Evapotranspiration and Water Consumption

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**PREFACE**

Terrestrial evapotranspiration (ET) is the main process of water circulation in the hydrological cycle. Water is transformed into vapor and transported from the land surface to the atmosphere. This water exchange usually involves a phase change of water from liquid to gas, which absorbs energy and cools the land surface. ET is an essential variable for energy and water balances on the Earth’s surface. The process of evaporation (E) from soil and transpiration (T) from vegetation occurs simultaneously for vegetated areas. In terrestrial water balance, ET is the second largest term after precipitation. The three foremost factors controlling ET are availability of water, amount of available radiant energy, and transport mechanism to remove the water vapor from any surface. The previously mentioned elements in turn depend on other variables such as air temperature, wind speed, land surface temperature, vegetation cover, vapor pressure, and soil moisture that vary for different geographical regions, seasonality, and diurnal cycle. In this chapter, an overview of remote sensing principles and sensors on surface energy flux estimation is presented, with additional reviews of energy retrieval models and case studies on a regional and field scale.

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**8.1 Introduction**

Evapotranspiration (ET) is an important variable for energy and water balances on the Earth’s surface. The energy fluxes influence the main process of water circulation in the hydrological cycle, as liquid is transformed into vapor and transported from the land surface to the atmosphere. Therefore, estimation of land surface energy fluxes is essential for many environmental monitoring applications including water resources management, agricultural efficiency, global vegetation analysis, climate dynamics, and meteorological and ecological applications. Understanding the distribution of ET is essential for many environmental monitoring applications including water resources management, agricultural efficiency, global vegetation analysis, climate dynamics, and ecological applications. The evaporation plus transpiration from a vegetated surface with unlimited water supply is known as potential evaporation (PE) or potential evapotranspiration (PET), and it constitutes the maximum possible rate due to the prevailing meteorological conditions. Actual evaporation is the amount of water that is evaporated during a normal day that averages that if, for instance, the soil becomes dry, the actual evaporation is the amount of water that has been evaporated and not the amount of water that could have been evaporated if the soil had had an infinite amount of water to vaporize.

Over the course of the last three decades, hydrologists, environmental engineers, and scientists trusted on meteorological station-based observations as a primary method for estimating ET. Sometimes these methodologies are insufficient to observe the spatially distributed ET over large regions that only focuses on PET instead of actual ET (AET). Their scales are substantially different from those of other
methods, which can estimate ET at higher temporal resolution, for example, 30 min, at finer spatial resolution. However, satellite data with high spatial and sometimes temporal resolution with large areal coverage provide added advantage for ET estimation. Remote sensing–based ET retrieval has been a subject of many studies [3–8,40,42,46].

As demand for water increases, water managers need to know how much water is actually consumed in agriculture, urban, and natural environments. Increased demand for scarce water supplies has shifted water management strategy from increasing water supply to innovatively managing water use at sustainable levels. However, in order to more effectively allocate limited water, water resources managers must understand water consumption patterns over large geographical areas. There is a particular need to understand and measure the ET flux where irrigated agriculture is the primary consumptive use in arid and semiarid regions. In a broader sense, measurement of ET would be useful in all watersheds where streamflow must satisfy demand by current and future sustainable use. Because of the variability of region and seasons, water managers who are responsible for planning and adjudicating the distribution of water resources need to have a thorough understanding of the ET process and knowledge about the spatial and temporal rates of ET.

This chapter is focused on how numerical methods and remote sensing data are utilized to estimate the Earth’s energy fluxes within the perspective of water resource monitoring. Section 8.1 outlined the fundamental theories of ET and their assumptions. Section 8.2 examines the leading remote sensing-based ET estimation methods. Section 8.3 focuses on how the basic theory and the understanding of surface energy balance (SEB) can be used to relate satellite-derived land surface variables to ET retrievals. Agricultural applications of ET products are discussed in Section 8.4. Afterward, the commonly used energy balance estimation models and satellite sensors are briefly reviewed, and two case studies are presented on AET retrieval algorithms that integrate satellite remote sensing data. The last section concludes and highlights ongoing developments and topics that require additional research.

