Vegetation Indices to Aid Areal Evapotranspiration Estimations

Jozsef Szilagyi[1]

Abstract: Multiyear (1982–1990) monthly areal evapotranspiration (AET) was modeled with the Morton approach at the Solar and Meteorological Surface Observation Network stations within the conterminous United States. The AET values were correlated with satellite-derived, monthly maximum-value-composited Normalized Difference Vegetation Indices (NDVI) at half-degree resolution over the growing season (April–October). Generally, the strongest monthly correlation was obtained when the NDVI values were related to the AET estimates of the previous month. Geographically, both the monthly and growing-season averaged NDVI-AET relationships were best over the prairie (with an $r=0.66\pm0.21$ and 0.55 ± 0.22, and a RMSE$=26.75\pm12.62$ and 6.24 ± 1.67 mm month^{-1}, respectively) and worst along the coastline and in the most humid, southeast region of the conterminous United States, where the Morton approach may function improperly.

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Introduction

In regional water-balance calculations and watershed modeling, one of the greatest unknowns is areal evapotranspiration (AET). Generally, this variable is calculated from other estimated variables of the water balance, such as soil moisture. In spatially distributed watershed models, soil moisture is rarely monitored at the scale of the model's resolution (i.e., grid cells or subcatchments), yet AET is often estimated at that scale. Since many watershed models infer AET from the moisture status of the soil, a question arises over how to upscale from point measurements of soil moisture status to the subcatchment or watershed scale of AET. Ongoing research in remote sensing of soil moisture (Schultz and Engman 2000) may one day provide a solution. An approach that estimates spatially distributed AET *independent* of the watershed/water-balance model could greatly increase model accuracy and/or reliability, since known values of AET would decrease the number of unknown variables/parameters to be estimated and, also, optimized parameters of the model could be validated with the help of independently obtained values of AET. This is especially important, since Jakeman and Hornberger (1993) showed that the number of unknown parameters/variables that can efficiently be estimated from the information content of a rainfall/runoff record is very limited.

Vegetation indices have been used in the past quarter century for crop-yield monitoring (Tucker et al. 1979). With the emergence of space technology, satellite-derived vegetation indices, such as the Normalized Difference Vegetation Index (NDVI $=[\mathrm{NIR}\text{-}R]/[\mathrm{NIR}+R]$, where NIR and R are the spectral responses of the vegetated surface at the near-infrared and red bands, respectively), have become essential for gathering biophysical information on the vegetation status of large, arbitrarily defined regions. Since the vegetation status (e.g., greenness) integrates the effects of numerous environmental factors, these indices can be correlated with different hydrological variables, such as AET (Seevers and Ottmann 1994; Nicholson et al. 1996; Szilagyi et al. 1998; Szilagyi and Parlange 1999; Szilagyi 2000).

Different authors drew differing conclusions about the applicability of NDVI to estimate AET. For example, Seevers and Ottmann (1994) and Nicholson et al. (1996) pointed out that the NDVI-AET relationship is strong mainly in humid environments. Szilagyi et al. (1998) emphasized that the correlation may not necessarily deteriorate with the growing aridity of the environment, provided that a time-lag is considered between the two variables. In light of this latter finding, it may be worthwhile to investigate how the relationship behaves within a large geographic area, such as the conterminous United States, with changing environmental conditions, most importantly climate, and vegetation cover. The potential existence of a clear spatial patter in the NDVI-AET relationship may help define biophysical conditions prerequisite for the successful application of vegetation indices in watershed/water-balance modeling.

