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M E M O R A N D U M

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SUBJECT: Selected Methodology for Long-Term (1965-2000) Solar Radiation and Potential Evapotranspiration Estimation for the SFWMM2000 Update

Introduction:

Long-term daily (1965-2000) potential or reference evapotranspiration at several sites is required as input to the South Florida Water Management Model (SFWMM) and the Natural System Model (NSM). In these models, actual evapotranspiration is calculated by spatial interpolation of the reference or potential evapotranspiration between the sites, and by the application of landscape-specific crop coefficients that are a function of water depth. These landscape-specific crop coefficients are obtained by calibration as part of the SFWMM calibration/verification effort. Several potential methods for estimating potential or reference evapotranspiration for use in these regional long-term continuous simulation models were examined and are explained in detail in a separate memorandum (Irizarry-Ortiz, 2003). The selected method for potential evapotranspiration estimation is presented in detail below.

Methodology:

The SFWMD Simple Method (Abtew, 1996; Equation 1) was selected to provide estimates of long-term historical (1965-2000) *wet marsh potential ET* for long-term hydrological modeling. This assures some degree of consistency with estimates of potential ET by the Simple Method which are regularly posted for eleven sites on the SFWMD DBHydro database as meteorological data becomes available.

$$ET_p = \frac{K_1 * R_s}{\lambda} \quad (1)$$

ET_p:	wet marsh potential evapotranspiration	[mm d^{-1}]
K_1 :	coefficient (0.53 for mixed marsh, open water and shallow lakes)	
R_s :	solar radiation received at the land surface	[MJ m^{-2} d^{-1}]
λ :	latent heat of evaporation	[MJ kg^{-1}]

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It is important to keep in mind that due to the difference in roughness characteristics between marsh and reference grass surfaces, the crop coefficients developed with respect to a grass-reference ET may need to be modified for use with wet marsh potential ET.

Due to the scarcity of solar radiation and cloud cover data, the self-calibrating K_r method (Hargreaves and Samani, 1982; Allen, 1997; Equation 2) was chosen for estimating solar radiation (R_s) for potential ET estimation since it depends on a single parameter with low spatial variability.

$$R_s = \tau R_a = K_r (T_{\max} - T_{\min})^{0.5} R_a \tag{2}$$

R_s	:	solar radiation received at the land surface	[MJ m^{-2} d^{-1}]
τ	:	atmospheric transmissivity	
K_r	:	empirical coefficient	
T_{max}	:	mean daily maximum temperature over the period of interest	[^oC]
T_{min}	:	mean daily minimum temperature over the period of interest	[^oC]
R_a	:	extraterrestrial solar radiation	[MJ m^{-2} d^{-1}]

Extraterrestrial solar radiation (R_a) is calculated from latitude and time of year by integrating the instantaneous radiation intensity at the outer atmosphere from sunrise to sunset:

$$R_a = \frac{24*60}{\pi} G_{sc} d_r (\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s) \tag{3}$$

Ra	:	extraterrestrial solar radiation	[MJ m^{-2} d^{-1}]
G_{sc}	:	solar constant = 0.8202 (Duffie and Beckman, 1991)	[MJ m^{-2} min^{-1}]
d_r	:	relative distance from the sun to the Earth	
w_s	:	sunset hour angle	[rad]
φ	:	station latitude	[rad]
δ	:	declination of the sun	[rad]

The relative distance from the sun to the Earth (d_r), the declination of the sun (δ) and sunset hour angle (w_s) are given by:

$$d_r = 1 + 0.033\cos(\frac{2\pi J}{365}) \tag{4}$$

$$\delta = 0.409\sin(\frac{2\pi J}{365} - 1.39) \tag{5}$$

$$w_s = \arccos(\tan\varphi \tan\delta) \tag{6}$$

J : Julian day of the year

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The K_r method was applied at 17 NOAA stations with long-term (1965-2000) daily temperature data to provide long-term estimates of R_s for hydrologic modeling. For Lake Okeechobee, the average estimated R_s at Canal Point, Moore Haven and Belle Glade was used. The NOAA temperature data was thoroughly checked and patched to correct systematic errors, trends, and missing values with the purpose of producing the best possible temperature dataset for R_s and ET estimation (Lyons, in preparation).