8.2 ET Estimation Paradigms

Over the past two decade, accuracy of ET estimation methods has been improved that are attributable to the new and increasingly sophisticated techniques. In general, there are well-established ET retrieval techniques, for example, hydrological methods, direct measurement, micrometeorological methods, and empirical or combination of the previously listed methods [44]. Some of these methods are very accurate but can only offer point measurements of ET, which are insufficient for large-scale assessment. Hydrologic models can estimate ET estimates but demand immense ground-based observations, which is often inaccessible for much of ecosystems and watersheds around the world. Recently, satellite remote sensing-based ET retrieval has emerged as a practical method with the accessibility of shear amount of remote sensing estimates and development of several modeling techniques. The following sections discuss different methods used for ET retrievals.

8.2.1 Meteorological Network–Based ET Estimation

8.2.1.1 Penman–Monteith Equation

The Penman and Penman–Monteith equations were developed to use surface radiation, temperature, and humidity data to estimate ET. The Penman equation describes evaporation from an open water surface or from short vegetation [33]. The reference ET approach is established on the well-known Penman–Monteith reference ET Equation 8.1 adopted by the American Society of Civil Engineers (ASCE). More details on the estimation are outlined in [1,2]. The ASCE standardized reference ET equation is computed as

\[ \text{ET}_{\text{ref}} = \frac{0.408 \left( \Delta + \frac{g_d}{g_v} \right) \frac{h}{C_p} \left( T_v - T_a \right)}{1 + \frac{g_d}{g_v} \left( \frac{C_p}{C_v} - 1 \right) \left( \frac{h}{T_v} \right)} \]

where

- \( \Delta \) is the difference between saturation vapor pressure and actual vapor pressure
- \( g_d \) and \( g_v \) are the conductance of heat and vapor mass, respectively
- \( h \) is the soil heat flux
- \( C_p \) and \( C_v \) are the specific heat capacity of air and water, respectively
- \( T_v \) and \( T_a \) are the virtual and actual temperatures, respectively.
where

\[ ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(C_n / (T + 273))u_2(e_s - e_a)}{\Delta + \gamma(C_d u_2)} \] (8.1)

\[ \Delta = \text{the delta, the slope of the saturation vapor pressure–temperature curve (kPa °C }^{-1}) \]
\[ \gamma = \text{the psychrometric constant (kPa °C }^{-1}) \]
\[ C_n = \text{the numerator constant that fluctuates with reference type and calculation time step} \]
\[ C_d = \text{the denominator constant that changes with reference type and calculation time step} \]

8.2.1.2 Reference ET (\( ET_0 \)) and Crop Coefficients (\( K_c \)) to Calculate Actual ET

Meteorological network-based reference ET combined with crop coefficient provides AET at station scale. The crop coefficient approach to estimate ET was developed for agricultural crops but has been extended to natural ecosystems and has been adapted to remote sensing methods for ET retrieval. In agricultural applications, actual crop ET (\( ET_c \)) is related to \( ET_0 \) through an empirical crop coefficient (\( K_c \)) that must be determined experimentally (Allen et al., 1998). The crop water use is directly related to ET, and this can be determined by multiplying the reference \( ET_0 \) by a crop coefficient (\( K_c \)) as later shown in Equation 8.2:

\[ ET_c = ET_0 \times K_c \] (8.2)

where

\[ ET_c = \text{crop ET or crop water use (mm)} \]
\[ ET_0 = \text{calculated reference ET for grass (mm)} \]
\[ K_c = \text{crop coefficient} \]

Crop coefficients (\( K_c \)) are used with \( ET_0 \) to estimate specific crop ET rates. The crop coefficient is a dimensionless number that is multiplied by the \( ET_0 \) value to arrive at a crop ET (\( ET_c \)) estimate. The resulting \( ET_c \) can be used to help an irrigation manager schedule when an irrigation should occur and how much water should be put back into the soil.

The crop coefficient regulates the calculated reference \( ET_0 \) to obtain the crop ET \( ET_c \). Different crops will have a different crop coefficient values resulting in varying water demand. Crop coefficients vary by crop, stage of growth of the crop, and by some agricultural practices. For example, if \( ET_0 = 0.25 \text{ in./day} \) (for June 8, 2012) and \( K_c = 1.20 \) (for apple in June), then, using Equation 8.2, \( ET_c \) will be 0.30 in./day.

8.2.1.3 Pan Evaporation

Pan evaporation (\( E_{pan} \)) is one of the first methods that has been used for several centuries to show a rough estimate of PET. In simple terms, (\( E_{pan} \)) is the volume of water evaporated from the pan certain time, usually in an entire day. Several types of evaporation pans are used for evaporation measurements at meteorological stations, but the most commonly used is the U.S. Weather Bureau Class A pan evaporimeter.