Methodology

Bouchet's (1963) Complementary hypothesis relates AET to potential (E_p) and wet-surface evaporation (E_w) via

$$\mathrm{AET}=2E_w-E_P \tag{1}$$

The first term on the right-hand side of Eq. (1) can be calculated by a Priestley-Taylor (Priestley-Taylor 1972) approach, while the second term can be calculated by a Penman-like (1948) combination equation (Katul and Parlange 1992; Parlange and Katul

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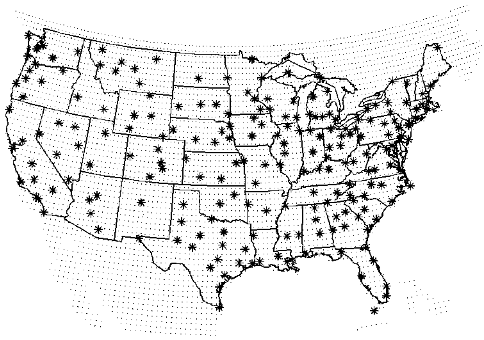

Fig. 1. Location of 210 SAMSON stations and spatial resolution of NDVI data

1992). Morton et al. (1985) published a FORTRAN program, called *WREVAP*, for the operational estimation of AET, using Eq. (1). *WREVAP* requires as inputs the following meteorological variables averaged over the calculation period (weeks to months): air temperature, humidity, and incident global radiation. The three variables for deriving AET have been obtained at 210 stations of the Solar and Meteorological Surface Observation Network (SAMSON) for the years 1961–1990 over the conterminous United States (Fig. 1).

Monthly, maximum-value-composited NDVI values at half-degree resolution for the whole globe can be downloaded from the University of New Hampshire EOS-WEBSTER site (http://eos-webster.sr.unh.edu/) for the 1982–1993 period. See Fig. 1 for the spatial resolution of the NDVI data over the study area. The selection of the maximum value for each pixel within the composite period is intended to minimize the effect of clouds in the image.

Concurrent and one-month-shifted mean monthly AET values for the growing seasons (April–October) of 1982–1990 (the temporal overlap of the two datasets) were paired with the monthly NDVI values of the pixel closest to the respective SAMSON station. Restricting the analysis to the growing season minimizes the unwanted effect of possible snow cover on the ground and minimizes NDVI errors due to cloudiness resulting from regional frontal systems typical of winter conditions in the higher latitudes. AET is dominated by vegetation transpiration in the growing season for well-vegetated surfaces (Maidment 1993, p. 426). NDVI can only reflect this transpirational part of AET due to its construction (Szilagyi 2000), as is explained below. This property of the NDVI, however, does not automatically diminish its potential usefulness for annual AET estimation (often required in regional water-balance calculations), since the highest monthly AET values, giving the bulk of the annual value, occur in the growing season.

Before presenting the results, an important feature of the *WREVAP* model should be mentioned. According to Morton (1983), the AET estimates can be seriously corrupted near sudden changes in environmental conditions, such as coastlines, where the advection of heat and water vapor in the lower atmosphere may be a significant part of the energy and mass balances of the area, not accounted for in the model.

First, the monthly NDVI and concurrent monthly mean AET values were correlated for the 210 SAMSON stations [Fig. 2(a)], followed by a 1 month shift (i.e., $NDVI_{i+1}$ versus AET_i, where i is an arbitrary month within the growing season) between the two variables [Fig. 2(b)], as was suggested by Di et al. (1994). In the second case, the correlations improved noticeably (marked by wider filled circles) for almost all stations. Note the prevalent positive correlations between the monthly values, except in the southeast region. A moderate/high positive correlation is not surprising, since both variables follow a well-defined annual cycle, as do most geophysical variables, especially at midlatitudes, due to the marked change of seasons. Consequently, even a high correlation value may mean very low explanatory power between the variables.

