15)
31	(3,17)	(3,15)
32	(4,17)	(4,15)
33	(8,12)	(7,12)
34	(8,13)	(7,13)
35	(8,14)	(7,14)
36	(8,12)	(8,11)
37	(9,12)	(9,11)

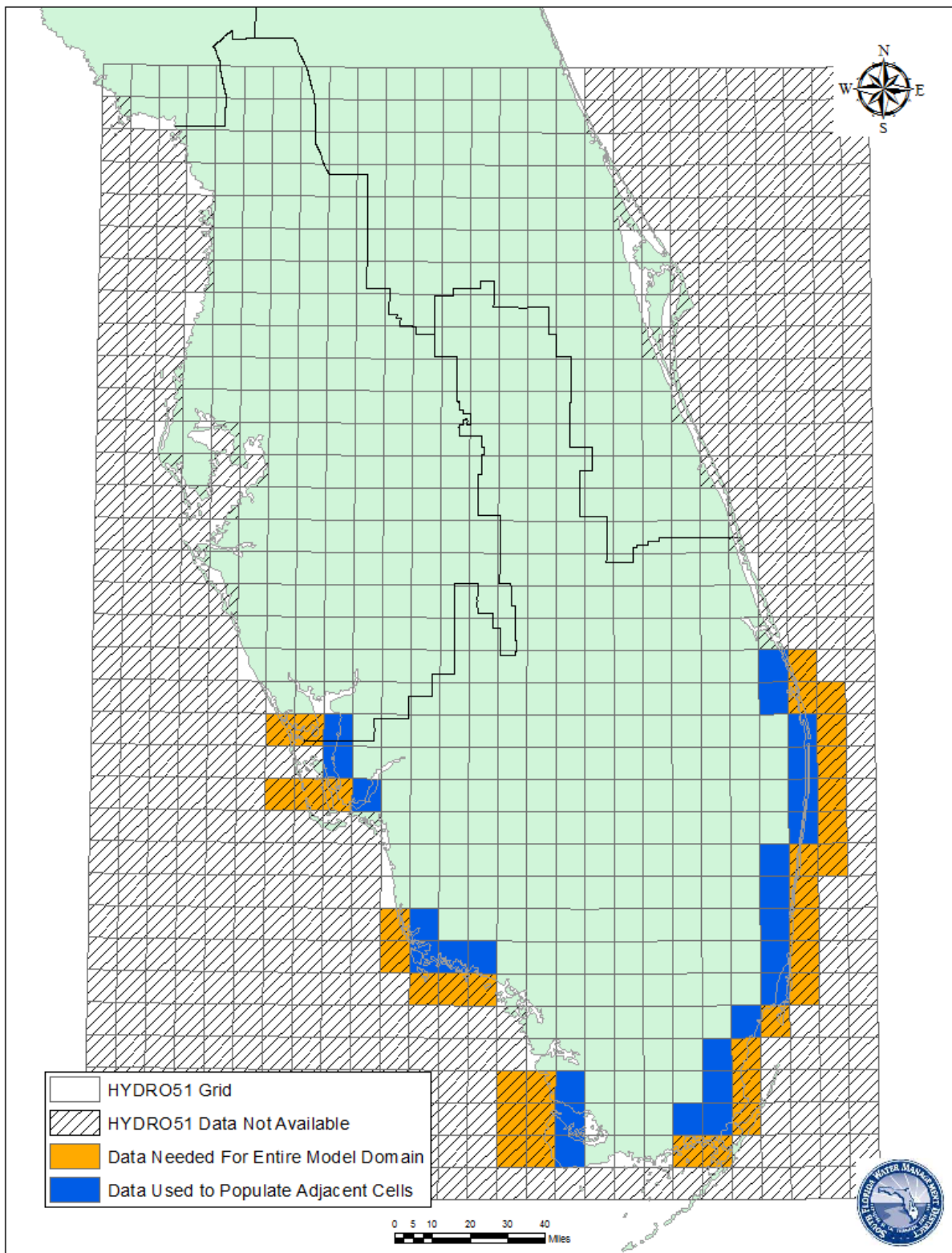


Figure A-1. HYDRO51 cells used to populate "No Data" cells.

NLDAS

Data from the NLDAS 1/8th degree grid needed to be expanded in order to provide coverage for the entire domain of the ET_o grid. Table A-2 below identifies the cells used to populate the “No Data” cells and shown in Figure A-2. It is important to note that centers of the NLDAS grid are not depicted; boundaries of the 1/8 degree grid were shown for simplicity.

Table A-2. NLDAS cells used to populate “No Data” cells.

No.	(Row,Column) of Cells Populating “No Data” Cells	(Row,Column) of “No Data” Cells
1	(10,34)	(10,34)
2	(11,34)	(11,34)
3	(12,34)	(12,34)
4	(13,34)	(13,34)
5	(14,34)	(14,34)
6	(15,34)	(15,34)
7	(16,34)	(16,34)

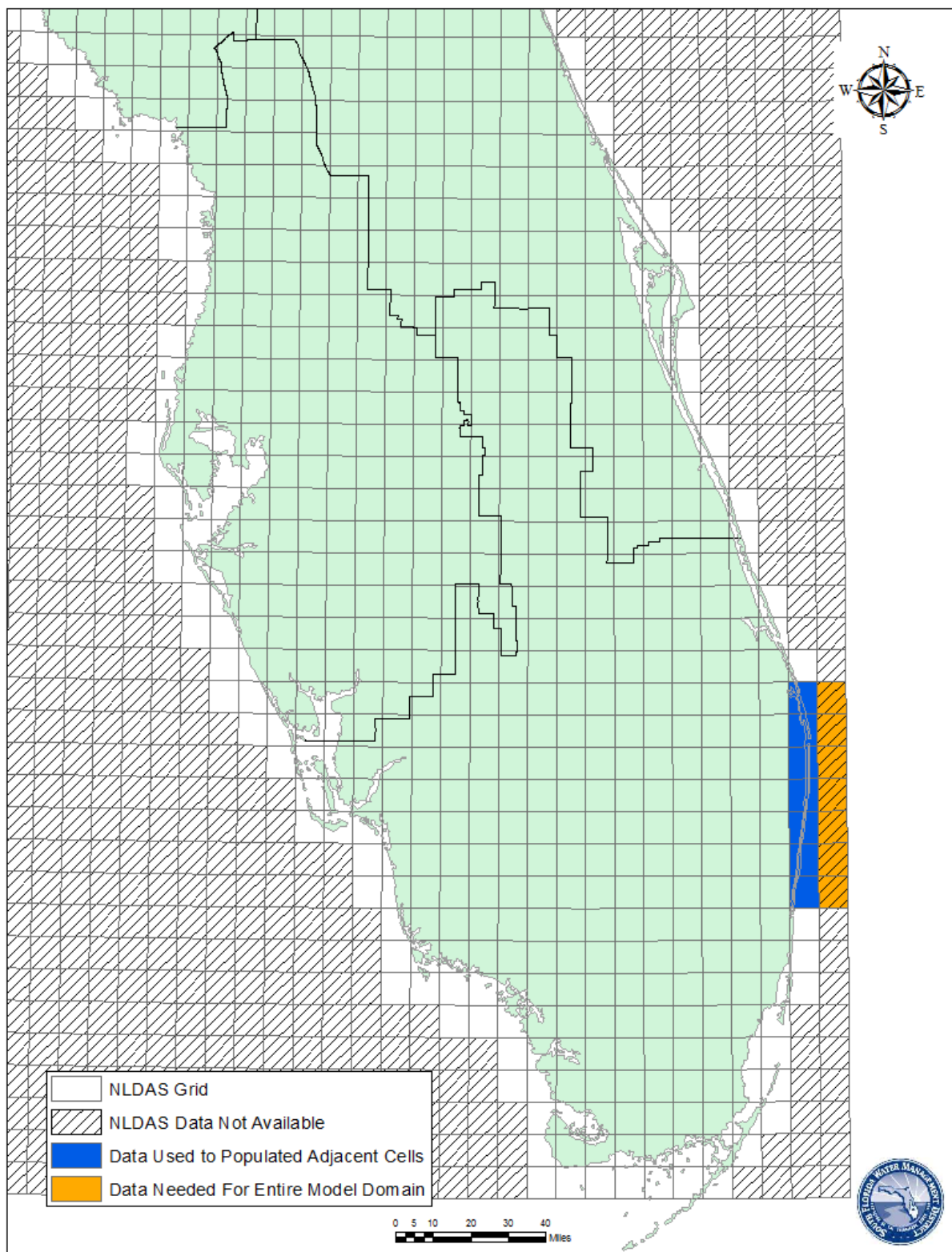


Figure A-2. NLDAS cells used to populate "No Data" cells.

Appendix B

Comparison of Previous and New Reference ET (1965-2005)

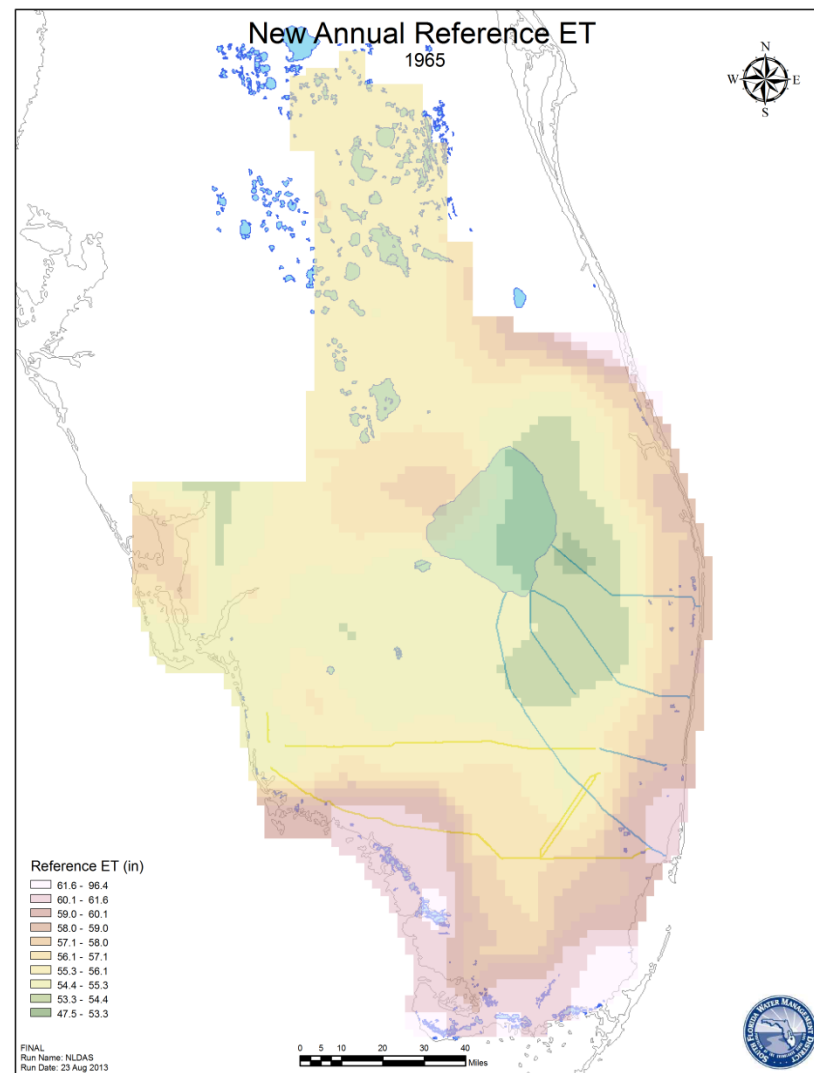
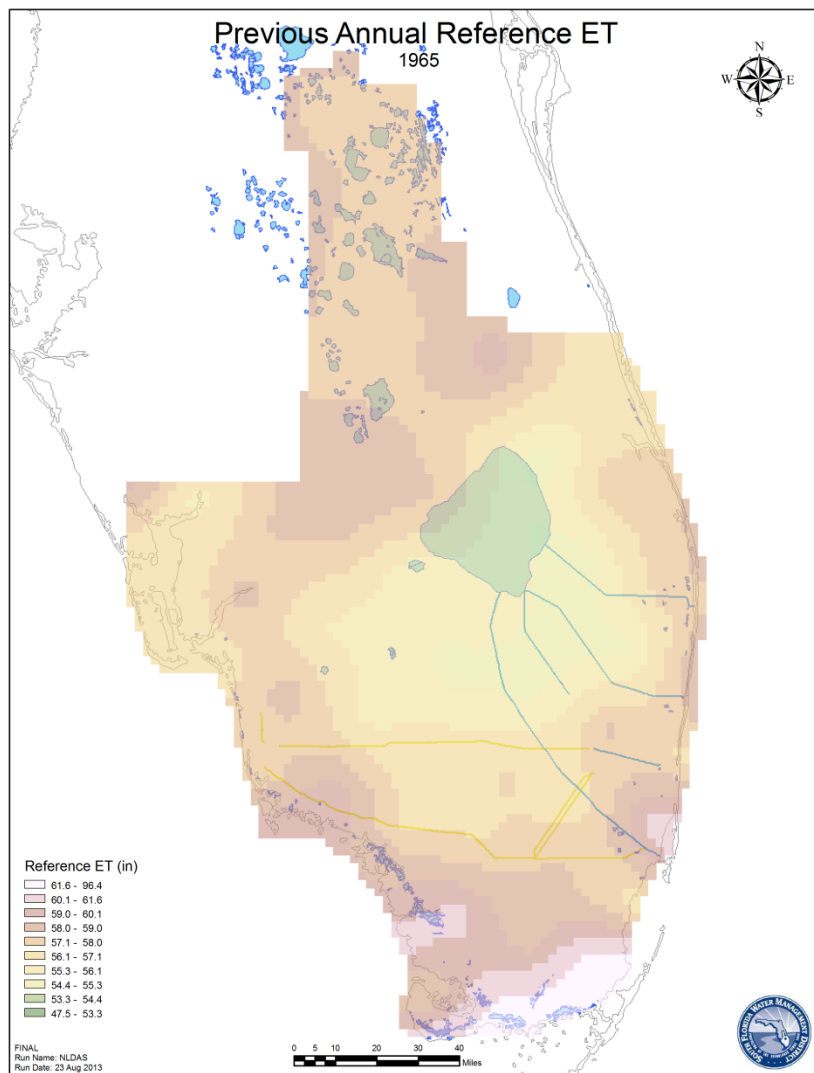


Figure B-1. Comparison of previous and new reference ET for 1965.

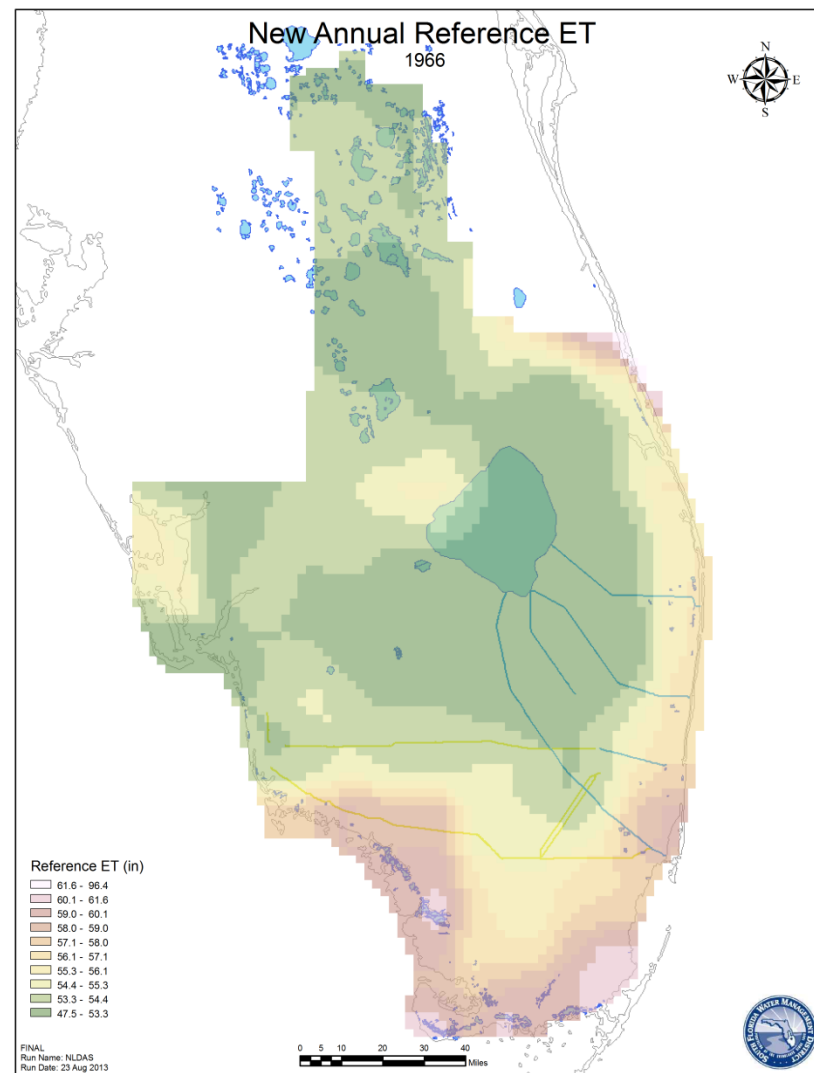
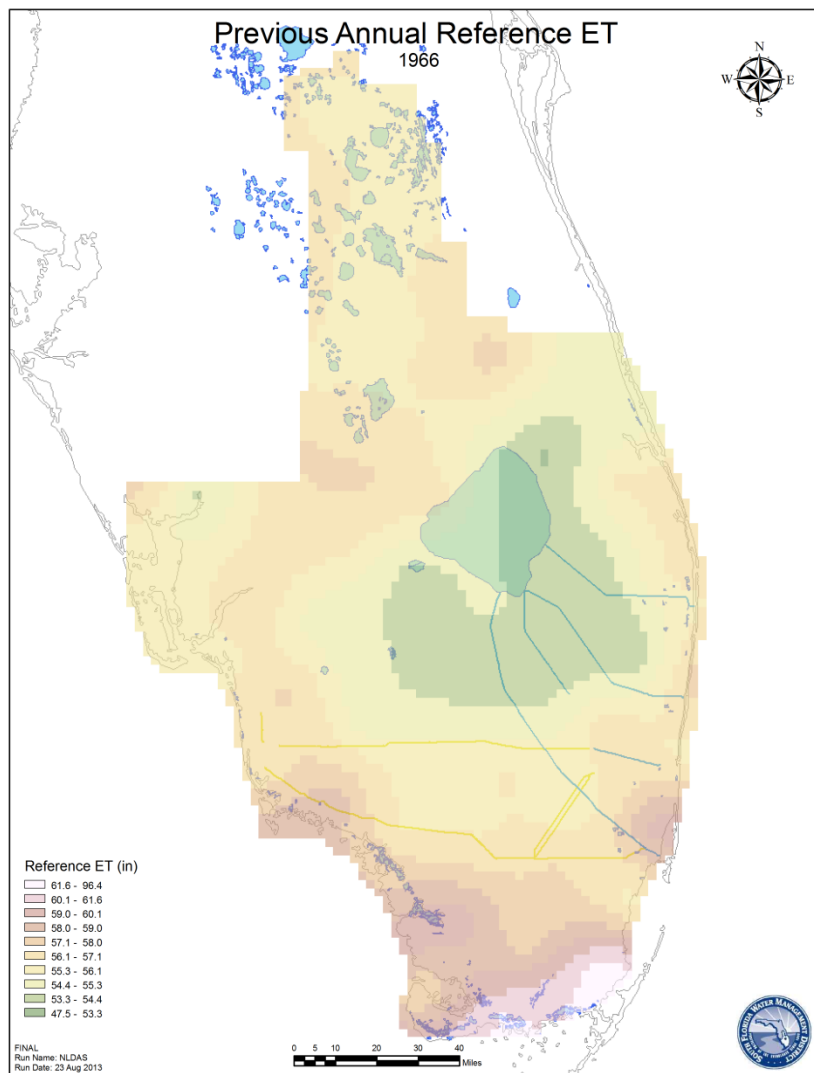


Figure B-2. Comparison of previous and new reference ET for 1966.

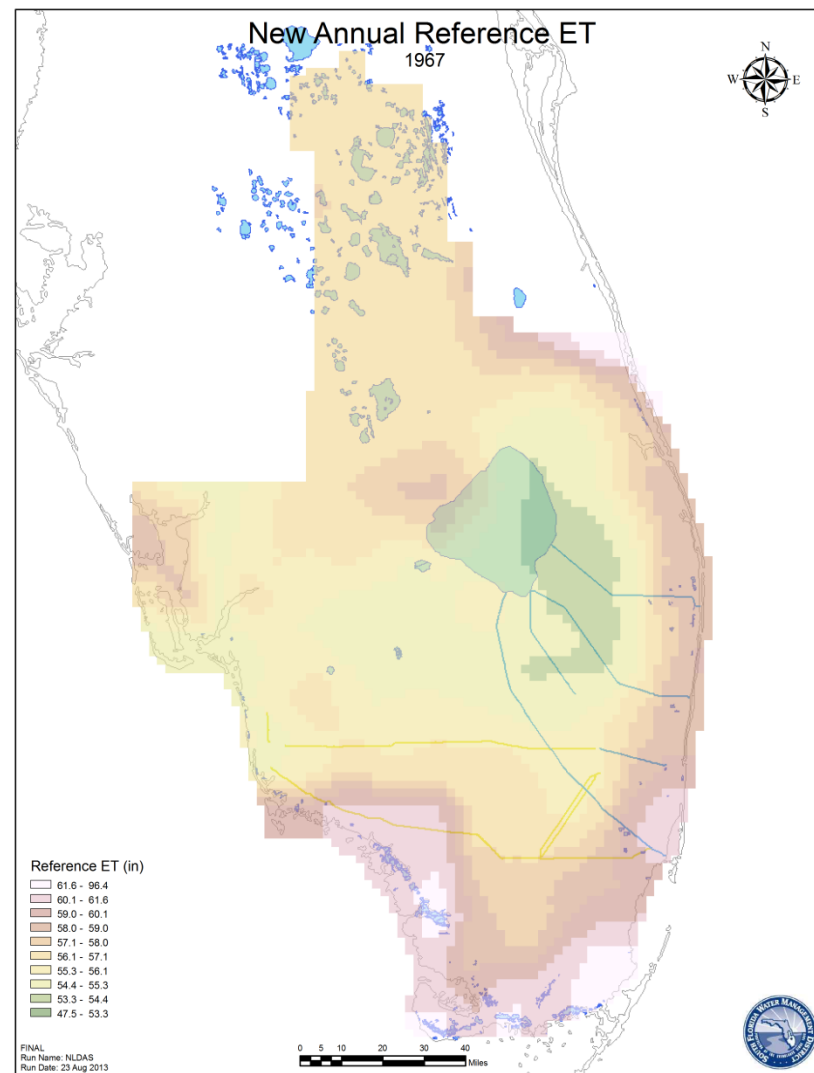
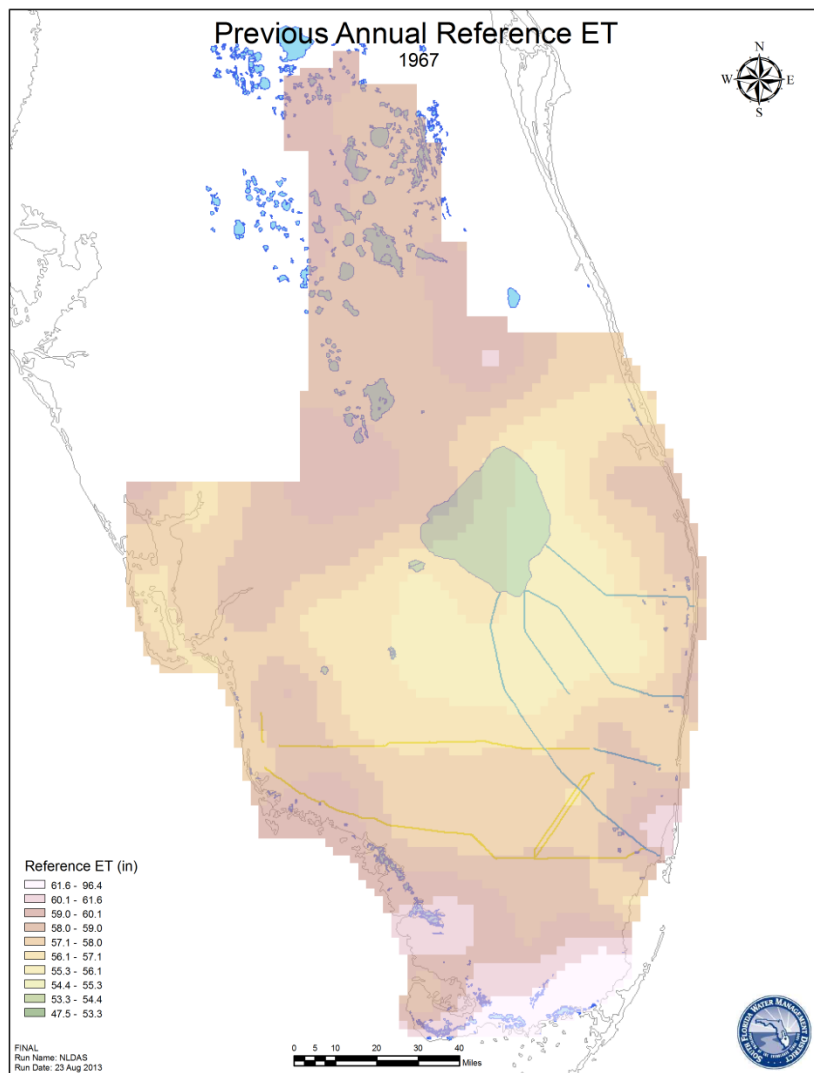


Figure B-3. Comparison of previous and new reference ET for 1967.

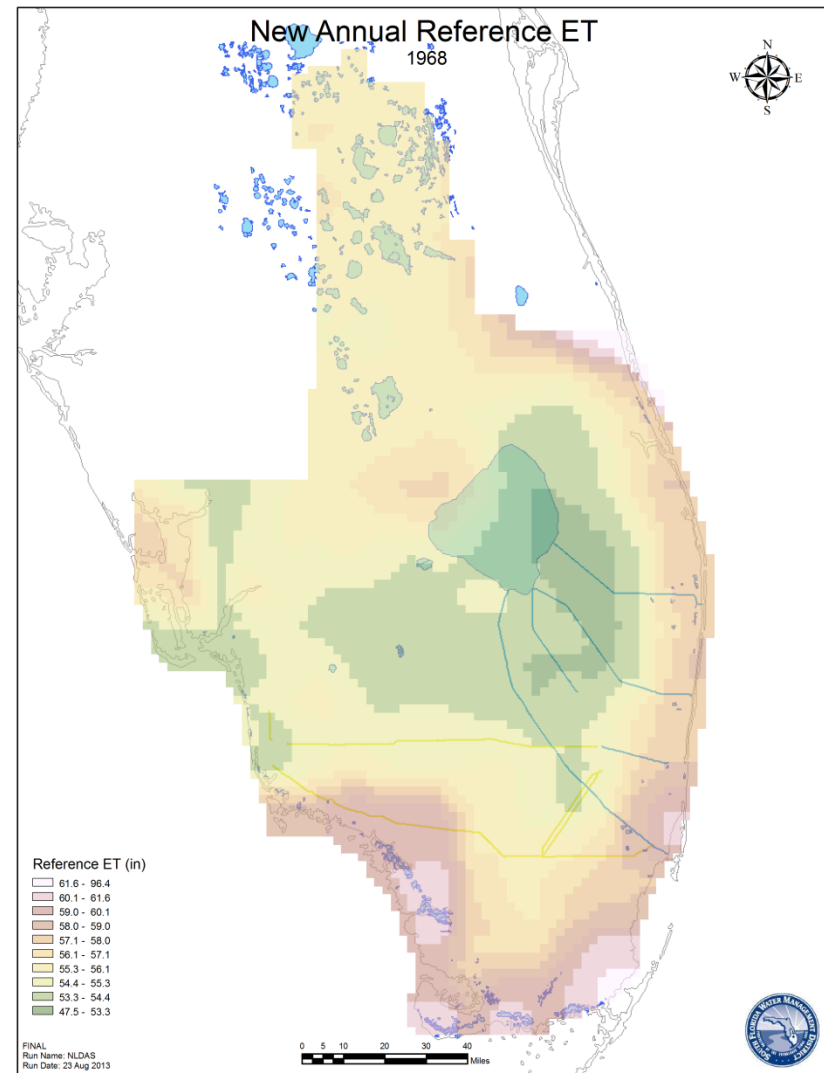
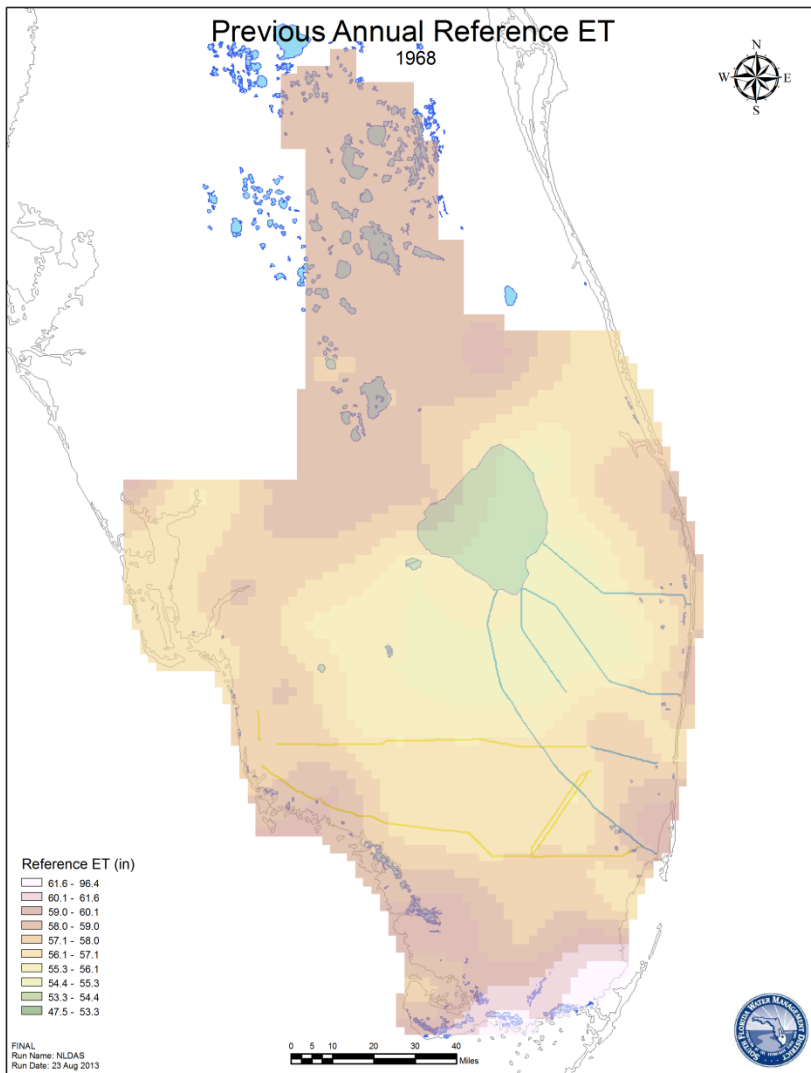


Figure B-4. Comparison of previous and new reference ET for 1968.

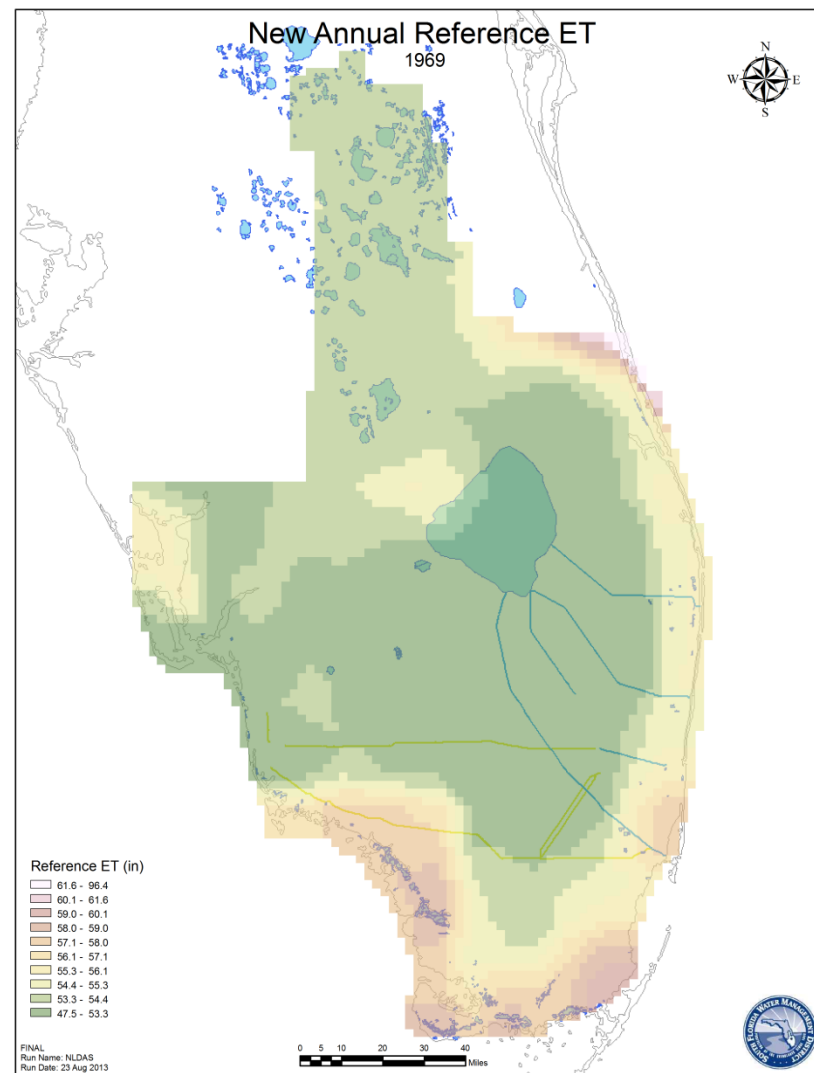
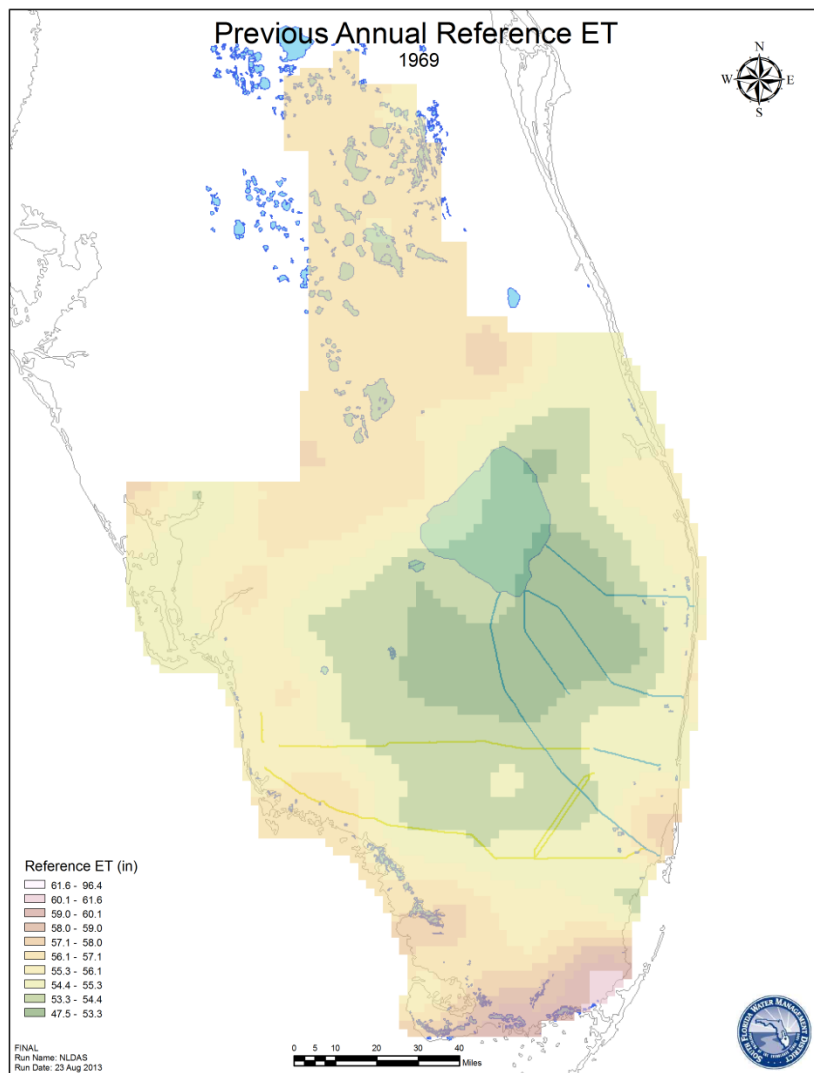


Figure B-5. Comparison of previous and new reference ET for 1969.