The step-by-step process for pan evaporation measurements described by [10] is as follows: (1) The pan is set up in the field; (2) a known quantity of water is used to fill the pan and the water depth is
measured; (3) the water is allowed to evaporate for a 24 h time period and again water depth is measured (simultaneously, the precipitation during that time period is measured); (4) after 24 h, another water depth measurement is taken; (5) the amount of evaporation per time unit, which is the difference between the two measured water depths, plus precipitation amount during the 24 h time period is calculated using Equation 8.3 shown in the following:

\[ E_{\text{pan}} = P + (h_1 - h_2) \]  

where

- \( E_{\text{pan}} \) denotes daily pan evaporation (mm/day)
- \( P \) is the daily precipitation that is simultaneously measured at the same location and with the same unit as pan evaporation
- \( h_1 \) and \( h_2 \) are water surface heights measured in the evaporation pans for the previous and present measurements, respectively

### 8.2.2 Water Balance–Based ET Calculation

At a watershed scale, runoff is roughly the balance between precipitation received from the atmosphere and ET (green water) lost to the atmosphere. ET consists of evaporation from soil, evaporation from intercepted precipitation by plants, and transpiration via plant tissues.

If we consider a watershed the only water input from precipitation (\( P \)), then the only paths that water can take are into the soil as groundwater recharge/flow (\( D \)), surface runoff through streamflow (\( Q \)), and back to the atmosphere as AET. The precipitation is therefore “balanced” by the sum of these respective processes. A water balance budget is depicted by the typical water balance Equation 8.4 as

\[ P = Q + S + \text{AET} \]  

We may be able to measure \( P \) as precipitation (from rain gauges), \( Q \) as the river discharge (from stream measurements), and \( S \) as the change of terrestrial water storage (from monitoring wells), but we may not be able to measure AET. Because of the large spatial scale on which the water balance equation is often applied, it may be difficult to measure all terms accurately and to “close” the equation, that is, the left-hand side of the equation should balance out the right-hand side of the equation.

### 8.2.3 Energy Balance and Radiation Balance–Based ET Retrieval

The ET process requires source of heat energy to convert water from the liquid to the vapor state. This is ultimately supplied by net radiation (\( R_n \)), the amount of incident solar radiation (\( R_s \)) that is absorbed at the Earth’s surface; a simplified equation for the SEB is

\[ \lambda ET = R_n - H - G \]  

where the available net radiant energy \( R_n \) (W m\(^{-2}\)) is combined between the soil heat flux \( G \) and the atmospheric convective fluxes (sensible heat flux \( H \)) and latent heat flux \( LE \), which is readily converted to ET. The \( R_n \) and other variables (\( H \) and \( G \)) of Equation 8.5 can be solved using remotely sensed data of surface characteristics such as vegetation cover, surface temperature albedo, and leaf area index. The basic concept is to calculate the energy coming from the sun less any radiation that gets reflected (or emitted as thermal infrared [TIR] radiation) back to the atmosphere. This net radiation (\( R_n \)) is the energy available for ET, some of that \( R_n \) can be felt as the sensible heat flux (\( H \)), some of it is stored in the soil and other objects such as woody material, and the rest of the energy is absorbed by water that can be
converted to water vapor for ET. A certain amount of energy per mass of water is required to vaporize water, and this is called the latent heat of vaporization.

### 8.3 Remote Sensing–Based Evapotranspiration Models

Notable advancement has been made in AET estimation by assimilating satellite remote sensing data into existing models [27,35]. In comparison to meteorological network-based in situ observations, satellite ET estimation has the benefit of better areal footprint, moderate resolution, and reliable quality [31,32]. Data availability, cost-effectiveness, and easy manipulation of these products are the added advantages. Furthermore, over the last two decades, several ET estimation prototypes have been developed that utilize these remote sensing and supplementary ground-based data products [13,22,41]. These developments in remote sensing ET estimation have been applied in North America, Asia, Africa, and many other countries around the world [36]. Remote sensing ET algorithms mainly solve the SEB of the land surface for latent heat flux ($\lambda ET$) at the time of satellite overpass. However, further research work is needed on high-resolution satellite remote sensing–based ET retrievals for decision-making and operational water management in real time.

