An assessment of actual evapotranspiration and soil moisture functions based on local-scale data in Alabama

Lisa Lugo Kuzy

Follow this and additional works at: https://louis.uah.edu/uah-dissertations

Recommended Citation
https://louis.uah.edu/uah-dissertations/280

This Dissertation is brought to you for free and open access by the UAH Electronic Theses and Dissertations at LOUIS. It has been accepted for inclusion in Dissertations by an authorized administrator of LOUIS.
AN ASSESSMENT OF ACTUAL EVAPOTRANSPIRATION AND
SOIL MOISTURE FUNCTIONS BASED ON LOCAL-SCALE DATA
IN ALABAMA

Lisa Lugo Kuzy

A DISSERTATION

Submitted in partial fulfillment of the requirements
for the Degree of Doctor of Philosophy
in
The Joint Civil Engineering Program of
The University of Alabama at Birmingham
The University of Alabama in Huntsville
to
The Graduate School
of
The University of Alabama in Huntsville
May 2023

Approved by:

Dr. Walter L. Ellenburg, Research Advisor and Committee Member
Dr. Ashraf Al-Hamdan, Committee Chair
Dr. Vikalp Mishra, Committee Member
Dr. Nasim Uddin, Committee Member
Dr. Michael Anderson, Department Chair and Committee Member
Dr. Shankar Mahalingam, College of Engineering Dean
Dr. Jon Hakkila, Graduate Dean
Abstract

AN ASSESSMENT OF ACTUAL EVAPOTRANSPIRATION AND SOIL MOISTURE FUNCTIONS BASED ON LOCAL-Scale DATA IN ALABAMA

Lisa Lugo Kuzy
A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Civil and Environmental Engineering Department
The University of Alabama in Huntsville
May 2023

Large-scale models and remote technology are widely used for the estimation of the energy budget at a global scale. The interaction of energy fluxes and soil water at the vegetation root zone is the driving force that controls the evapotranspiration process. Although the importance of soil moisture, it can only be measured at a point scale, given the great heterogeneity of soil profile. Large-scale models struggle to capture the spatial heterogeneity of soils, and remote sensing can only observe the surface level soil moisture, omitting the root zone. Studies have shown evapotranspiration estimates (specifically from Remote Sensing) and can provide needed information for characterizing root zone soil moisture, but these studies are mixed, and few have looked at the Southeast United States. To better understand the relationship between soil moisture and evapotranspiration in the humid Southeast environment this study looked at in situ soil moisture and derived soil water balance model evapotranspiration estimates. Findings for this specific region show that, at the transition between evapotranspiration regimes, the critical soil moisture at the root level is lower than soil moisture at the surface level (less than 6 cm depth), particularly in areas with medium to fine soil texture.
Acknowledgments

I would like to thank the University of Alabama in Huntsville for allowing me to work as a teaching assistant for most of my time as a graduate student. It reminded me how much I enjoy teaching.

I would like to thank my advisors Dr. Lee Ellenburg and Dr. Vikalp Mishra for their support and professional guidance and for their commitment in my research. Also, I would like to thank the committee members Dr. Ashraf Al-Hamdan, Dr. Mike Anderson, and Dr. Nassin Udim for their advice and assistance.

I would like to express thanks to my colleagues in the Civil and Environmental Engineering department: Muhammad Usama and Eman Abdou. Thank you for your encouragement, support, and friendship.

This effort would have been impossible without the love, and encouragement of my family, my husband Chuck, and my kids Marki, Dani, and Jose. Thanks as well to my mother, sister, and brothers in Paraguay, for loving and praying daily for me.
Table of Contents

Abstract........................................................................................................................................... ii

Acknowledgements.......................................................................................................................... iv

Table of Contents............................................................................................................................ v

List of Figures...................................................................................................................................... vii

List of Tables......................................................................................................................................... x

Chapter 1. Introduction ......................................................................................................................... 1

Chapter 2. Literature Review ................................................................................................................. 4

2.1. Actual Evapotranspiration (AET) Determination Methods ......................................................... 9

2.2. Potential Evapotranspiration (PET) Determination Methods ...................................................... 11

2.3. Modeling the correlation between Available Water Content and Evapotranspiration ........ 15

Chapter 3. Methodology ..................................................................................................................... 20