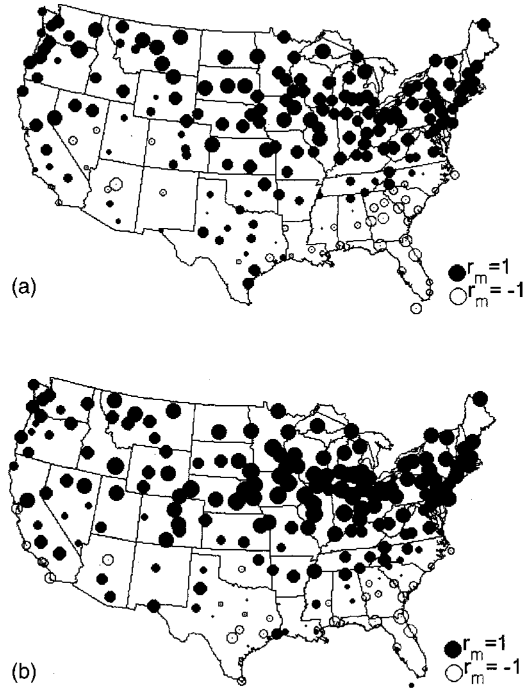

Fig. 2. (a) Correlation coefficients (r_m) for monthly concurrent NDVI and AET values (filled circles designates positive, empty circle denotes a negative correlation with area of circle proportional to magnitude of r_m; (b) r_m for 1 month-shifted monthly values

One might argue that a lag between AET and NDVI exists because, when precipitation is high in a month, the NDVI will be high the following month, and conversely, since it takes some time for the vegetation to use it from soil moisture storage and since soil moisture supports vegetation for some time during dry spells before plants start to wilt. Szilagyi et al. (1998) showed that NDVI is more strongly related to lagged AET than lagged precipitation. Also, NDVI had higher correlation with AET than with precipitation for water-cycle averaged values (Szilagyi 2000). This is so because plant photosynthesis and transpiration are inseparable processes (Wiegand and Richardson 1990). An increase/decrease in photosynthetic activity and thus in AET results in an increase/decrease of green biomass within a certain time lag. NDVI responds to any change in green biomass, because NDVI is a measure of the total amount of photosynthetically active tissue (Wiegand and Richardson 1990) over a given area.

Results and Discussion

The real explanatory power of the NDVI-AET relationship can be checked by comparing the growing-cycle mean value of NDVI with the growing-cycle mean value of AET (Fig. 3). Averaging the NDVI and AET values over the growing season automatically removes the seasonal trends in the two variables, thus, any spuri-

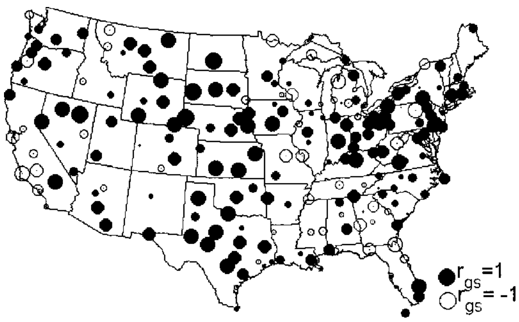

Fig. 3. Correlation coefficients ($r_{\rm gs}$) for mean growing-season NDVI and AET values

Fig. 5. Relative degree of vegetation-cover heterogeneity around SAMSON sites (the smaller the circle, the more homogeneous the vegetation cover is assumed in surrounding area)

ous correlations between the variables are also eliminated. Note that the largest continuous region of the highest positive correlations overlaps almost perfectly with the prairie region of the conterminous United States. The second largest concentration of positive values is in the midwestern states of Indiana and Ohio. Note also the apparent concentration of no or even negative correlations along the coast and Central Valley region of California and in the most humid, southeastern states, as well as in the Great Lakes region. This is most probably so because in these areas the Morton approach may not work properly due to the significant energy and moisture transport from adjacent extensive water bodies (the oceans or the Great Lakes), as was mentioned earlier.

Fig. 4 shows a histogram of the correlation coefficients ($r_{\rm gs}$) for growing-season mean NDVI and AET in comparison with normally distributed independent (i.e., 210×9 value pairs) random values. It can be seen that there are 36 stations having a correlation coefficient larger than 0.6, as compared with 5 if the growing-season-averaged NDVI and AET values were truly unrelated.