In this chapter, the main satellite remote sensing ET estimation algorithms, that is, the Surface Energy Balance Algorithm for Land (SEBAL) [7,8] and later Mapping EvapoTranspiration with high Resolution and Internalized Calibration (METRIC) [3,4], are briefly introduced.

#### 8.3.1 Surface Energy Balance Algorithm for Land

Emerging technologies based on satellite remote sensing are developed and refined for several operational ET algorithms that are now routinely used in hydrological studies at different spatiotemporal resolutions ranging from field to basin and global scales. These applications in ET calculations have advanced the understanding in agricultural water use and in some cases groundwater resources management at different scales and diverse ecosystems. The central and technical basis of SEBAL methods is to calculate the $\lambda ET$ as the residual of the energy balance equation. The process is based on a complete energy balance for each satellite-retrieved pixel, where ET is predicted from the residual amount of energy remaining from the classical energy balance. SEBAL computes that the $R_n$ is net radiation flux, $G$ is soil heat flux, and $H$ is sensible heat flux to the atmosphere as explained in the following.

##### 8.3.1.1 Net Radiation ($R_n$)

The most common method for net radiation ($R_n$) calculation is by subtracting all outgoing radiant fluxes from all incoming radiant fluxes and includes solar and thermal radiation:

$$R_n = R_S \downarrow - \alpha R_S \downarrow + R_L \downarrow - R_L \uparrow - (1 - \varepsilon_o)R_L \downarrow$$

(8.6)

where

- $R_S \downarrow$ is incoming short-wave radiation (W m$^{-2}$)
- $\alpha$ is surface albedo (dimensionless)
- $R_L \downarrow$ is incoming long-wave radiation (W m$^{-2}$)
- $R_L \uparrow$ is outgoing long-wave radiation (W m$^{-2}$)
- $\varepsilon_o$ is broadband surface thermal emissivity (dimensionless)

The $(1 - \varepsilon_o)R_L \downarrow$ term represents the fraction of incoming long-wave radiation reflected from the surface.

##### 8.3.1.2 Soil Heat Flux ($G$)

Soil heat flux ($G$) is the rate of heat storage in the soil and vegetation due to conduction. General applications compute $G$ as a ratio $G/R_n$ using an empirical equation by Bastiaanssen (2000) representing values near midday:
where

\( T\bar{s} \) is surface temperature (K)

\( \alpha \) is surface albedo

The Normalized Difference Vegetation Index (NDVI) is used to predict surface roughness and emissivity.

### 8.3.1.3 Sensible Heat Flux \((H)\)

Sensible heat flux \((H)\) is defined by the bulk aerodynamic resistance equation, which uses aerodynamic temperature \( (T_{aero}) \) and aerodynamic resistance to heat transfer \((r_{ah})\):

\[
H = \frac{\rho_{air} C_{pa} (T_{aero} - T_{at})}{r_{ah}}
\]

where

\( \rho_{air} \) is air density \((\text{kg m}^{-3})\)

\( C_{pa} \) is specific heat of dry air \((1004 \text{ J kg}^{-1} \text{ K}^{-1})\)

\( T_{at} \) is mean air temperature (K)

\( T_{aero} \) is mean aerodynamic temperature (K)

which is defined for a uniform surface as the temperature at the height of the zero plane displacement \((d, m)\). The earlier Equations 8.5 through 8.7 establish the basic interpretation of SEB.

### 8.3.2 Mapping Evapotranspiration at High Resolution with Internalized Calibration

METRIC \([4]\) is an extension of SEBAL, through integration with reference ET, which is computed using ground-based weather data as recorded by weather networks. As the name implies, METRIC approach adapts an internalized calibration approach to identify hot and cold pixels. These two varying conditions from within a satellite image are selected to fix boundary conditions for the energy balance and to internally calibrate the sensible heat computation. This internal calibration somewhat eliminates the need for exhaustive atmospheric correction of the data products, that is, temperature or albedo. The satellite image is simplified as a combination of vegetated areas and soil surface. This landscape is differentiated by the fractional canopy coverage \((f_c)\), with the value ranging between 0 and 1, and is related to Moderate-Resolution Imaging Spectroradiometer (MODIS) NDVI:

\[
f_c = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}
\]

The SEB computation is then based on the determination of the relative instantaneous ET fraction \((ET_f)\) given by

\[
ET_f = \frac{\lambda E}{H + \lambda E} = \frac{(H_{dry} - H) / (H_{dry} - H_{wet}) \lambda E_{wet}}{R_n - G}
\]