3.1. Study Area .................................................................................................................................... 20

3.2. Data Preparation .......................................................................................................................... 27

3.2.1. Quality control of SCAN stations data .................................................................................. 27

3.2.2. Cumulative Distribution Function for Soil Moisture correction ........................................... 28

3.3. PET Estimation ............................................................................................................................. 33

3.4. AET Determination ....................................................................................................................... 37

3.5. Determination of \( f_{AW} \) and \( f_{PET} \) ...................................................................................... 44

Chapter 4. Analysis of Results ............................................................................................................ 46

4.1. PET Data Analysis ....................................................................................................................... 46

4.2. AET Data Analysis ....................................................................................................................... 54

4.3. SWBM Strength and Limitations ............................................................................................... 64
4.4. $f_{PET} - f_{AW}$ Analysis ........................................................................................................ 65

4.5. Linear and Piecewise Approximations ............................................................................. 67

4.5.1. Analysis at 4-in Depth .................................................................................................. 67

4.5.2. Analysis at 2-in Depth .................................................................................................. 69

4.5.3. Variability with Soil Texture ....................................................................................... 85

4.5.4. SM Variability with Location and Average Annual Precipitation .................. 86

4.6. Discussion ......................................................................................................................... 89

Chapter 5. Conclusions and Contributions ............................................................................ 93

References .................................................................................................................................. 97
List of Figures

**Figure 2.1** Relationships between fractional available water and fractional ET .......... 18

**Figure 3.1** Location of SCAN stations in Alabama .................................................. 22

**Figure 3.2** Map of Alabama Soils ............................................................................. 23

**Figure 3.3** Bragg station Bias in SM at 8 in layer, for the range period 2018-2021 ...... 29

**Figure 3.4** CDF for the SM 8 in layer at Bragg Station ............................................. 30

**Figure 3.5** Corrected value of SM 8 in layer after the CDF ...................................... 30

**Figure 3.6** Adjusted 8-in and 4-in SM after CDF Bragg Station ............................... 31

**Figure 3.7** Mean monthly PET from the Penman Monteith, Priestley Taylor, Blaney
Criddle, and Hargreaves-Samani estimations ......................................................... 37

**Figure 3.8** SWBM framework of AET daily estimation ............................................ 39

**Figure 3.9** Daily SWBM with cumulative components of the daily model ............... 42

**Figure 3.10** SBM parameters – Bragg Station time series Dec 2009 to Feb 2010 ........ 43

**Figure 3.11** SBM parameters – Bragg Station time series Jun-to-Aug 2017 ............. 43

**Figure 3.12** Penman Monteith PET and SWBN AET time series for Bragg Station .... 44

**Figure 4.1** PET empirical estimations time series for WTAR Station ....................... 49

**Figure 4.2** Mod16 PET and Penman Monteith PET time series for WTARS Station ..... 51

**Figure 4.3** Linear Regression MODIS PET – Penman Monteith PET ..................... 53

**Figure 4.4** SM and Components of the SWBM ....................................................... 56

**Figure 4.5** Time series Penman Monteith PET and SWBM AET .............................. 57

**Figure 4.6** Time series Penman Monteith PET and SWBM AET Selma Station ........ 58

**Figure 4.7** Linear Regression MODIS AET and SWBM AET by station .................... 63
Figure 4.8 AAMU Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in......... 75

Figure 4.9 Bragg Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in. .......... 75

Figure 4.10 Cullman Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in. ....... 76

Figure 4.11 Hodges Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in. .......76

Figure 4.12 Isbell Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.........77

Figure 4.13 Koptis Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in. .......77

Figure 4.14 Morris Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.........78

Figure 4.15 Perdido Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.......78

Figure 4.16 Selma Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.........79

Figure 4.17 Stanley Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.........79

Figure 4.18 Sudduth Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.......80

Figure 4.19 Tuskegee Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in......80

Figure 4.20 Wedowee Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.....81

Figure 4.21 WTARS Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in. ....81

Figure 4.22 USDA Soil Texture and location of Stations.........................................................83