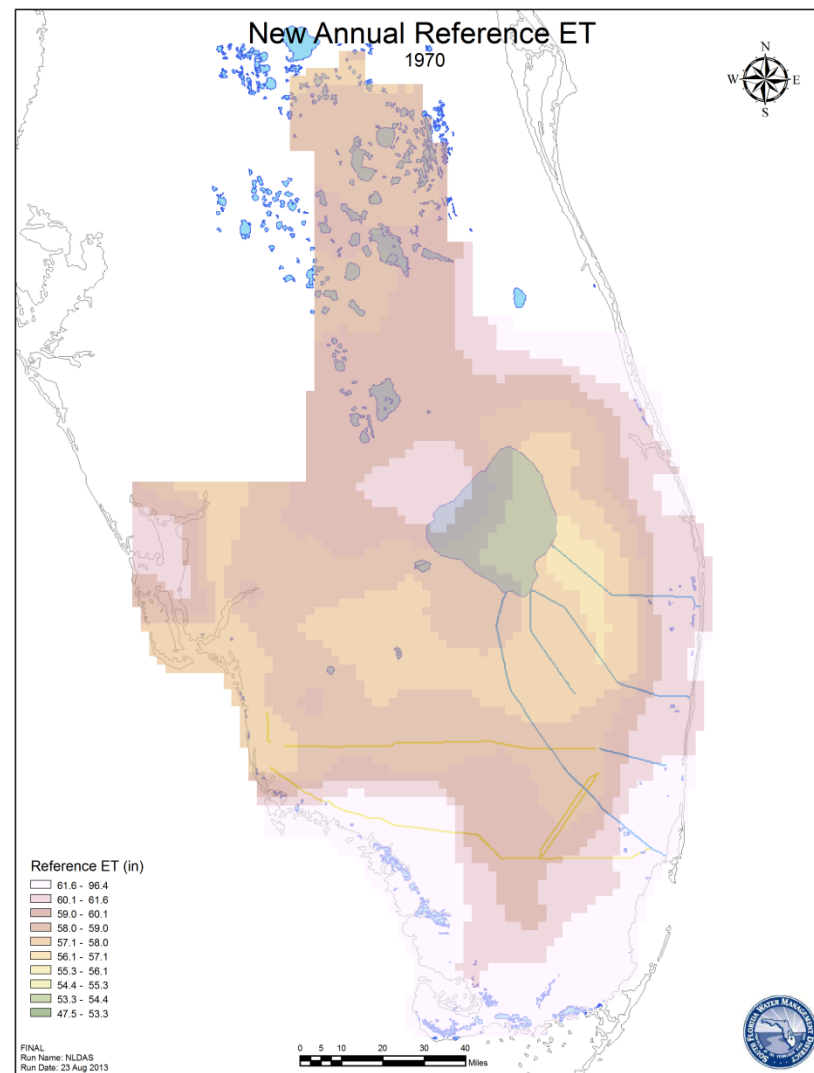
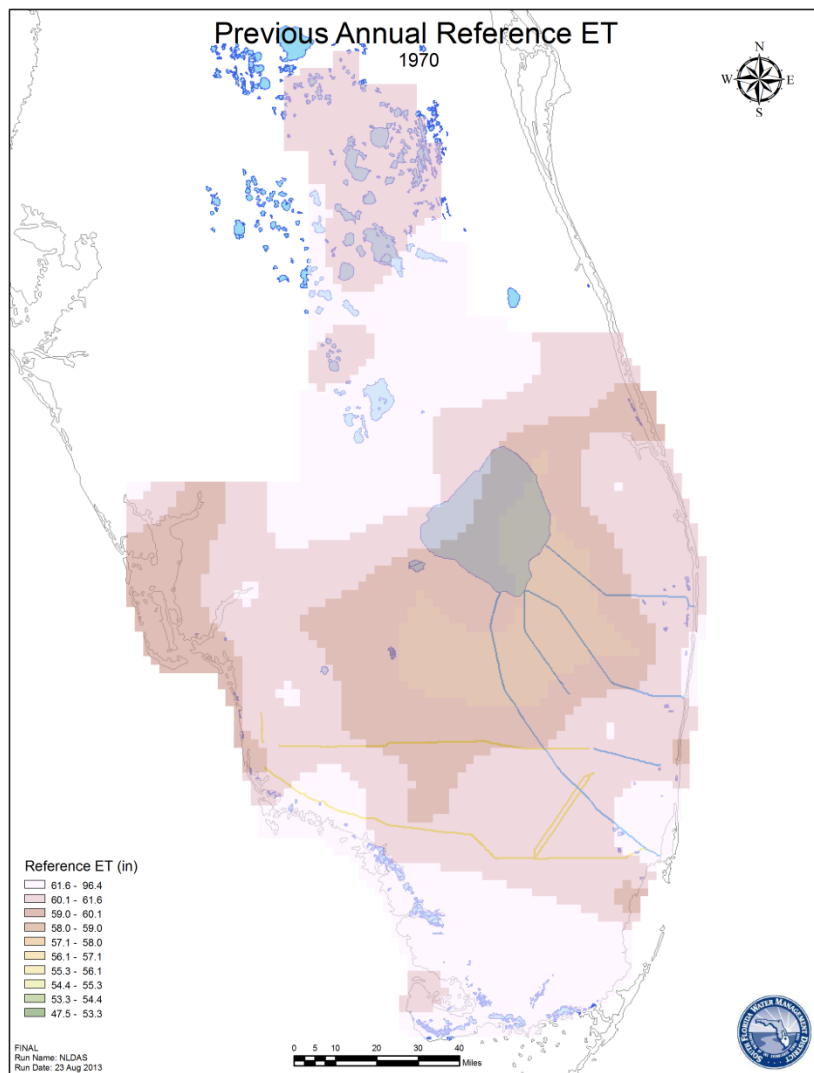


Figure B-6. Comparison of previous and new reference ET for 1970.

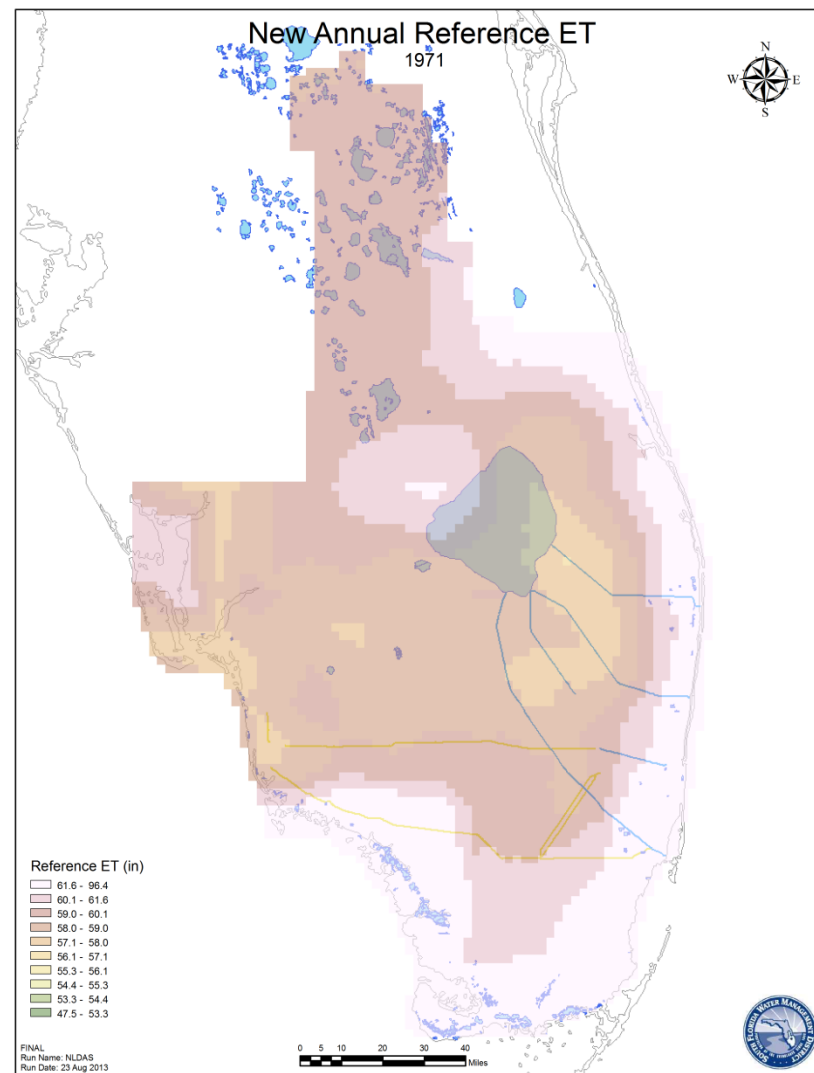
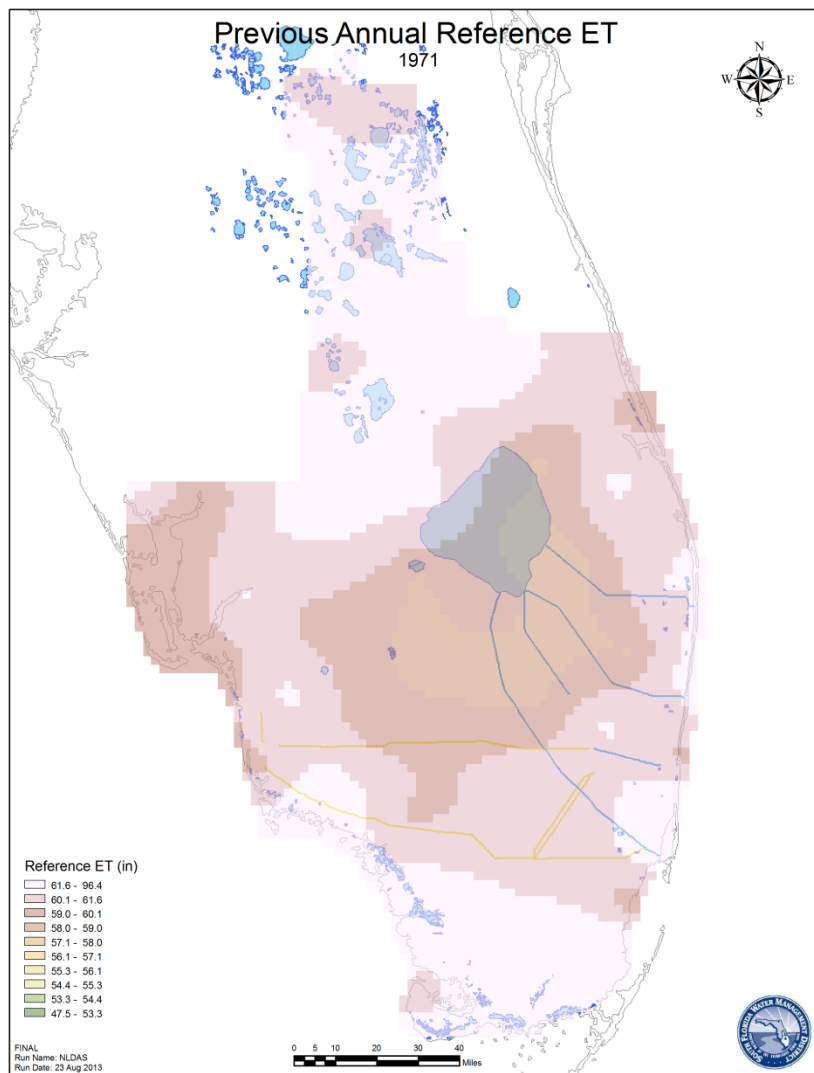


Figure B-7. Comparison of previous and new reference ET for 1971.

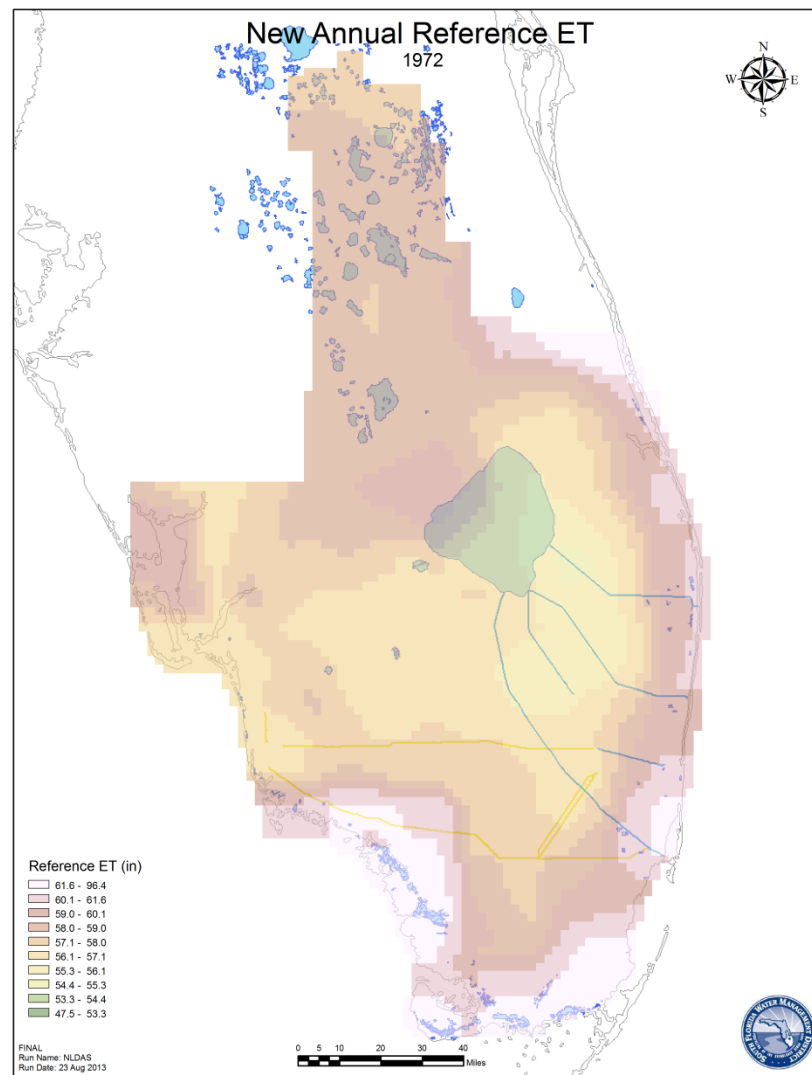
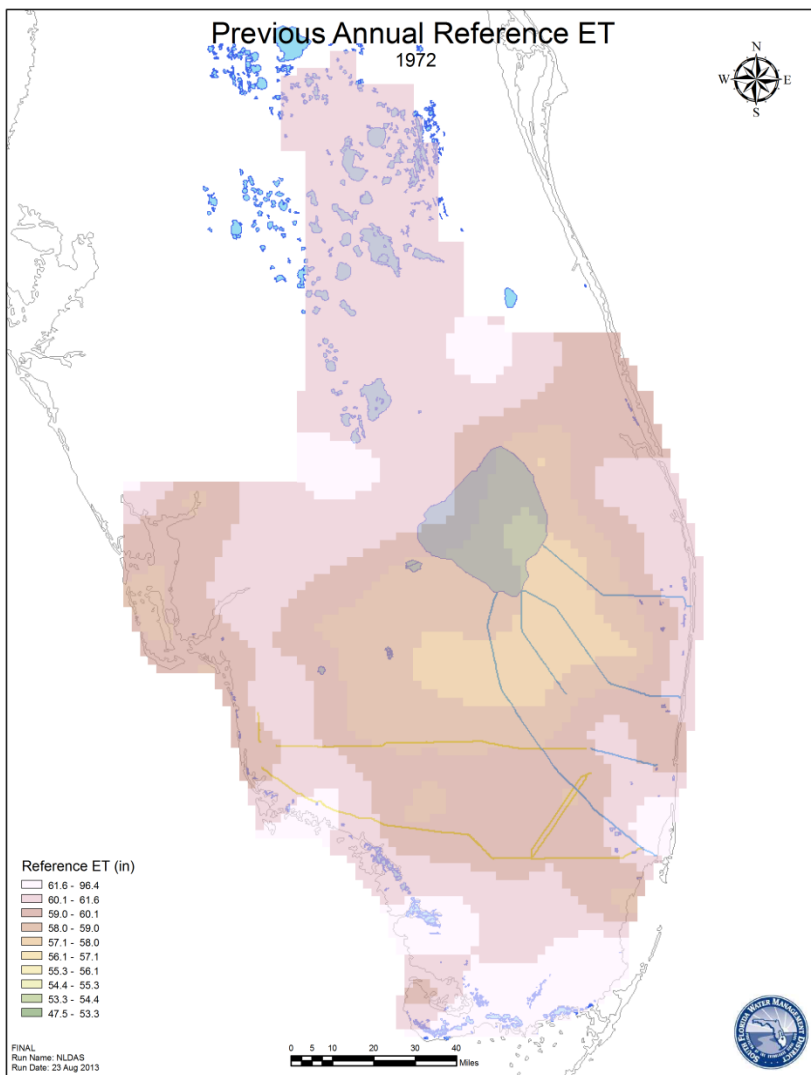


Figure B-8. Comparison of previous and new reference ET for 1972.

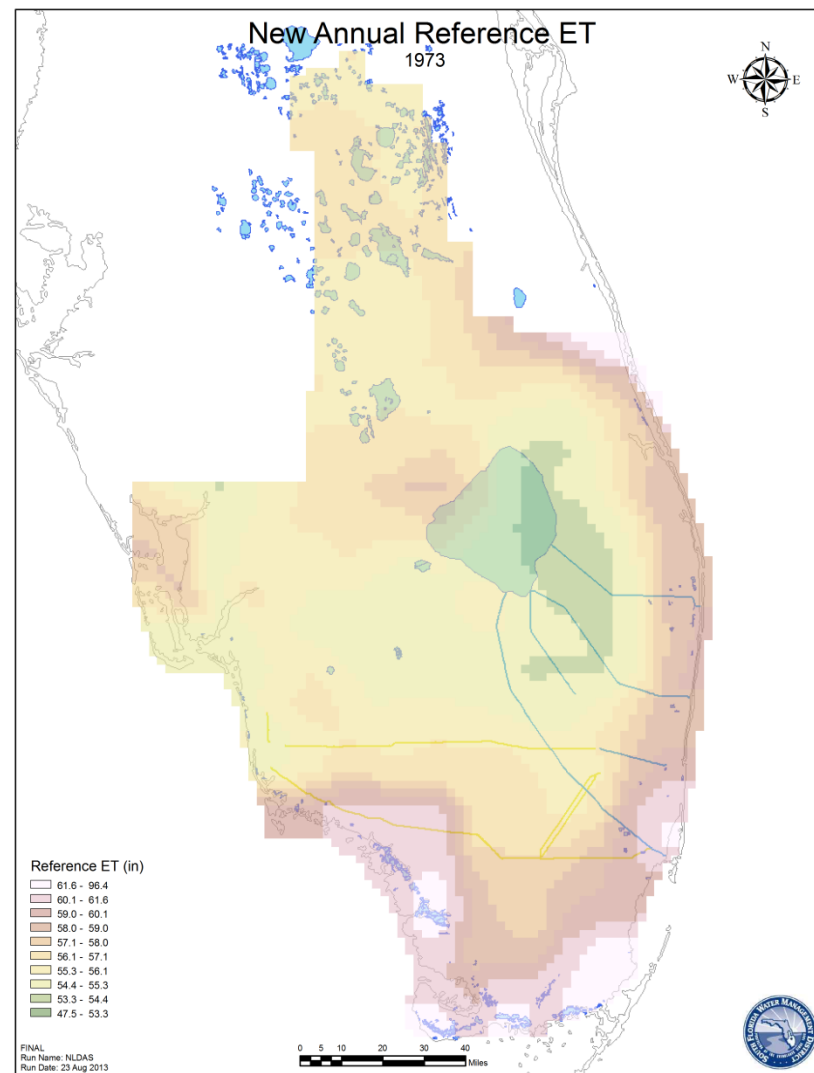
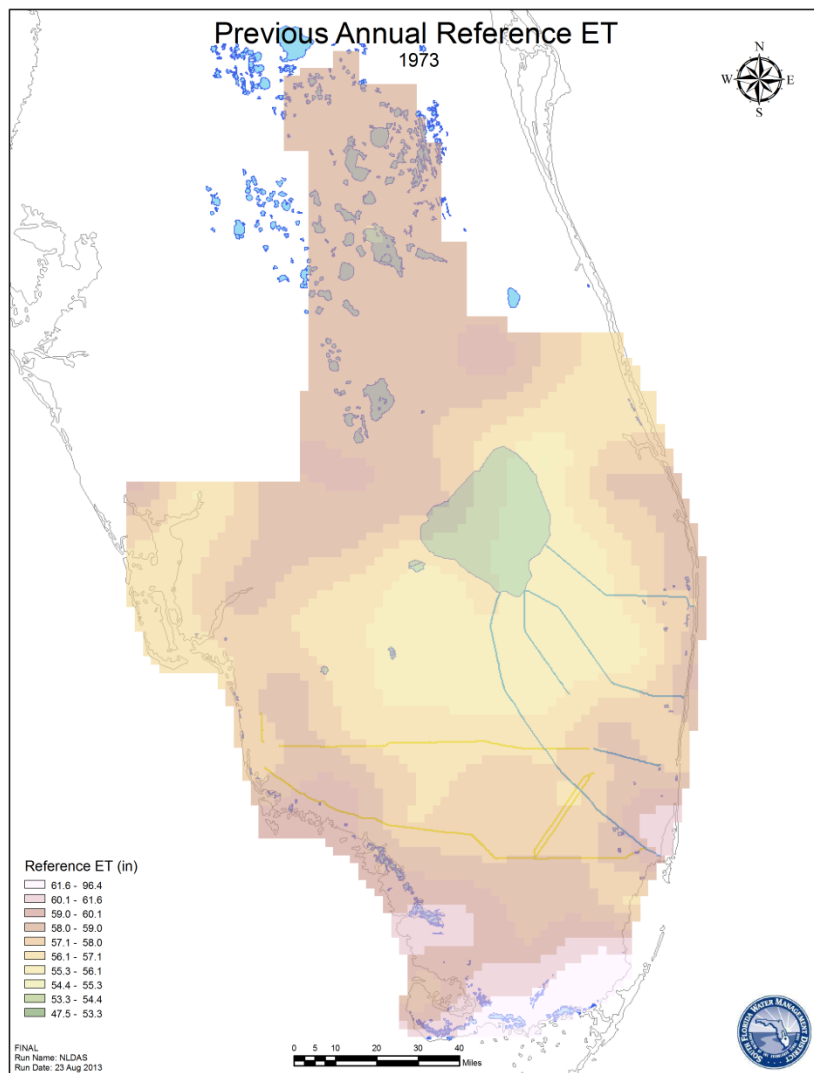


Figure B-9. Comparison of previous and new reference ET for 1973.

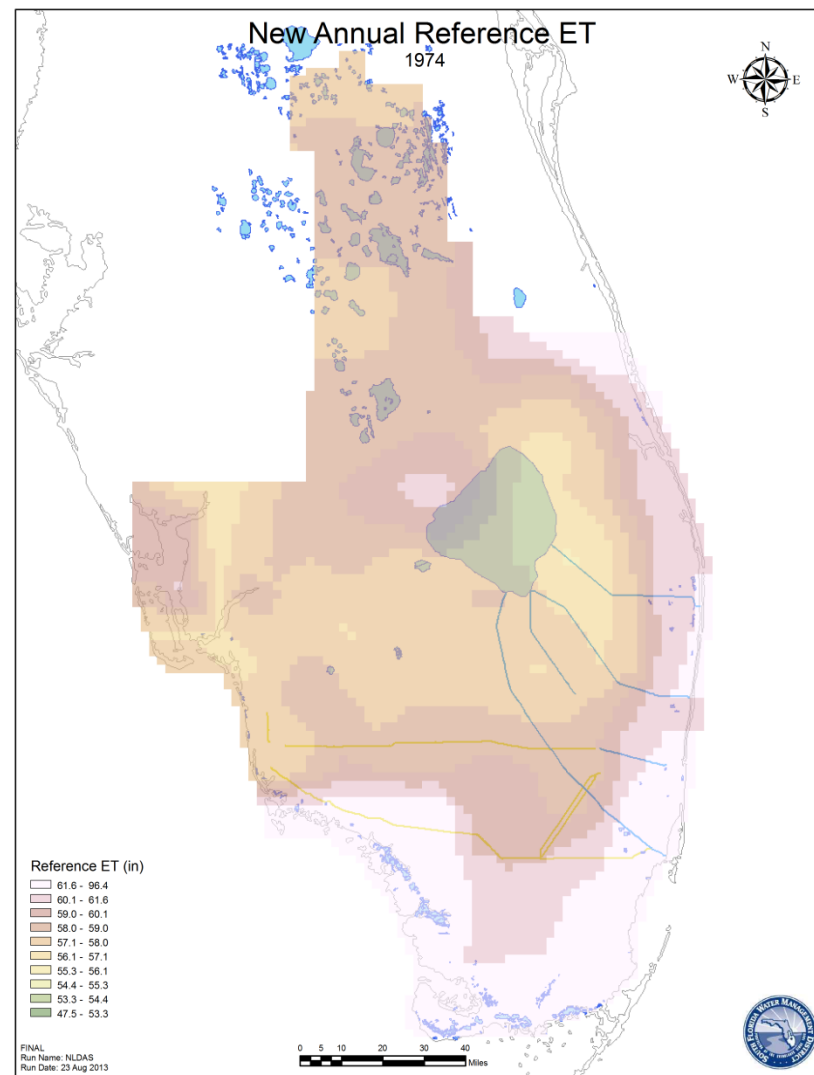
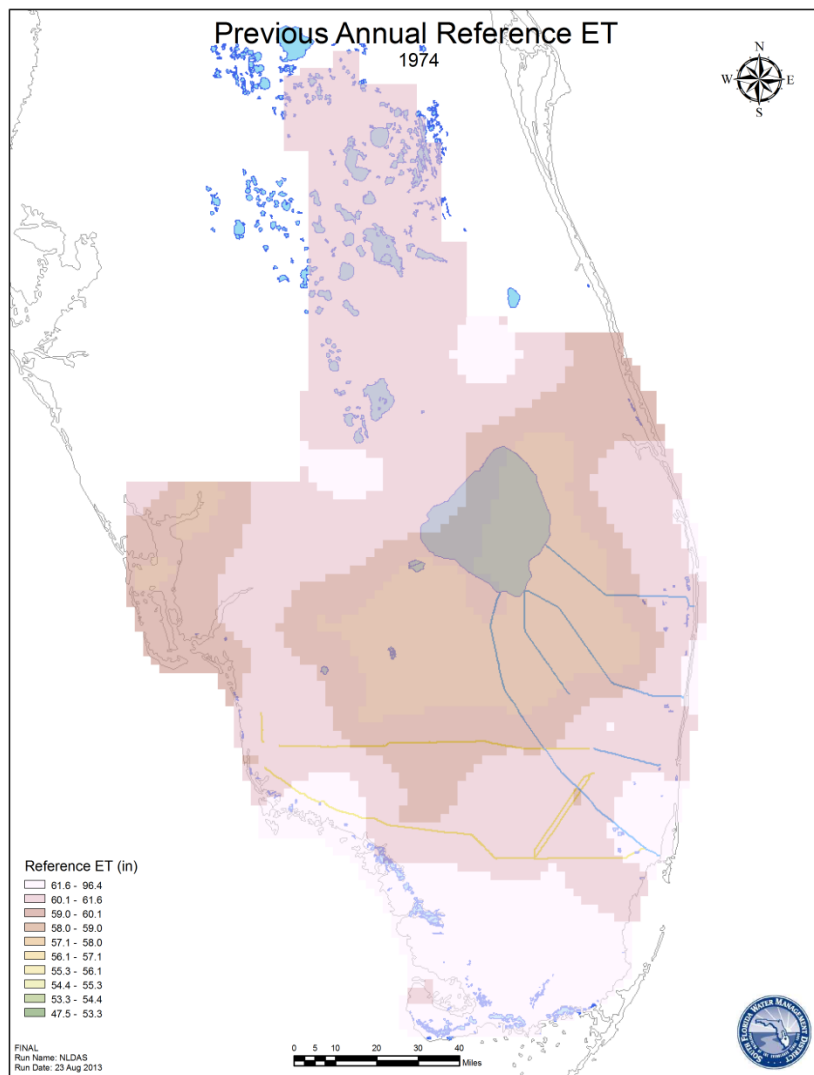


Figure B-10. Comparison of previous and new reference ET for 1974.

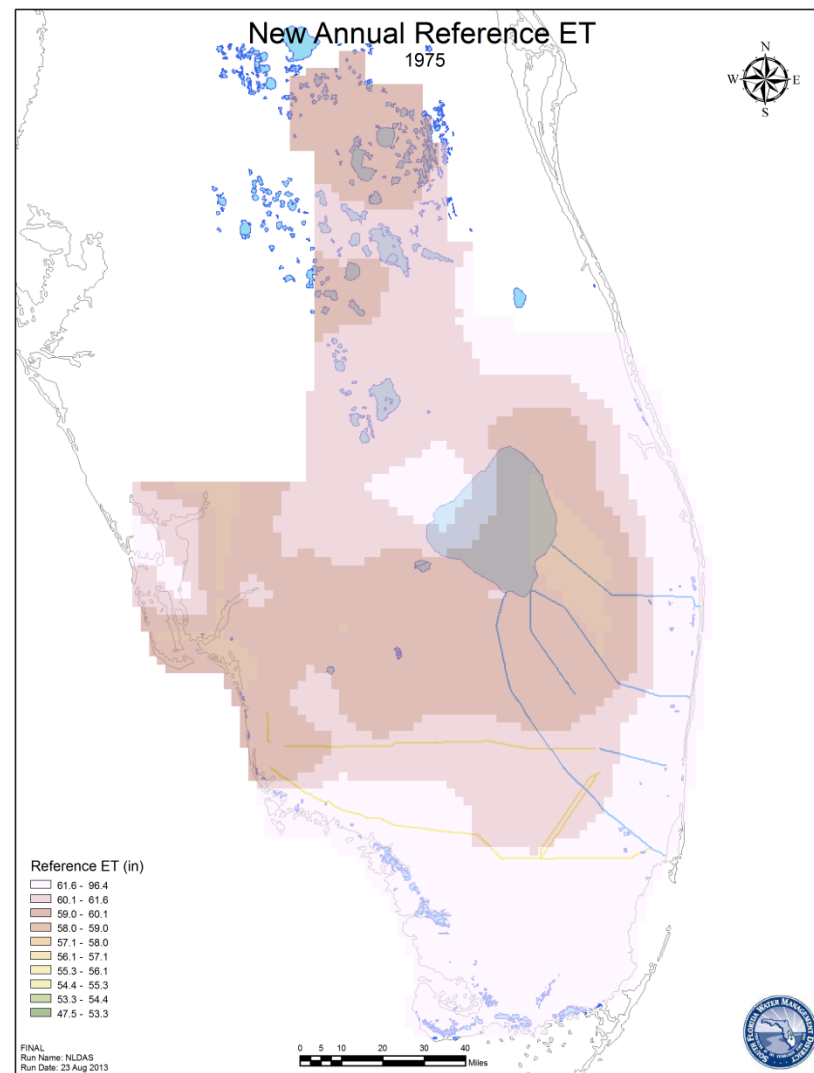
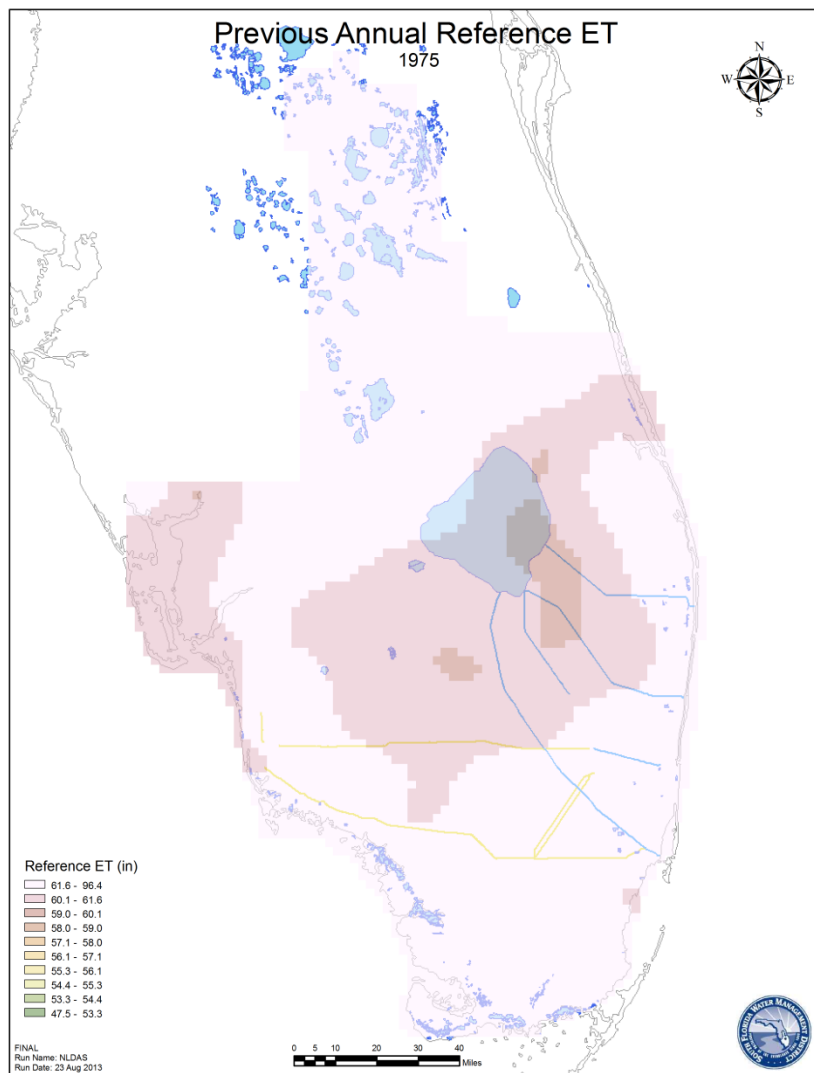


Figure B-11. Comparison of previous and new reference ET for 1975.