A simplified approach to estimate the \(ET_f\) is to assume, according to \([4, 26, 37]\), that dry-hot pixels exhibit low ET and wet-cold pixels show highest ET over the study domain, and the temperature of cold and hot pixels is used to estimate relative elements of ET on a pixel basis. Therefore, the
$ET_f$ can also be estimated for each pixel by using Equation 8.10 to each of the MODIS land surface temperature (LST) image:

$$ET_f = \frac{T_{hot} - T_{i,j}}{T_{hot} - T_{cold}}$$  \hspace{1cm} (8.11)

where

- $T_{hot}$ is the mean value of hot pixels
- $T_{cold}$ is the mean value of the cold pixels designated for a given scene
- $T_{i,j}$ is the LST value for any MODIS pixel in the scene

Rationally, the $ET_f$ is used in combination with reference $ET$ ($ET_r$) described in Equation 8.1 to calculate the per pixel instantaneous AET ($ET_a$) estimates in a given scene according to METRIC:

$$ET_a = ET_f \cdot ET_r$$  \hspace{1cm} (8.12)

A fundamental hypothesis of this approach is that the $ET_f$ value is nearly constant, which is revealed on other studies [3,11,39]. This permits instantaneous retrieval of $ET_f$ at MODIS overpass times and then to be inferred to daily mean ET. The daily ET can be calculated as

$$ET_{daily} = \sum_{i=1}^{day} (ET_f \times ET_r)$$  \hspace{1cm} (8.13)

where

- $ET_{daily}$ is the daily AET (mm day$^{-1}$)
- $i$ is temporal resolution of calculated reference ET

The next section describes several ET estimation techniques and studies water consumption variability by different authors at different scales, that is, local [28], regional [26], and global scale [29,31,32].

### 8.4 Evapotranspiration and Water Consumption Variability

#### 8.4.1 Climate Variability and ET Estimation

The impact of the human activities on the terrestrial water cycle by unsustainable direct consumption for domestics, industrial and major portion for agricultural use is putting the already scarce freshwater resources at risk of depletion [24,25]. Furthermore, climate change projections show an impact on the global water cycle with higher frequency of extreme events and intensified ET globally [20]. This will ultimately influence the availability of the scarce water resources. Thus, consistent ET estimates are critical for the development of techniques that can be deployed for sustainable water resource use at the required spatiotemporal resolutions, especially in irrigation water management [9,18,19]. Conventionally, in order to estimate the spatial distribution of ET, meteorological observations are needed through a network of instruments that provided data at that particular location. These data are then interpolated to study ET at a regional scale.

#### 8.4.2 Evapotranspiration Trends

To date, long-term changes in ET have been evaluated by studying reference evaporation using measurements of pan evaporation. One of earlier research work published showed that, on average, pan evaporation had decreased over North America, Europe, and Asia from the beginning of 1950 until the 1990s.
[19,34]. Recent studies have reiterated this to be an overall trend throughout the northern latitudes. For instance, over the last half century, decreases in pan evaporation have been reported in India [12], China [43], and parts of Europe [30], although some mixed trends have also been reported, for example, East Asia [47], and similar anomaly in the Middle East [14,16]. Another comprehensive study on the decrease of pan evaporation over the conterminous United States for the past half century is presented by [19]. One of the critical points in most of these studies is that mean observations are used over a wide area with some sites showing decreasing trend, while others with increasing anomalies.

### 8.4.3 Water Consumption Variability at Different Spatial and Temporal Scales

#### 8.4.3.1 Local Case Studies

A meteorological gauged river basin in central Oklahoma, near Lovell, OK, with an area of approximately 1033.59 km² was studied. The catchment includes very diverse land use/land cover (LULC) from agriculture (Garfield County) to urban (Oklahoma County). The annual precipitation is around 870 (mm), and average high and low temperatures are 21°C and 8°C, respectively. The study watershed is in a semiarid region where the agriculture activities were mainly sustained by irrigation. This study evaluates the possible closure of the heat balance equation using unique environmental monitoring network and to estimate $ET_a$ and determine the variation with regard to varying types of LULC in urban settings.