In order to guarantee reasonable estimates the following two constraints were incorporated into the R_s estimation:

- A constant upper bound for the transmissivity is set to 0.75 across South Florida (i.e. clear-sky transmissivity defined as 75% of the extraterrestrial solar radiation; Smith, 1991).

- A lower bound for the transmissivity is set at 10% of the clear-sky transmissivity.

For each NOAA station, the K_r was selected so that the long-term average annual wet marsh potential ET estimated by the Simple method (Equation 1) matched an expected north to south gradient (Visher and Hughes, 1969). Figure 1 shows that the selected K_r values do not vary significantly from station to station with generally lower values in the interior (e.g. minimum value of 0.154 at Devils Garden) and higher values near the coast (e.g. maximum of 0.210 at Miami International Airport). In general, the selected K_r values agree with Hargreaves' (1994) recommendation of using K_r=0.16 for interior regions and K_r=0.19 for coastal regions. Annual timeseries and summary statistics of wet marsh potential evapotranspiration estimated at 17 NOAA stations and Lake Okeechobee are presented in Table 1.

Spreadsheets used for the calculation of *wet marsh potential evapotranspiration* at the 17 NOAA stations plus Lake Okeechobee can be found at:
/net/noles/usr2/users/dlyons/ALL/ET/Temperature/PM_Simple_ETo_Cal/PM_SimpleETo_Kr/
A spreadsheet (ETp_1965-2000_17stn_plsLOK_Kr.xls) summarizing the results for the 17 stations plus Lake Okeechobee can be found in the same directory.

Previously, the inverse-distance squared method was used to interpolate reference ET (SFWMD, 1999). For the SFWMM2000 update, the TIN method was selected for spatially-interpolating the wet marsh potential ET across a 2-mile x 2-mile resolution super-grid covering most of South Florida (Figure 2). Due to the scarcity of stations where wet marsh potential ET was estimated, it was found that the TIN method results in a smoother spatial variation of potential ET.

The executable for the C program used in calculating the TIN weights for each 2x2 grid cell can be found at: /opt/local/share2/bin/gr_thsn on linuxserv1. Input files to this program can be found at: /home/polar/hcorrea/gr_thsn/ETp_recomputed/.

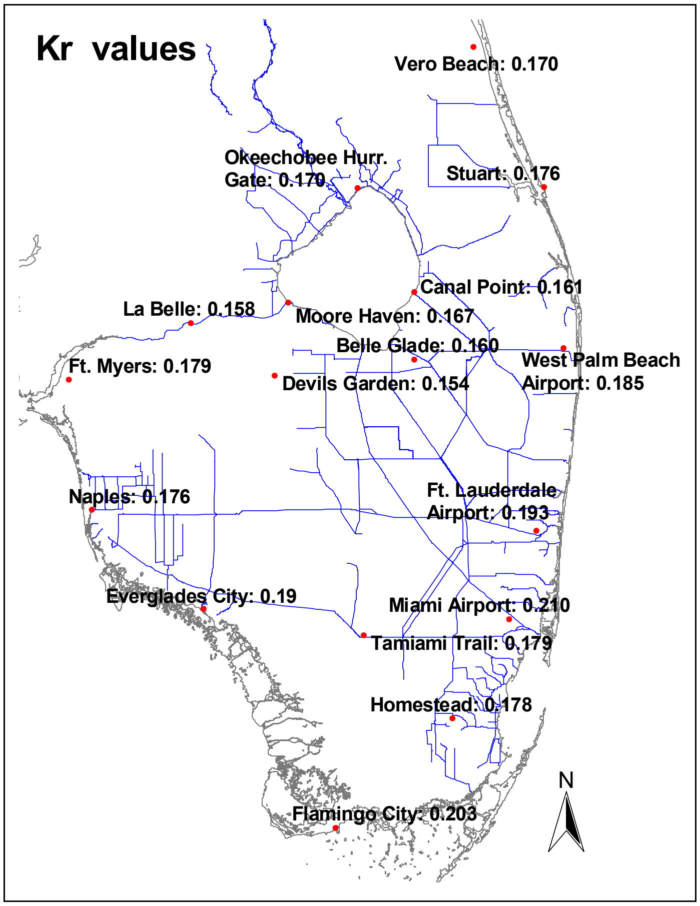

Figure 1. Selected K_r values for 17 NOAA stations with long-term daily temperature data.