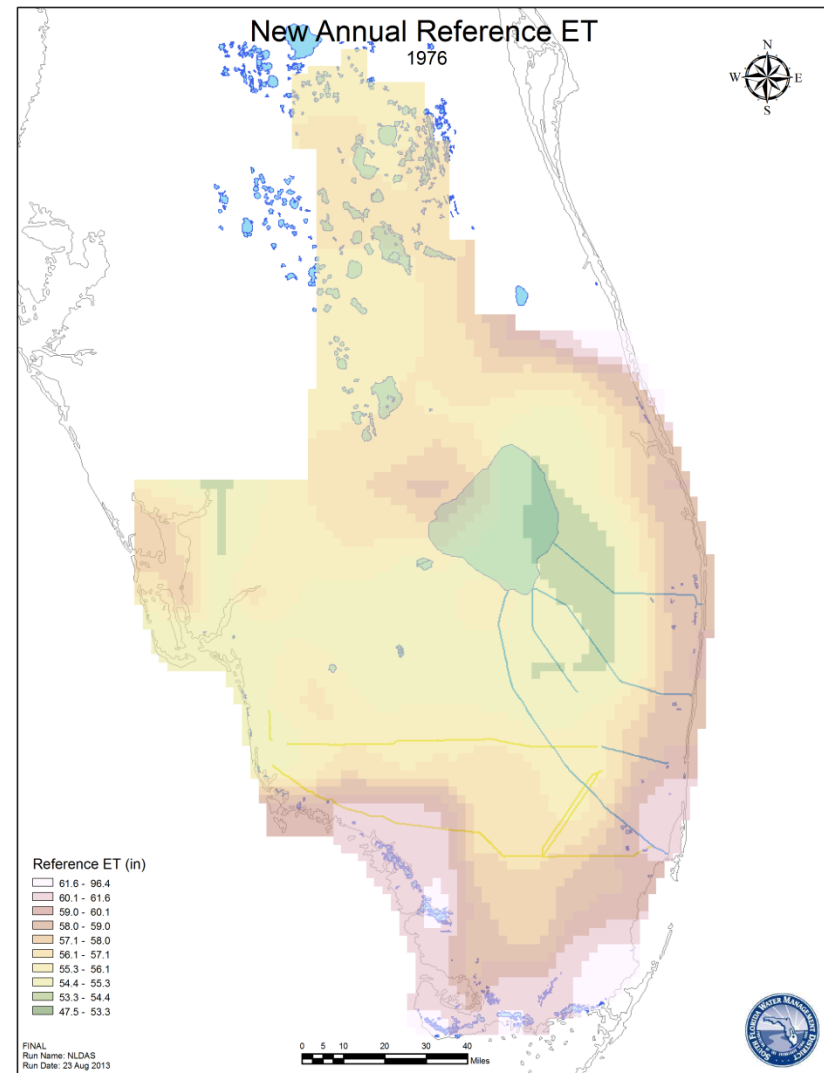
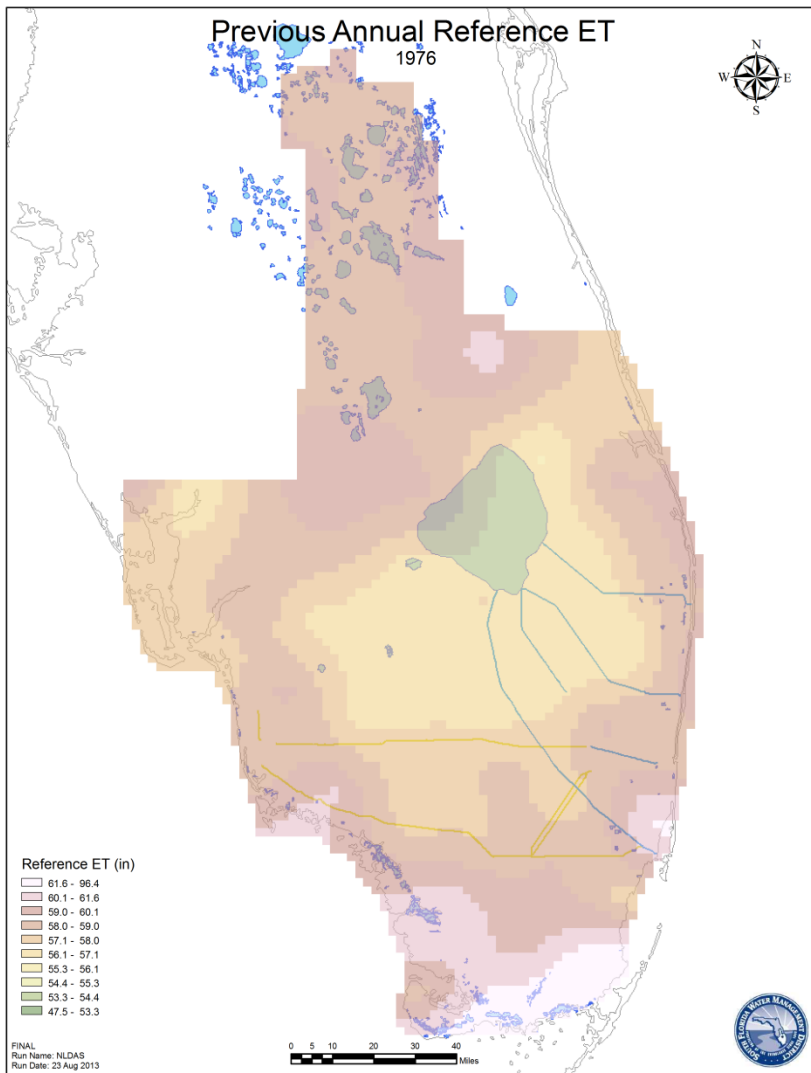


Figure B-12. Comparison of previous and new reference ET for 1976.

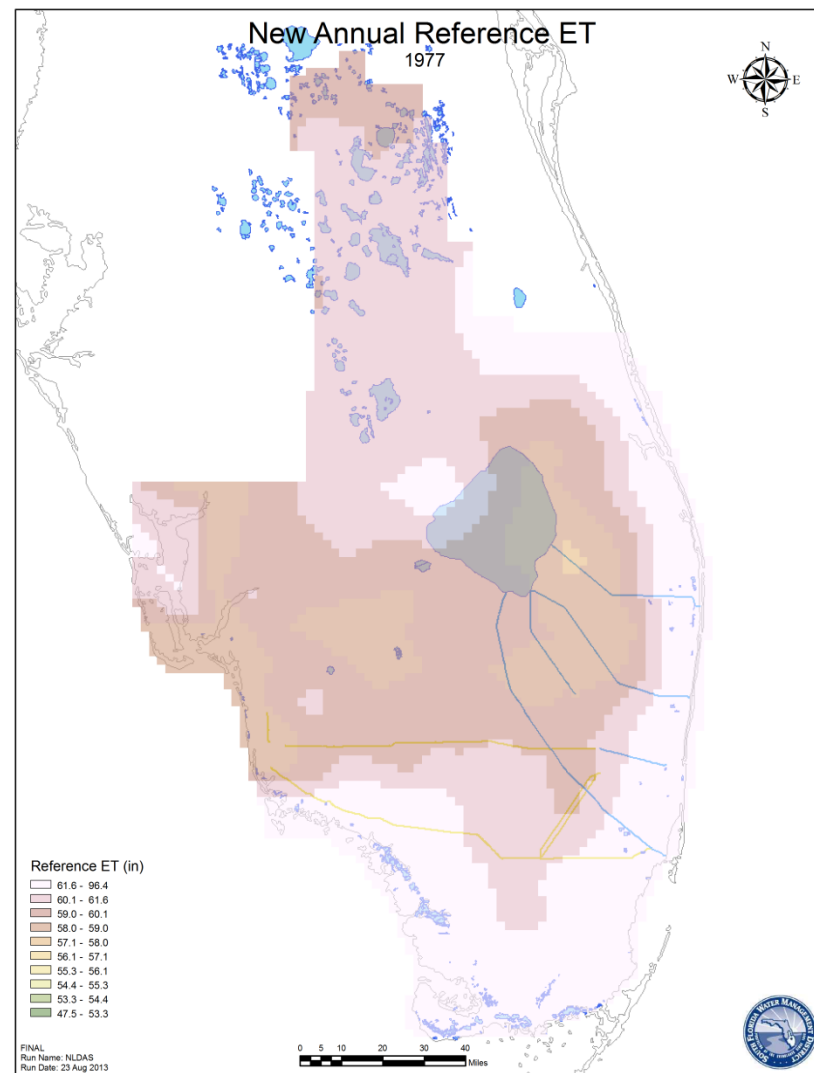
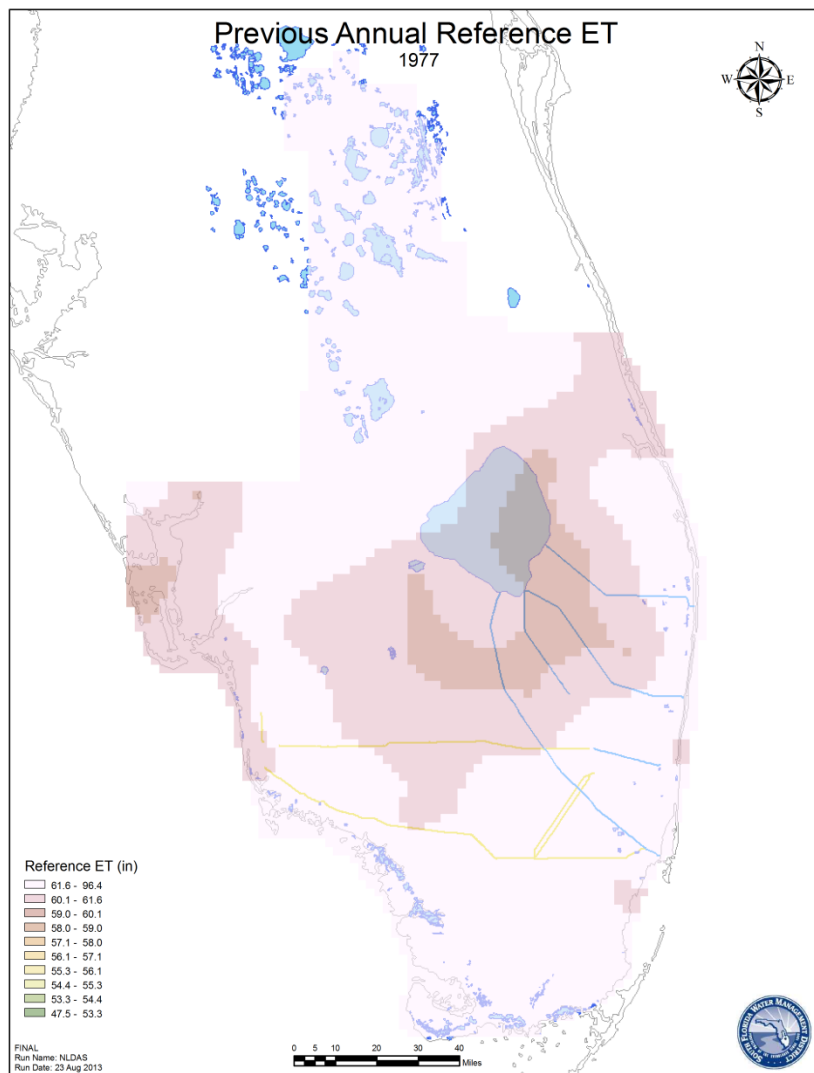


Figure B-13. Comparison of previous and new reference ET for 1977.

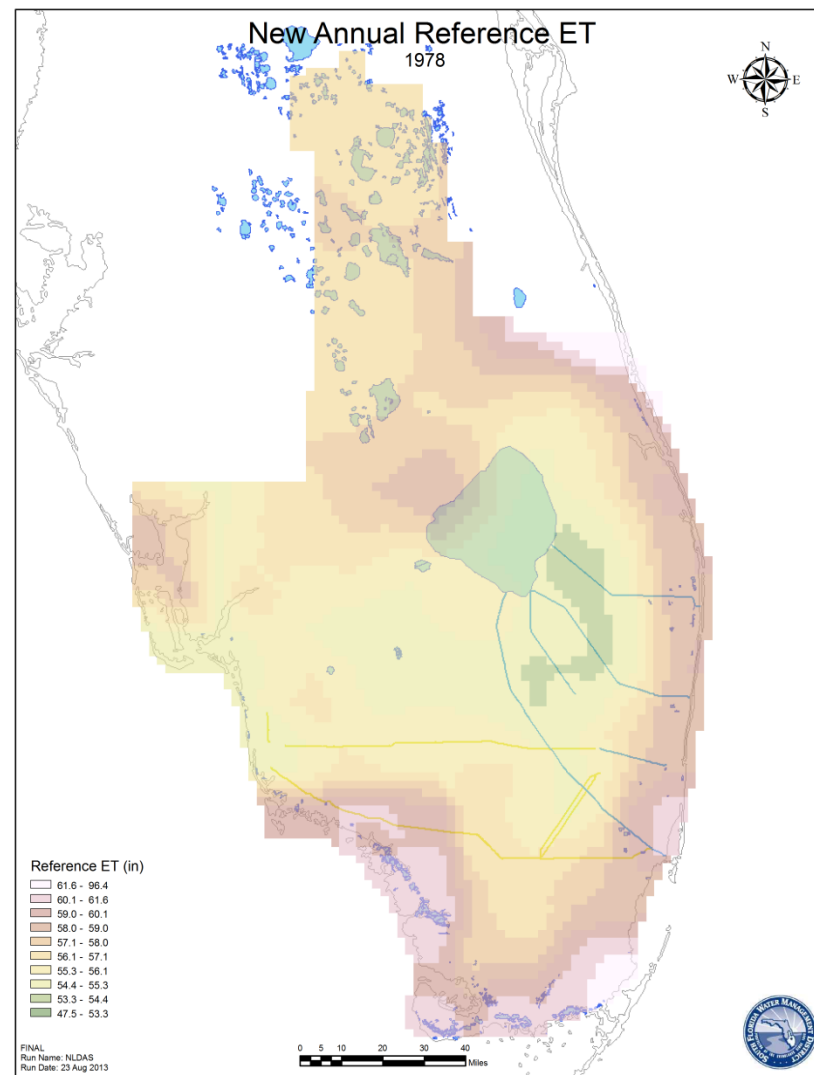
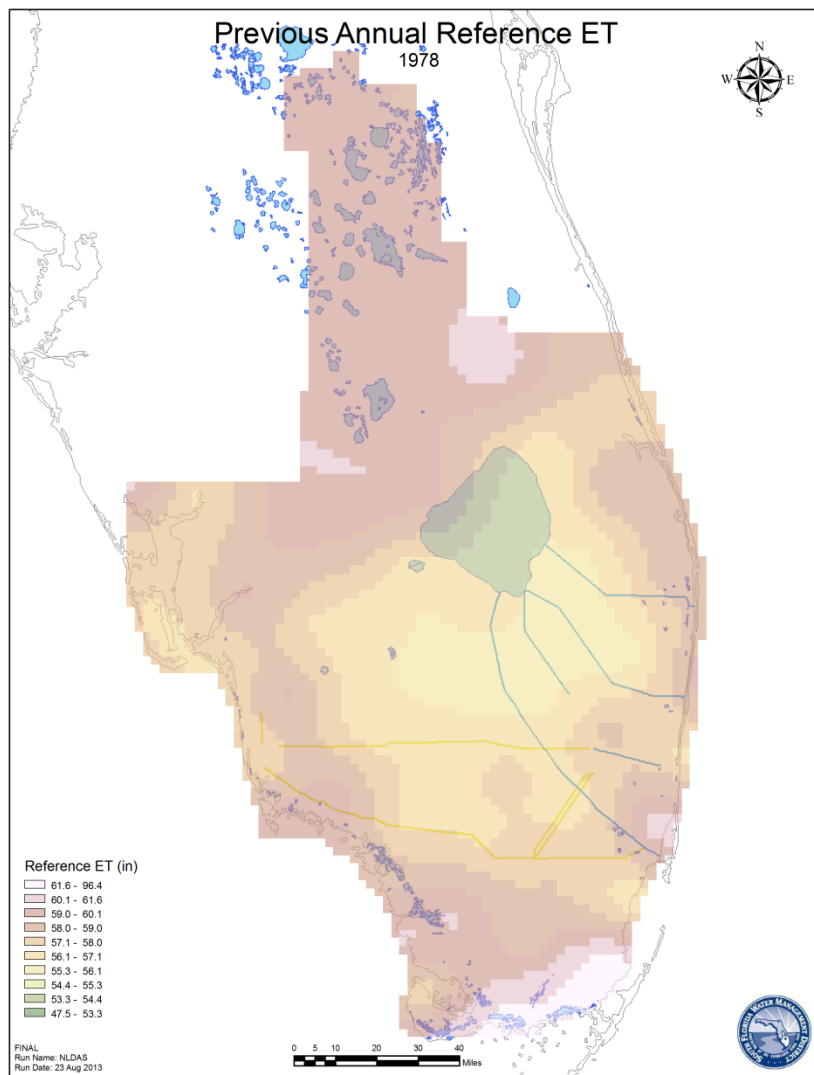


Figure B-14. Comparison of previous and new reference ET for 1978.

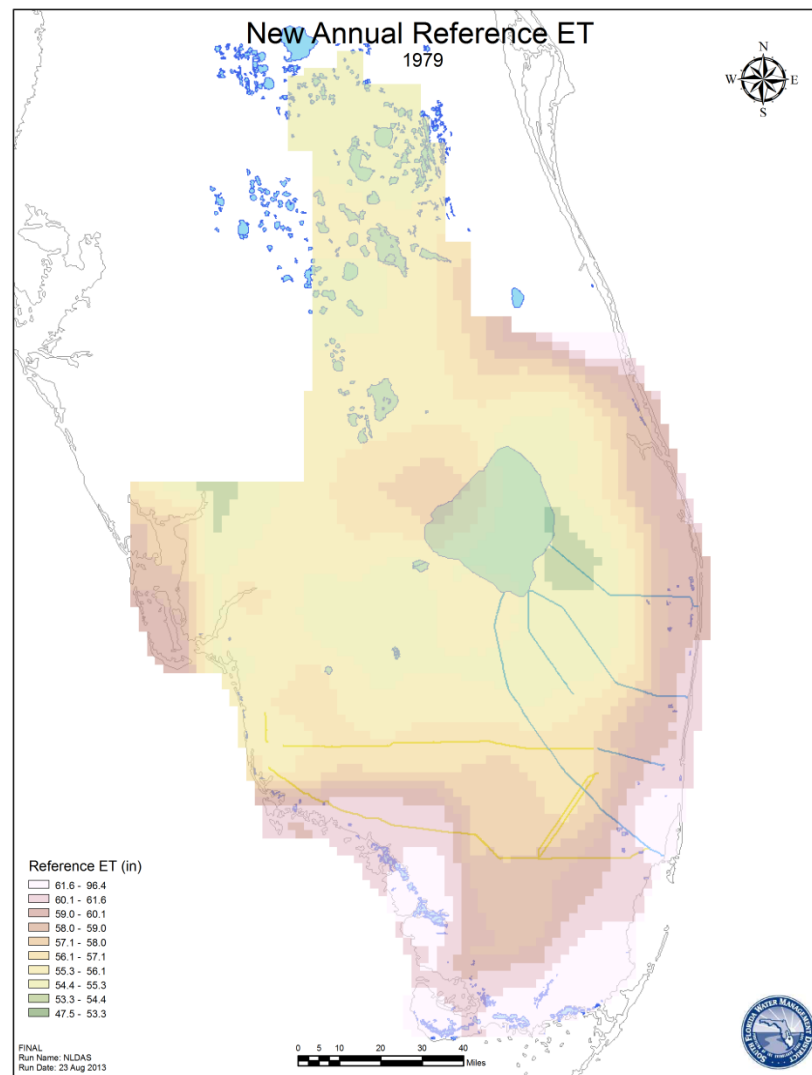
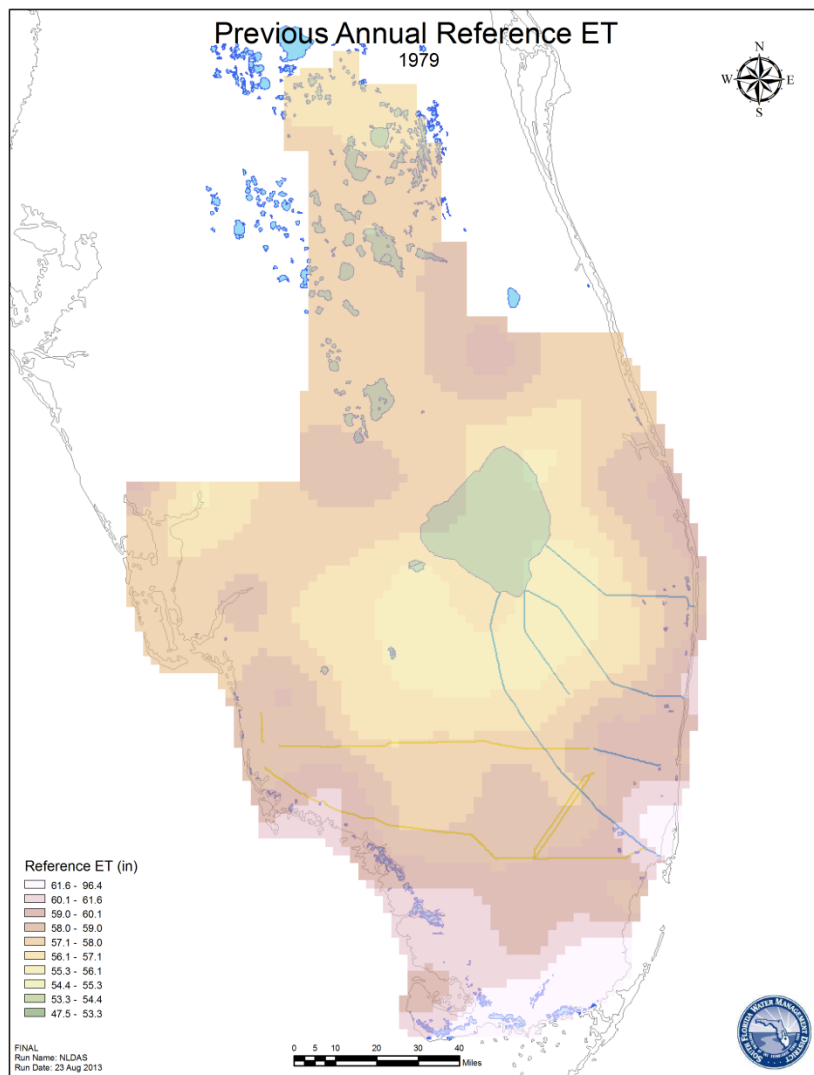


Figure B-15. Comparison of previous and new reference ET for 1979.

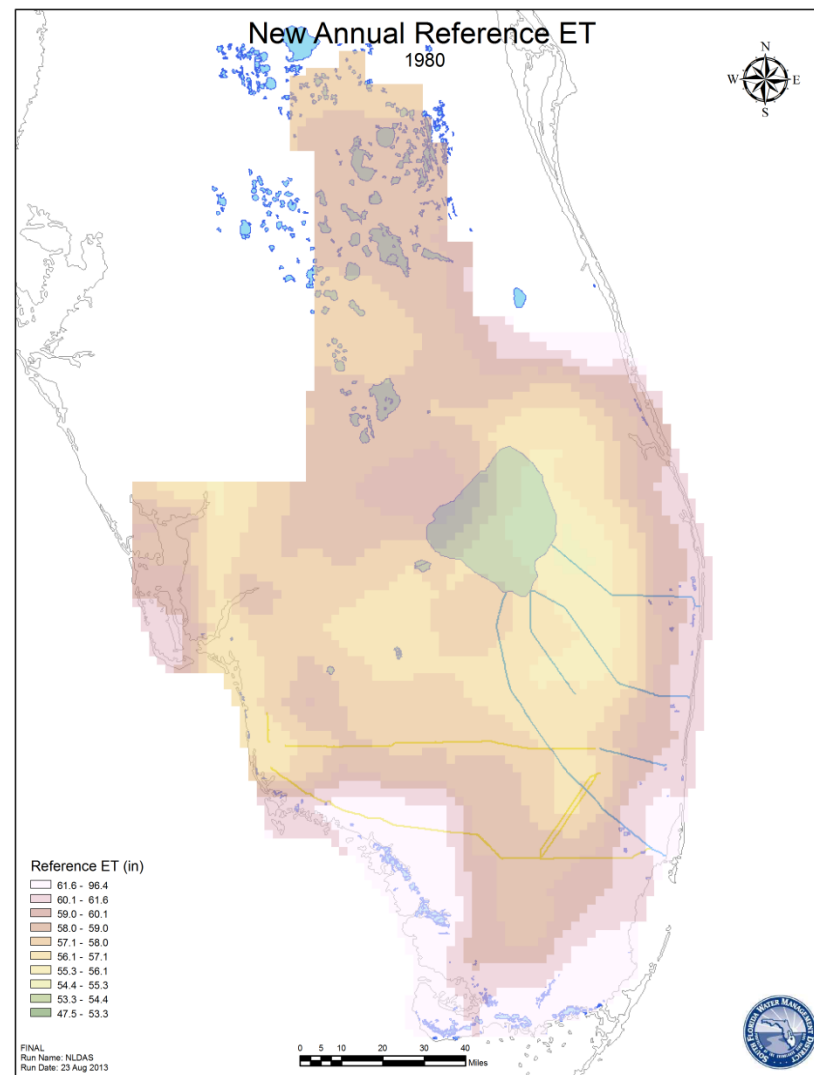
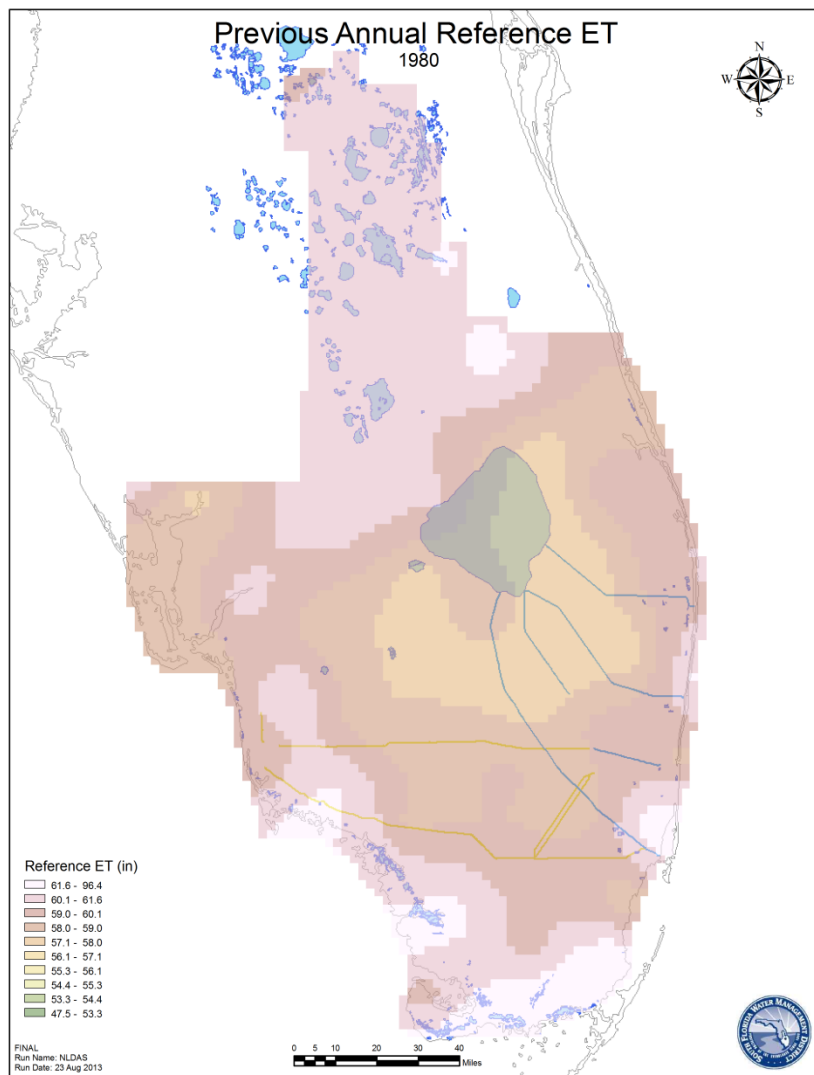


Figure B-16. Comparison of previous and new reference ET for 1980.

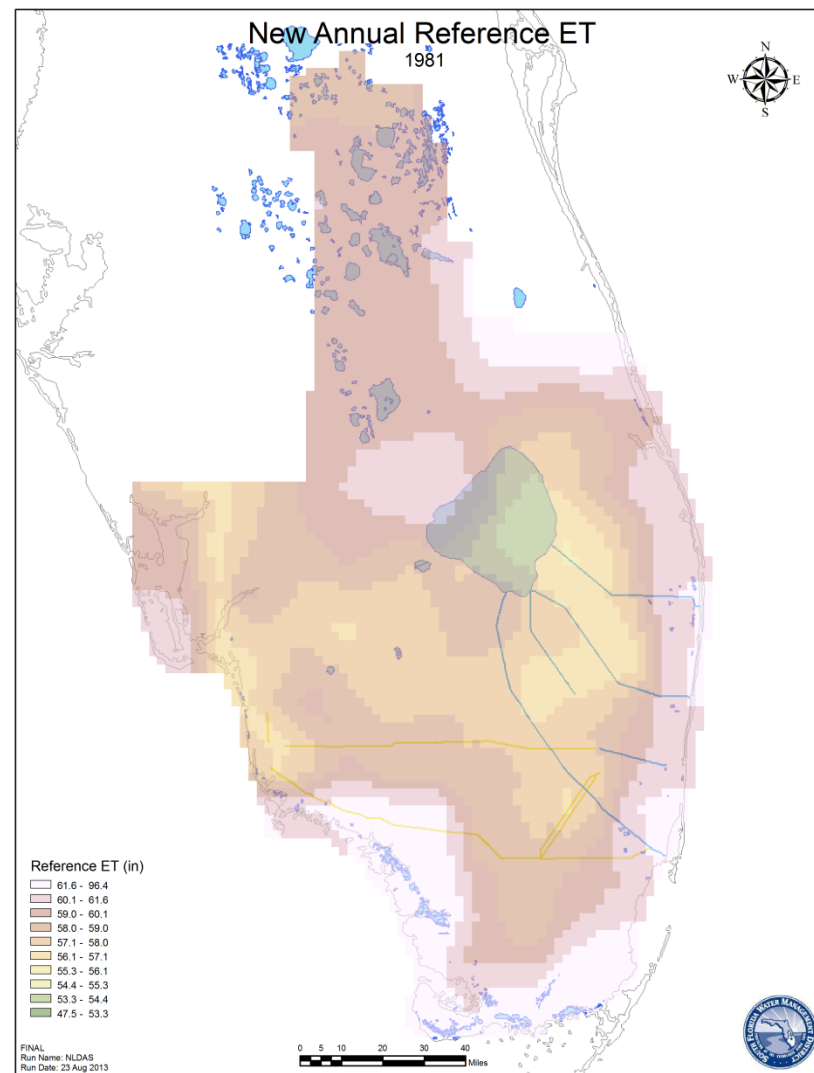
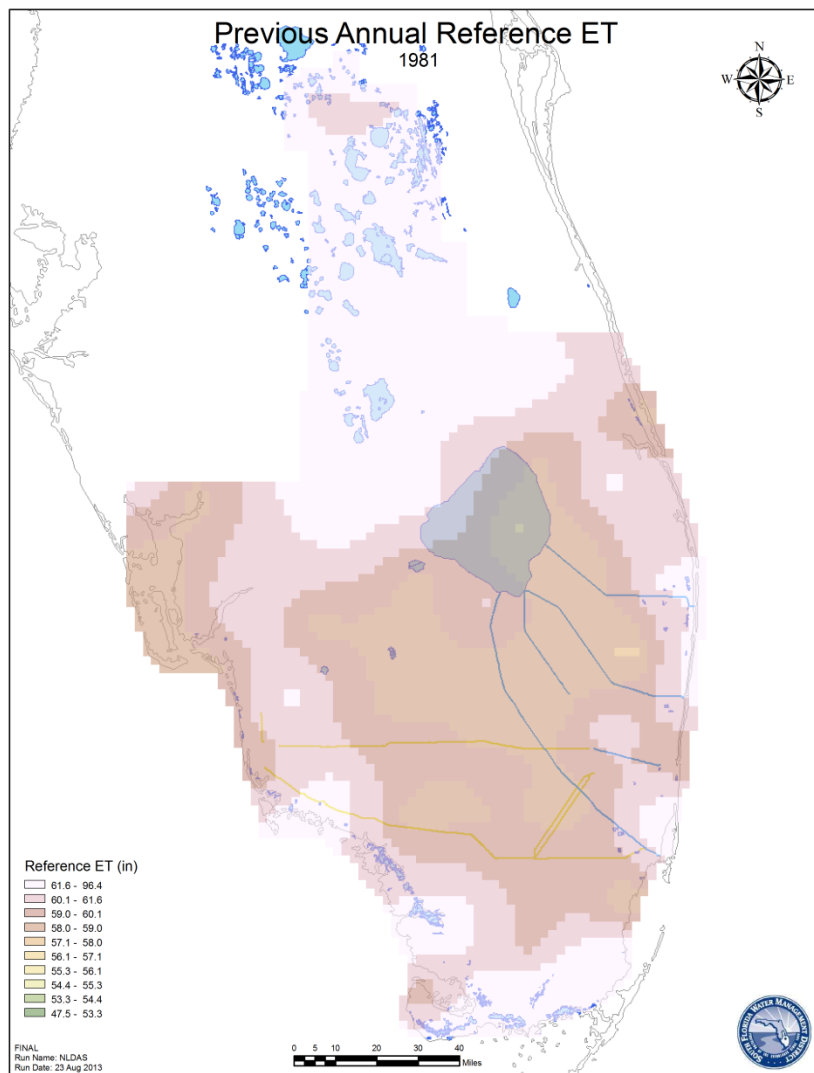


Figure B-17. Comparison of previous and new reference ET for 1981.

