Estimation of historical and future evapotranspiration

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ABSTRACT

A method is presented to estimate long-term, historical evapotranspiration (ET). Daily values of a commonly-used index (i.e., reference ET) were computed using readily-available, long-term air temperature data. Reference ET data were then coupled with monthly vegetation factors derived from contemporary eddy covariance measurements of ET to compute daily values of historical ET. Future ET was described probabilistically based on the computed, historical sample of ET corrected for long-term trends in air temperature. The method is exemplified using a 108-year dataset of minimum and maximum daily air temperature at a weather station and a two-year record of ET measurements at a nearby forested wetland. Estimates of long-term ET are useful for assessment of climatic variability and in calibration of hydrologic models used for water resources planning. Probabilistic descriptions of future ET are critical to strategic irrigation design and to stochastic simulations of hydrologic flow models to evaluate future water availability.

INTRODUCTION

Evapotranspiration (ET) generally is a large part of the water budget for terrestrial settings. Of the approximately 80 cm/yr of mean precipitation over the land surfaces of the Earth, about 50 cm/yr is returned to the atmosphere as ET (Brutsaert, 2009). Estimation of this atmospheric flux is a critical component of irrigation design and hydrologic analyses. ET can be measured using micrometeorological (Baldocchi and others, 1988), mass-balance (Nachabe et al., 2005; Jia et al., 2006) and satellite-based (Bastiaanssen et al., 1998; Anderson et al., 2007) methods.

Although methods exist to measure ET, it is often desirable to have estimates of historical and future ET outside of the time range of available ET measurements. Hydrologic simulations for water resources planning generally rely on calibration of hydrologic models for a historical period to evaluate and enhance model reliability. Historical ET data are needed input for hydrologic model simulations during these calibration periods. Future estimates of ET are needed for irrigation design and for scenario simulations of hydrologic models. Given meteorological uncertainty, future estimates of ET are probabilistic by necessity. A probabilistic description of future ET can be obtained from an analysis of the variations in historical ET, assuming that the statistical nature of ET is stationary or that any non-stationarities (e.g., trends) can be removed. The quality of estimates of future ET depends on the extent to which the full probabilistic population of ET is sampled in the historical ET record and will therefore increase with increasing sample size (i.e., longer period of historical ET record). The longest datasets available for estimating ET generally are those that rely on simple meteorological measurements. In the United States, many National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) stations have monitored daily minimum and maximum air temperature for more than a century. Minimum and maximum daily air temperatures are the only data requirements for computing daily values of a commonly-used index of ET (i.e., reference ET) by the Hargreaves equation (Hargreaves and Allen, 2003). Reference ET is related to (true) ET by "crop" or "vegetation" factors. The Hargreaves equation has been demonstrated to be a reliable surrogate for the more sophisticated and widely-accepted, but more data intensive, Penman-Monteith reference ET equation (Hargreaves and Allen, 2003; Allen et al., 2005). Generic, empirical methods have been applied to estimate long-term ET (Burt and Shagedanova, 1998), but field measurements of ET are more credible for a particular site. The objective of this paper is to demonstrate the utility of a 108-year record of air temperature data, coupled with two years of micrometeorological (eddy covariance) measurements of ET, for estimating long-term historical ET and the probabilistic nature of future ET.

METHODS

Long-term daily reference ET values were computed using the Hargreaves equation and a 108-year record (1902-2008) of daily minimum and maximum air temperature data from the Indian Mills 2 W NWS weather station (NOAA, 2009) located in a rural setting at 39° 49' N and 74° 47' W in southern New Jersey, USA. Eddy covariance measurements of ET were made over a two-year period (2005-2006) at a forested site at 39° 53' N and 74° 31' W about 24 km from the NWS weather station. Monthly crop factors during 2005-2006 were computed based on the ratio of monthly measured ET to reference ET. Historical daily ET was computed for 1902-2008 using computed reference ET and an annually-invariant pattern of monthly crop factors. Long-term, linear trends in air temperature data were removed such that the resulting record represents multiple statistical realizations of the present-day (2008) probabilistic structure. Hargreaves ET was computed using the detrended air temperature record, and present-day probability density functions of monthly and annual ET were approximated as histograms of the 108-year record.