Figure 4.23 Precipitation regions and Scan Stations in Alabama..............................................89
List of Tables

Table 3.1 Soil Characteristics in Station locations.......................................................... 24
Table 3.2 Location of SCAN stations in Alabama............................................................ 26
Table 3.3 Percentage of data corrected after CDF function by Station.......................... 32
Table 3.4 Statistical Performance of PET versus the Penman-Monteith model ............. 36
Table 3.5 Parameters of the daily Soil Water Balance Model ...................................... 38
Table 4.1 Statistical Performance of Priestley Taylor, Blaney-Criddle, and
Hargreaves-Samani PET estimation .............................................................................. 50
Table 4.2 Averaged Monthly Penman Monteith PET (mm) for SCAN Stations .......... 52
Table 4.3 Evaluation of $R^2$ for Penman Monteith PET and MOD16 PET....................... 54
Table 4.4 Aggregated Monthly SWBM AET (mm) for SCAN Stations ...................... 59
Table 4.5 Evaluation of $R^2$ for SWBM AET and MOD16 AET for Scan Stations .... 62
Table 4.6 Soil Characteristics by Station ....................................................................... 70
Table 4.7 Regression Analysis by Station for layer 2-in depth ...................................... 71
Table 4.8 Regression Analysis by Station for layer 4-in ................................................. 72
Table 4.9 Regression Analysis by Station for layer 8-in ................................................. 73
Table 4.10 SM critical at the 2-in, 4-in, and 8-in layer...................................................... 74
Table 4.11 Averages $\Omega$ value and SM critical by layer and soil group. ...................... 86
Table 4.12 Averages $\Omega$ value and SM critical by layer and zones of precipitation .... 87
Chapter 1. Introduction

Water retained in the soil in the form of soil moisture (SM) is a central component of the global hydrological budget (Mishra et al., 2018). Although SM represents only 0.05% of the total water in the global hydrological cycle (Robinson et al., 2008) and 0.001% of the available freshwater, it is one of the essential climate variables due to its importance in the global climate system. Soil Moisture presents a large temporal and spatial variability at regional and global scale, and is influenced by multiple factors: precipitation, soil texture, vegetation, topography, and land use. Soil Moisture fluctuations provide a direct measure of drought events (Sadri et al., 2020), and the main mechanism for depletion of SM is the Actual Evapotranspiration (AET) (terrestrial evaporation and plant transpiration). The root-zone SM controls the AET taking place at the atmosphere-soil/vegetation interface, hence plays a key role in the regulation of water and energy budgets (Shukla & Mintz, 1982). In terms of food security, agricultural simulation models rely on accurate SM specifications for reliable crop yield prediction (Grassini et al., 2015). However, obtaining accurate SM measurements or estimates is challenging especially in climate data-limited regions worldwide (Brocca et al., 2017).

Three main sources of AET and SM datasets can be mentioned (Beck et al., 2020; Chen & Dudhia, 2001; Han et al., 2023; Kishné et al., 2017): in situ soil moisture and climate data collection, satellite observations, and soil moisture and atmospheric energy products from hydrologic land surface model (LSM). Local stations and their networks
provide in-situ and timeseries climate data and SM from different depths (P. Zhang & Shao, 2015) but, they are geographically limited and located mostly in mid-latitude regions (Ray et al., 2017). Therefore, SM moisture data from stations is typically only used for calibration and validation of large-scale hydrological models (Romano, 2014). Satellite observations allows the retrieval of AET and SM at global scale, however their SM estimations are mainly valid for depths less than 5 cm from the surface (O. & Orth, 2021), and are also affected by spatiotemporal gaps. Land Surface Hydrological Models can produce AET and SM products at global scale, but their variability in estimations is significant among products due to different inputs and parametrizations used (Kim et al., 2020; Koster et al., 2009; Moran et al., 2004). Thus, considering that hydrological-based regional and large-scale modeling requires entire root zone SM information for the AET-SM water and energy balance equations, the current state of methodologies to estimate these factors is not sufficient to effectively drive the models. Therefore, it is required to extend the research of the interaction SM and AET to the depths of root-zone. This aspect is of key importance for improved predictions of SM at global scale, and therefore has motivated this study.