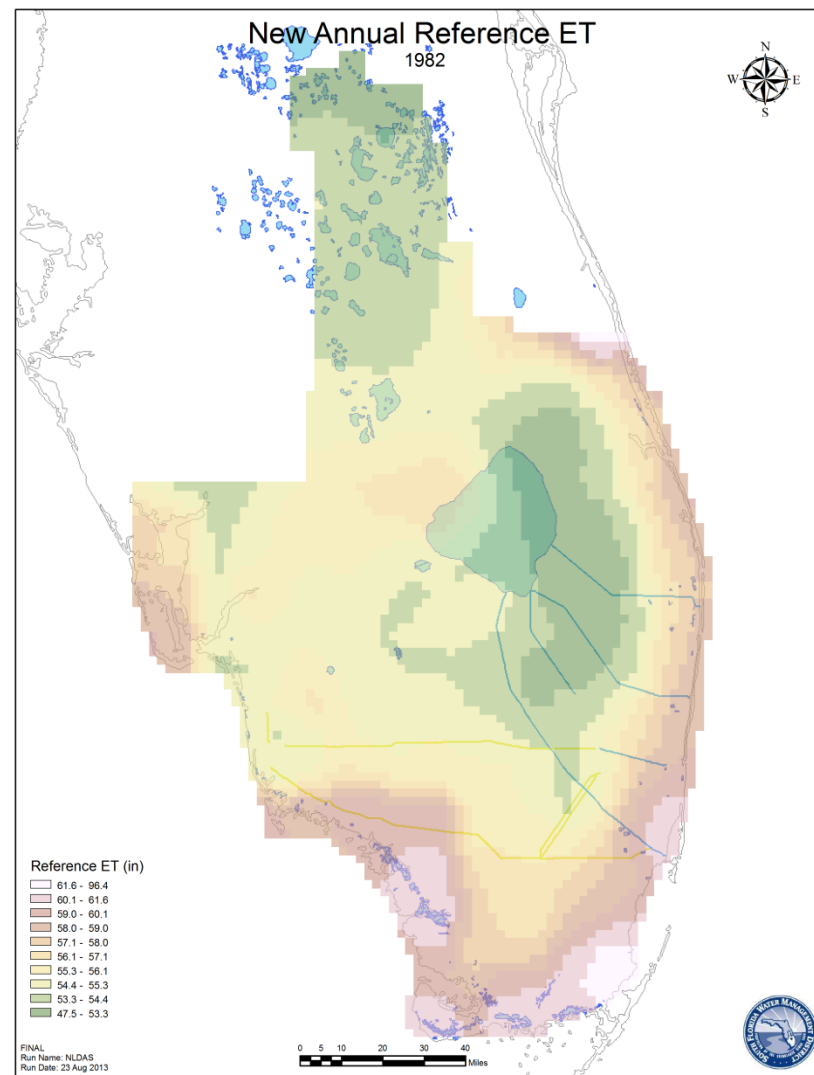
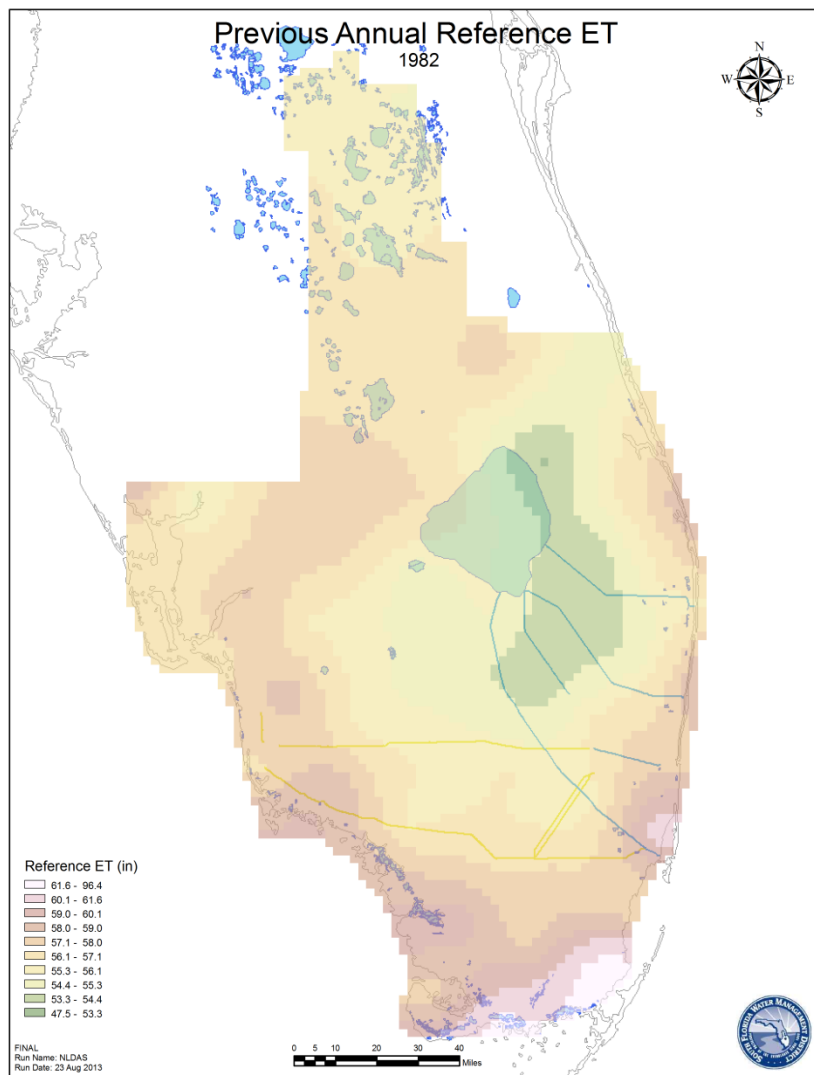


Figure B-18. Comparison of previous and new reference ET for 1982.

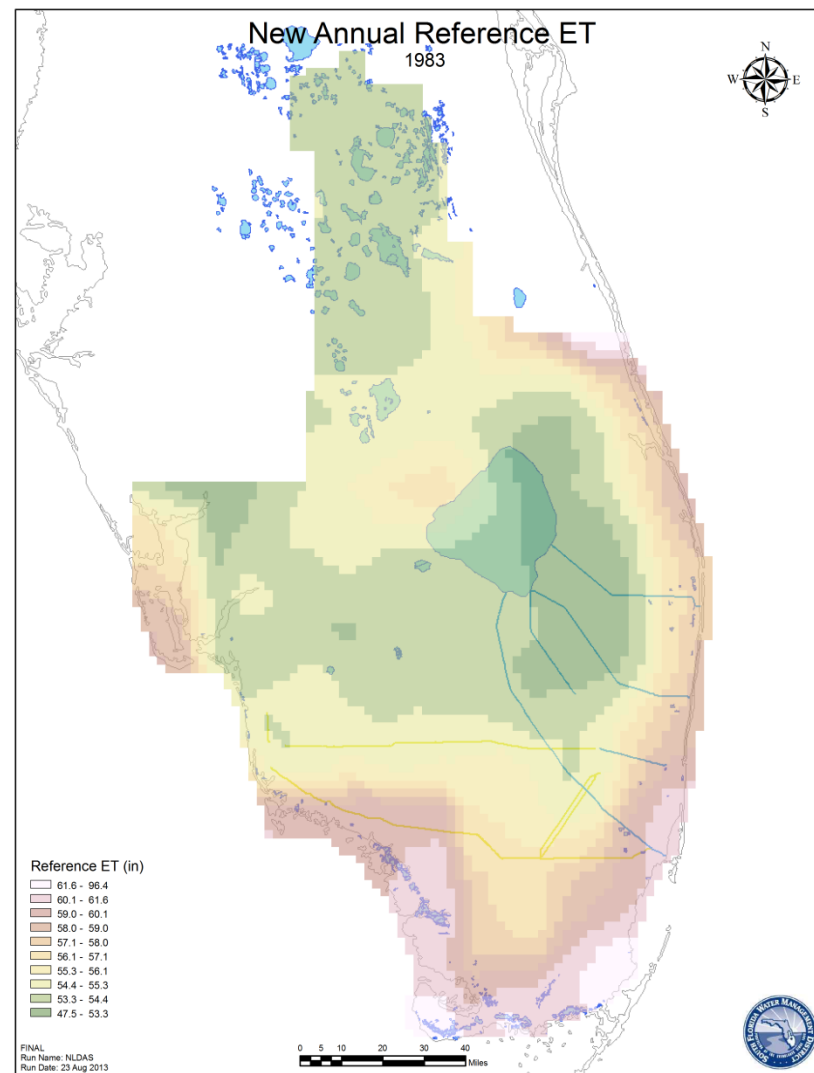
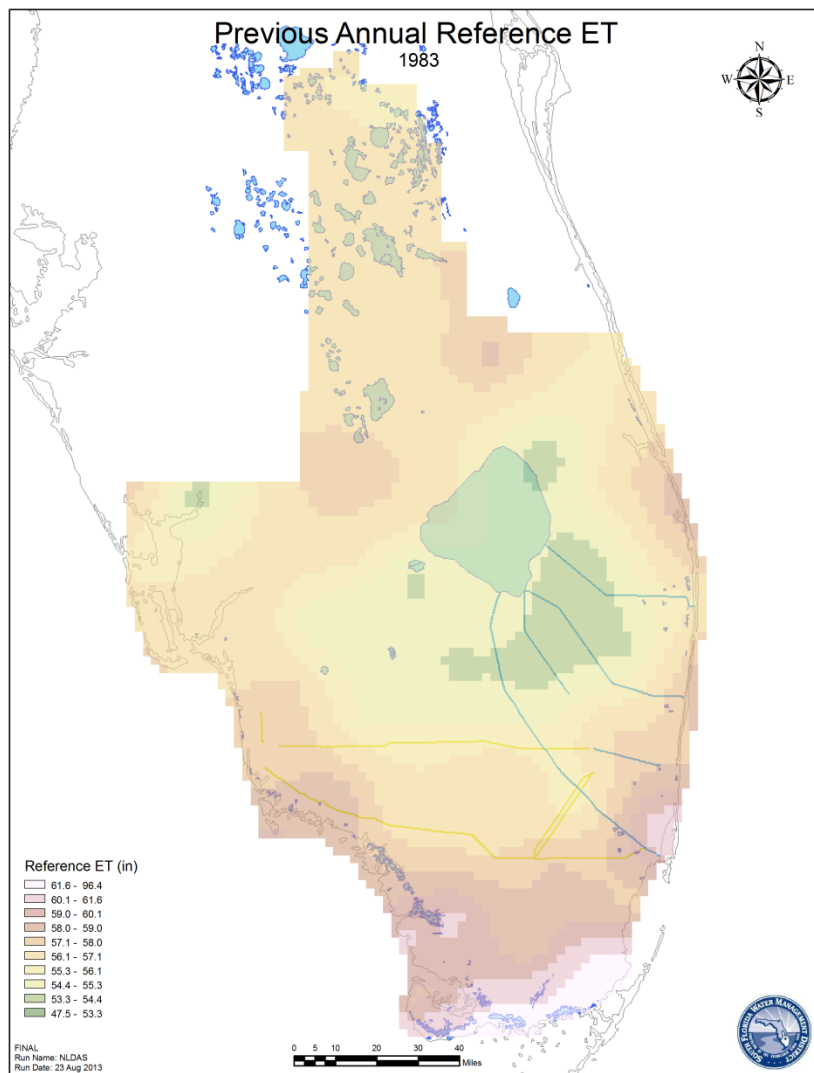


Figure B-19. Comparison of previous and new reference ET for 1983.

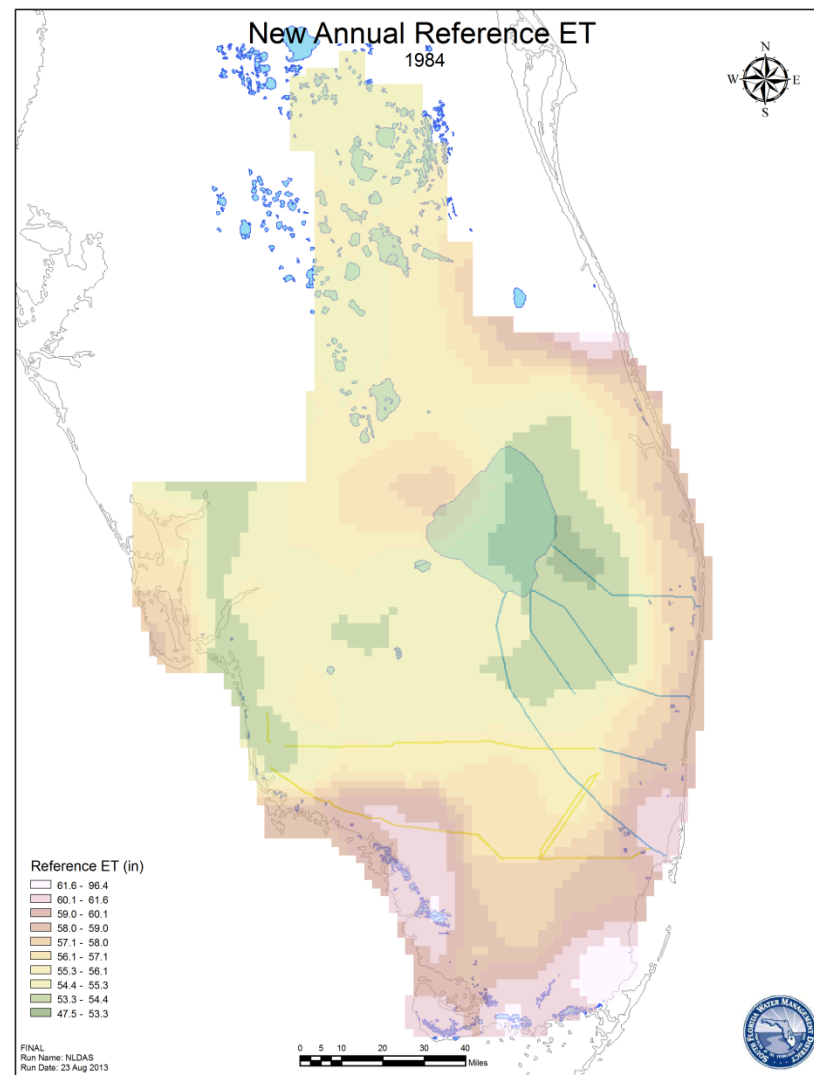
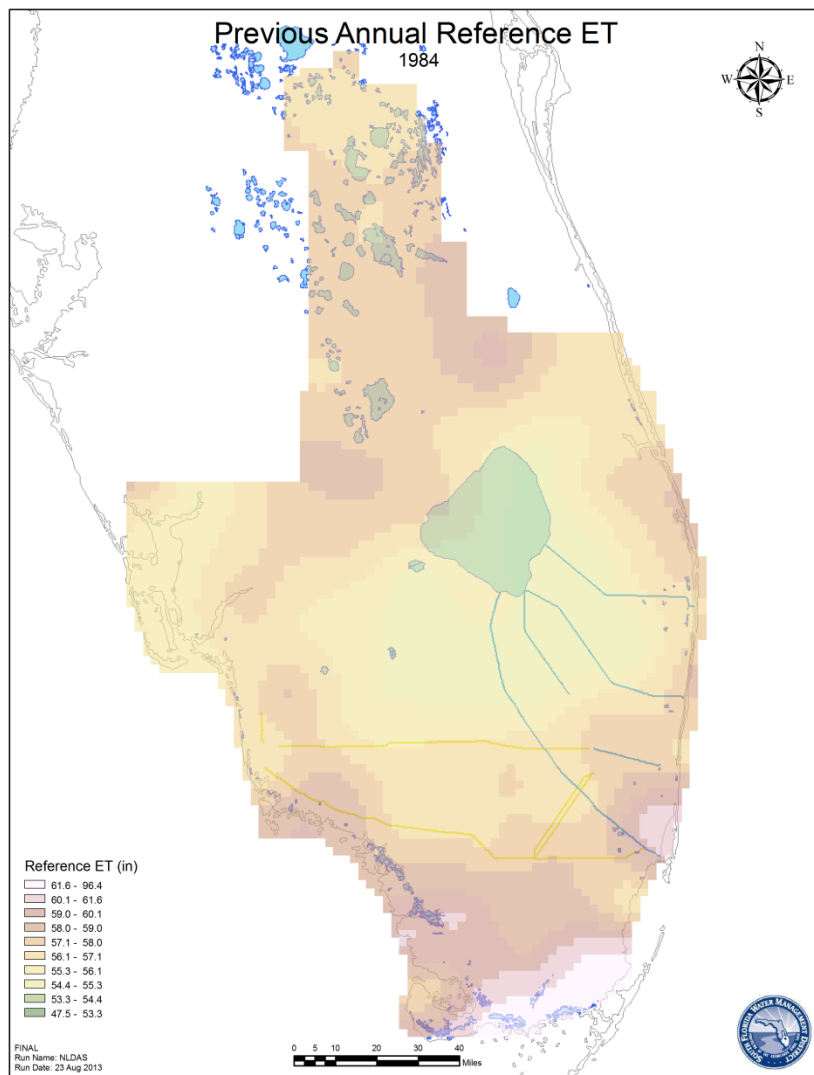


Figure B-20. Comparison of previous and new reference ET for 1984.

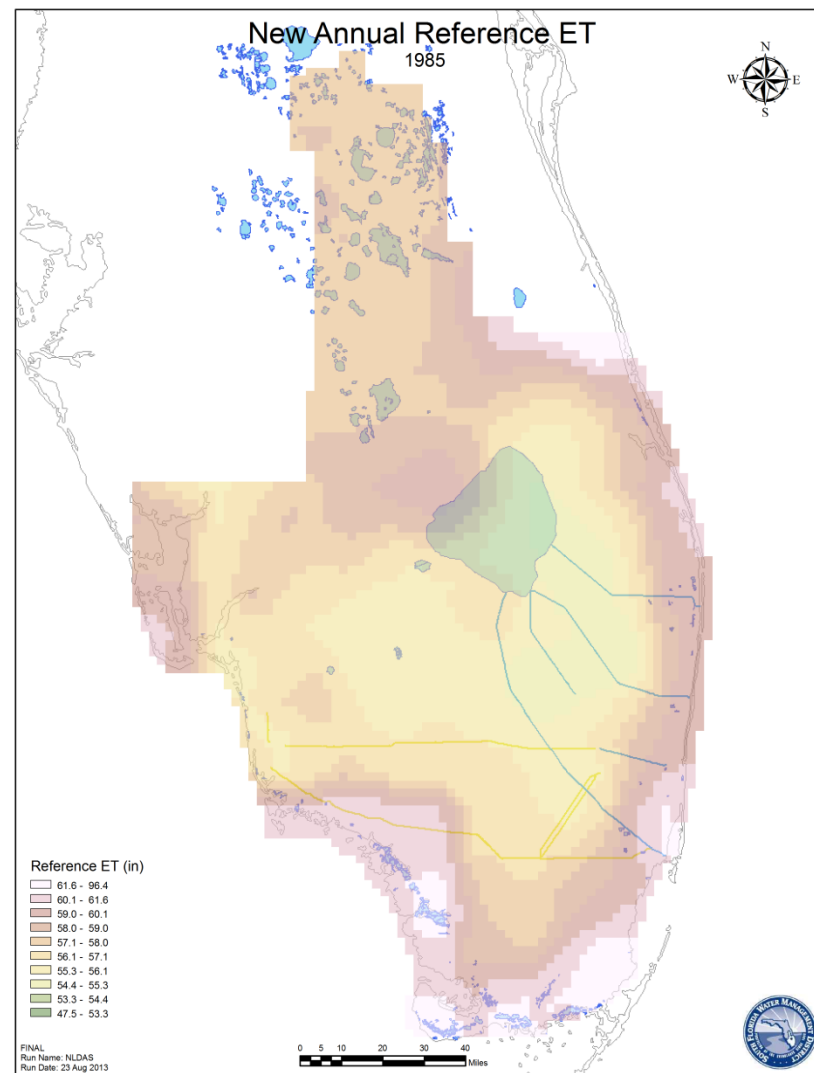
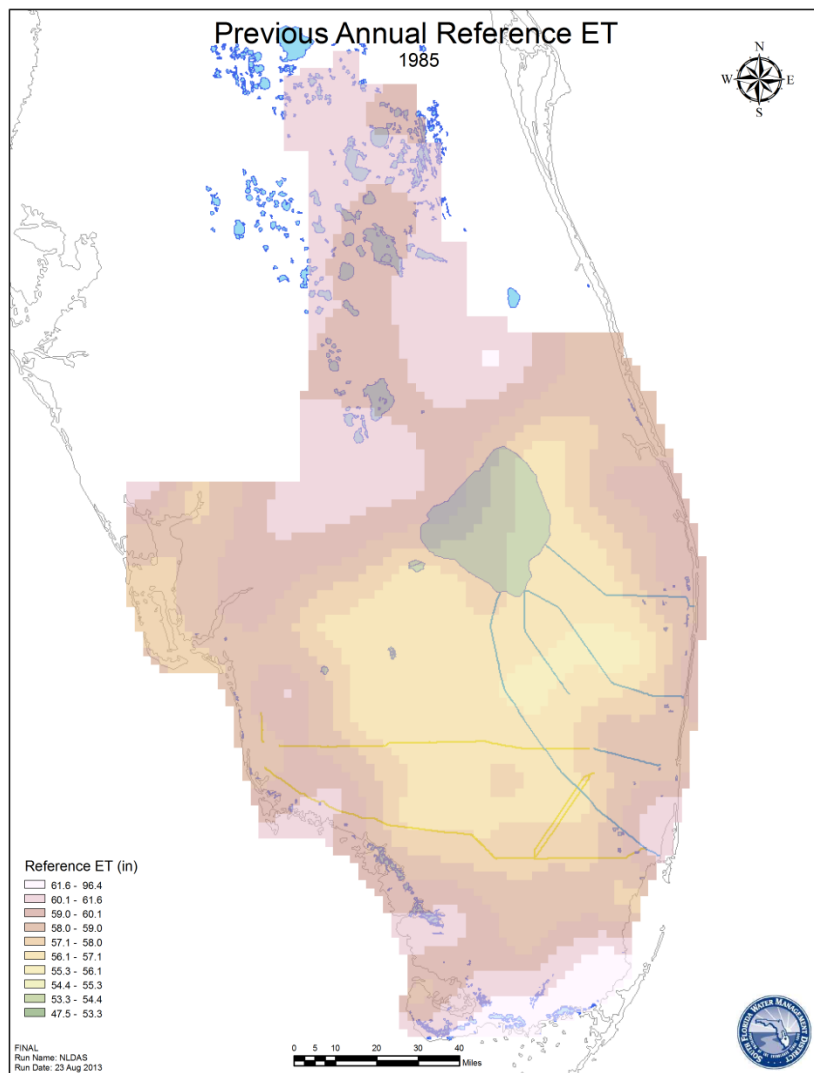


Figure B-21. Comparison of previous and new reference ET for 1985.

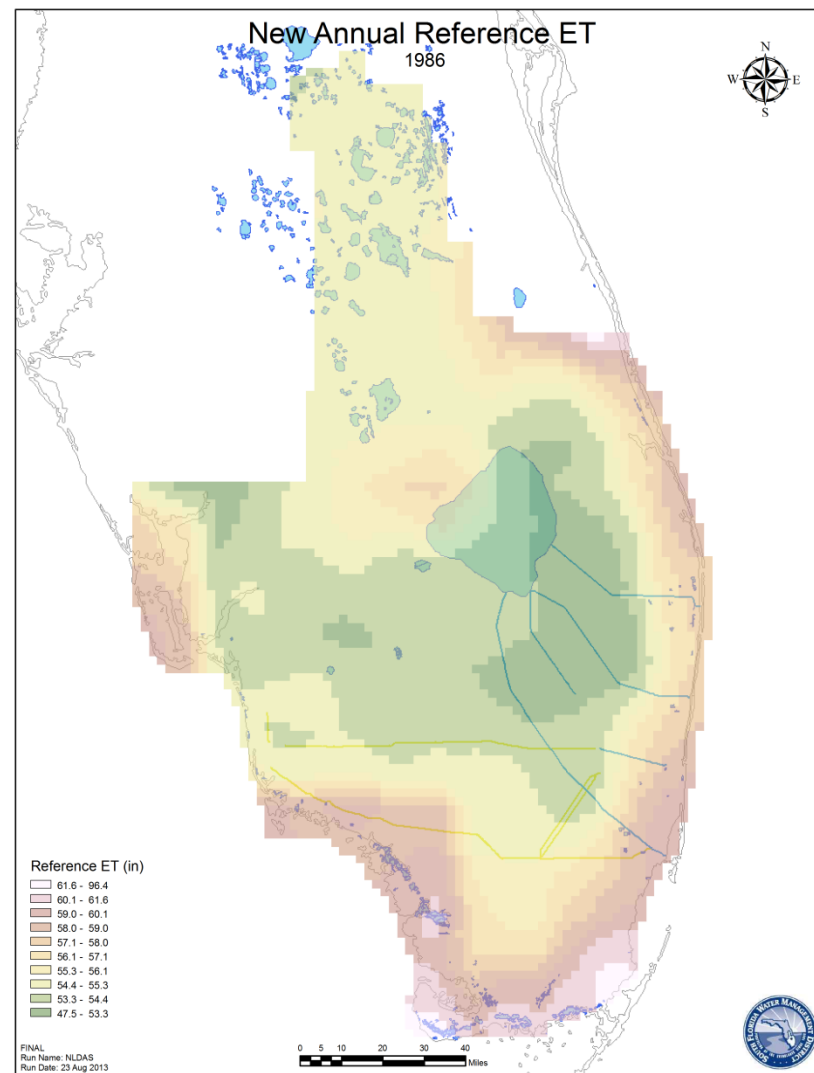
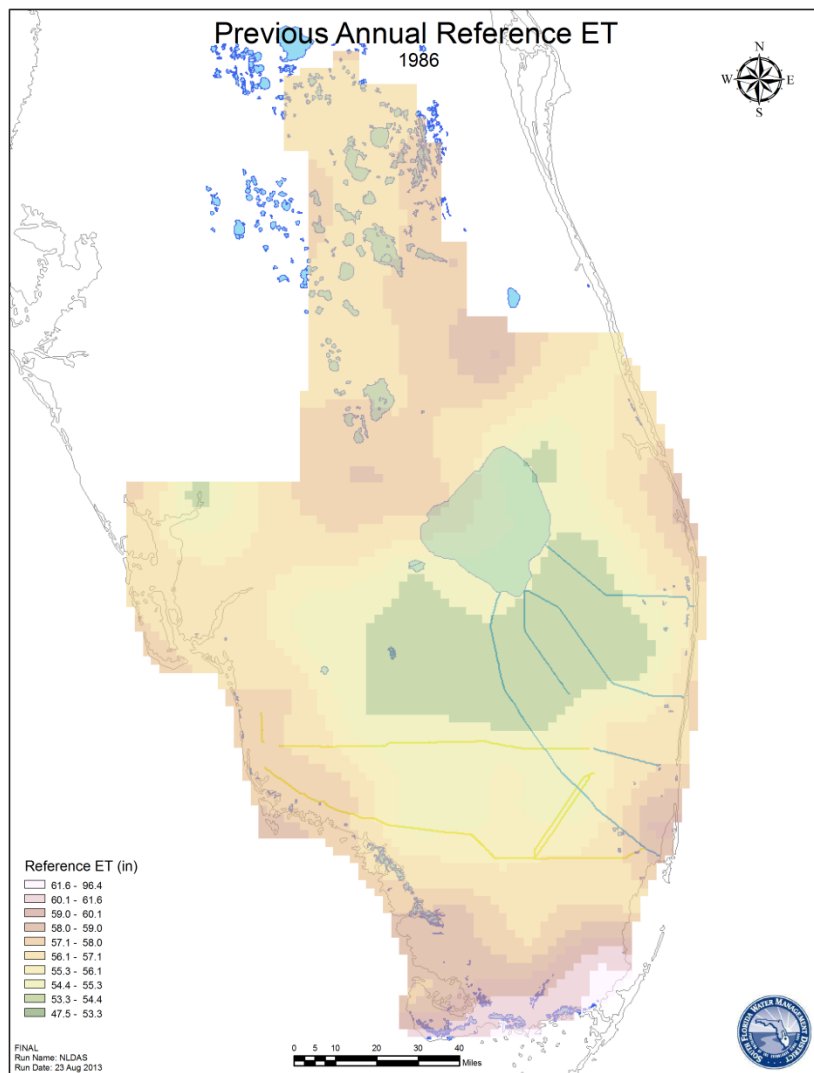


Figure B-22. Comparison of previous and new reference ET for 1986.

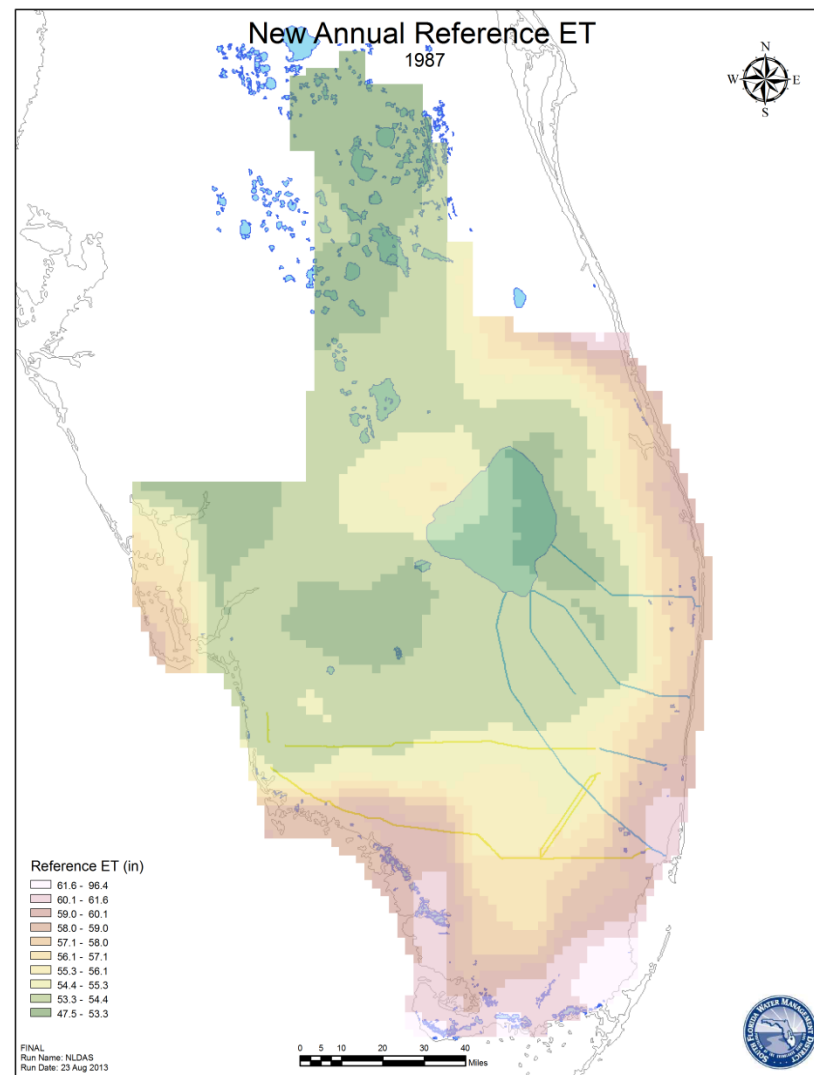
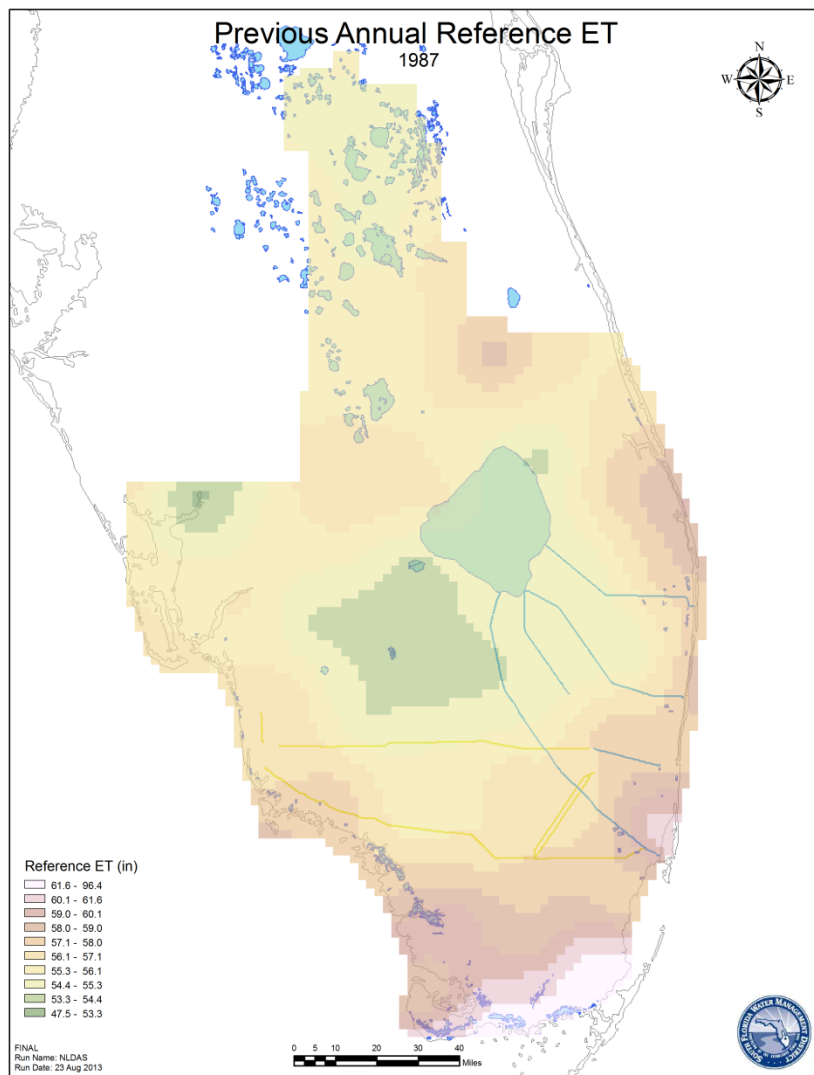


Figure B-23. Comparison of previous and new reference ET for 1987.