The remotely sensed $ET_a$ estimates were compared with calculated $ET_a$ based on water balance over this watershed. The study sites and the LULC of the area are shown in Figure 8.1. In order to study the

![Figure 8.1](image_url)  
**FIGURE 8.1** (a) Spatial variations of the $ET_a$ (mm) over the study area in 2005. (b) Upper left side is Landsat false color image. Part (b) located at the right side shows local spatial variations of the $ET_a$ (mm) at agricultural areas, and part (b) located at the lower right side shows local spatial variations of the $ET_a$ (mm) at urban areas near a water body on July 31, 2005. Note: AET stands for the actual ET. Darker shade shows high ET values. (Cited from Liu, W. et al., *J. Appl. Remote Sens.*, 4(041873), 041873, 2010.)
ET$_a$ for distinctive LULC types, seven types of LULC were chosen in the watershed that include agriculture lands, water bodies, forests, grassland, wetlands, urban areas, and shrublands.

This study presents the retrieval of remotely sensed ET$_a$ by SEB approach and examines the spatio-temporal variations of ET$_a$ in terms of four types of LULC in the urban region of Oklahoma. Landsat 5 data and Oklahoma Mesonet (http://www.mesonet.org) data were used for AET estimation. Statistics were extracted by overlaying the LULC map of the whole study area. Figure 8.1b shows that the ET$_a$ values for irrigated croplands are high during crop growing season, but the yearly ET$_a$ values for agriculture are not necessarily higher than those for grass- and shrublands. This can be attributed mainly to the low ET values for the croplands during nongrowing seasons in comparison to the other two vegetated lands. The top three values of the ET$_a$ associated with designated types of LULC include water bodies, wetlands, and forests, and all ET$_a$ values are over 800 mm per year (Table 8.1). Figure 8.2 shows that for the year 2005 ET$_a$ values in the agriculturally dominant Garfield County are generally higher than those in Oklahoma County except for water bodies and densely vegetated areas. The urbanized areas mostly have lower ET values because of the lower soil moisture accessibility. Thus, the energy transformation is mainly limited in the form of sensible heat exchange.

Using site-specific flux towers and a water budget model at the basin scale, ET estimates are evaluated. Figure 8.3 compares SEB-based ET estimate at the regional level, that is, for different types of LULC that significantly reflects different values in urban and rural regions. Overall, wetlands have the highest ET, wetlands and forests present a higher rate of ET than grass and agricultural lands, and the highly urbanized areas have the lowest ET. With seasonal water use computed for distinctive types of land cover, those estimates of ET$_a$ could help create decision-making tactics to improve water management. The estimates ET$_a$ reveal that the higher the ET, the lower the development levels in urban regions.

However, ET calculated through SEB potentially has systematic errors. The sources of these errors include the characteristic adjustment bias of Landsat LST data. With a single thermal band, obtaining the LST from Landsat data is very difficult and might cause systematic errors. Consequently, the LST derived from Landsat data might have bias due to varying emissivity of infrared radiation. In addition, the ground truth observations might also have some measurement errors. Nevertheless, the estimation of ET using a high-resolution satellite remote sensing technology in urban regions can be still deemed as promising. Such a method complements the usual procedures that exclusively rely on ground- and point-based ET measurements.

### 8.4.3.2 Regional ET Patterns

A simplified form of the SEB method is employed to retrieve AET while maintaining the major rules of METRIC and SEBAL method. The principal basis of SEB is employed to calculate ET as the residual of the energy balance. This technique computes the AET by integrating the MODIS daily products and Oklahoma Mesonet meteorological network, that is, MOD/METRIC (thereinafter M/M-ET) was developed for southern plains in the United States and evaluation over Oklahoma. The goal of this
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FIGURE 8.2 Spatial variations of the $ET_a$ (mm) in the study area, 2005. Note: Darker shade shows high ET value. (Cited from Liu, W. et al., J. Appl. Remote Sens., 4(041873), 041873, 2010.)

FIGURE 8.3 Temporal variability of ET by land use intensities in Oklahoma County during the 2005: (a) monthly and (b) annual ET. (Cited from Liu, W. et al., J. Appl. Remote Sens., 4(041873), 041873, 2010.)
study was to evaluate the possibility of applying the M/M-ET for a functioning AET retrieval method suitable for regional scales, for example, the scale of irrigation projects, rather than individual fields in near real time.