The novelty of this research is the analysis at local scale of the association between AET and SM profile (from surface to root-zone), for several types of soil profiles, through the state of Alabama in the Southern US region, based on real daily data collected by the Soil Climate Analysis Network (SCAN) (Schaefer et al., 2007). A soil water balance model of AET was created and evaluated based on the in-situ data. Functional relationships between evapotranspiration and fraction of soil water availability were analyzed based on texture and location. It is expected that these relationships will
expand the understanding of AET-SM dynamics in the SE region, based on soil profiles, providing key information for estimations on a greater scale.

Thus, the study has three purposes: a) to determine daily reference evapotranspiration for Alabama in the SE region based on local data and existing estimation methodologies, b) to develop and evaluate a daily soil water balance model to obtain daily AET, c) to model the relationship of fractional evapotranspiration and fractional available water content based on time-series local data.
Chapter 2. Literature Review

In terms of vegetation, SM can be expressed as plant Available Water Capacity (AWC), which is the volume of water in the soil available for plant growth, obtained by the difference between the volume of water corresponding to the Field capacity or soil moisture retained in the ground after it has been fully saturated and allowed to drain freely (after two or three days), and the volume of water corresponding to the Permanent wilting point or SM at which plants start to wilt, and can no longer extract water from the soil. The AWC concept was historically introduced in the agricultural field, to assist farmers in the management of crop irrigation (Denmead & Shaw, 1962). Qualitatively, Field Capacity is expressed as the volumetric soil moisture after the saturated soil is exposed to a suction pressure (or drying by water removal) of -0.33 MPa, and Wilting Point is expressed as the volumetric soil water content after saturated soil is exposed to a suction pressure of -1.5 MPa (Briggs & Shantz, 1912). The available water fraction, $f_{AW}$, is defined as the ratio of the actual plant available water and the available water capacity in the soil profile defined as:

$$f_{AW} = \frac{\theta - \theta_{wp}}{\theta_{fc} - \theta_{wp}}$$

(2.1)

where $\theta_{fc}$ and $\theta_{wp}$ are the volumetric soil water contents at field capacity and wilting point, respectively.
Under atmospheric conditions, the Actual Evapotranspiration or AET (soil moisture evaporation and transpiration of the plant) is a major factor in depletion of AWC. If depletion of SM continues without recharge of water in the soil, the plant would start experiencing moisture stress, that could lead to permanent inability of the plant to extract water from the soil, and wilt (Denmead & Shaw, 1962). Thus, moisture stress is strongly connected to the AET, the physical and biological interaction plant-soil to extract/yield water, the texture of the soil, vegetation type (deep or shallow rooted, deciduous, evergreen, etc.), among other factors. In ideal situations when the system plant and soil can both fully produce evaporation and transpiration, as when the soil is irrigated or at field capacity, the system reaches what it is denominated reference or Potential Evapotranspiration (PET) (Penman, 1948). In conditions of water deficits or moisture stress, AET would always be a fraction of PET. The fraction of AET to PET is denominated $f_{PET}$, or fractional PET. Another important element to mention in the evapotranspiration process is the control that the plant exerts over the transpiration through the stomata of the leaves. When the atmospheric demand for water increases (atmospheric vapor pressure deficit), the plant responds by closing its stomata, reducing transpiration and water loss, and conserving SM. When the vapor pressure decreases, the plant opens its stomata increasing transpiration and water loss to maintain the uptake of carbon dioxide (Denmead & Shaw, 1962).

The evaporative fraction ($EF = E / Rn$), defined as the ratio of turbulent flux energy over land surfaces responsible of evaporation and plant transpiration (Nichols & Cuenca, 1990), is a key factor to define two main evapotranspiration regimes: the energy-limited, and the SM-limited regime (Budyko: Climate and Life - Google Scholar, n.d.;
Gan et al., 2021). The EF is independent of SM content in the energy-limited AET regime, which corresponds to SM values above a specified critical SM value ($\Theta_{critical}$).