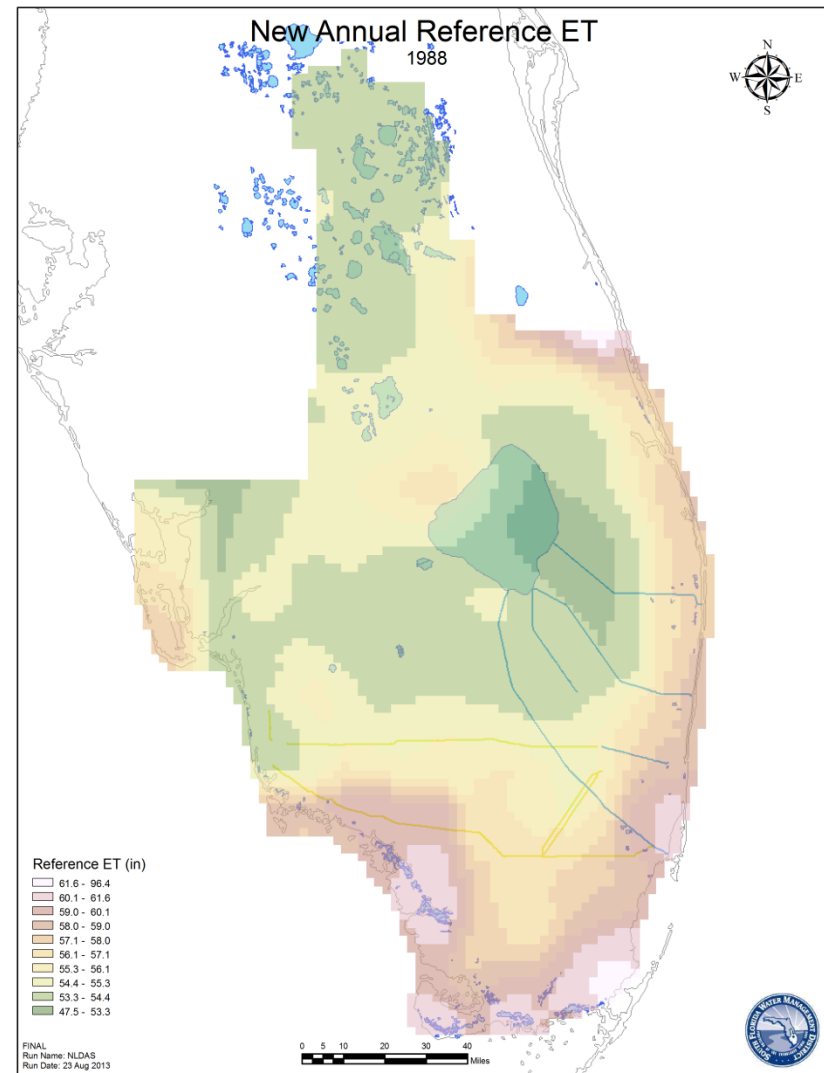
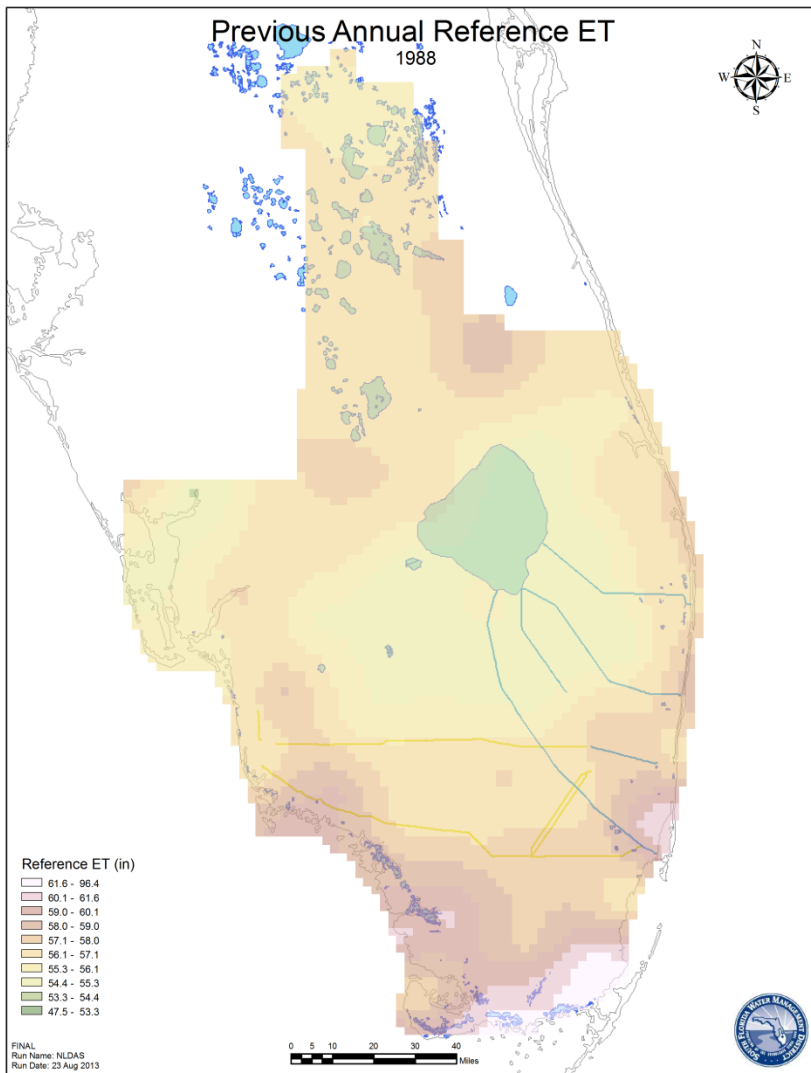


Figure B-24. Comparison of previous and new reference ET for 1988.

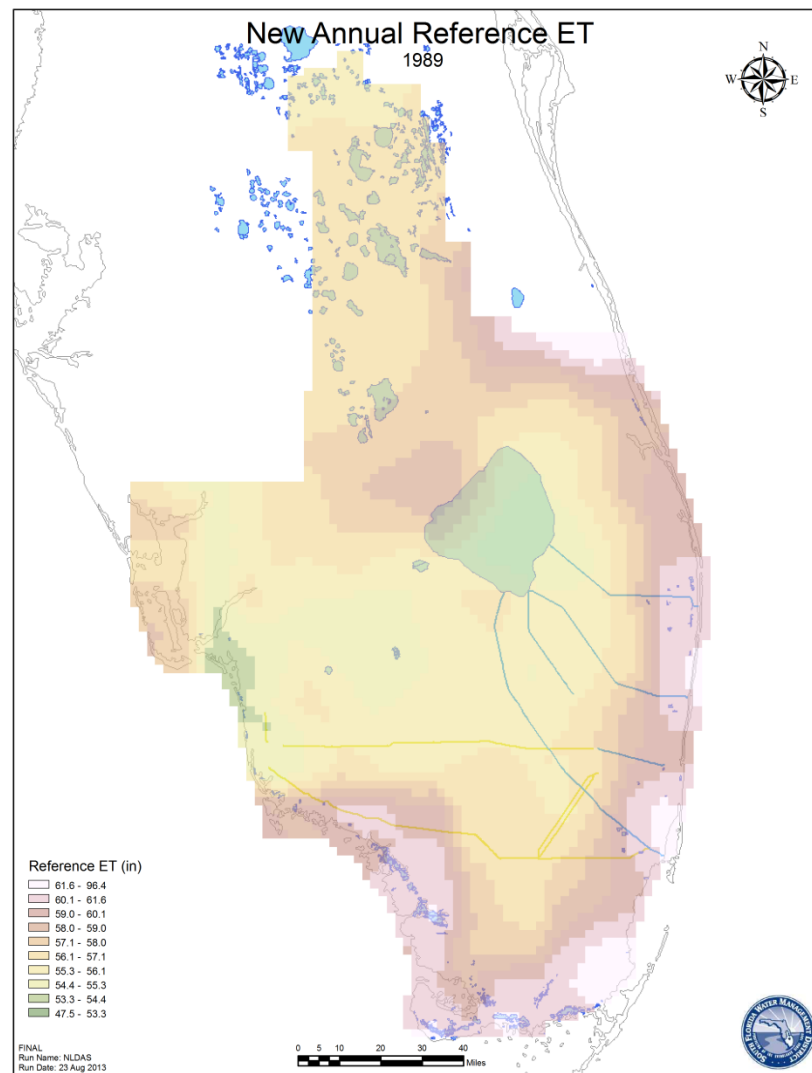
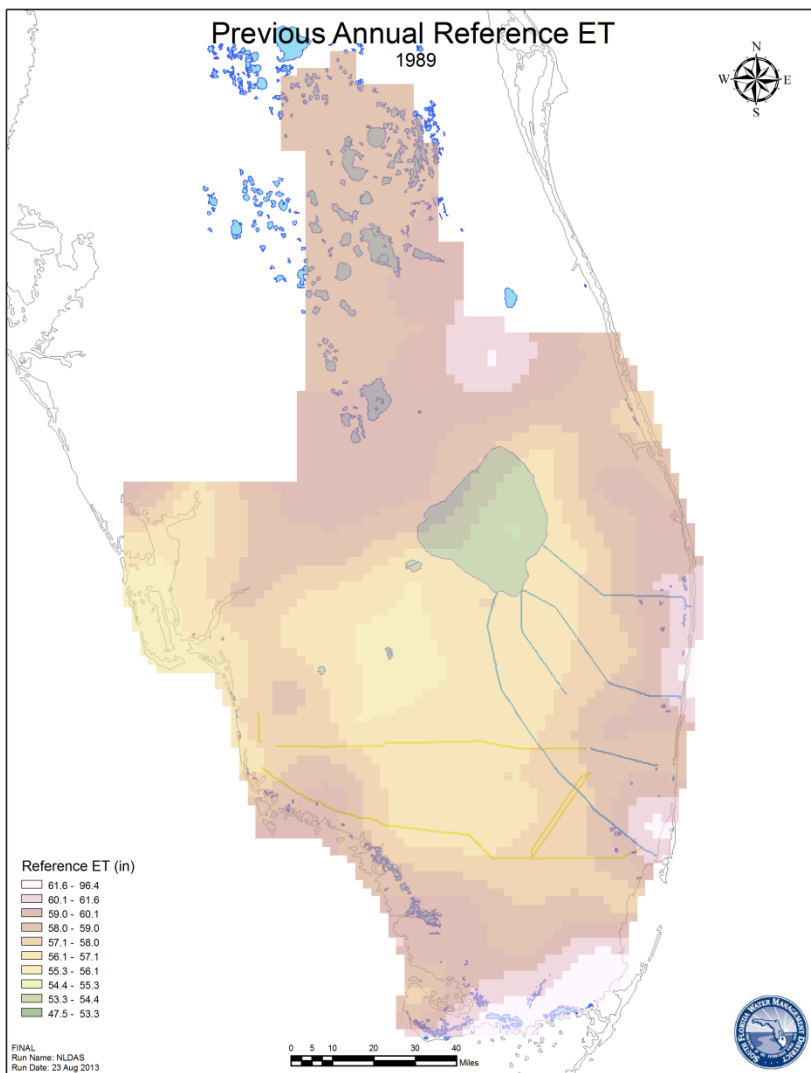


Figure B-25. Comparison of previous and new reference ET for 1989.

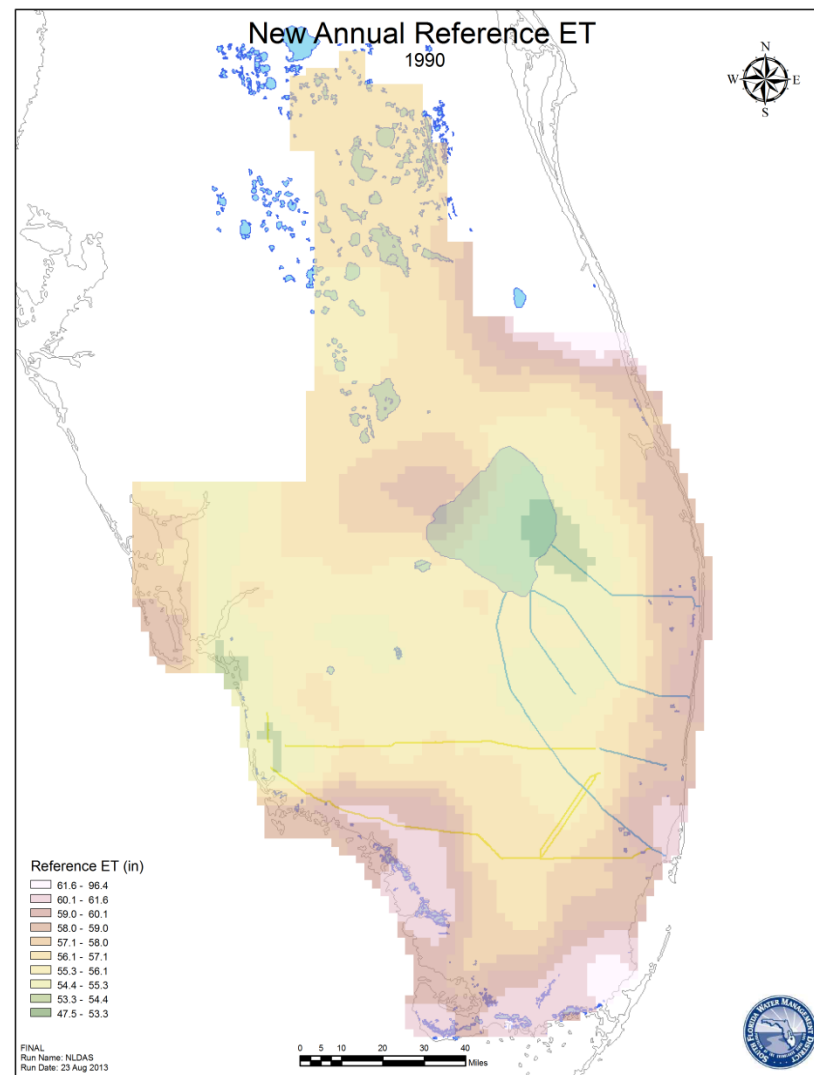
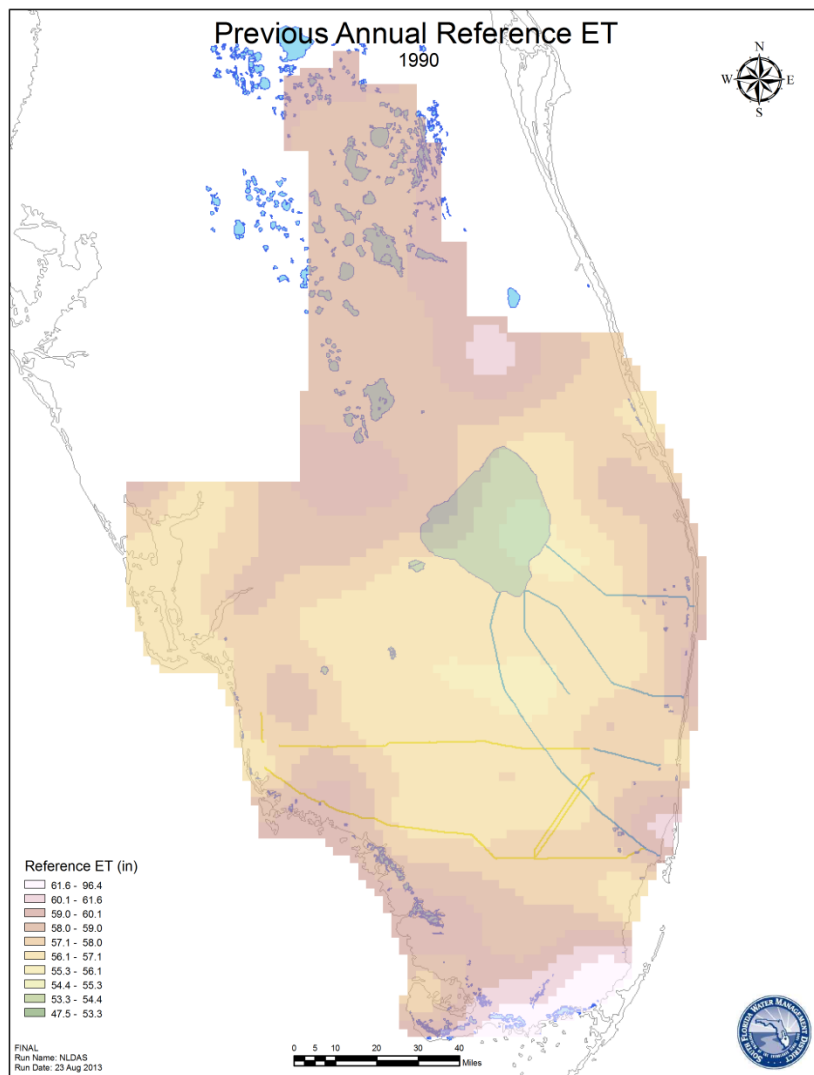


Figure B-26. Comparison of previous and new reference ET for 1990.

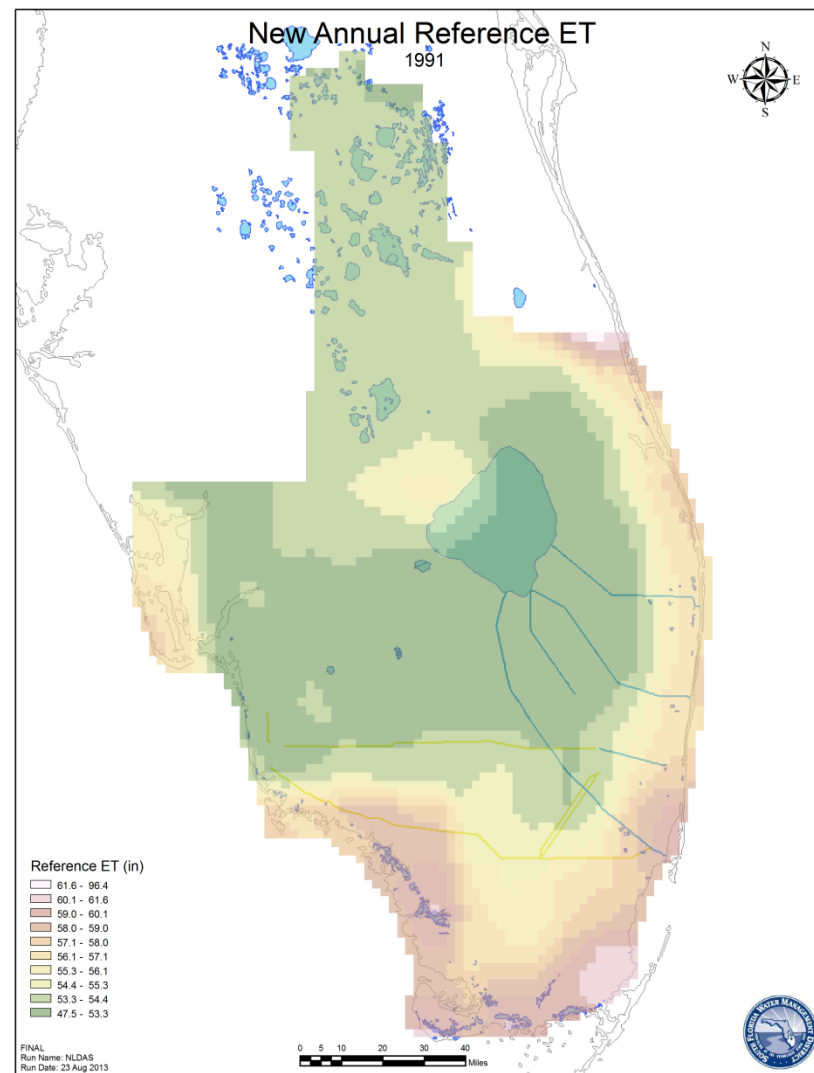
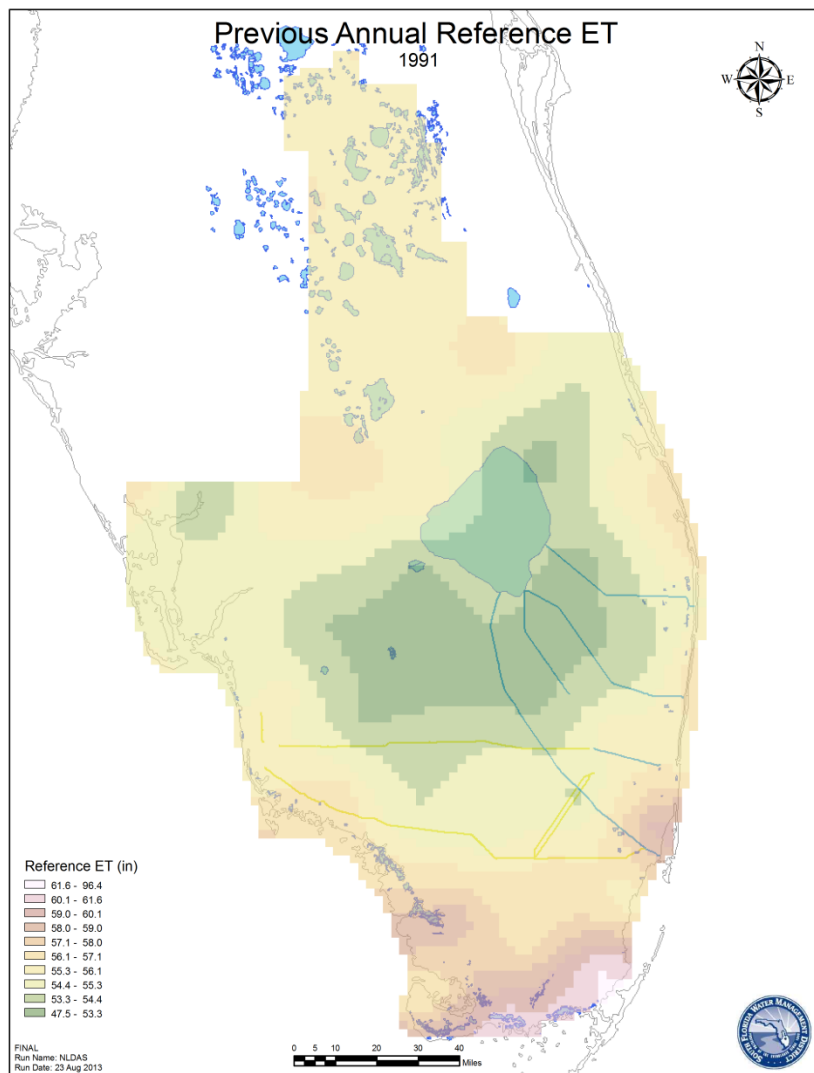


Figure B-27. Comparison of previous and new reference ET for 1991.

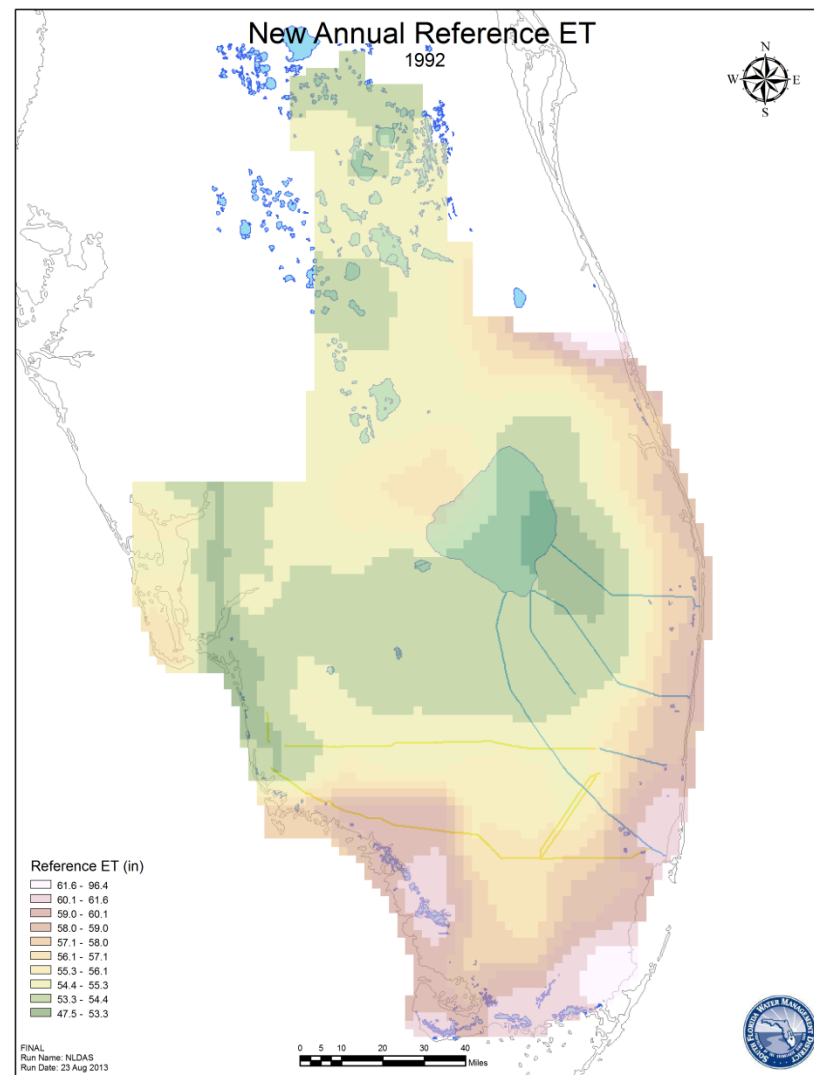
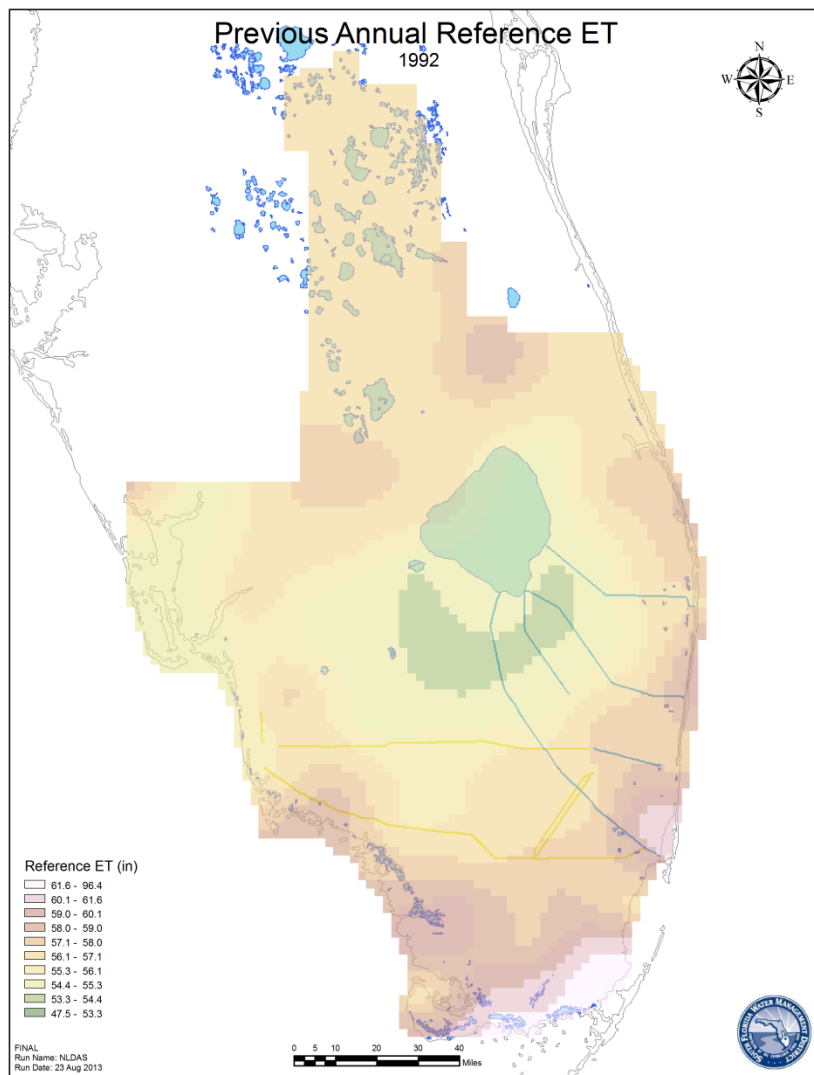


Figure B-28. Comparison of previous and new reference ET for 1992.

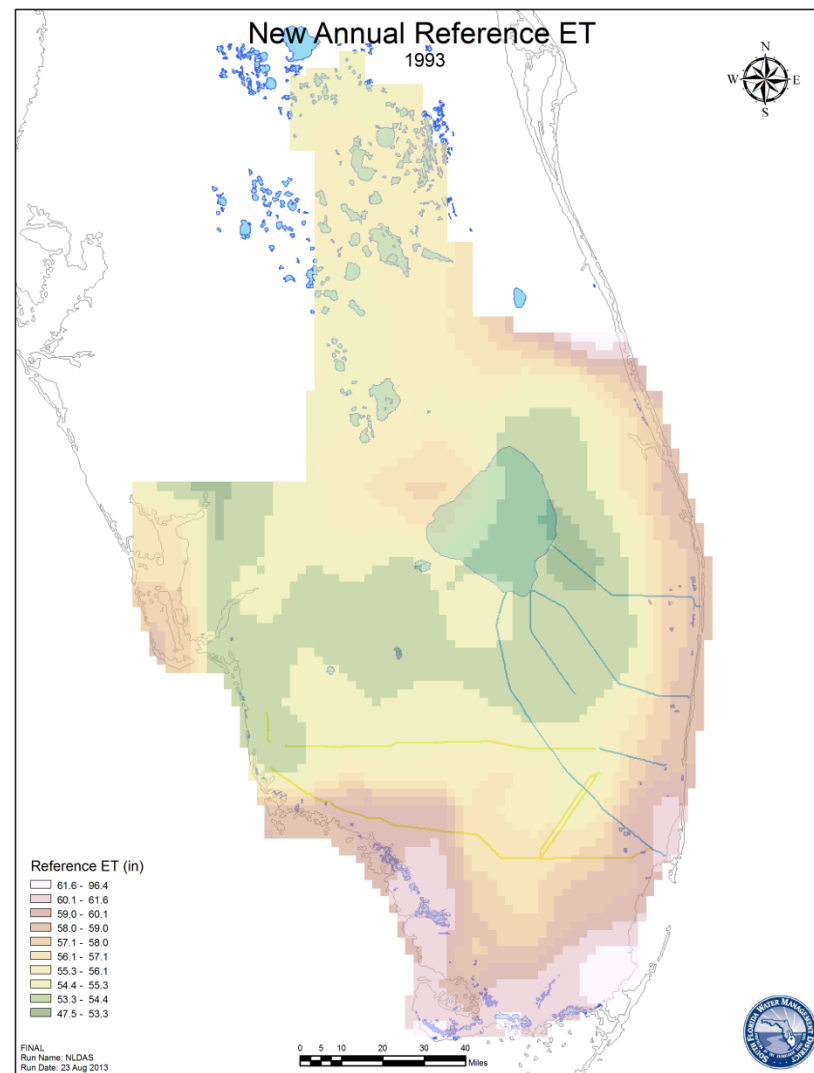
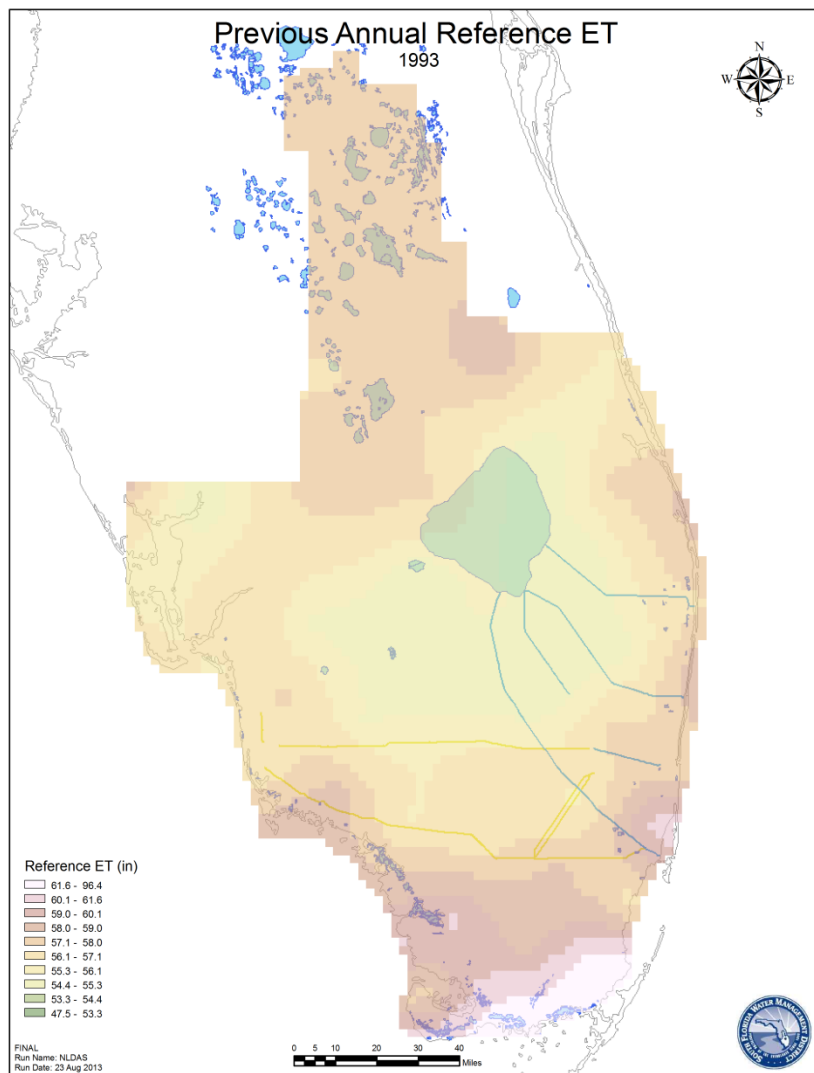


Figure B-29. Comparison of previous and new reference ET for 1993.