Hargreaves Reference Evapotranspiration

The Hargreaves equation (Hargreaves and Allen, 2003) is widely used in agricultural studies to estimate reference ET. Reference ET is defined as the ET from an actively-growing, well-watered grass or alfalfa cover of a specific height range (Allen and others, 2005). The Hargreaves equation requires minimum and maximum daily air temperatures, which are commonly measured at weather stations. The coefficients and form of the equation are empirical and were developed based on comparison with data from precision weighing lysimeters with reference-condition grass land covers. The Hargreaves equation is based on an empirical relation between ET and the two most important explantory variables for this term – incoming solar radiation and air temperature (1). Another empirical relation (2) is used to relate incoming solar radiation to extraterrestrial radiation and a variable highly correlated with cloud cover (daily temperature range). Combining these equations leads to the Hargreaves equation (3).

$$ET_0 = aR_s(T + b) \quad (1)$$

$$R_s = K_{RS}R_a \quad (2)$$

$$ET_0 = aK_{RS}R_a(T + b)T_r^{0.50} \quad (3)$$

ET_0	is reference ET, in the same water evaporation units as R_S (for example, millimeters per day)
R_s	is incoming solar radiation on land surface, in the same water evaporation units as ET_0
R_a	is extraterrestrial radiation, in the same water evaporation units as ET_0
T	is average daily air temperature, in degrees Celsius
T_r	is daily temperature range, in degrees Celsius
a	is an empirical coefficient equal to a value of 0.0135
b	is an empirical coefficient equal to a value of 17.8
K_{RS}	is an empirical coefficient often estimated as 0.16 and 0.19 for inland and coastal areas, respectively.

In this study, as suggested by Hargreaves and Samani (1985), the product aK_{RS} was set equal to 0.0023. R_a can be estimated using an analytical expression of latitude and day of year (Allen and others, 2005). T and T_r are usually estimated as the average and difference, respectively, of maximum and minimum daily air temperature.

Measurement of Evapotranspiration - Eddy-covariance Method

The eddy covariance method (Baldocchi and others, 1988) was used to measure ET and sensible heat flux from the forested site using methods similar to those of Sumner and Jacobs (2005). The eddy covariance method is a conceptually simple, one-dimensional approach for measuring the turbulent fluxes of vapor and heat above a surface. The time-averaged product of measured values of vertical wind speed (w) and vapor density (ρ_v) is the estimated vapor flux (ET) during the averaging period. Because of the insufficient accuracy of instrumentation available for measurement of wind speed and vapor density, this procedure generally is performed by monitoring the fluctuations of wind speed and vapor density about their means, rather than monitoring their actual values. The vapor flux relation, and a similar relation for sensible heat transport, are represented by (4) and (5).

$$ET = \overline{w\rho_v} = \overline{w'\,\rho_v'} \quad (4)$$

$$H = \rho_a C_p \overline{wT_a} = \rho_a C_p \overline{w'T_a'} \quad (5)$$

ET	is evapotranspiration, in grams per square meter per second;
w	is wind speed perpendicular to the surface, in meters per second;
ρ_v	is vapor density, in grams per cubic meter;
H	is sensible heat flux, in watts per square meter;
ρ_a	is air density, in grams per cubic meter;
C_p	is specific heat capacity of the air, in joules per gram per degree C;
T_a	is air temperature, in degrees C; and
	overbars and primes represent temporal averaging and instantaneous fluctuations about the mean, respectively.