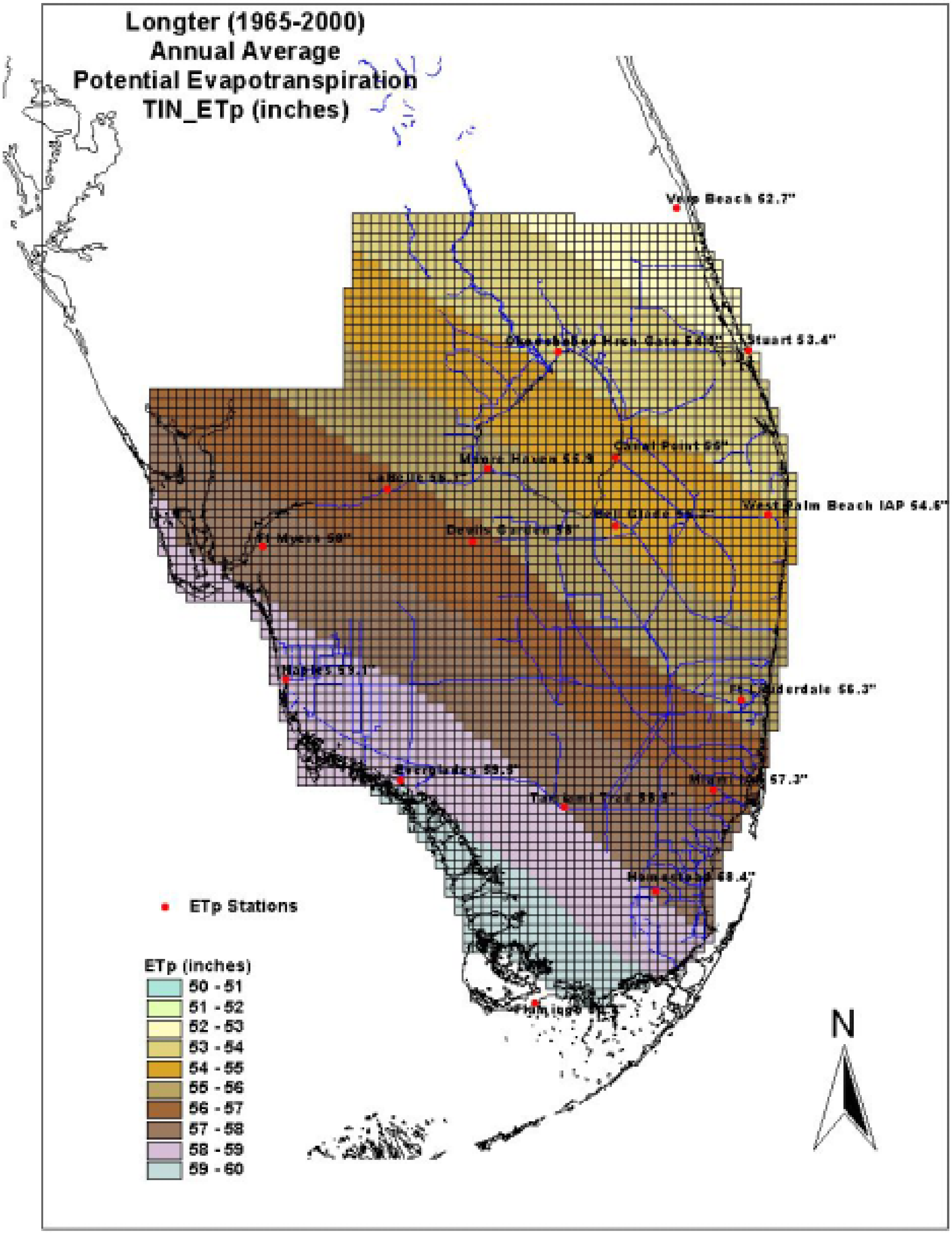

Figure 2. Estimated annual average wet marsh potential evapotranspiration (in/yr) for a 2-mile x 2-mile super-grid which includes the SFWMM and NSM grids.

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Table 1. Annual timeseries and summary statistics of wet marsh potential evapotranspiration estimated at 17 NOAA stations plus Lake Okeechobee.