Bouchet's Complementary hypothesis [Eq. (1)] assumes homogeneous surface conditions (Szilagyi 2001). An arbitrary measure of vegetation heterogeneity (*vh*) is introduced as

$$vh=\frac{\sigma\times v}{d} \tag{2}$$

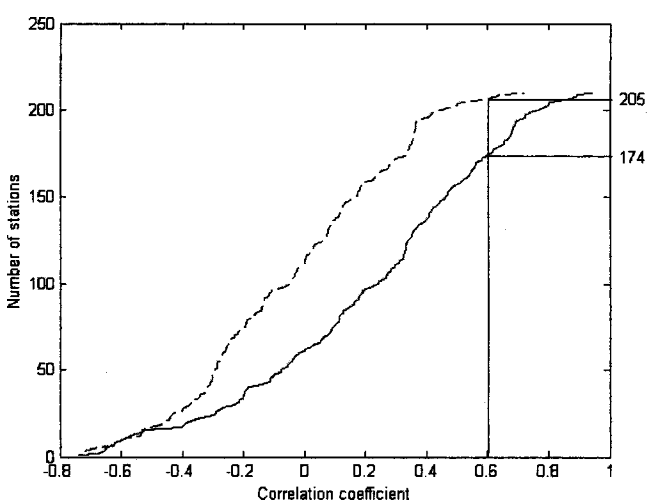

Fig. 4. Cumulative histograms of $r_{\rm gs}$ (solid line) and of correlation coefficients of randomly generated pairs of normally distributed 210×9 values

where σ=standard deviation of the vegetation-class codes; v=number of distinct vegetation classes; and d=range of the vegetation-class codes (i.e., maximum code value minus minimum code value). The vegetation codes are from the United States Geological Survey's (USGS) Land Use/Land Cover 1 km resolution digital raster map (http://edcdaac.usgs.gov/glcc/nadoc2_0.html) representing vegetation cover in 1992–1993. vh was calculated in a 30 km radius around the SAMSON station locations. vh is similar to v, except that vh attempts to take into account the distribution of the number of observations among the classes, unlike v. Fig. 5 shows the vegetation-cover heterogeneity around the SAMSON sites. The smaller the circle is, the more homogeneous the area. Note that the most homogeneous region (the area of the smallest circles) overlaps with much of the prairie region of the conterminous United States and so with much of the largest continuous region of high correlations of the detrended variables in Fig. 3 (the area of the largest full circles). In this region, the one-month-shifted mean monthly correlation (and its standard deviation) between NDVI and AET is 0.66 ($\pm$0.21, a sample size of 32), while the same for the growing-season means is 0.55 ($\pm$0.22). The corresponding root-mean-square errors (RMSE) and their deviations are 26.75$\pm$12.62 and 6.24$\pm$1.67 mm month^{-1}, respectively.

To demonstrate how NDVI tracks AET in this region, standardized NDVI and 1 month-shifted AET time series over consecutive growing seasons are shown in Figs. 6(a–c) for three stations with high monthly correlation (r_m) values. In this region, by having knowledge of the long-term mean annual AET (often estimated as the difference between the long-term precipitation and runoff for watersheds) and the long-term standard deviation of the monthly AET values, one can obtain time series of AET from similar time series of NDVI. This is demonstrated in Fig. 7, where the monthly growing season AET values were estimated with the help of the standardized growing season NDVI values [see Fig. 6(b)] in the area around Sioux City, South Dakota. The annual AET is estimated as 600 mm by using a runoff ratio of about 0.1 (Milly 1994) and a mean annual precipitation of 660 mm (USGS 1970; CDS 1998). Assuming that the wintertime monthly AET values are practically zero [in the winter the average daily mean temperature is around or below 0°C in the area (USGS 1970)], δ_E, the annual relative amplitude of monthly AET (see Appendix), can be taken as unity. The standard deviation of the growing season monthly AET values, $\sigma_{\rm gs}$, thus becomes (see Appendix) 35.35 mm month^{-1}. The monthly AET values were estimated as

$$\mathrm{AET_{est}}=\mathrm{NDVI}^*\sigma_{\rm gs}+\overline{E}_{\rm gs} \tag{3}$$