Assessment of the M/M-ET measurements is on a daily, 8 day, and regular basis at both field and watershed scales. Two distinctive field sources explained in the following texts are used to compare the assessed results: one with metrological towers for latent heat flux observation and the other with Mesonet sites for crop ET. The location of these sites is illustrated in Figure 8.4. The observations of latent heat flux from the two Atmospheric Radiation Measurements (ARM) (http://www.arm.gov)

**FIGURE 8.4** Seasonal AET based on M/M-ET with Mesonet site locations at Grant and Canadian Counties during 2004. (Cited from Khan, S.I. et al., *Int. J. Remote Sens.*, 31(14), 3799, 2010.)
AmeriFlux eddy covariance tower sites were used for the comparison. These sites are located at the ARM Southern Great Plain (SGP) extended facilities in Lamont and El Reno, Oklahoma. The two Mesonet sites at El Reno and Medford with crop ET data are also selected for the evaluation.

The estimated ET is also compared with the crop ET at the selected sites during wheat growing season for multiple years. Figures 8.5 and 8.6 show the daily time series and scatter plots for both Medford and El Reno sites for years 2005 and 2006, respectively. The estimated ET is in good agreement with the observed crop ET. There is an underestimation of −7% and slight overestimation with 3% at Medford site for 2005 and 2006, respectively. Similarly, the ET estimates from the model agreed strongly with the observations at the Medford site with correlation coefficient of 0.84 and 0.80 for 2005 and 2006, respectively. M/M-ET calculations at El Reno show slightly higher biases but overall in agreement with the measurements. The correlation coefficient values also indicate that the ET estimates correlate measurements at the El Reno site relatively well with values of 0.82 and 0.51 for 2005 and 2006, respectively. A detailed analysis of these results is provided in [26].

8.4.3.3 Global ET Variability

Global terrestrial ET retrieval at a fine spatial scale was never achieved before until the satellite-driven estimation of the terrestrial ET, using one of the satellite sensors the MODIS onboard the Aqua satellite
launched on May 4, 2002, with 36 spectral bands, 20 reflective solar bands, and 16 thermal emissive bands. MODIS provides exceptional data observing vegetation and surface energy [23], which is utilized to develop a remotely sensed ET model [31]. The moderated resolution global terrestrial ET algorithm is developed and refined by the Numerical Terradynamic Simulation Group (NTSG), a research laboratory at the University of Montana in Missoula. The derived data product is known as the “MOD16” that is defined as an “evaporation fraction (EF),” the energy budget equivalent of an index actual to PET, over the global land surface with 1 km resolution every 8 days [31] (Figure 8.7).

ET-relevant MODIS data related to ET retrieval are LST and emissivity (MOD11), surface reflectance products (MOD09), vegetation index (MOD13), and albedo (MOD43B3) obtained by assimilating the bihemispherical reflectance data modeled. All these listed NASA land products are quality-controlled data sets that account the atmospheric conditions in terms of cloud cover and aerosol content, algorithm choices, processing failure, and error estimates. These data sets were acquired from the Land Processes Distributed Active Archive Center (LP DAAC) at the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, with the standard Hierarchical Data Format (http://lpdaac.usgs.gov). For more information on MODIS, please refer to http://modis.gsfc.nasa.gov.

Another global reference ET product is generated by extracting the meteorological variables from the Global Data Assimilation System (GDAS) analysis fields. The GDAS data are produced at 6 h temporal resolution and coarse spatial resolution of 1° by the National Oceanic and Atmospheric Administration

![Figure 8.6](image-url) Comparisons of crop ET (wheat) and SEB-based MM-AET estimates at Mesonet El Reno site. Panels (a) and (b) show the 2005 time series and scatter plot and (c) and (d) are for 2006.
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(NOAA). The GDAS fields that are used as input to the reference ET calculation include air temperature, atmospheric pressure, wind speed, relative humidity, and solar radiation (incoming, outgoing, long wave, and short wave). Here, we provide the summary of the comparison between Mesonet $ET_0$ and GDAS $ET_0$ that was conducted primarily at daily time scale (Figure 8.8).

Figure 8.8 presents a statistical evaluation of daily ET estimates for years 2005 and 2006. The bias values in all groups are within the range of −7.12% to 7.19%. The lowest bias is 1.53%, observed at Mesonet station number five. The lowest absolute bias is 14.69%, observed in GDAS estimates. Correlation coefficient (CC) for all groups are above 0.9. The maximum CC obtained is about 0.94 in Mesonet station number six. The RMSEs from all stations are within 28.67% and Mesonet station six gave the best result among all sites (RMSE = 19.70%). As shown in Figure 8.8, GDAS $ET_0$ and Mesonet $ET_0$ have shown strong linear correlations among the 11 Mesonet stations for the years 2005 and 2006. However, the variations among the stations shown in Figure 8.8 can be attributed to different LULC types and microclimate difference within the SGP.