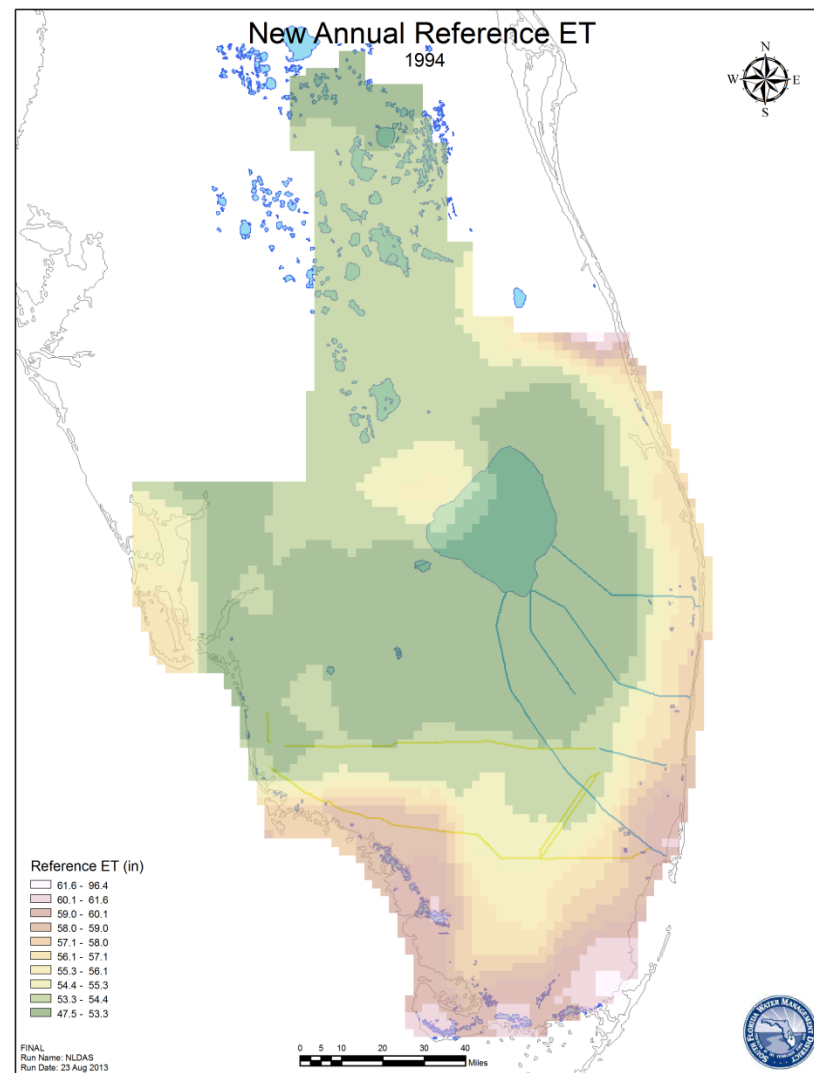
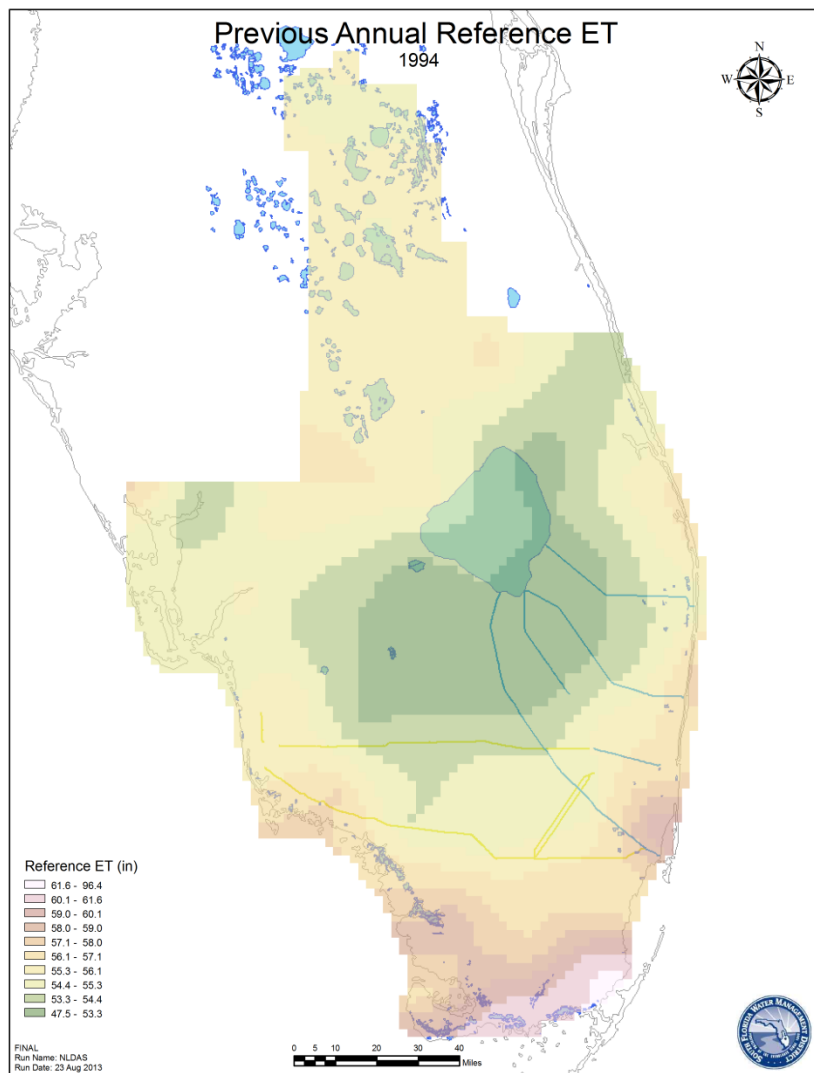


Figure B-30. Comparison of previous and new reference ET for 1994.

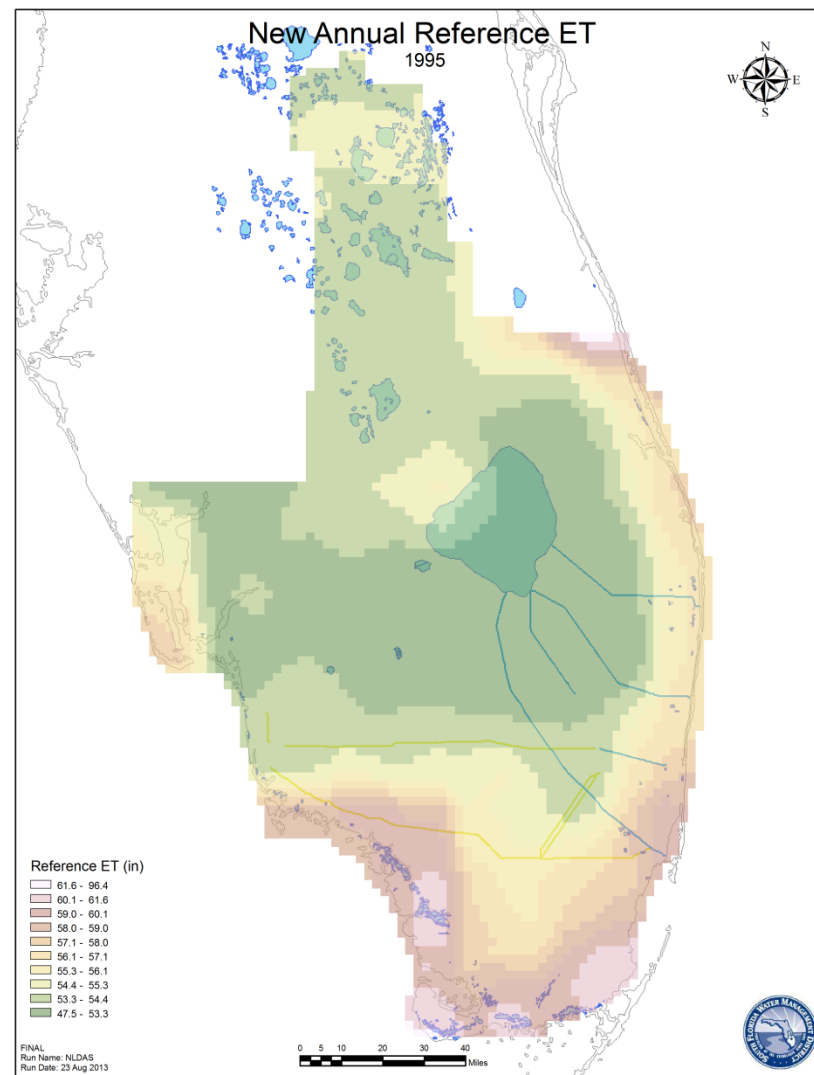
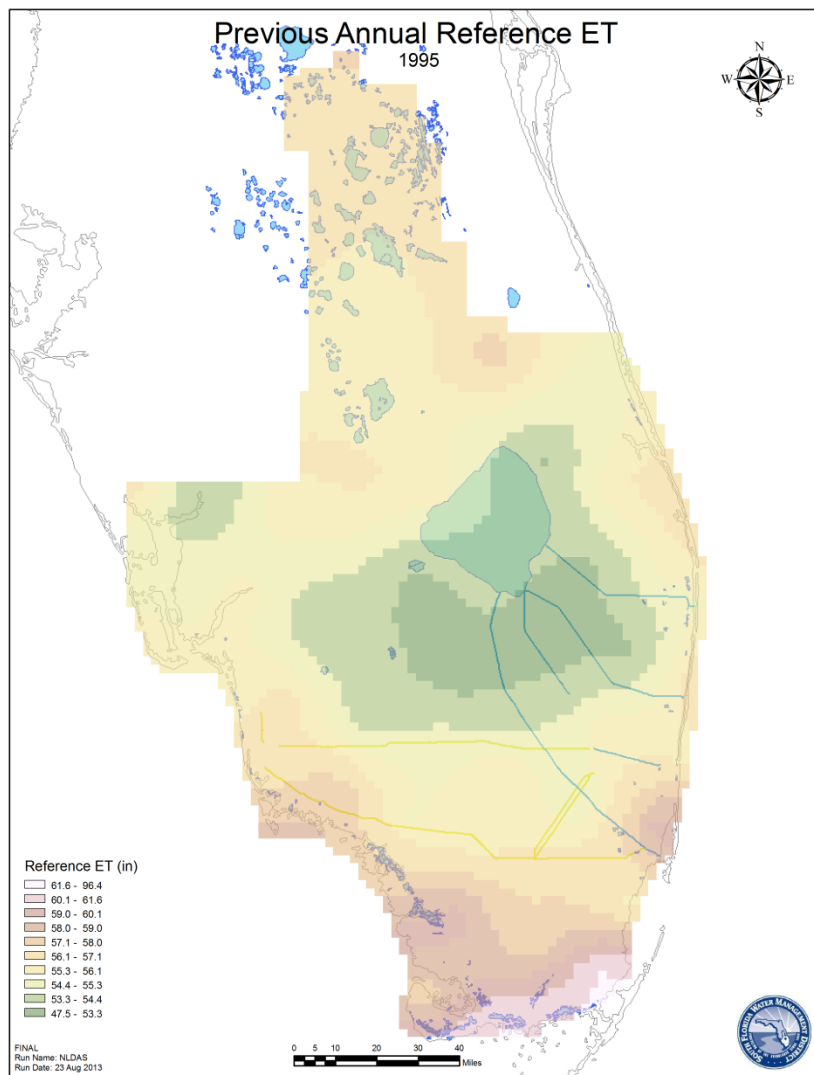


Figure B-31. Comparison of previous and new reference ET for 1995.

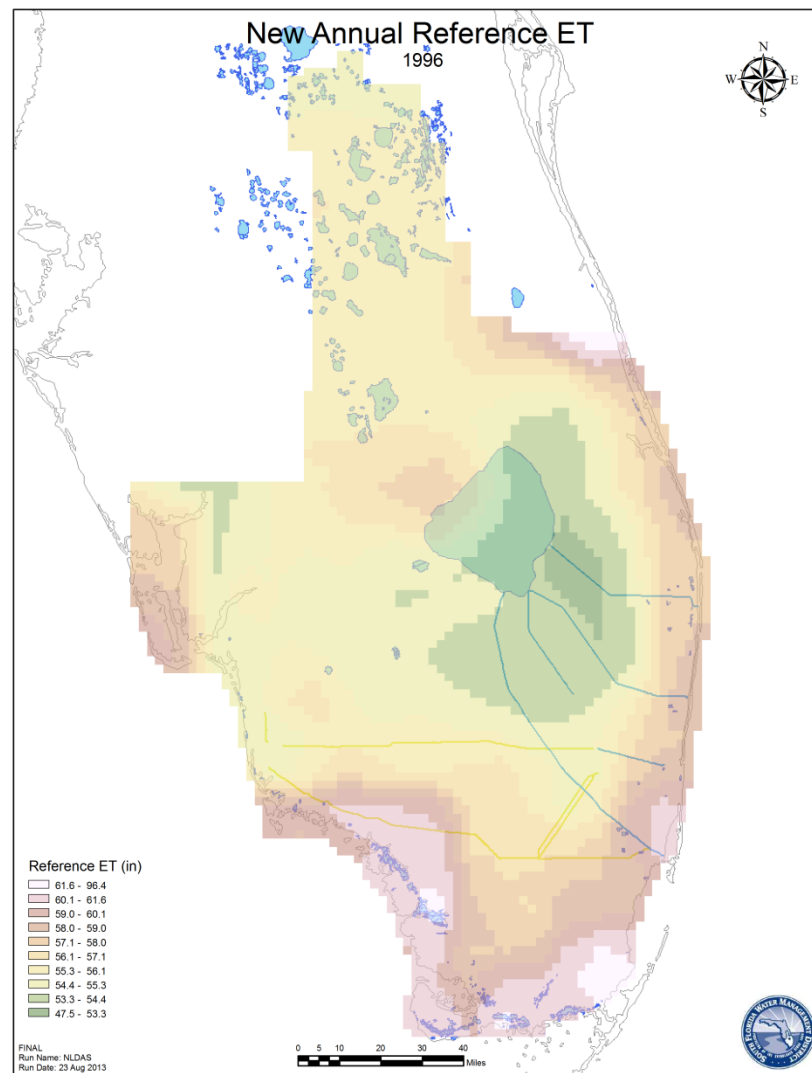
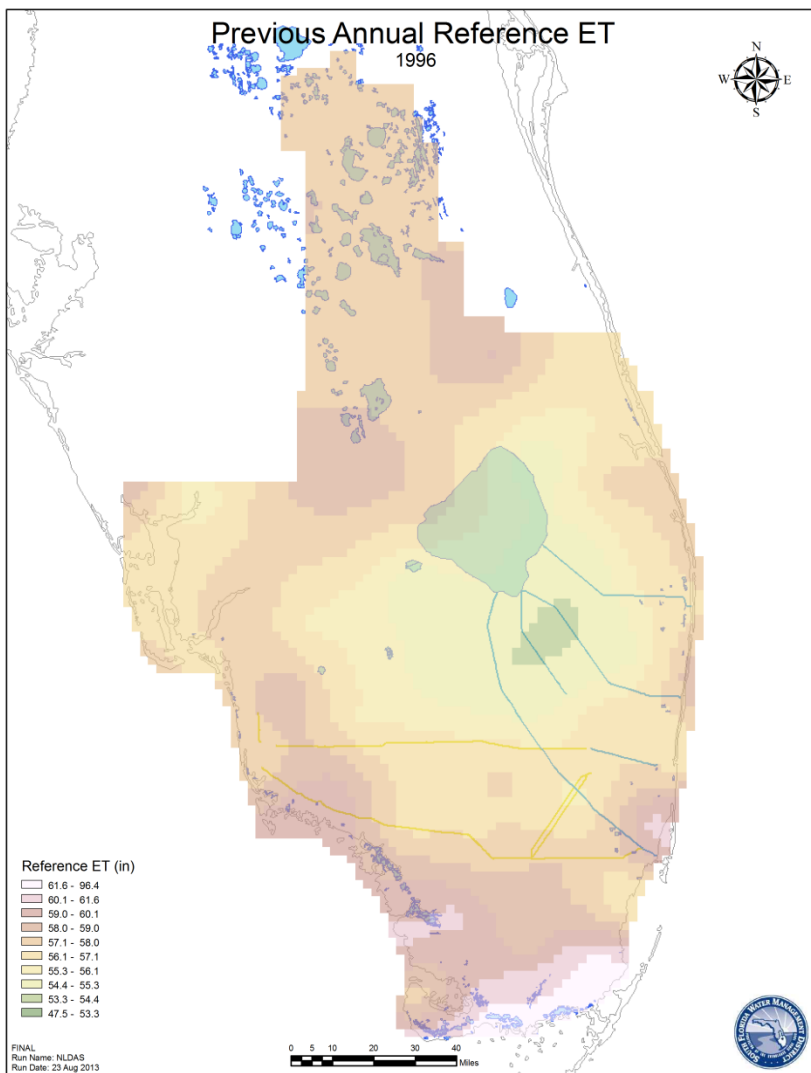


Figure B-32. Comparison of previous and new reference ET for 1996.

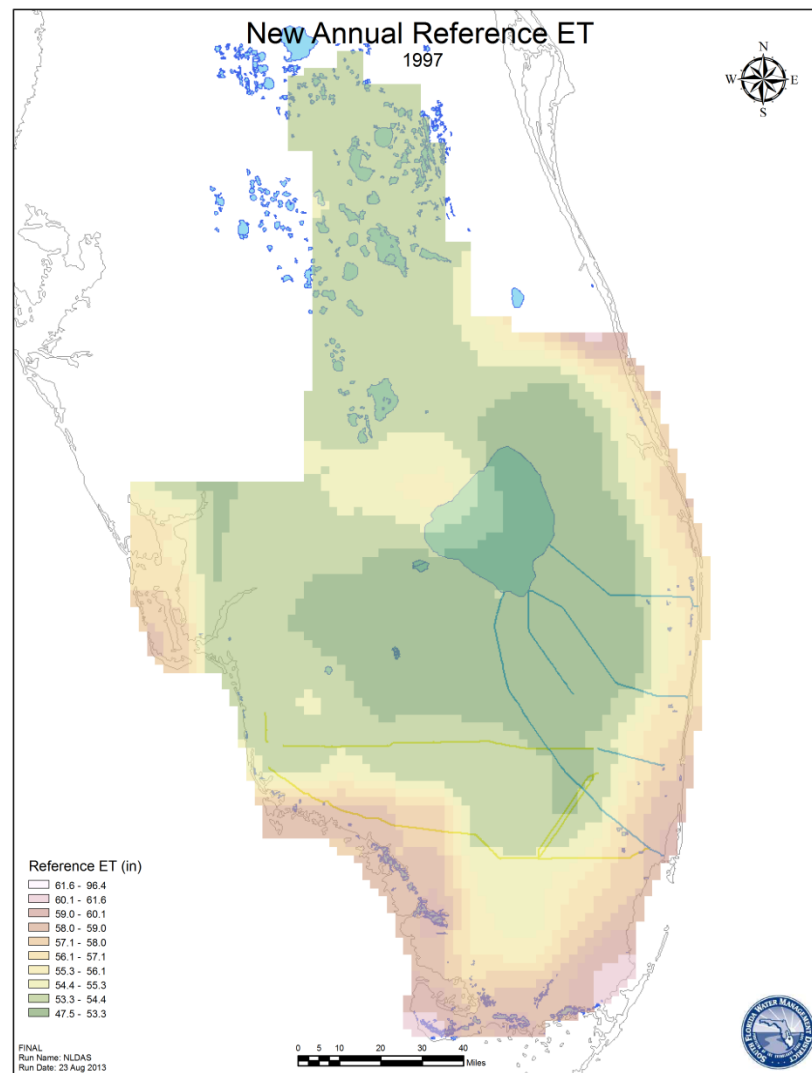
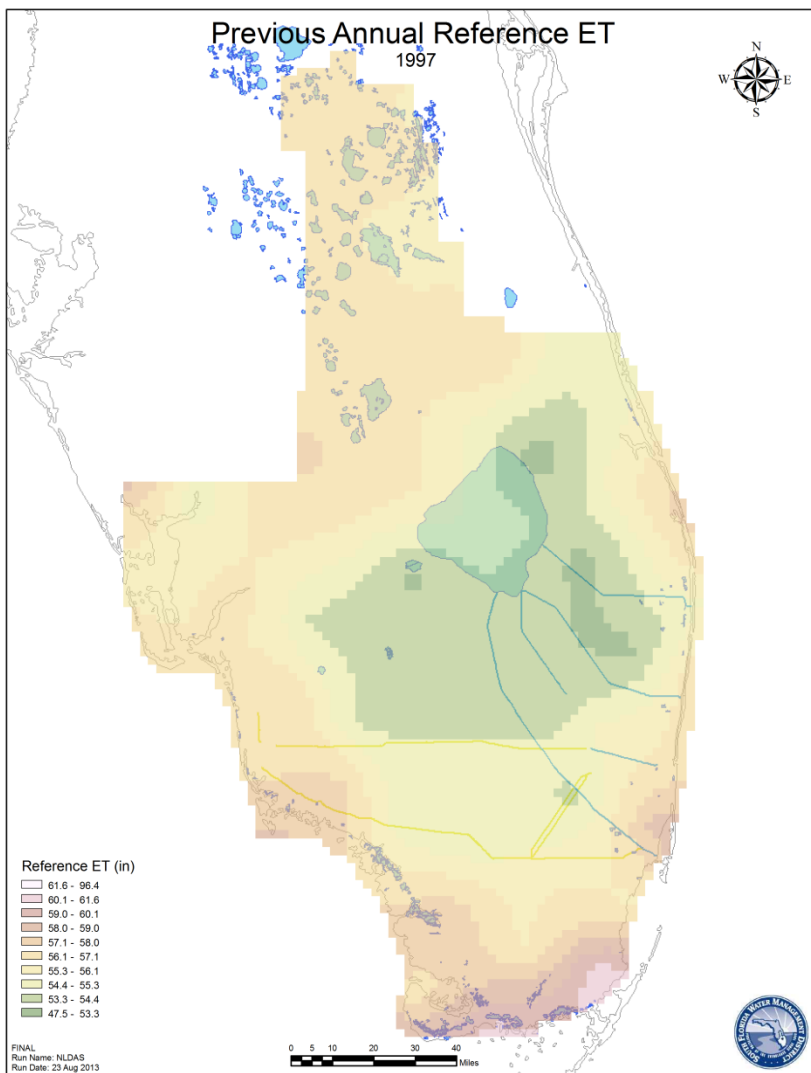


Figure B-33. Comparison of previous and new reference ET for 1997.

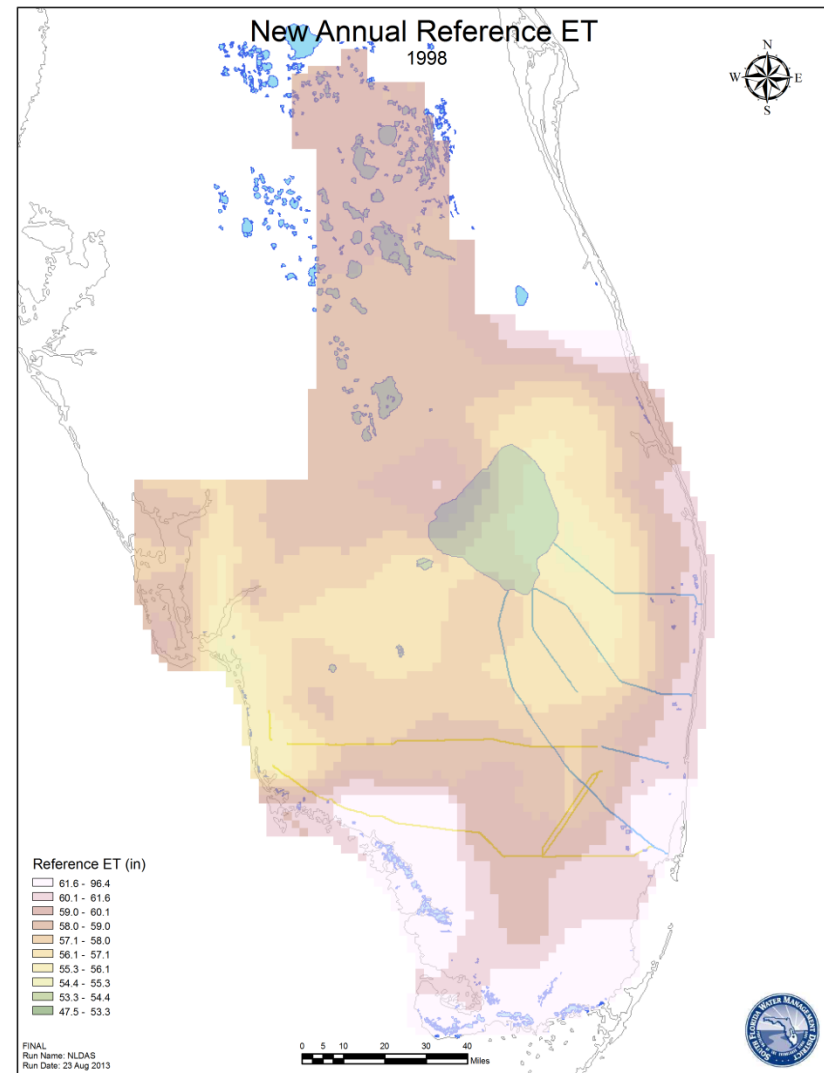
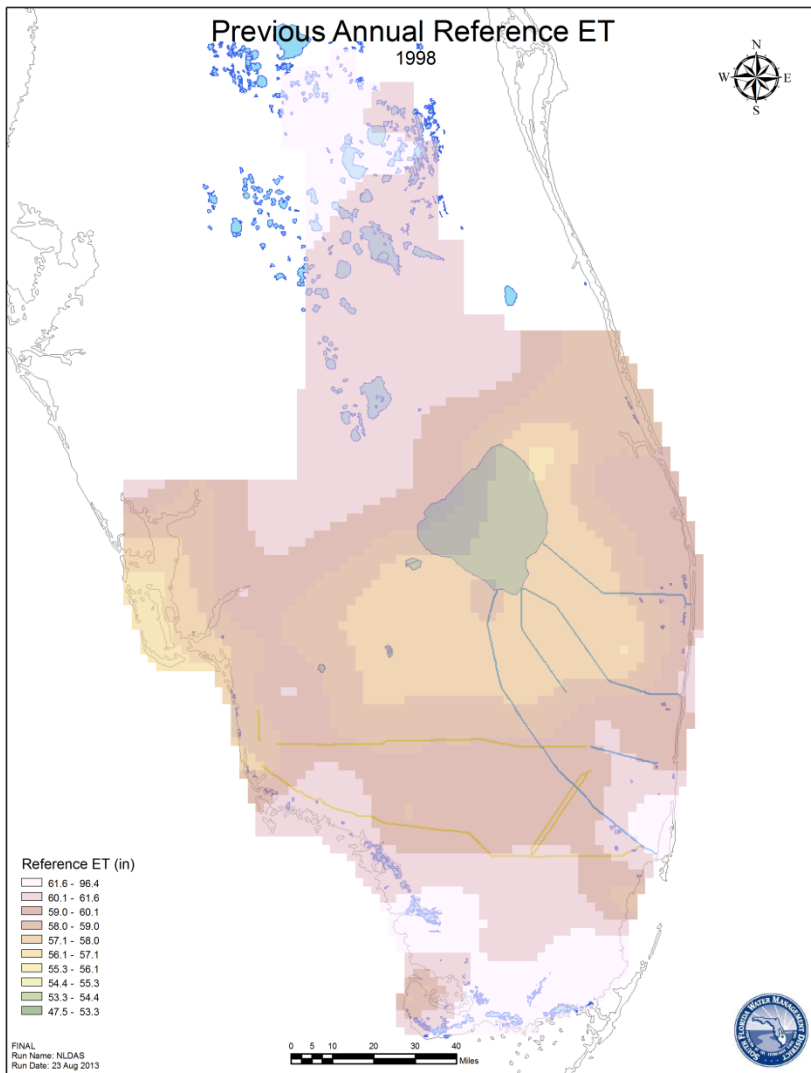


Figure B-34. Comparison of previous and new reference ET for 1998.

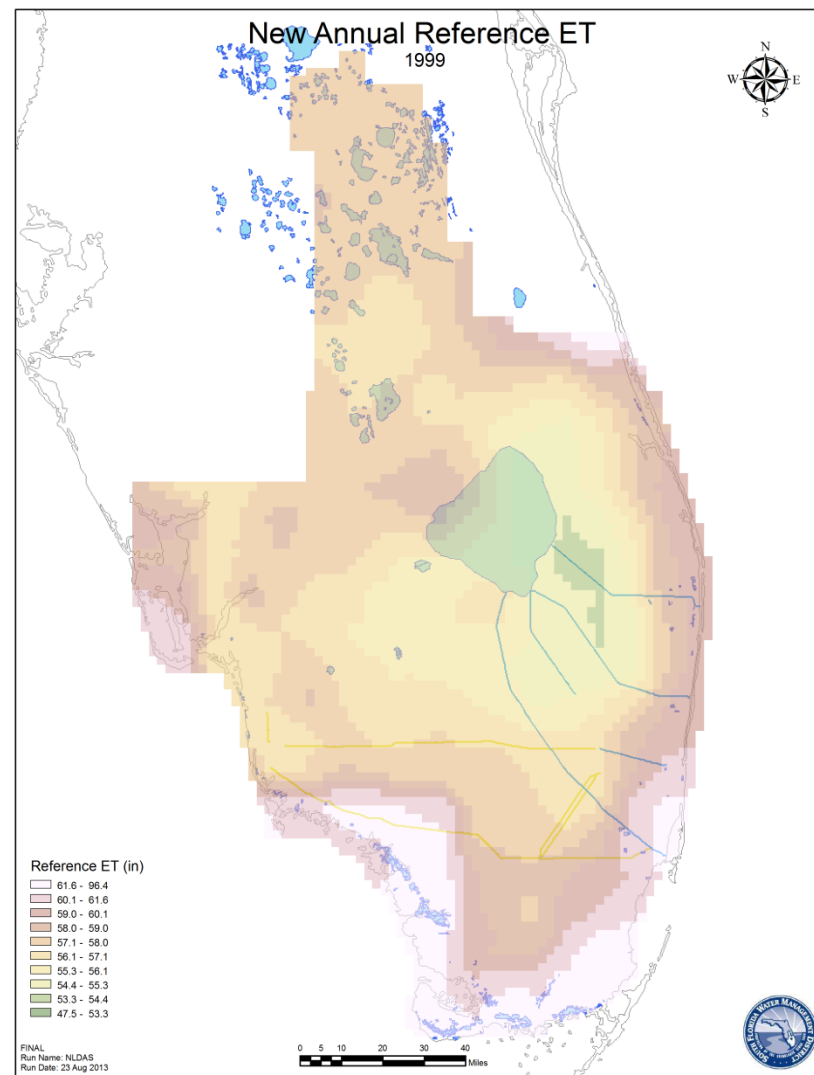
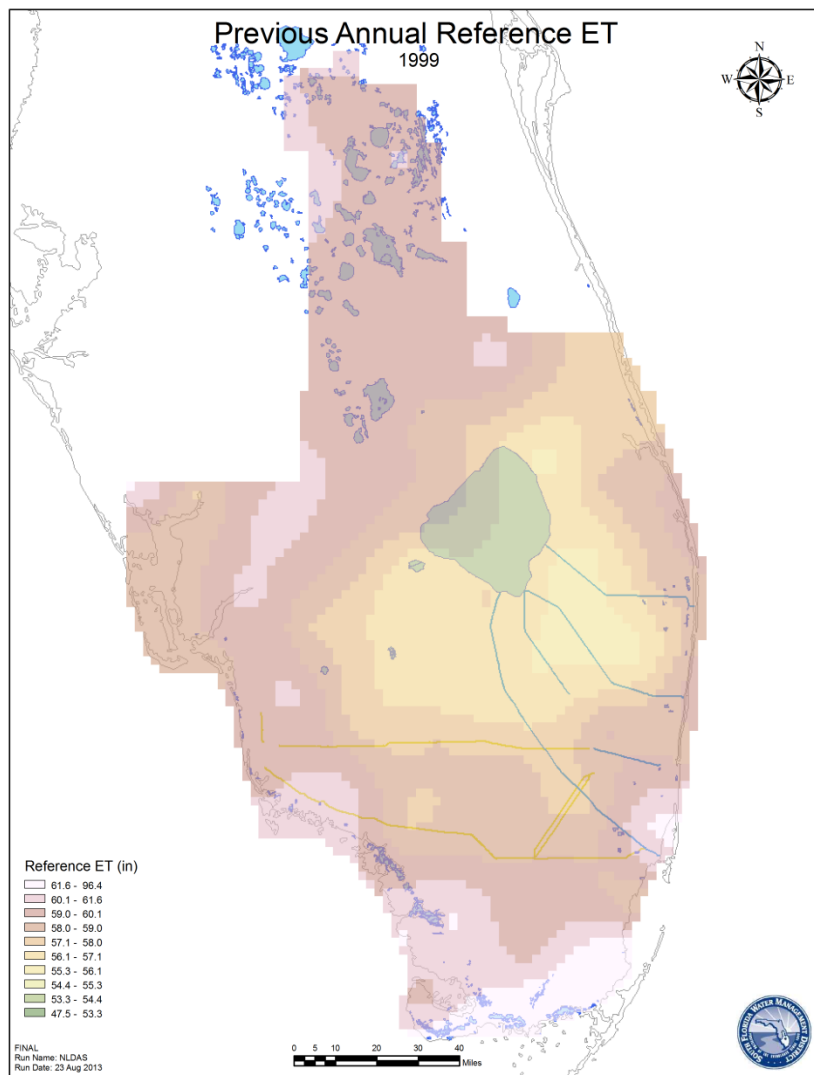


Figure B-35. Comparison of previous and new reference ET for 1999.

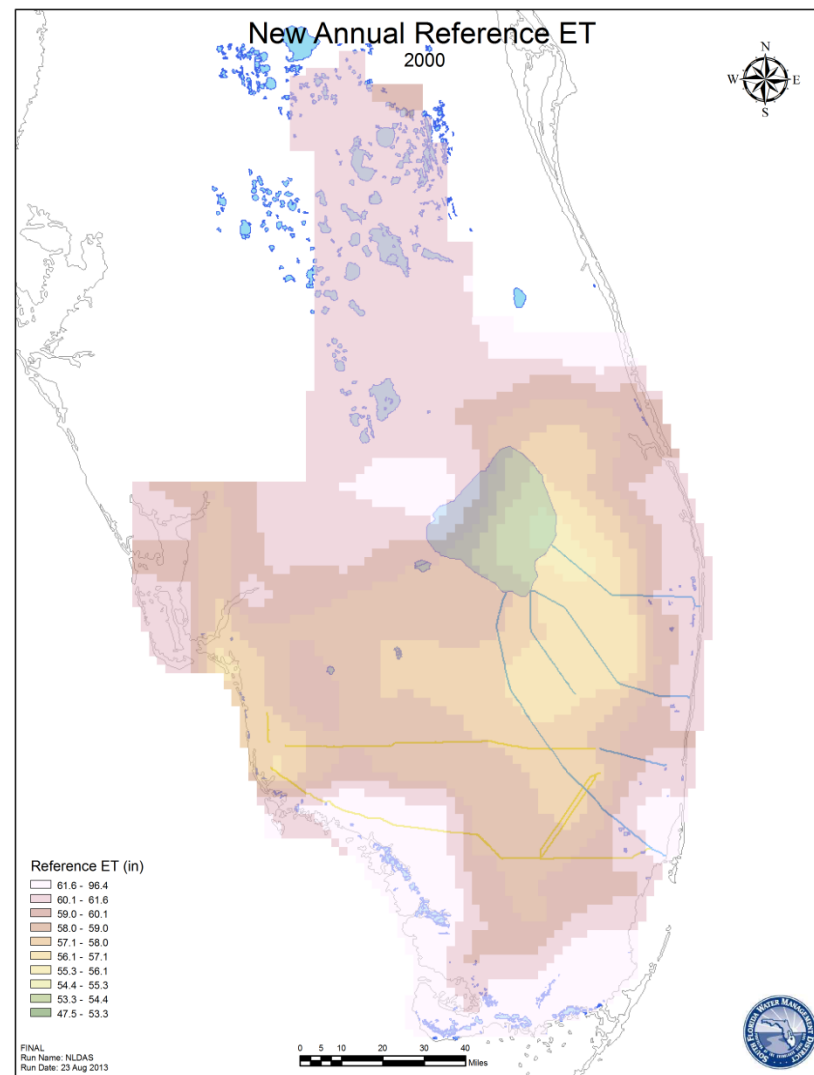
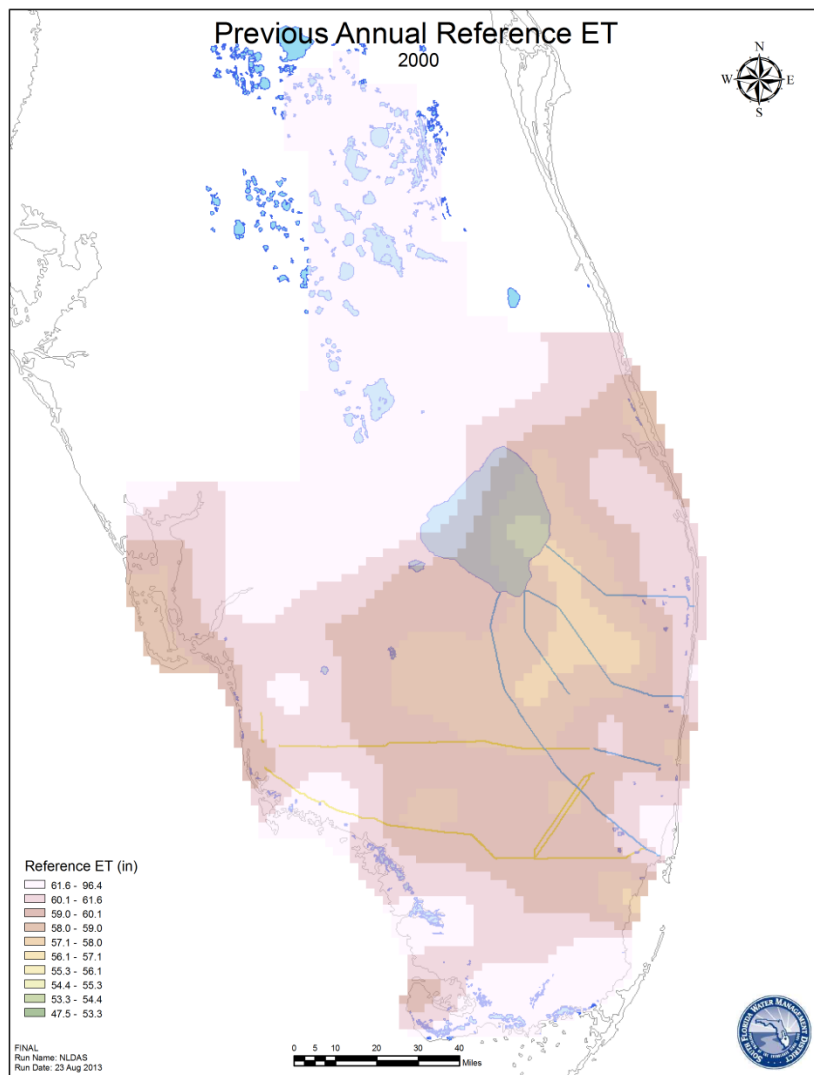


Figure B-36. Comparison of previous and new reference ET for 2000.