The SM-limited AET regime (also known as water limited regime) takes place when the SM drops below the critical SM. Below the wilting point (WP), the AET ceases to occur. Thus, in accordance with the effect of SM on evapotranspiration variability, three climate or SM regimes can be identified (Koster et al., 2004; Seneviratne et al., 2010). In the first two regimes, the wet (SM greater than the critical SM), and the dry (SM below the wilting point), the SM has no effect on evapotranspiration variability. In the last regime, the transitional (SM greater than wilting point and below critical SM), the evapotranspiration variability and subsequent responses to the atmosphere, are significantly constrained by SM. In this last situation, as SM declines, evapotranspiration also decreases, thus increasing the sensible heating of the lower atmosphere (Berg et al., 2014; Berg & Sheffield, 2018). Transition between both regimes has a direct impact on climate extremes such as heatwaves and flash drought (Dong et al., 2022).

The degree to which water is firmly bound to the soil matrix, also known as soil suction or soil water potential, is directly related to the SM content. With decreasing SM content and increasing soil suction, it is harder for plant roots to retrieve the moisture remaining in the soil, and evapotranspiration may consequently decrease. Therefore, the role of SM is crucial to the evapotranspiration process (Seneviratne et al., 2010).

Several methodologies are available to measure and monitor SM at local and larger scale. Local-scale sources are generally based on sensors buried in the ground at several specified depths in the soil profile to retrieve soil information, allowing the collection of time-series data. Despite the reduced spatial scale of local stations, they
have high temporal resolutions that is essential for the study of SM variability, and the factors affecting the profiles and the dynamics of SM (Dorigo et al., 2013). Local stations are also a source for calibration, interpretation, and validation of larger scale model-based products (Jacobs et al., 2004). A detailed description and discussion of available technology for local SM measurement is presented in Romano (Romano, 2014). Networks of local stations are spread-out around the world. Management and harmonization of the volume and diversity of SM data from different networks is currently a challenge and the necessary data quality control to minimize errors is addressed by several authors (Dorigo et al., 2010, 2011, 2013; Gruber et al., 2013). The Soil Climate Analysis Network (SCAN) is managed by the Natural Resources Conservation Service (NRCS) of the US Department of Agriculture. The SCAN network has 239 stations in US territory (Schaefer et al., 2007), with some stations collecting data since 1996. SCAN stations report: snow water equivalent, precipitation, soil temperature, air temperature, SM and snow depth, but not all these parameters are recorded by all the stations. The state of Alabama contains 18 operational SCAN monitoring stations. For larger and broader scales, land surface models (LSM) and remote sensing sources provide inputs for estimating SM. Microwave instruments are frequently utilized for remote sensing observations from satellites, some of which are: the Soil Moisture and Ocean Salinity (SMOS) from the European Space Agency (ESA), Soil Moisture Active Passive (SMAP), AMSR-E, AMSR2, TMI, WINDSAT, SMM/I, AirMOSS from NASA, with different products for the estimation of SM and other parameters. Dense vegetation and clouds reduce the estimations of satellite-based models (Randall et al., 2007). Limited vertical resolution, interference from vegetation, limited sensitivity to soil
characteristics, limited temporal coverage, and difficulties with calibration and validation are some of the limitations of remote sensing and satellite data to estimate SM at the root zone. These drawbacks emphasize the requirement for more ground-based data to raise the precision of SM forecasts at the root zone (Mu et al., 2011). These satellite products differ in their spatial and temporal resolutions, accuracy, and the range of land surface variables they measure. However, they all provide valuable information on SM dynamics at a global or regional scale and are useful tools for improving our understanding of the water cycle and for supporting a range of applications, including agriculture, hydrology, and weather forecasting.