8.5 Applications of ET Estimates in Agriculture

Assimilating meteorological network measurements and satellite remote sensing estimates with best possible spatial and temporal resolution can overcome many of the limitations associated with low spatial coverage of field-scale ET estimation models. Consequent applications of ET estimates have begun the era of precise agricultural water use monitoring and management techniques at diverse scales and various ecosystems. The World Bank estimates that 70% of freshwater use is for agriculture. In arid and semiarid regions, ET is the major source of water removal from the land surface. Particularly in arid regions, approximately 90% of the annual rainfall can be evapotranspired, and therefore, ET determines the freshwater recharge and discharge from aquifers in these environments [21]. The United States irrigates over 50 million acres of agricultural land and 32 million acres of recreational landscapes. Therefore, estimation of spatially distributed ET from agricultural areas is critical as irrigation consumes the main
portion in water use [17,38]. In brief, AET estimation at various scales is vital to water monitoring and sustainable agricultural management.

### 8.5.1 Agricultural Water Use Efficiency

Conventionally, water management models are used for irrigation scheduling that are established on water allocations, and not on actual water consumed, in part because irrigation water use is complex to estimate from direct observations. As discussed at the beginning of this chapter, the traditional techniques of estimating ET classically provide potential or reference ET at points, rather than spatial distribution of AET. Furthermore, these techniques require immense ground observations that may be
difficult to obtain at large scales. Satellite remote sensing is a promising tool for estimating the spatial
distribution of ET at regional (and larger) scales. Different methods have been developed to use satellite
remote sensing data in surface flux estimation schemes.

ET is the term used for total water consumption of the crop; it includes water loss due to evaporation
and plant transpiration. Agricultural water use efficiency (WUE) is defined as crop yield per accumu-
lated AET for the growing season:

\[
WUE = \frac{\text{Crop yield}}{\text{AET}}
\]  

(8.14)

Accurate computation of WUE is possible only with reliable AET estimates, therefore making ET esti-
mation an important variable in agricultural productivity that can ultimately help water manager to
increase the amount of crop per unit of water consumed.

### 8.5.2 Water Deficit and Water Stress Indices

The association of surface temperature and water stress is based on the theory that as vegetation tran-
spires, the evaporated water cools the leaves in the surrounding and temperature. In a drought condi-
tion, the vegetation becomes water stressed leading to low transpiration and thus an increase in the
surface temperature of the plants. Water or moisture stress is often quantified in terms of the reduc-
tion of ET from the potential rate (PET) expected under non-moisture-limiting conditions. Satellite
remote sensing instruments with TIR instruments provide land surface information. In this regard, the
Evaporative Stress Index (ESI) proposed by [5,6] quantifies variance in the actual to PET. This method
uses fine- and moderate-resolution TIR imagery from polar-orbiting systems to generate daily ET maps
at subfield scales.

### 8.6 Summary and Conclusions

ET is the most vital process in the hydrologic cycle and an essential variable in various disciplines such
as hydrology, agriculture, ecology, and climate science. Even in the same climatic and meteorological
conditions, AET may exhibit remarkable spatial variability across different vegetated regions, agricul-
tural land use practices, and differing types of built-up urbanized areas. Spatially distributed ET estima-
tion for agricultural areas is a challenging and important task, as irrigation consumes the largest share
in water use in arid and semiarid regions. Furthermore, with the projected climate change, these areas
might be adversely affected, as it will intensify ET, globally impacting the scarce water resources.

Traditional ET retrieval methods typically present reference ET at point scale and do not contain
information on the spatial variation of ET. Recent advances in satellite remote sensing of ET have
showed advances in water resource monitoring at local, regional, and global scales. Integrating satellite
data with available ground-based measurements by using a simplified surface energy balance (SSEB)
method renders opportunities to utilize remote sensing data products for sustainable water manage-
ment. The ability to map ET and moisture availability has broad applications in monitoring droughts
and consumptive water use, planning for irrigation, predicting local and regional water demand, and
providing important boundary conditions to hydrological and weather forecast models.

### References