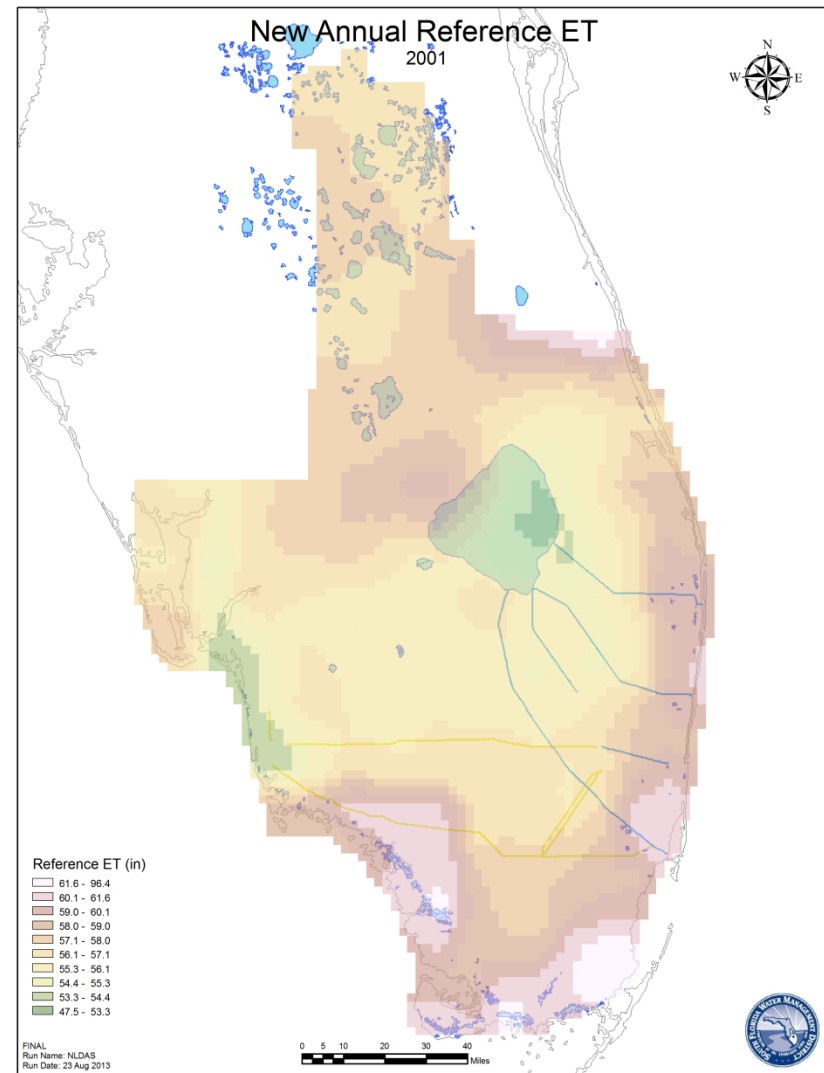
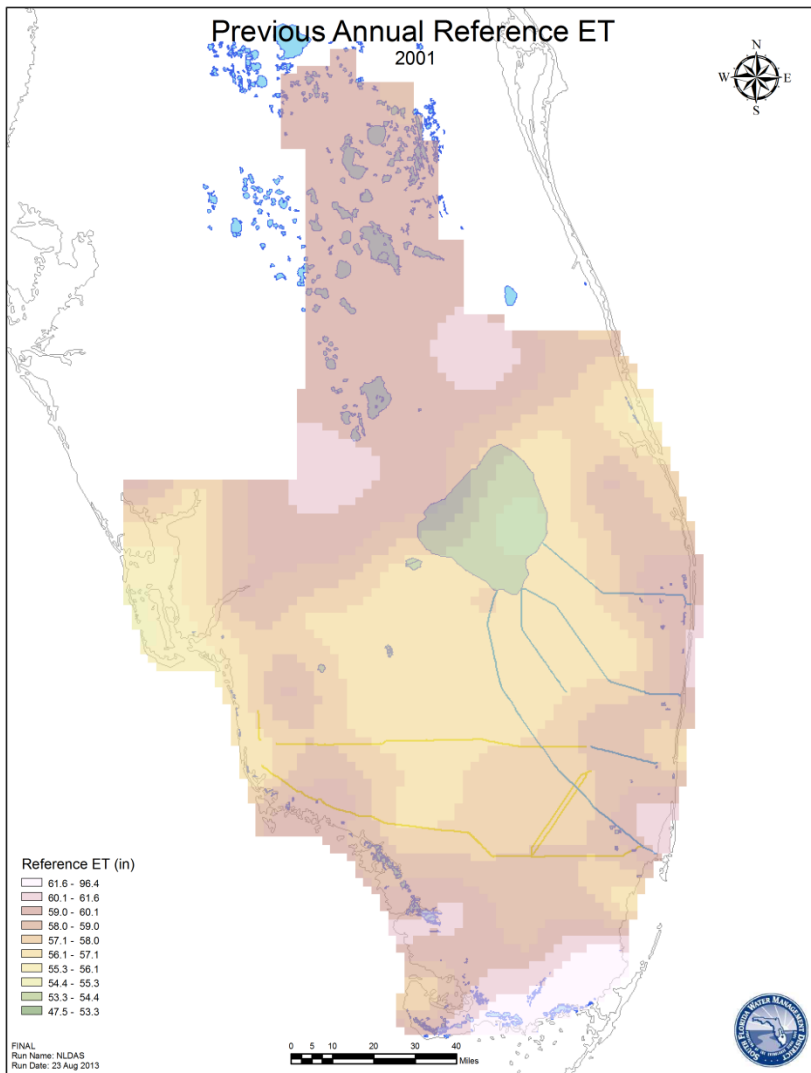


Figure B-37. Comparison of previous and new reference ET for 2001.

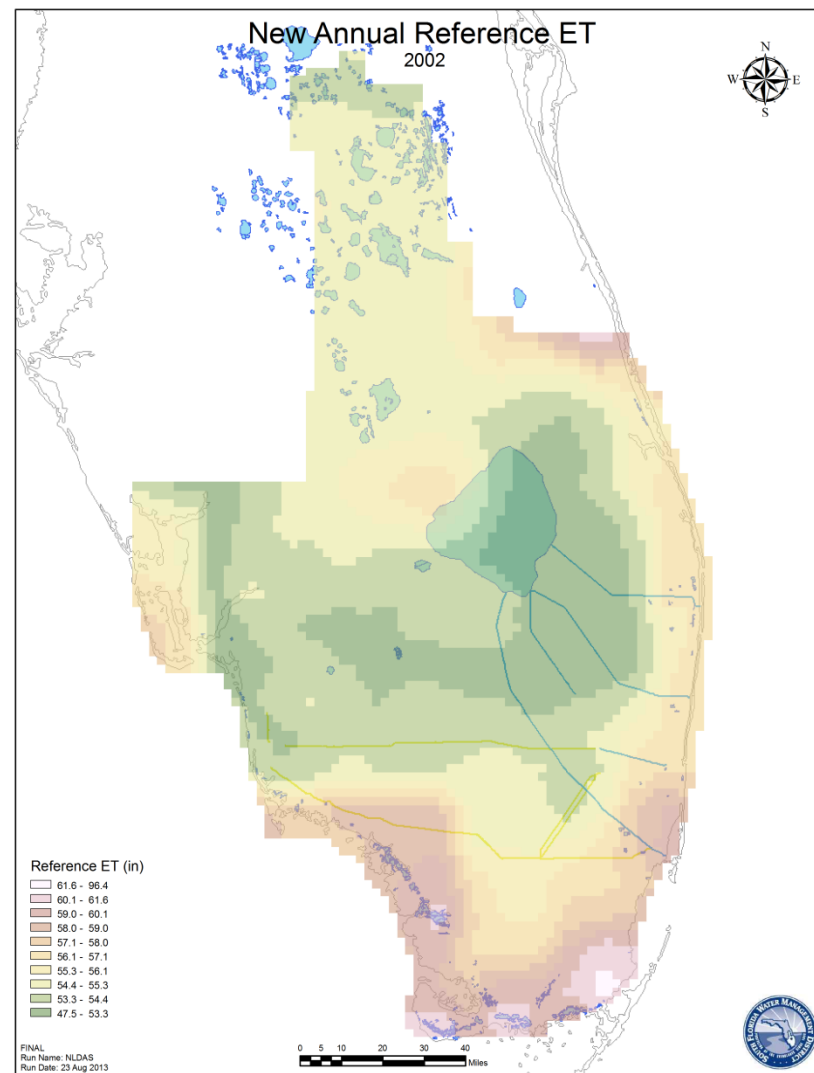
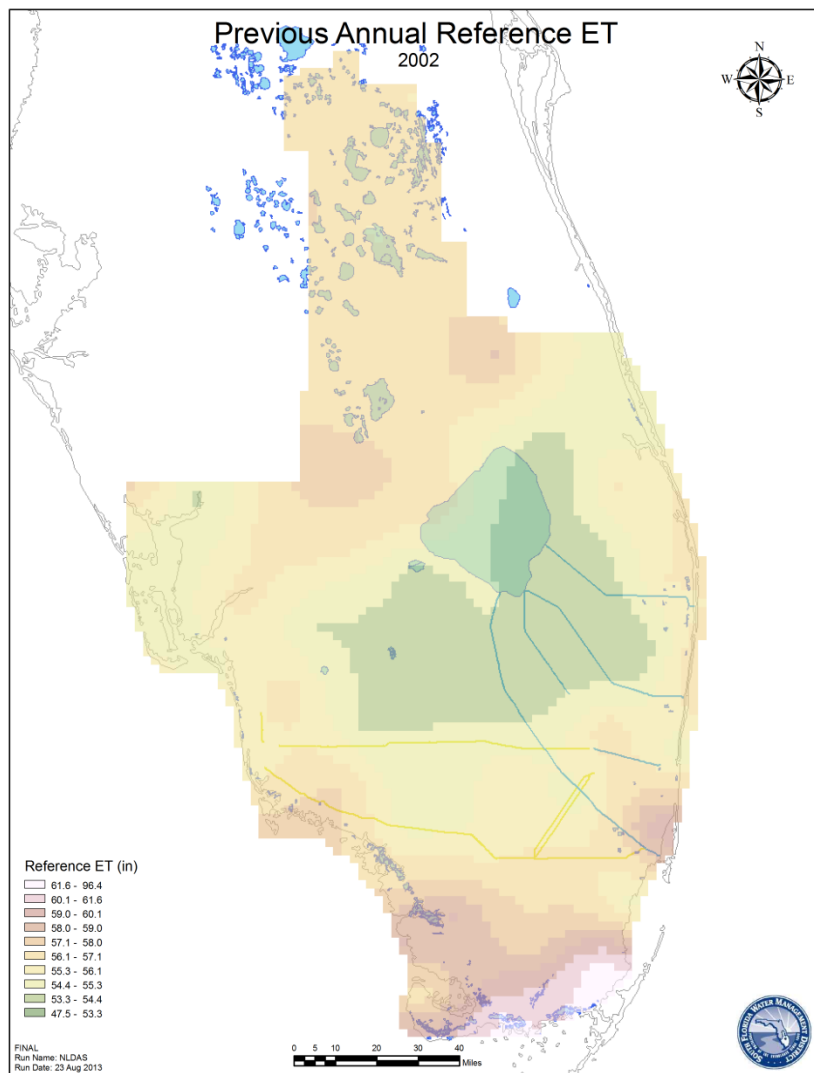


Figure B-38. Comparison of previous and new reference ET for 2002.

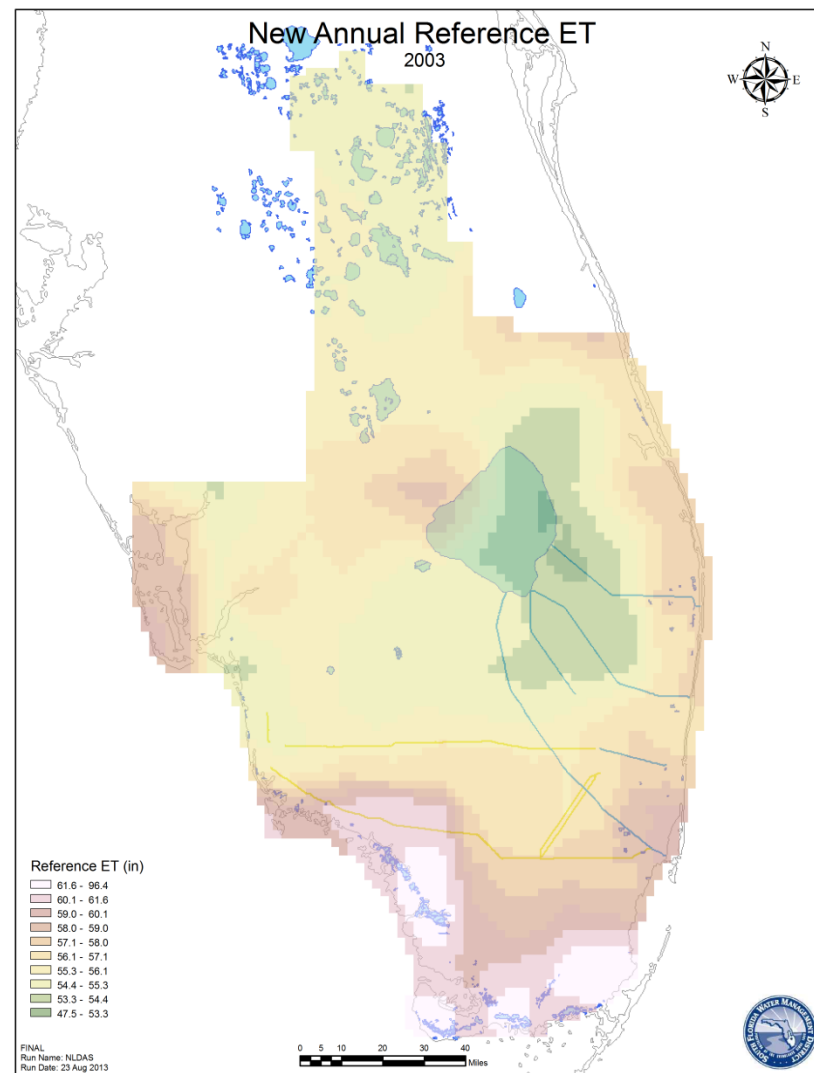
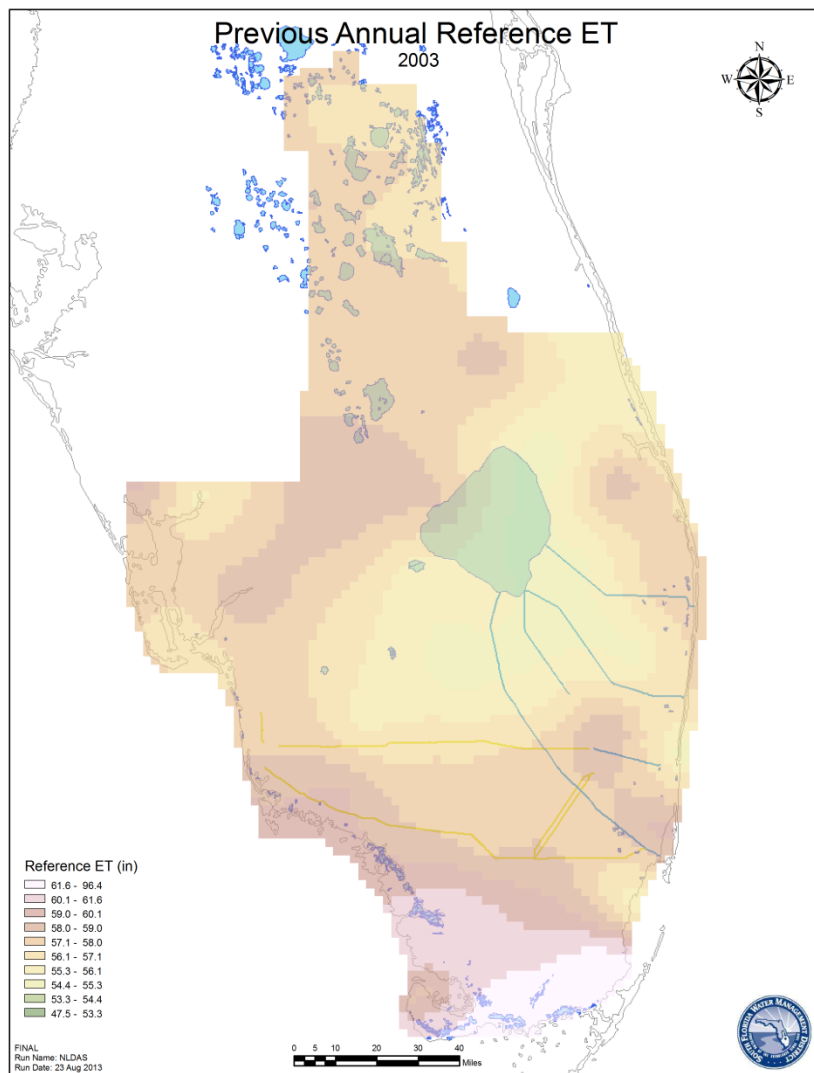


Figure B-39. Comparison of previous and new reference ET for 2003.

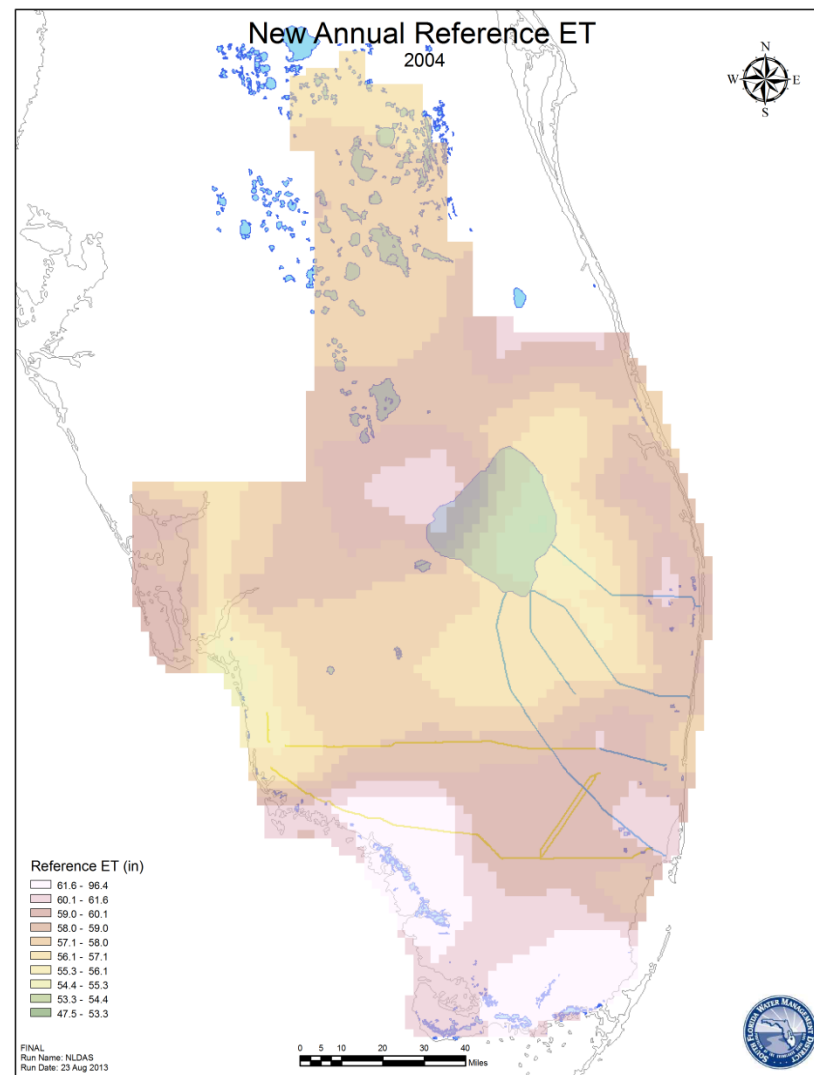
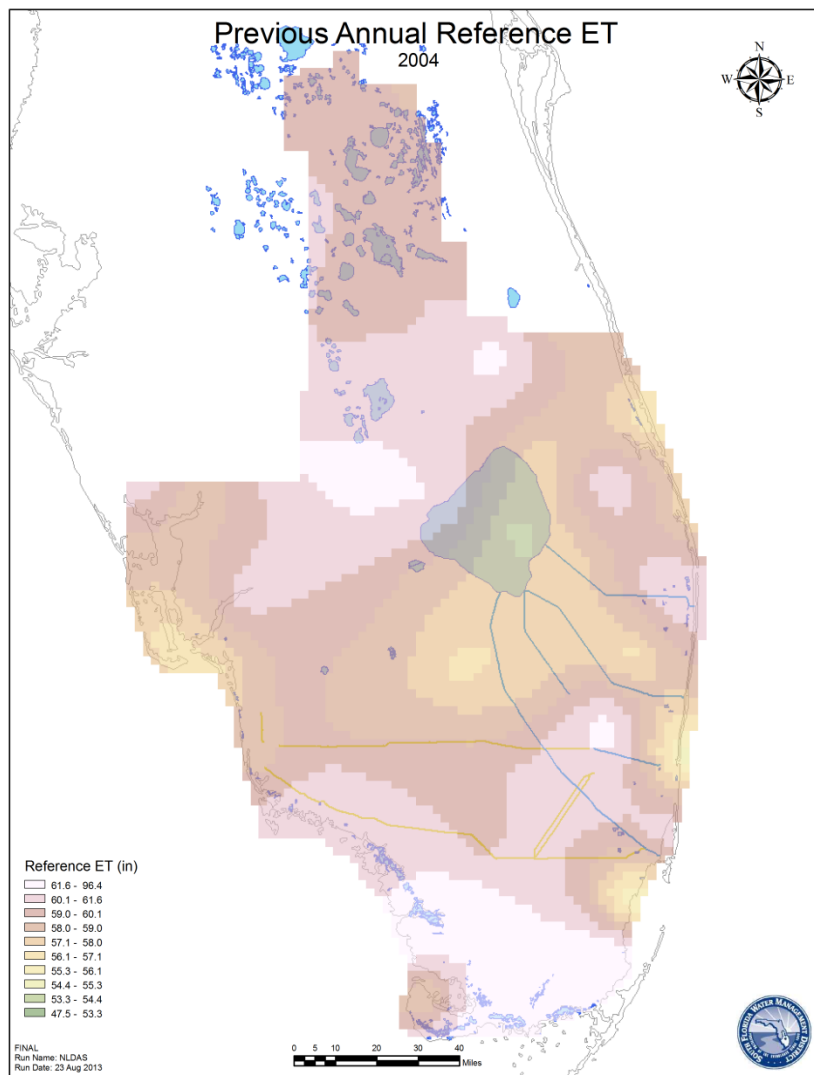


Figure B-40. Comparison of previous and new reference ET for 2004.

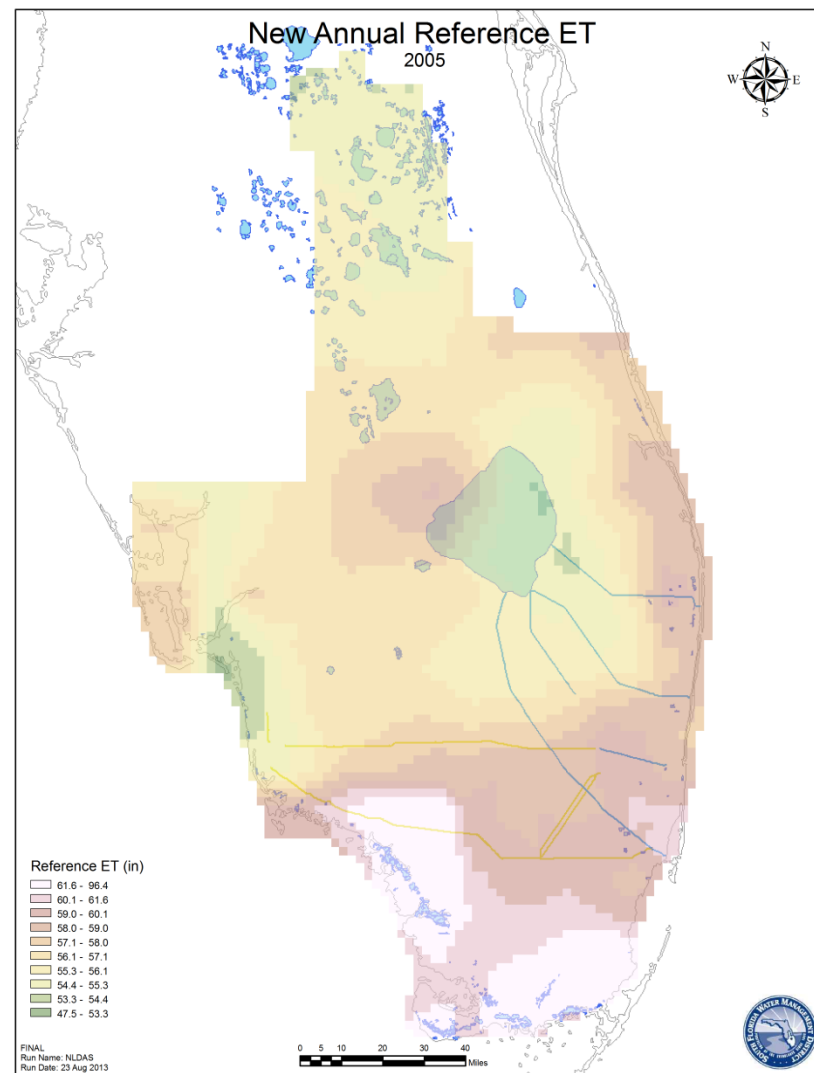
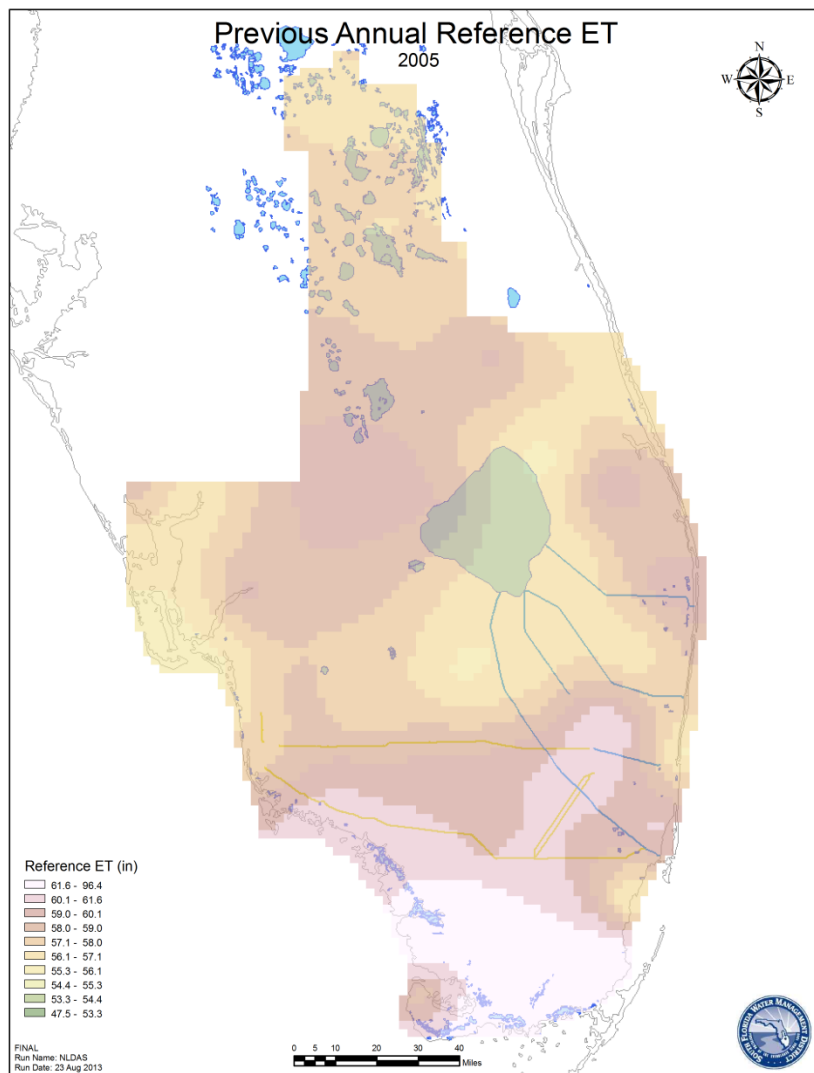


Figure B-41. Comparison of previous and new reference ET for 2005.

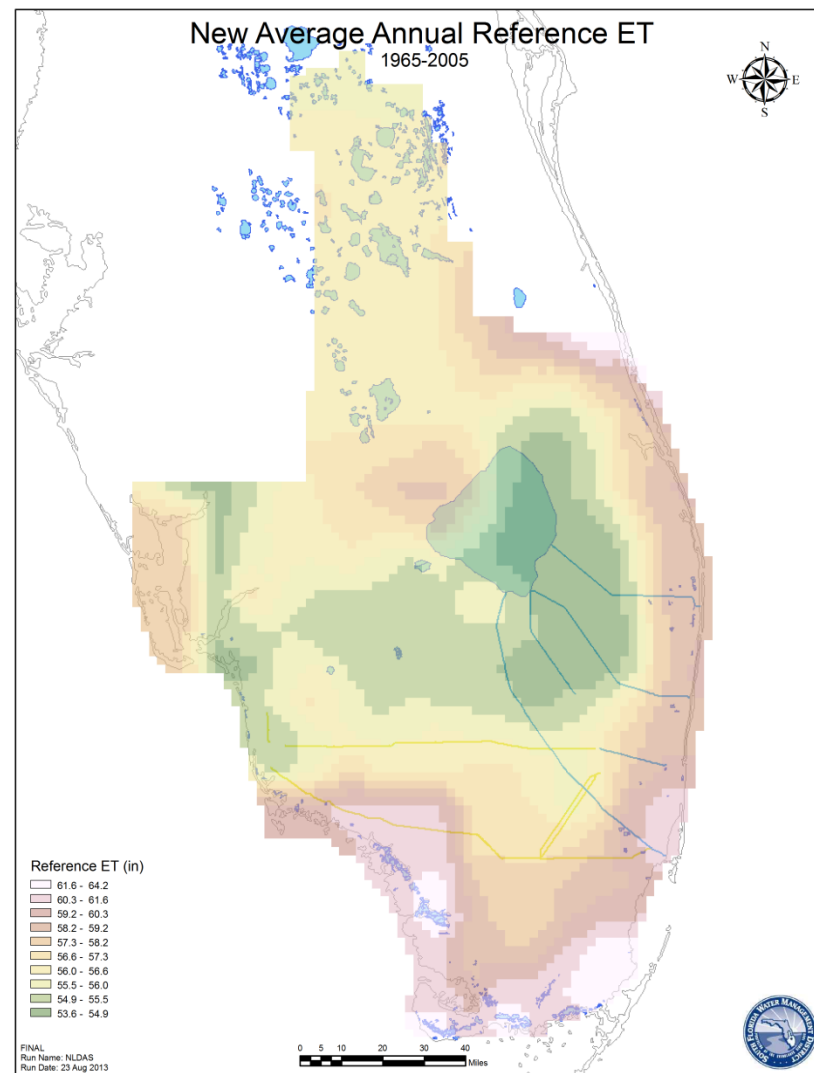
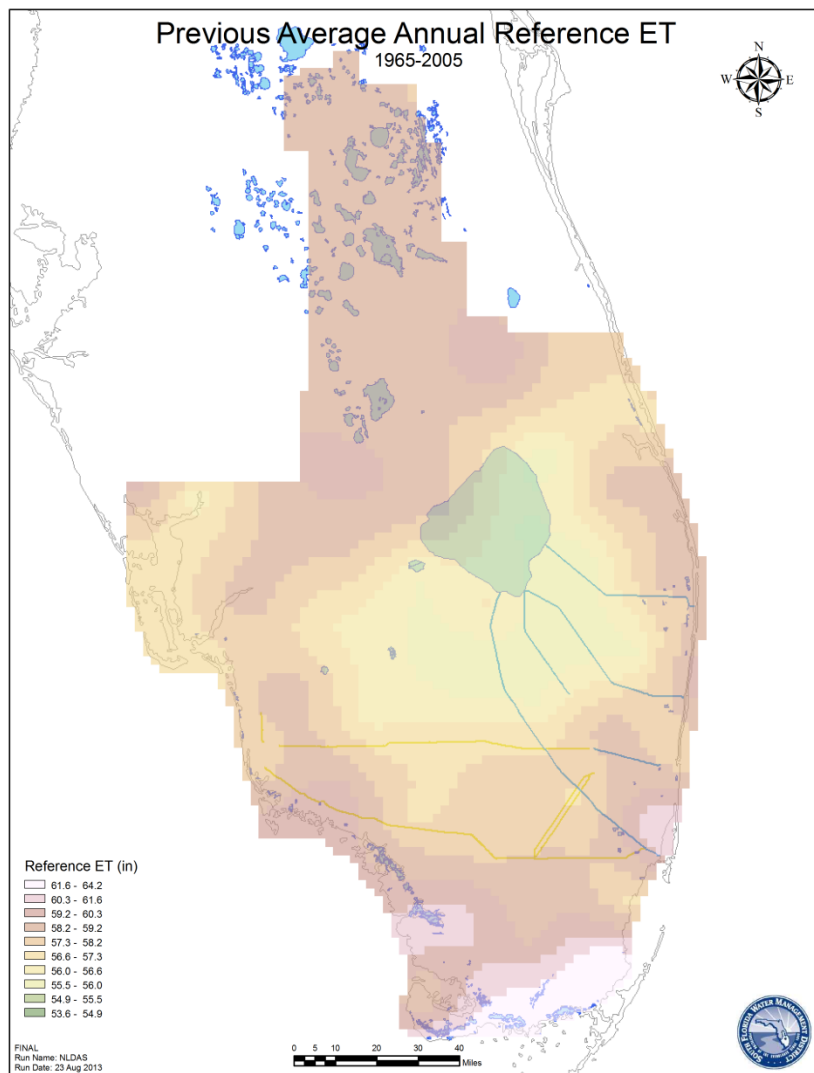


Figure B-42. Average annual (1965-2005) comparison of previous and new reference ET.