Computer simulations of the physical and biogeochemical processes that occur on the land surface are known as land surface models (LSM). They are used to estimate how much energy, water, and carbon will be exchanged between the land and the atmosphere. Some drawbacks of LSM are models complexity, the quality and quantity of input data required for large scale modeling, uncertainties of parametrizations, model bias, and accuracy of the representation land-atmosphere interactions (Koster et al., 2009; Shukla & Mintz, 1982). There are available several LSM to estimate SM, among them: The Community Land Model (CLM), the Noah Land Surface Model Global Land Data Assimilation System (GLDAS), the Simplified Simple Biosphere Model (SSiB), among others. These models differ in their structure, complexity, and the range of land surface processes they simulate. However, they all aim to estimate SM and other land surface variables to improve our understanding of the land-atmosphere interactions and to improve weather and climate forecasts.
2.1. Actual Evapotranspiration AET Determination Methods

The Actual Evapotranspiration AET process is difficult to observe or measure and presents a great variability at different spatial-temporal scales. A review of the available methodologies for AET measuring and AET estimation is offered and discussed by several authors (Jovanovic & Israel, 2012; Rana & Katerji, 2000; Verstraeten et al., 2008; Zhao et al., 2013). Direct or indirect AET measurement is based on the quantification of factors involved in the evapotranspiration process: soil water content (SM), plant-surface characteristics (plant density, canopy roughness, albedo, etc.) climatic variables (solar radiation, wind speed, thermodynamic characteristics of the atmosphere at surface level, etc.). AET measurement methods include the hydrological approach: soil-water balance, weighing lysimeters; the micro-meteorological approach: Energy Balance/Bowen ratio, Aerodynamic method, Eddy Covariance; the plant physiology law-based approach: Sap flow method, Chambers System; and the scintillometer method. The hydrological approach quantifies ET over long periods of time (weeks to months, agricultural growing season). The micro-meteorological method is based on the analysis of energy transfer from the surface to the atmosphere. The Plant-physiology method measures the plant water consumption and transpiration. In general, measurement of AET is based on physical or analytical formulations, but, depending on available data, empirical and statistical approaches have been also formulated. Analytical formulations are mostly based on the Penman-Monteith surface energy balance model. For crop management, AET could be obtained in function of a reference surface evapotranspiration (PET), or based on the soil water balance model (Rana & Katerji, 2000).
The soil water balance simulation models (SWBM) can be classified as mechanistic or analogue models. The mechanistic models are based on the physical principles of soil water diffusion, based on soil water potential gradients governed by Darcy’s law and continuity principle. The soil is divided into several layers, and a rigorous description of hydrological parameters is required for every layer of soil. Several methodologies are available to solve the equations of water transfer, and the scale of evaluation plays an important role for methodology adoption (Connolly, 1998). Difficulties of the mechanistic models are associated to the water transfer functions adopted and the simulation of the boundaries soil-vegetation-atmosphere (Rana & Katerji, 2000).

The analogue models, also called lumped hydrological models, are mostly formulated for crop management and catchment or field scales and consider the soil as sequence of water reservoirs (or buckets) that are filled after precipitation or irrigation and emptied by evapotranspiration and drainage. These models could either consider the effect of runoff (calculated through empirical functions) and capillarity, or not take these factors into consideration. The SM content is input as Available Water Content (AWC) and the base time for calculations is one day or periods of 5 to 10 days (Lhomme & Katerji, 1991). Another feature of lumped models is the adoption of spatially averaged parameters (Pérez-Sánchez et al., 2017). The advantage of the analogue models is that some of the formulations require few inputs that can be retrieved from agrometeorological networks, as is performed in this study, through climate data retrieved from SCAN agrometeorological stations.
At a catchment scale (L. Zhang et al., 2001), the soil water balance model (SWBM) can be represented as:

\[ P = ET + R + D + \Delta S \]  

(2.2)

where \( P \) is precipitation, \( ET \) is evapotranspiration, \( R \) is surface runoff, \( D \) is recharge to groundwater, and \( \Delta S \) is the change in soil water storage.

Soil water balance models for crop fields scales (smaller scale than catchment), usually consider the dynamics of crop root growth, the variability of SM in the active root zone of crops, under irrigated and rain-feed condition, and the influence of the AET on the balance of the model (Gassmann et al., 2011; Panigrahi & Panda, 2003). This concept will be later adapted to produce the one-layer SWBM that is developed in this study.