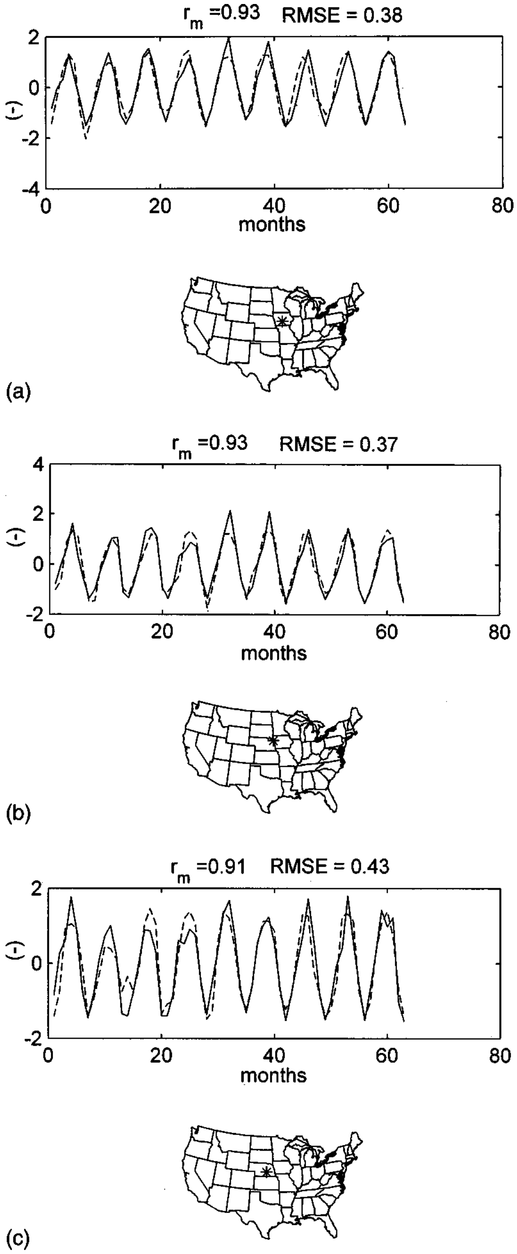

Fig. 6. Standardized growing-season NDVI (solids lines) and 1 month-shifted AET time series (1982–1990) for three locations with high r_m values within prairie region

where the star denotes the standardized NDVI values; and $\overline{E}_{gs} = 76.65$ mm month^{-1} is the mean AET value for the growing season. The calculation of $\overline{E}_{gs}$ is also described in the Appendix.

In summary, the following can be stated: (1) monthly growing season and growing-season mean NDVI correlate moderately well with 1 month-lagged monthly and growing season mean areal evapotranspiration calculated by the Morton approach over areas (i.e., the prairie region of the United States) where land cover is most homogeneous; and (2) the correlation deteriorates in areas (coastlines, southeast United States, areas with contrasting land cover) where the assumptions of the Morton approach may be violated.

In the writer's view, vegetation indices have not yet been fully exploited for AET estimation purposes. This is probably so because AET cannot be measured directly. NDVI may hold the potential of complementing the few AET estimation techniques, of which Morton's approach (and Bouchet's Complementary relationship in general) is probably the most rigorously tested (Morton 1983). NDVI has the unique property of being spatially distributed, thus fitting the need for spatially distributed hydrologic models.