Instrumentation capable of high-frequency resolution must be used in an application of the eddy covariance method because of the relatively high frequency of the turbulent eddies that transport water vapor. Instrumentation included a three-axis sonic anemometer (Campbell Scientific, Inc. (CSI) CSAT3) and a krypton hygrometer (CSI KH2O) to measure or infer variations in wind speed/air temperature and vapor density, respectively. Eddy covariance sampling frequency was 8 Hertz with 30-min averaging periods. The eddy covariance instrumentation was placed on a Rohn 45G communications-type tower at a height about 1.5 times the mean canopy height of about 15 m. Ancillary measurements of air temperature and relative humidity (Vaisala HMP45C) were made to allow computation of vapor density and the specific heat and density of air. Data were processed and stored in a CSI 10X datalogger near ground-level. Missing eddy covariance flux data can result from scaling of hygrometer windows or from moisture on the anemometer or hygrometer but are usually gap-filled with empirical relations.

The source area for flux measurements defines the area (upwind from measurement location) contributing to the measurement. Schuepp and others (1990) provided an estimate of the source area for turbulent flux measurements based on an analytical solution of a one-dimensional diffusion equation for a uniform surface cover. Assuming mildly-unstable conditions typical of daytime conditions when heat and vapor fluxes are highest, this method estimated that 80 and 90 percent of the source area for the daytime turbulent flux measurements was within an upwind distance of about 205 and 435 m, respectively. The source area is primarily (~75 percent) composed of wetlands with a pitch pine/cedar forest, but uplands covered by oak/pine forest are also present.

Eddy covariance data were adjusted for energy-budget closure as suggested by Twine and others (2000). Two common alternatives to adjust flux measurements for energy budget closure were used: preservation of the Bowen ratio ($H/\lambda E$) and preservation of the measured H. The energy-budget equation represents an accounting of energy fluxes for the plant canopy (6) and was applied at the daily time scale.

$$R_n - G - S = \lambda E + H \tag{6}$$

Latent heat flux (λE) is the energy removed from the canopy in the liquid-to-vapor phase change of water and is the product of the heat of vaporization of water (λ) and the evapotranspiration rate (E). Net radiation (R_n) is the net short- and long-wave radiation transfer above the plant canopy and was measured with a net radiometer (Radiation and Energy Balance Systems, Inc. Q-7). Heat stored in the plant canopy (S) and transferred to the subsurface (G) were assumed to be negligible over a daily interval. Also, the energy involved in fixation of carbon dioxide is usually considered negligible (Brutsaert, 1982).

RESULTS

About 27 percent of the 30-min eddy-covariance flux measurements at the forested site were missing and gap-filled with linear relations between λE and H with R_n. However, the fraction of energy flux gap-filled was small (5 and 7 percent of λE and H, respectively) because missing data generally occurred during periods of low energy flux. Daily energy-budget closure was applied to the energy fluxes. Energy-budget closure by preservation of sensible heat flux resulted in ET values that were about 7 percent higher than those produced by preservation of the Bowen ratio; the former method does not rely on krypton hygrometer data and was chosen in this study as the preferred method because of a multi-month failure of the krypton hygrometer in 2005.

Measured ET at the forested site showed a strong seasonal pattern with day-to-day variations largely related to variations in cloud cover and the resulting variations in solar radiation (Figure 1). Measured annual ET was 805 and 797 mm in 2005 and 2006, respectively, and Hargreaves reference ET was 1,190 and 1,181 mm, in 2005 and 2006, respectively. Annual precipitation at the Indian Mills NWS station was 1319 and 1262 mm, in 2005 and 2006, respectively; both data collection years were representative of the long-term (1902-2008) mean annual precipitation of 1276 mm at this station.

Daily ET at the forested site was well correlated with daily reference ET ($r^2 = 0.82$) at the weather station indicating that a constant vegetation factor (mean value of 0.68) could be successfully applied to reference ET to simulate ET. However, use of an annually-invariant, monthly pattern of vegetation factors (Figure 2) increased the correlation between measured and simulated daily ET ($r^2 = 0.85$). Figure 1 illustrates that simulated ET performs well in reproducing weekly or longer, low-frequency trends relative to measured values but does not capture some of the higher-frequency, day-to-day variability as well.