Year	LOK	La Belle	Devils Garden	Ft Myers	Naples	Everglades City	Flamingo	Homestead	Tamiami Trail	MIA	Ft. Lauderdale	WPBIA	Canal Point	Belle Glade	Moore Haven	Okeechobee Hurr. Gate	Stuart	Vero Beach
Kr	N/A	0.158	0.154	0.179	0.176	0.190	0.203	0.178	0.179	0.210	0.193	0.185	0.161	0.160	0.167	0.170	0.176	0.170
1965	55.27	56.57	54.88	57.96	59.53	62.05	59.58	61.53	60.80	57.74	58.76	55.87	55.16	56.25	54.39	56.14	52.66	52.69
1966	52.74	54.92	53.90	56.94	57.94	60.51	56.77	58.36	56.16	56.85	57.67	53.80	53.13	53.83	51.25	54.77	51.78	52.01
1967	56.58	58.40	55.75	56.46	59.36	60.73	58.52	60.24	63.63	54.76	57.70	57.05	56.86	56.49	56.38	53.21	54.85	54.47
1968	54.57	57.37	54.53	57.70	58.36	60.22	57.89	59.07	59.78	55.59	58.36	56.27	54.31	54.79	54.61	53.97	54.87	53.17
1969	53.03	56.72	53.54	53.86	58.11	60.46	58.24	57.29	56.65	58.07	57.37	53.63	53.77	53.04	52.30	50.78	52.73	50.73
1970	54.75	58.85	55.27	55.86	60.22	58.52	58.93	59.37	53.54	56.73	57.92	54.79	55.18	53.65	55.41	51.84	55.93	52.94
1971	56.90	61.77	58.13	57.34	61.43	60.25	61.70	61.54	61.22	58.62	60.41	57.96	56.89	55.59	58.21	56.08	53.13	53.75
1972	55.60	59.76	56.42	59.32	60.88	58.41	59.34	58.77	58.83	55.98	58.19	54.90	54.34	54.04	58.41	55.23	52.56	52.61
1973	55.71	57.06	56.50	59.23	61.91	60.27	60.01	58.02	59.57	54.62	57.74	54.32	55.03	54.40	57.70	55.47	52.47	51.50
1974	55.95	58.07	57.64	59.90	62.95	60.58	57.60	59.85	60.10	57.24	57.72	53.94	55.66	54.77	57.43	56.04	55.65	53.09
1975	56.29	58.97	56.33	59.61	62.70	58.42	60.72	59.97	59.04	57.45	56.73	54.92	56.09	55.04	57.75	55.73	55.75	54.59
1976	55.38	57.73	57.58	59.14	62.31	60.21	62.08	58.09	56.12	56.63	55.27	54.38	54.92	53.90	57.32	53.63	56.06	54.08
1977	55.66	58.69	56.96	57.89	61.44	59.61	62.38	58.36	57.40	56.14	55.13	55.03	54.66	54.54	57.77	52.47	53.77	53.75
1978	53.65	58.38	53.99	57.57	59.82	59.58	61.30	57.30	55.98	54.80	56.13	55.06	53.85	52.65	54.45	52.95	53.31	53.72
1979	53.84	56.35	54.59	57.93	60.48	57.97	60.21	57.48	58.29	52.95	56.48	54.57	54.01	52.68	54.83	52.07	50.32	52.24
1980	55.30	57.67	55.35	58.56	60.36	58.80	61.83	59.01	59.75	55.86	57.58	57.78	55.20	53.85	56.84	54.41	54.37	54.06
1981	57.27	59.41	59.09	60.05	63.16	60.43	63.72	59.75	62.67	59.88	59.25	57.32	55.96	54.93	60.92	57.32	55.32	55.58
1982	54.03	55.33	52.69	56.76	60.70	57.69	60.75	58.33	60.47	56.36	56.56	50.83	53.31	53.18	55.59	55.91	51.90	50.85
1983	54.50	54.48	53.74	54.26	59.79	57.51	60.58	58.16	57.95	59.52	58.15	52.08	53.43	55.99	54.09	55.69	51.86	52.57
1984	54.58	55.53	54.30	56.73	58.12	60.35	61.41	62.29	56.93	59.23	55.56	52.67	54.25	55.10	54.40	55.00	54.78	50.41
1985	56.16	56.87	59.21	58.30	57.75	60.30	62.75	57.98	61.93	61.09	57.03	54.34	54.33	56.71	57.44	54.11	54.18	51.41
1986	55.96	56.85	55.05	59.85	58.34	61.27	63.42	57.82	57.20	60.40	55.53	54.59	54.87	56.89	56.11	55.00	53.76	54.64
1987	55.65	55.08	55.81	58.74	56.96	60.21	62.85	56.81	56.57	59.10	54.64	53.79	54.00	56.82	56.12	55.25	53.09	53.13
1988	55.65	56.33	59.00	60.61	58.36	63.59	58.07	55.40	57.99	58.80	55.10	53.90	54.60	56.51	55.83	55.00	52.60	52.85
1989	57.94	57.56	59.25	61.41	58.70	56.99	57.89	58.52	64.46	60.38	56.12	55.87	57.08	57.80	58.93	57.62	54.25	54.85
1990	57.10	56.37	57.11	60.83	58.71	56.90	61.55	58.10	63.73	58.41	54.95	54.20	56.64	57.36	57.30	51.22	51.26	52.09