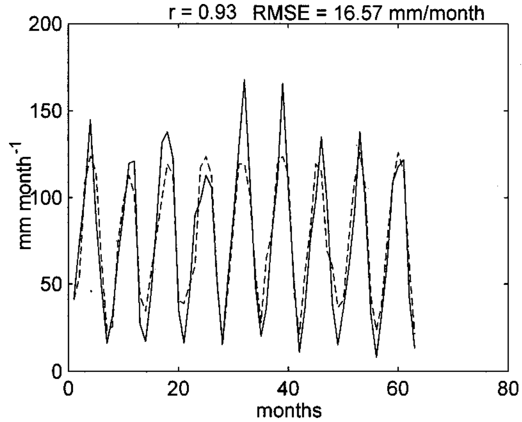

Fig. 7. *WREVAP*-calculated growing-season values (1982–1990) of monthly AET (solid line) and their NDVI-based estimates, for area around Sioux City, North Dakota

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Appendix

The seasonality of the monthly AET values can be parameterized (Milly 1994) as

$$E_t = \overline{E}[1 + \delta_E \sin(\omega t)] \tag{4}$$

where E_t estimates AET in month t; $\overline{E}$=annual mean value of AET; δ_E=mean annual relative amplitude of AET (i.e., $\{\text{mean}[\max(E_t)] - \overline{E})\}/\overline{E}$); ω=circular frequency (1 year=$2\pi/\omega$); and t=1 for May. $\delta_E \approx 1$ for the area around Sioux City, North Dakota. To relate δ_E to the standard deviation of the E_t values $\langle\sigma_E\rangle$, one can insert Eq. (4) into the equation estimating $\langle\sigma_E\rangle$:

$$\langle\sigma_E\rangle = \left[\frac{1}{N-1}\sum_{t=1}^{N}(E_t - \overline{E})^2\right]^{1/2} \tag{5}$$

where N=total number of months for calculations. For large N, one obtains

$$\langle\sigma_E\rangle \approx \frac{\sqrt{2}}{2}\overline{E}\delta_E \tag{6}$$

In the estimation of the monthly AET values in Eq. (3), the value of σ_{gs} was substituted by the value of $\langle\sigma_E\rangle$. This can be justified by the observation that Eq. (6) certainly underestimates the standard deviation of actual AET, because the AET values contain a random but unknown component as well, in addition to the seasonal changes. The standard deviation, σ_{gs}, of the growing season actual AET is most probably smaller than its annual value,

σ_E; thus, by default, one may estimate the former by $\langle\sigma_E\rangle$, which is already a reduced estimate of σ_E.

The mean growing season AET, $\overline{E}_{gs}$, was calculated as

$$\overline{E}_{gs}=\frac{1}{63}\sum_{year=1}^{9}\left(E_{t=0}+\sum_{t=1}^{6}E_t\right) \tag{7}$$

where $t=0$ in April, unity in May, and so on, starting over in each year, and the total number of years in the period 1982–1990 is nine.

Notation

The following symbols are used in this paper:

$\underline{d}$ = range of vegetation class codes;
$\overline{E}$ = mean annual AET ($L\cdot T^{-1}$);
$\overline{E}_{gs}$ = mean growing-season AET ($L\cdot T^{-1}$);
E_p = potential evaporation ($L\cdot T^{-1}$);
E_t = parameterized estimate of AET in month t ($L\cdot T^{-1}$);
E_w = wet surface evaporation ($L\cdot T^{-1}$);
N = total number of months with growing season NDVI and AET values;
r_m, r_{gs} = correlation coefficients for monthly and growing-season mean variables;
t = time index for months;
v = number of distinct vegetation classes;
vh = relative measure of vegetation heterogeneity;
δ_E = annual relative amplitude of monthly AET values;
σ = standard deviation of vegetation class codes;
σ_E = standard deviation of monthly AET values ($L\cdot T^{-1}$)
$\langle\sigma_E\rangle$ = standard deviation of E_t ($L\cdot T^{-1}$); and
σ_{gs} = standard deviation of monthly, growing-season AET values ($L\cdot T^{-1}$).

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