Long-term (1902-2008) daily values of historical ET were estimated based on annually-invariant vegetation factors and reference ET computed using long-term, daily air temperature data. Annual values of ET are shown in Figure 3. Historical annual ET was estimated to vary from 706 mm (1972) to 830 mm (2002) with an average of 760 mm.

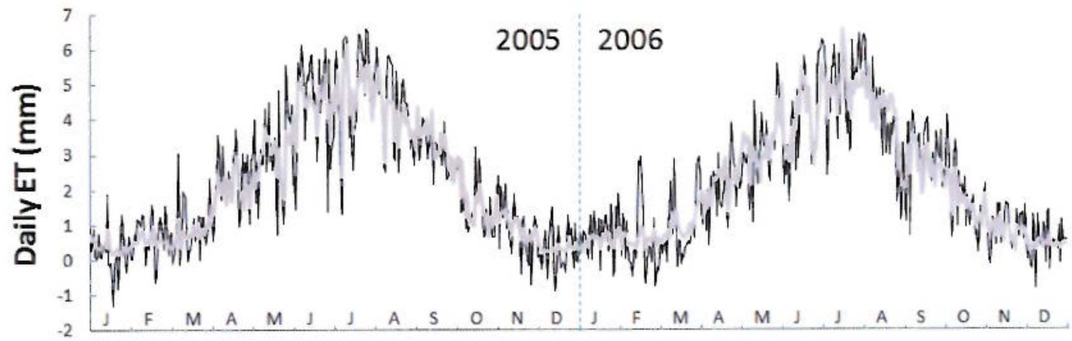

Figure 1. Measured (black) and simulated (grey) daily ET at forested site.

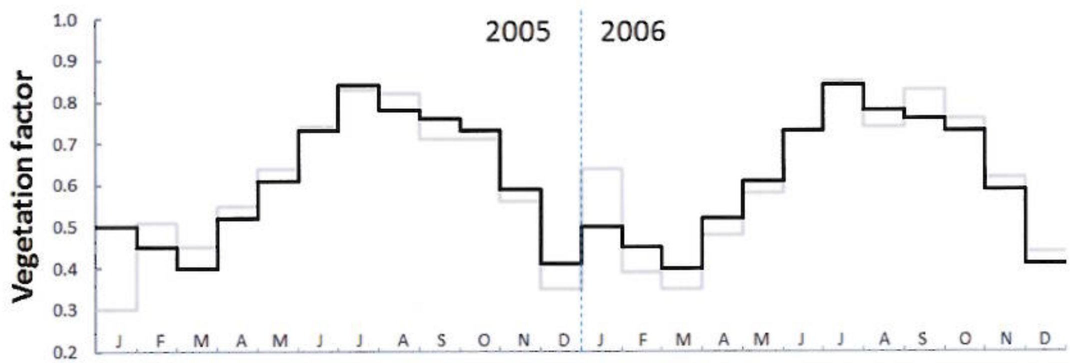

Figure 2. Annually-invariant (black) and measured (grey) monthly vegetation factors relating measured ET at forested site to Hargreaves reference ET at NWS station.