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Year	LOK	La Belle	Devils Garden	Ft Myers	Naples	Everglades City	Flamingo	Homestead	Tamiami Trail	MIA	Ft. Lauderdale	WPBIA	Canal Point	Belle Glade	Moore Haven	Okeechobee Hurr. Gate	Stuart	Vero Beach
Kr	N/A	0.158	0.154	0.179	0.176	0.190	0.203	0.178	0.179	0.210	0.193	0.185	0.161	0.160	0.167	0.170	0.176	0.170
1991	55.58	55.61	57.80	58.12	56.90	59.62	61.47	57.95	59.45	57.54	52.72	53.19	54.81	56.37	55.55	50.10	52.16	51.55
1992	55.38	54.66	57.45	58.23	57.35	57.69	61.20	59.44	59.79	58.21	54.26	54.71	54.61	56.23	55.30	52.79	52.86	53.44
1993	55.87	54.35	57.63	57.82	57.95	60.45	61.48	58.35	54.22	57.55	54.17	53.73	54.58	57.41	55.63	55.49	52.47	53.34
1994	53.90	56.24	58.28	57.11	55.85	59.39	60.74	59.24	56.36	55.41	51.19	54.97	53.30	55.05	53.35	52.68	51.93	51.59
1995	53.80	54.83	61.34	55.46	55.62	58.75	61.79	56.86	54.22	56.58	57.04	57.06	54.32	54.61	52.48	52.53	54.62	51.53
1996	55.72	54.60	61.28	57.27	58.11	62.45	62.67	56.75	58.31	57.51	54.99	53.58	55.46	56.03	55.66	53.70	54.03	51.88
1997	55.32	55.18	58.50	59.45	56.89	59.47	61.30	56.20	57.63	56.56	54.01	52.51	54.94	55.21	55.82	55.58	55.61	49.72
1998	54.67	53.60	58.50	56.51	56.33	56.20	63.82	55.19	56.44	56.20	54.42	53.33	54.86	55.10	54.05	54.62	51.79	51.06
1999	55.71	56.08	58.02	57.63	56.67	57.31	64.79	57.93	56.16	58.08	55.70	54.21	55.67	56.22	55.23	53.94	52.79	52.62
2000	58.19	55.22	56.82	58.85	57.49	58.12	58.63	57.32	56.67	57.53	55.02	53.94	58.24	58.99	57.32	54.81	52.52	53.09
Ann Ave	55.39	56.71	56.73	58.04	59.10	59.48	60.78	58.41	58.50	57.34	56.27	54.59	54.95	55.33	55.89	54.25	53.44	52.71
Stdev	1.25	1.81	2.14	1.71	2.07	1.63	1.98	1.57	2.70	1.81	1.91	1.57	1.16	1.51	1.99	1.78	1.48	1.36
Max	58.19	61.77	61.34	61.41	63.16	63.59	64.79	62.29	64.46	61.09	60.41	57.96	58.24	58.99	60.92	57.62	56.06	55.58
Min	52.74	53.60	52.69	53.86	55.62	56.20	56.77	55.19	53.54	52.95	51.19	50.83	53.13	52.65	51.25	50.10	50.32	49.72
Max-Min	5.45	8.16	8.64	7.56	7.53	7.39	8.02	7.10	10.92	8.14	9.22	7.12	5.12	6.34	9.66	7.52	5.74	5.86

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