2.2. Potential Evapotranspiration (PET) Determination Methods

The concept of PET was initially defined as the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water (Penman, 1956). Since the term “short crop” was ambiguous and could fit a great variety of agricultural crops (Lhommel, 1997), over the years the term PET was transitioned to the concept of Reference Evapotranspiration (ET0), which is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m in a fixed surface resistance of 70 sec m\(^{-1}\), and an albedo (portion of light reflected by the leaf surface) of 0.23, resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered and completely shading the ground (Allen et al., 1998).
The well-known Penman equation (Penman, 1948) was developed to estimate potential evaporation from an open water surface and is based in energy balance function. It is expressed in terms of hydro meteorological variables as:

$$\lambda E = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} E_a$$

(2.3)

where $R_n$ is the net radiation (MJm$^{-2}$h$^{-1}$), $G$ is the soil heat flux (MJm$^{-2}$h$^{-1}$), $\Delta$ is the slope of the saturation vapor curve pressure curve, $\gamma$ is a psychometric coefficient, and $E_a$ is drying power of air, expressed in terms of wind speed estimates, relative humidity, a wind function based on roughness or surface turbulence accounting, temperature, and atmospheric pressure.

**The Monteith** formulation of PET (Monteith, 1965) incorporates bulk vegetated surfaces resistance ($r_s$) to the Penman expression, and the resulting equation is now called the Penman-Monteith Equation which can be expressed for daily estimations of PET as:

$$\lambda ET = \frac{\Delta (R_n - G) + 86,400 \rho_a C_p (e_o^s - e_a) 1/r_{av}}{(\Delta + (1 + r_s^z/r_{av}) \gamma)}$$

(2.4)

where $\rho_a$ is the air density (kg/m$^3$), $C_p$ is the specific heat of dry air, $e_o^s$ is the mean saturated vapor pressure (kPa) which is calculated as the mean daily value of the maximum and minimum air temperature (°C), $r_{av}$ is the bulk surface aerodynamic resistance for water vapor (s/m), $e_a$ is the mean daily value of the ambient vapor pressure (kPa) and $r_s$ is the canopy resistance (s/m).

The United Nations Food and Agriculture Organization (FAO) proposed a revised methodology of the **Penman-Monteith** Equation (Allen et al., 1998) that is known as the
FAO-56 Penman-Monteith Equation. Some simplifications in the FAO-56 model include the introduction of the characteristics of the hypothetical reference crop that was mentioned earlier in this section (Allen et al., 1998). The new equation is expressed as:

\[
ET_0 = \frac{0.408\Delta (R_n - G) + \gamma u_2 (e_s - e_a) 900}{\Delta + \gamma (1 + 0.34u_2)} \left( \frac{T + 273}{T + 273} \right)
\]  \hspace{1cm} (2.5)

where \( ET_0 \) (mm/d) is the reference evapotranspiration rate (for our study equivalent to PET), \( T \) is the mean air temperature (°C), \( u_2 \) is the wind speed (m/s) at 2 m above the ground, \( R_n \) is the net radiation (MJm\(^{-2}\)h\(^{-1}\)) and \( G \) is the soil heat flux (MJm\(^{-2}\)h\(^{-1}\)). All data required for \( ET_0 \) can be obtained from weather stations, in our case, they are obtained from the SCAN network (Zotarelli et al., 2010). The Penman-Monteith is accepted as the most accurate and reliable method for estimating PET. It has been extensively tested and validated under a variety of climate and conditions (Allen et al., 1998, 2006; Droogers & Allen, n.d.-a). Satellite products that use the Penman-Monteith equation or a variable of it for PET estimations includes NASA MOD16 (moderate Resolution Imaging Spectroradiometer ET) for estimation of 8-day PET at 1 km spatial resolution; SSEBop (Simplified Surface Energy Balance operational); METRIC (mapping Evapotranspiration at high Resolution with Internalized Calibration), developed by the University of Idaho, and SEBAL (Surface Energy Balance Algorithm for Land), among others.