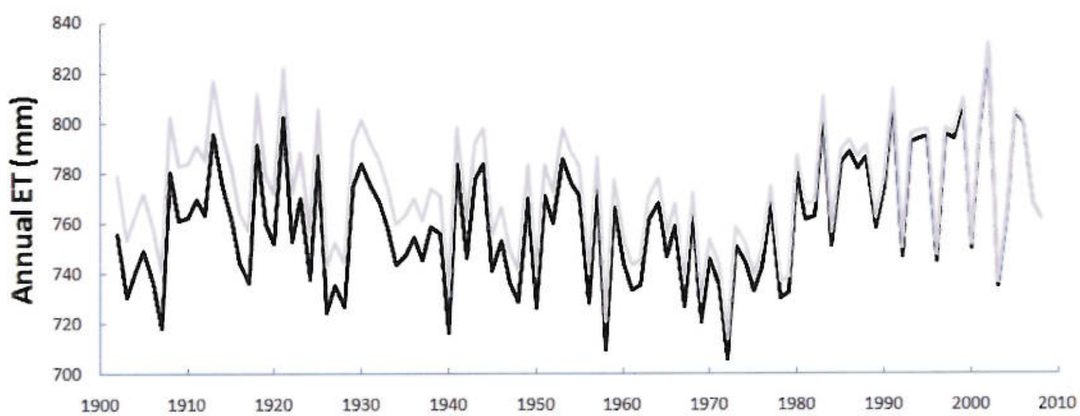

Figure 3. Computed historical ET (black) and trend-corrected statistical sample of expected future ET (grey).

A statistical sample approximating the probabilistic population of present-day (2008) ET was constructed by linearly detrending historical air temperatures. Long-term air temperature trends were computed for each month (Table 1). Most months showed a statistically-significant (based on a t-test at a 95 percent confidence level) warming trend over 1902-2008. However, the trends in minimum and maximum air temperature were largely parallel as the difference in these temperatures generally did not exhibit a statistically-significant trend. The time series of annual ET corrected for air temperature trends is shown in Figure 3.

Histograms of monthly and annual ET (at 5 and 10 mm resolution, respectively) were constructed based on the computed 108-year statistical sample of present-day ET (Figures 4 and 5). All ET histograms were unimodal. The monthly histograms indicate that the least and greatest absolute variability in ET is expected during the winter and summer months, respectively.

	Tmin	Tmax			Tmin	Tmax
January	0.0031	-0.0037		July	0.008	0.0096
February	0.0148	0.0177		August	0.0097	0.0166
March	0.006	0.0046		September	0.0019	0.0036
April	0.0083	0.0143		October	0.0021	-0.004
May	0.0005	-0.0001		November	0.0152	0.0099
June	0.0107	0.0121		December	0.0183	0.0158
				Annual	0.0082	0.008

Table 1. Regression-derived linear trends of minimum (Tmin) and maximum (Tmax) daily temperature and of daily temperature range (Tmax-Tmin) over 1902-2008 [units = °C/yr]. Trends that are significantly different from zero at the 95 percent confidence level are shown in shaded cells.

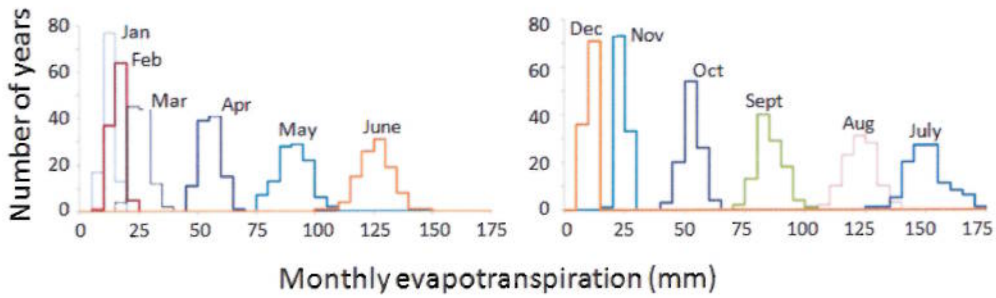

Figure 4. Histograms of expected future monthly ET.