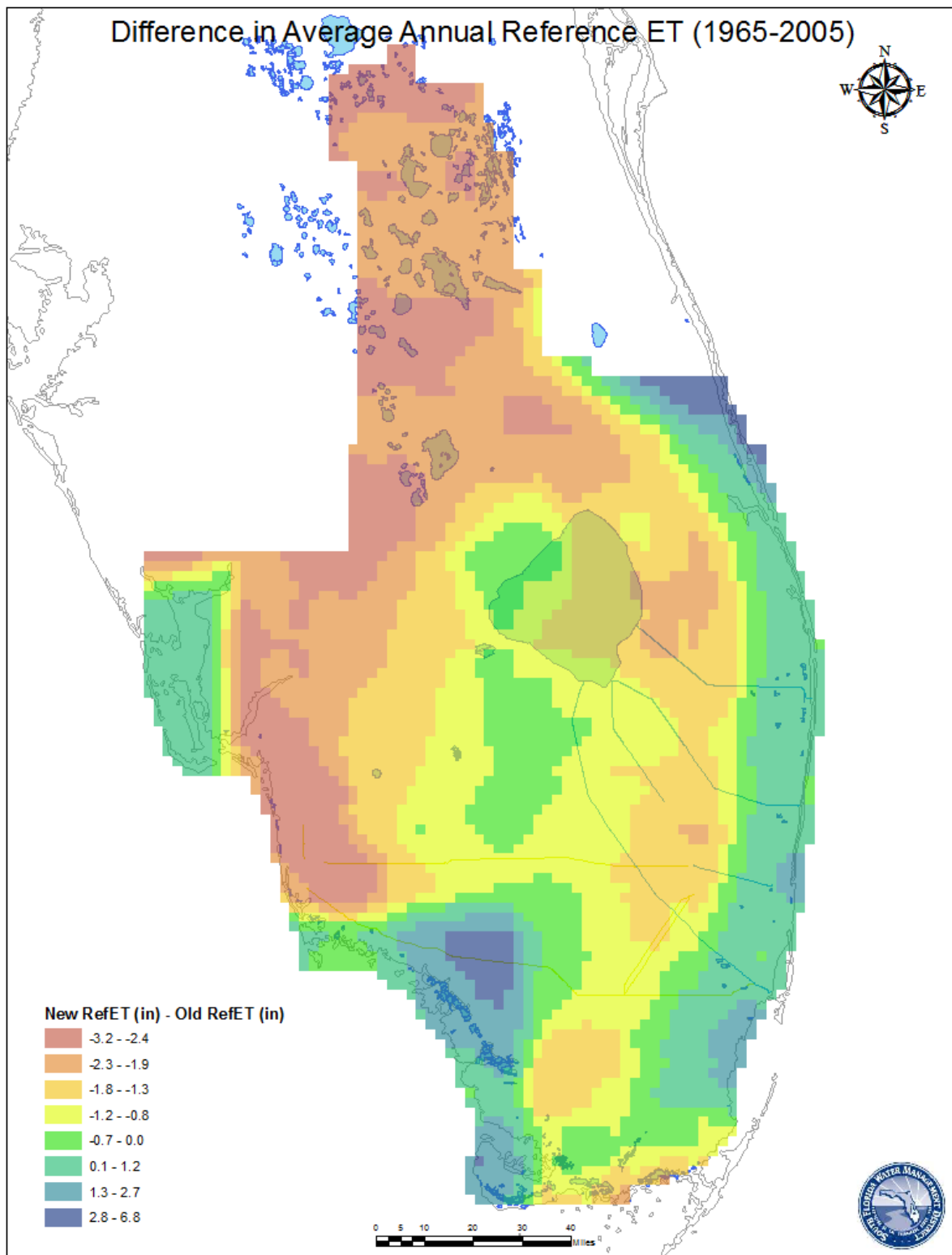


Figure B-43. Average annual (1965-2005) difference map of previous and new reference ET.

Appendix C

New Reference ET (2006-2012) and Climatic 30 Year Average (1981-2010)

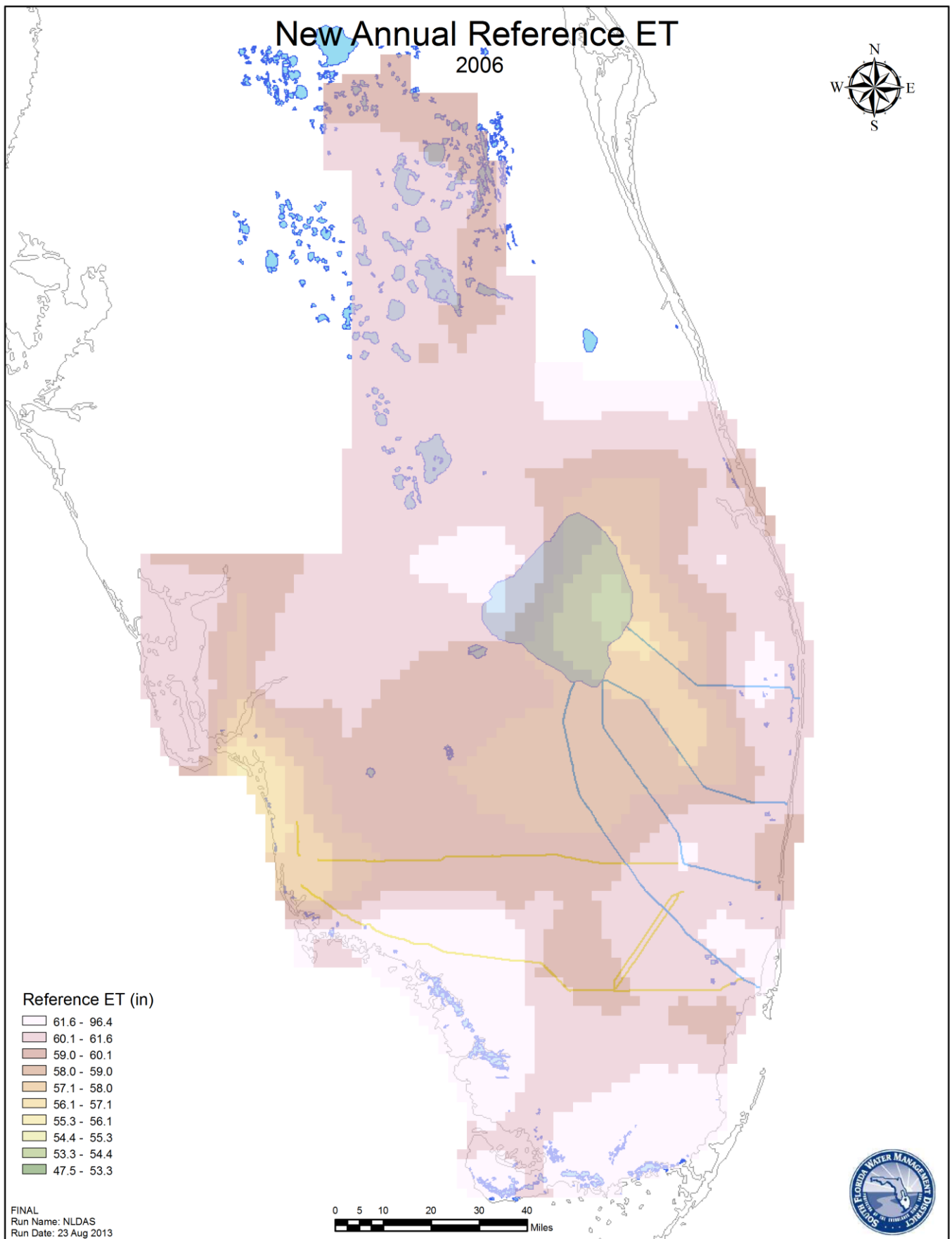


Figure C-1. Annual reference ET 2006.

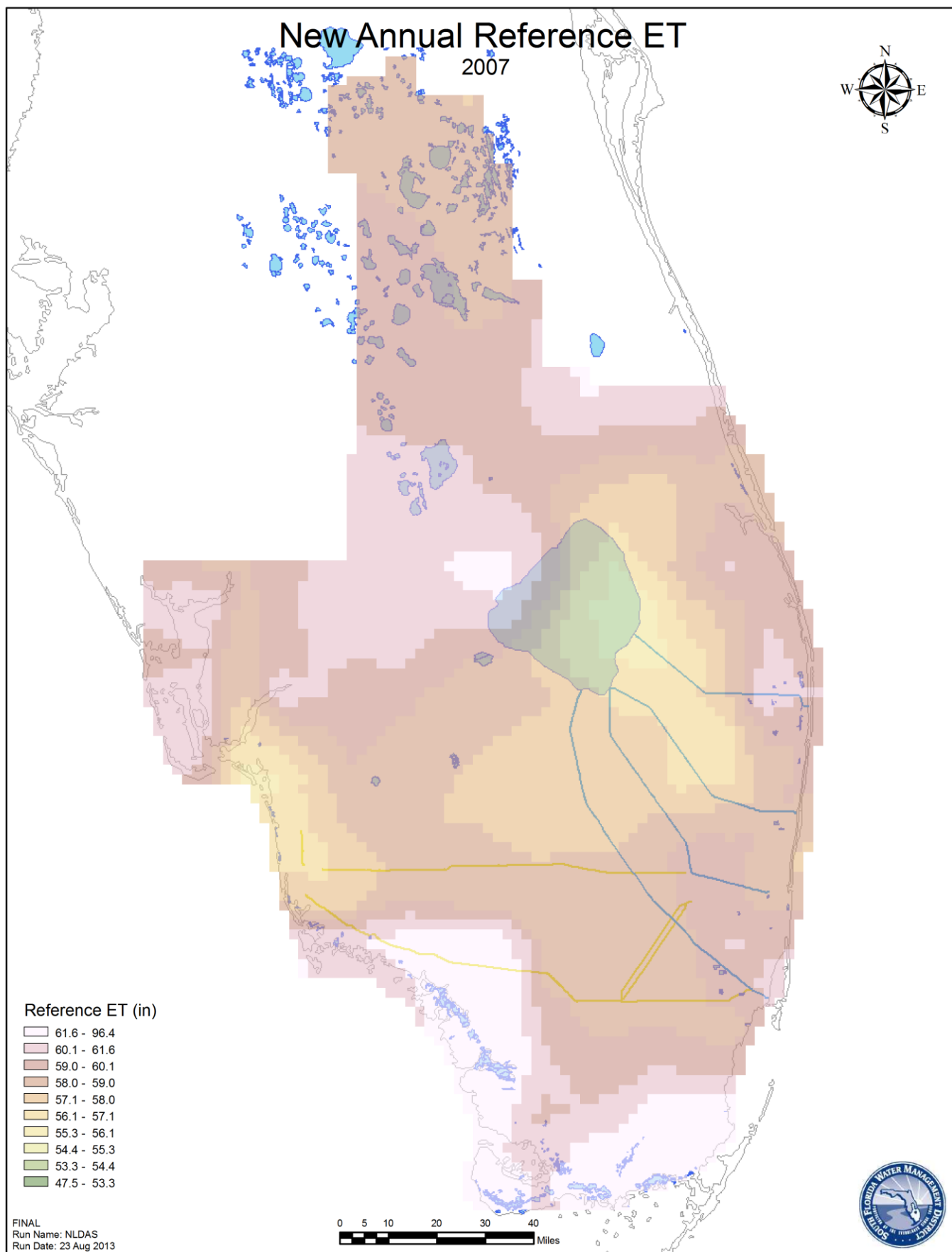


Figure C-2. Annual reference ET 2007.

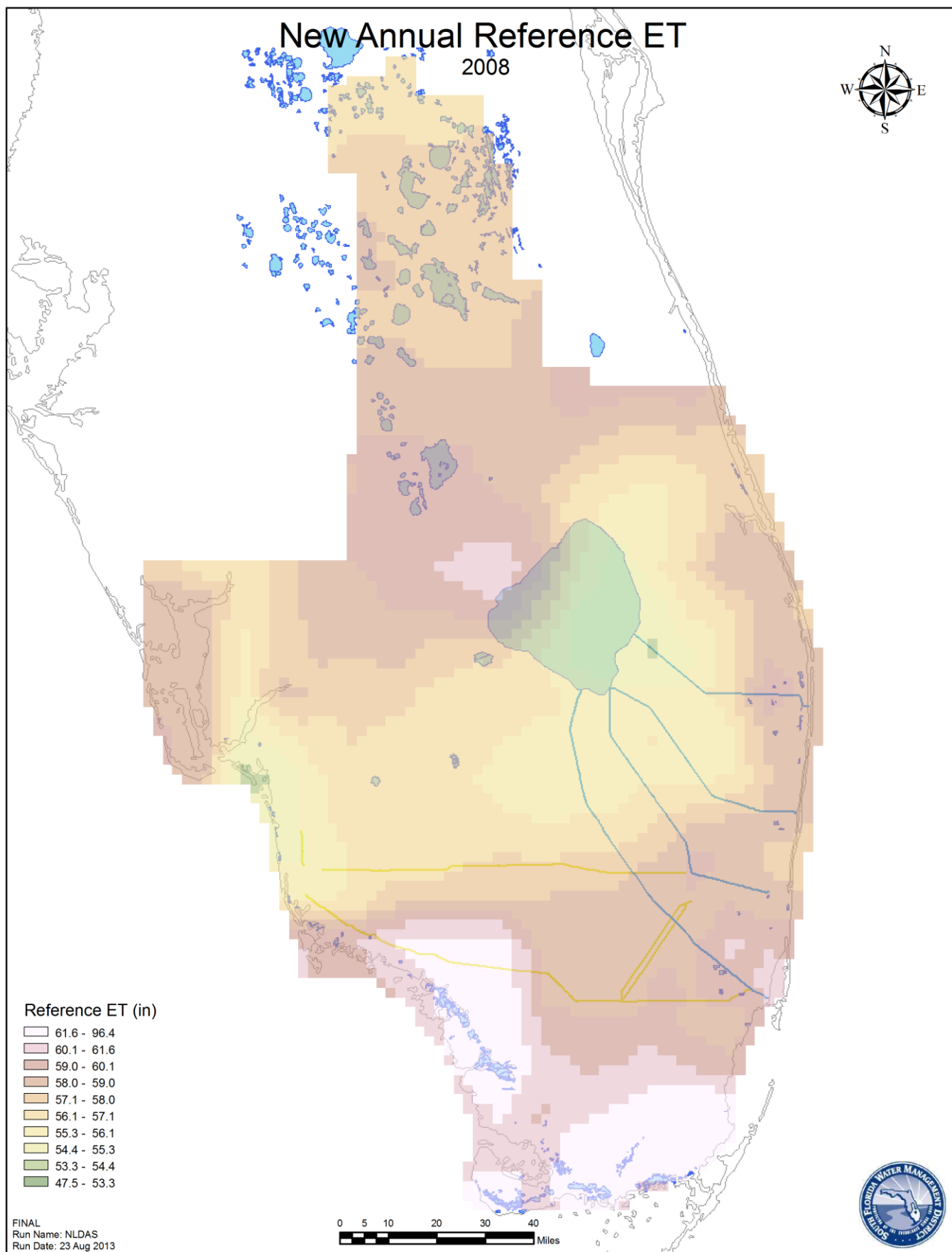


Figure C-3. Annual reference ET 2008.

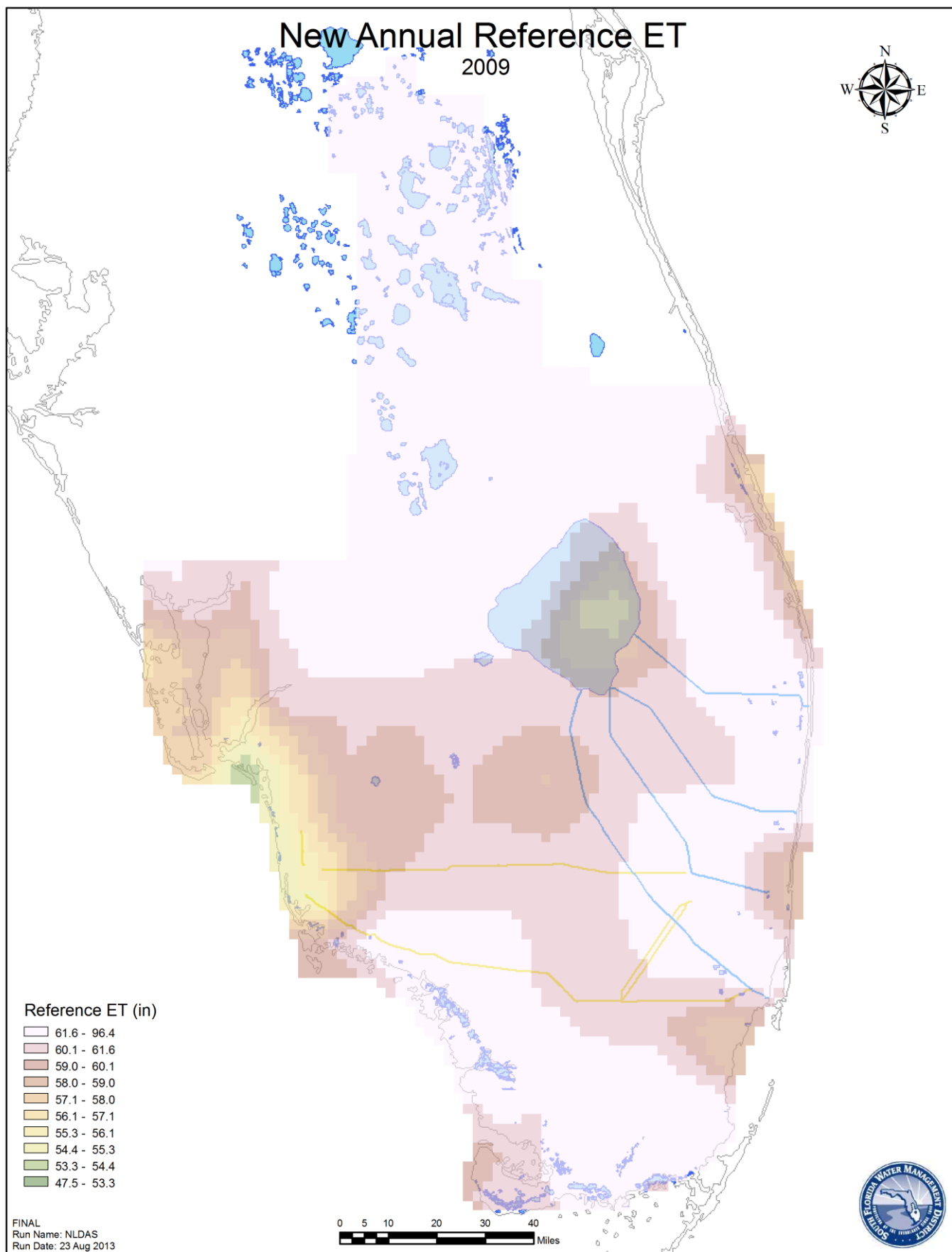


Figure C-4. Annual reference ET 2009.

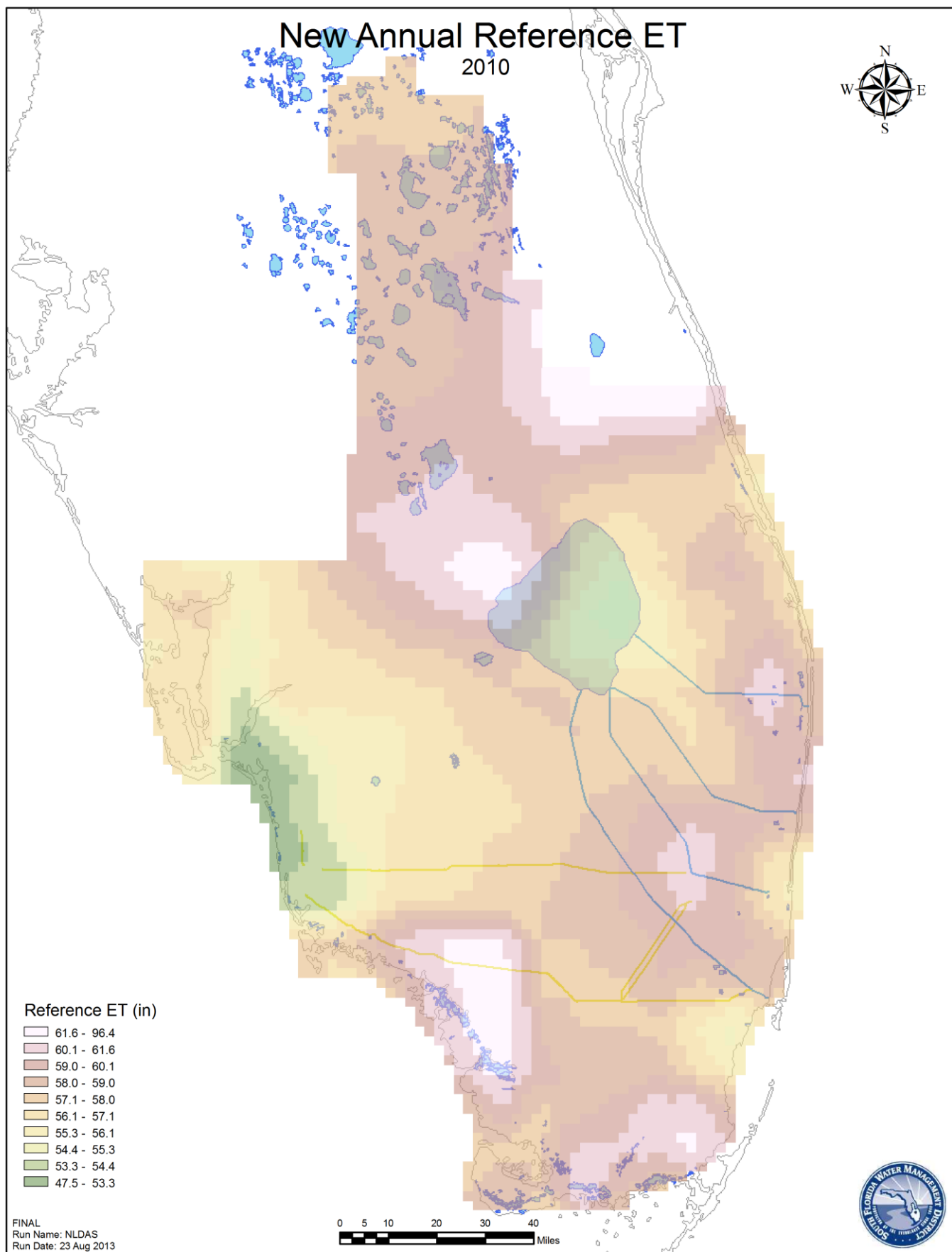


Figure C-5. Annual reference ET 2010.

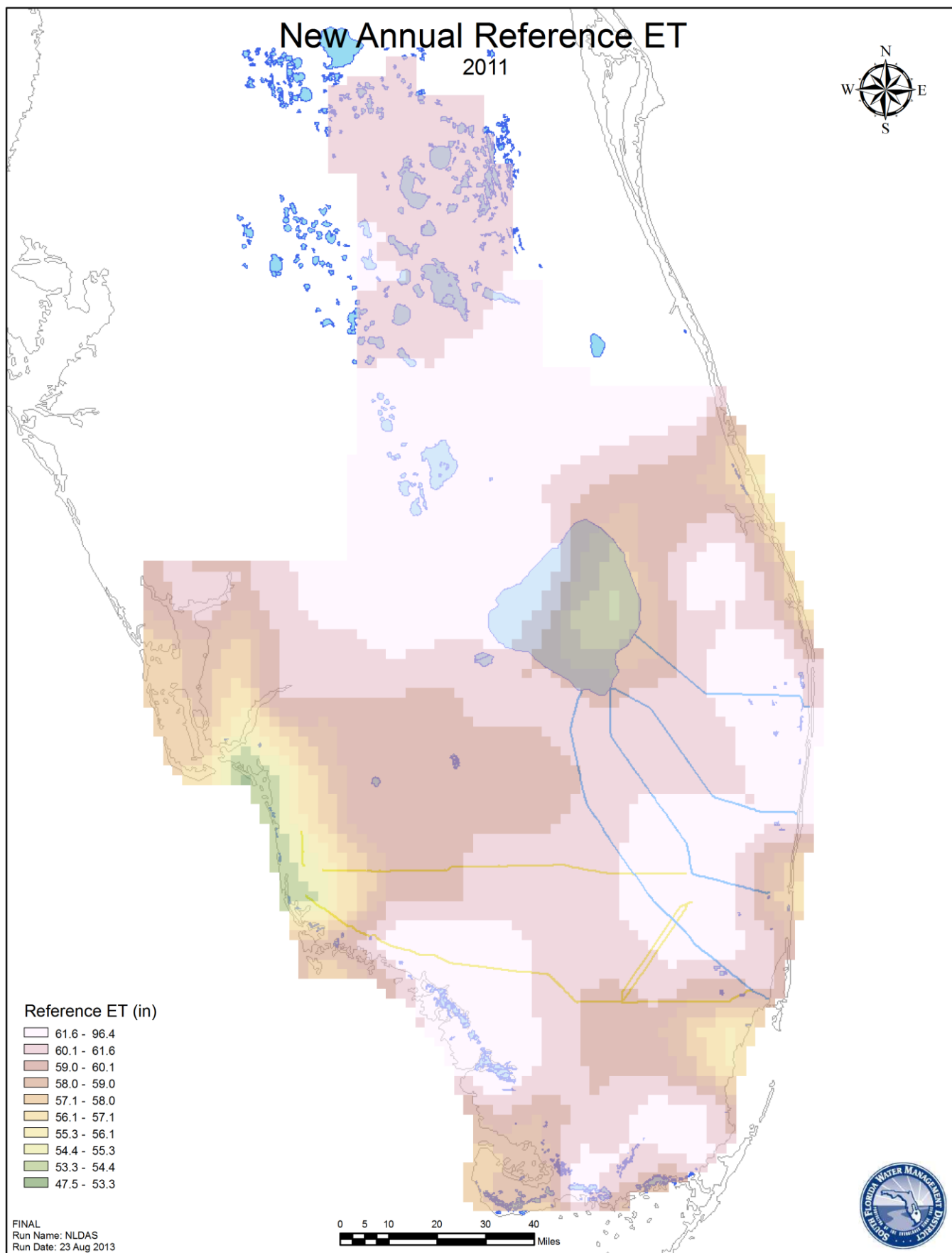


Figure C-6. Annual reference ET 2011.

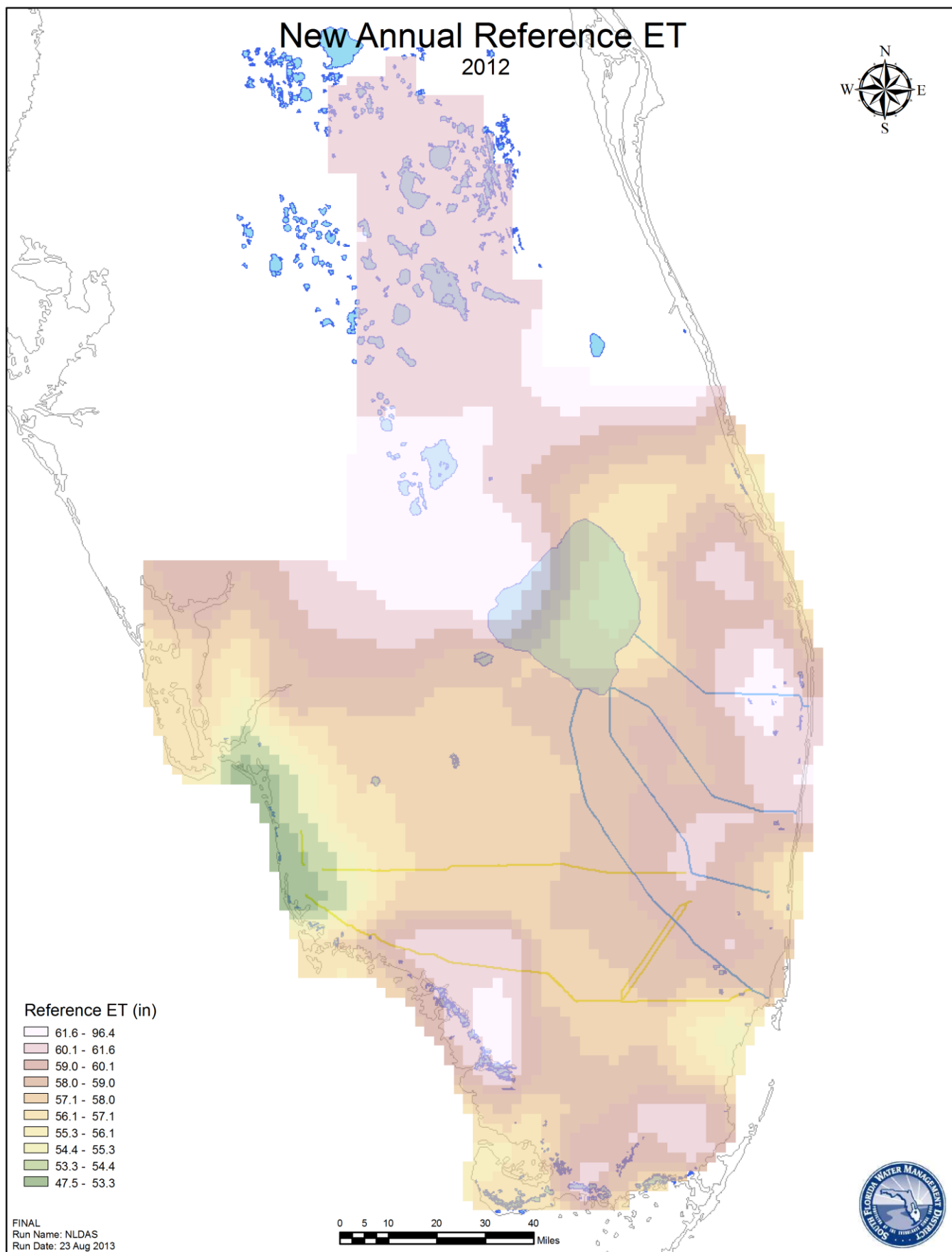


Figure C-7. Annual reference ET 2012.

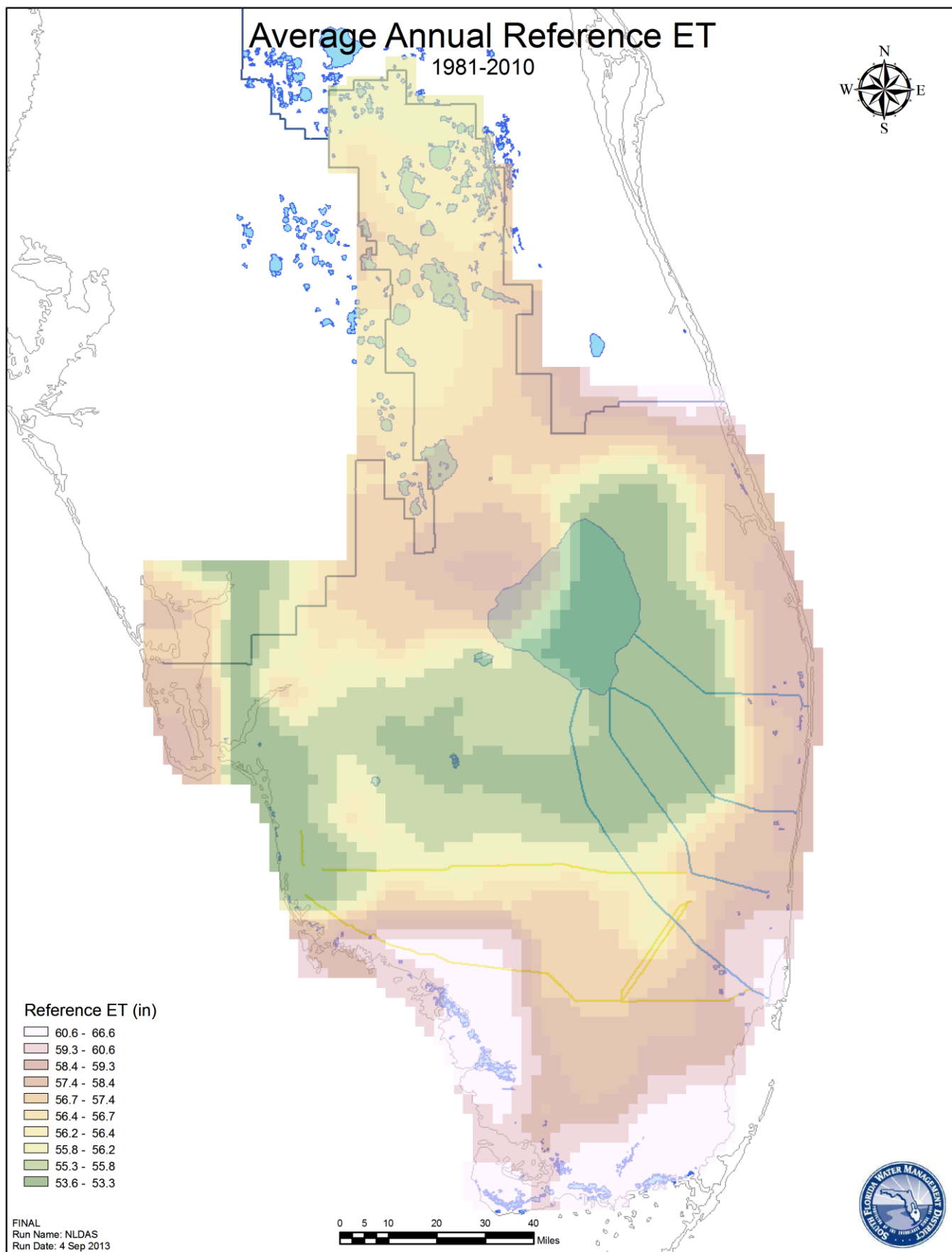


Figure C-8. 30 year climatic average (1981-2010).