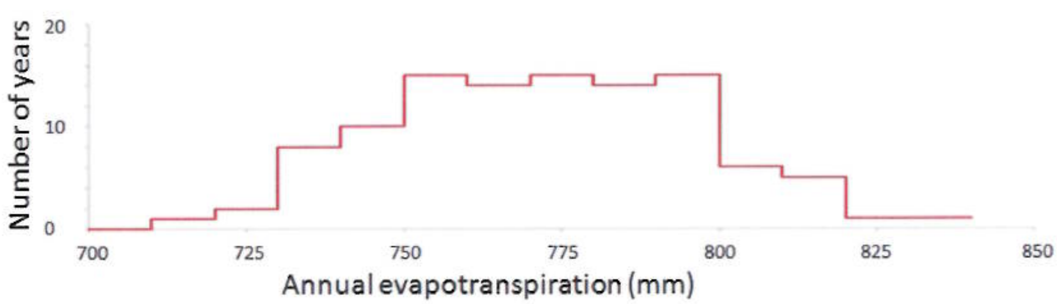

Figure 5. Histogram of expected future annual ET.

DISCUSSION

The present analysis assumed that the monthly pattern of vegetation factors was annually invariant. This assumption is reasonable for plant covers that are not subject to substantial moisture stress, such as irrigated crops or the predominantly wetland cover of this study. However, for plant covers that come under substantial moisture stress, incorporation of soil moisture availability, as a predictor variable for vegetation factor, may be necessary. Commonly-available long-term precipitation data could possibly serve as a suitable surrogate for sparsely-available soil moisture availability data.

Histograms of expected present-day ET provide a discrete approximation of the associated probability distribution functions (PDFs). PDFs of ET provide a means for water managers and scientists to anticipate the range of ET conditions in irrigation design or hydrologic simulation and to quantify the probability of occurrence of a particular threshold ET value. PDFs can be constructed for any arbitrary time period of interest, including monthly, seasonal, annual, or multi-year. Although the present analysis did not incorporate any expected future trend in air temperature related to climate variability or change, such a trend can readily be incorporated in the analysis to allow for estimation of temporally-evolving ET PDFs into the future.

The method described requires long-term meteorological data from weather stations to compute reference ET at specific locations and therefore lacks spatially-continuous estimates of reference ET. Assimilation of historical point meteorological data and spatially-continuous satellite data into numerical land-atmosphere models allows spatially- and temporally-continous reconstructions of meteorological conditions that could be used to compute spatially-continous (true) ET (Mesinger et al., 2006) or reference ET (Irizarry-Ortiz et al., 2007) for multi-decadal periods. However, these "reanalysis" products often are of shorter time periods (less than 50 years) than the frequently century-long datasets available at individual weather stations.

SUMMARY AND CONCLUSIONS

Historical (deterministic) and future (probabilistic) ET were estimated with minimal data requirements: a long-term (108 years) record of daily minimum and maximum air temperature at a weather station and short-term (two years), recent measurements of ET over a nearby forested wetland. The Hargreaves equation, requiring only daily temperature data, was used to compute long-term reference ET. An annually-invariant pattern of monthly vegetation factors was identified using the two-year record of measured ET. Historical ET from the forested wetland was computed as the product of daily reference ET and the vegetation factors. Probabilistic, future ET was derived from the computed, historical statistical sample of ET, corrected for long-term, linear trends in air temperature.

Long-term estimates of historical ET allow more robust calibration of hydrologic flow models and, therefore, more credible model-facilitated water resources planning.

Long-term, historical ET data also allow evaluation of the impact of climate variability on water availability. Quantification of probabilistic future ET is critically needed for strategic water resources planning to account for uncertainty in this major determinant of water availability.

ACKNOWLEDGEMENTS

Funding for field measurements of ET at the forested wetland site in southern New Jersey was provided through the Water Supply Fund in accordance with New Jersey Public Law 2001, Chapter 165. The authors would like to thank Rick Edwards of the U.S. Geological Survey for his extensive efforts to collect these data under frequently difficult circumstances. The authors also thank Getachew Belaineh and Chandra Pathak of the St. Johns River and South Florida Water Management Districts, respectively, for their useful technical reviews of this paper.

Note: Use of trade, product, or firm names in this publication is for description purposes only and does not imply endorsement by the U.S. Government.

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