Following Penman, several other authors developed formulations of evaporation prediction, mostly derived from the Penman equation. These estimations are particularly useful in locations where weather data availability is reduced. Following is a summary of the estimations that were relevant to this study.
The **Priestley-Taylor** Potential Evapotranspiration (Priestley & Taylor, 1972) is a simplification of the Penman formulation. Vapor deficit and convection terms are reduced to an empirical constant $\alpha$, and the only observation required is the radiation, and is denoted as:

$$PET = \alpha \frac{\Delta(R_n - G)}{\Delta + \gamma}$$

(2.6)

where $R_n$ is net radiation (mm/d), $G$ is soil heat flux (mm/d), $\Delta$ is the gradient of saturated vapor pressure (kPa/°C), and $\gamma$ is the psychometric factor (kPa/°C). The $\alpha$ factor accounts for the aerodynamic component and has a typical value of 1.26 for humid areas. For arid areas $\alpha$ ranges between 1.7 and 1.75.

The **Hargreaves-Samani** method is a temperature-based methodology to estimate PET. It is widely used as an empirical model for calculating PET in humid zones. It uses temperature and radiation data as inputs. Although it is a simple and efficient method, it may not accurately represent the effects of high humidity and cloud cover in humid zones (Touhami et al., 2014).

$$PET = 0.0032R_a(T_m + 17)$$

(2.7)

where $R_a$ is extraterrestrial radiation, $T_m$ is the daily mean air temperature (°C).

The **Blaney Criddle** estimation is another empirical model that is often used in humid zones. It uses temperature, solar radiation, and precipitation data to estimate PET, and it considers the effects of high humidity and cloud cover by using a correction factor based on the ratio of actual to potential evapotranspiration.

$$PET = p \ (0.457 \ T_{mean} + 8.128)$$

(2.8)
where \( p \) is the mean daily percentage of annual daytime hours, \( T_{\text{mean}} \) is the mean daily temperature (°C).

Different models can be suitable for different regions and climates, and the choice of the model depends greatly on the availability of data and the specific application of the PET estimate. The accuracy of the PET estimates can be improved by using high quality meteorological data and the incorporation of local information of the surface and vegetation cover (Allen et al., 2006).

### 2.3. Modeling the correlation Available Water Content and Evapotranspiration

Understanding the relationships between soil, plants, and atmosphere as well as the regional hydrological balance depends on the dynamic interactions between ET and soil water. However, estimating these interactions, can be challenging because measurements of soil water and ET are rarely obtained at the resolutions necessary to fully understand the interactions (N. Lu et al., 2011; Verstraeten et al., 2008; Zhao et al., 2013).

To characterize the water balance of agricultural and other ecosystems, several estimations have been developed, particularly at regional scale, for the relationship of atmospheric demand and the soil water available for vegetation growth. Following, some of them are presented.

The Noah LSM method to compute the relationship \( f_{\text{AW}} \) and \( f_{\text{PET}} \) is based on the effects of the direct soil evaporation and the canopy transpiration (Chen & Dudhia, 2001; Jacquemin & Noilhan, 1990) and is expressed as:
\[ f_{AW} = \frac{R_{c_{min}}}{(LAI)F_1F_2F_3 \left( 1 + \frac{\Delta}{R_r} - \frac{\Delta}{R_r C_H} - \frac{1}{C_H} \right)}. \]  \hspace{1cm} (2.9)

\( R_{c_{min}} \) represents the vegetation minimum stomatal resistance that is parameterized as a function of vegetation type and Leaf Area Index (LAI), \( R_r \) is function of surface air temperature and surface pressure, \( C_H \) represents the surface exchange coefficient, \( F_1, F_2 \) and \( F_3 \) are factors that represent the effects of solar radiation, vapor pressure deficit and air temperature on the canopy resistance, and they range from 0 to 1., \( f_{PET} \) represents the fraction of potential evaporation retrieved from the ALEXI (Atmosphere-Land Exchange Inverse) model.

Hain et al. (2009) presents a linear model based on the formulation of Wetzel (Wetzel & Chang, 1987). Here, \( f_{PET} \) and \( f_{AW} \) are linearly correlated by the plant factor \( B_c^* \), which represents the plant stomatal control on the canopy transpiration.

\[ f_{PET} = B_c^* f_{AW} \]  \hspace{1cm} (2.10)

The Non-Linear Model presented by Hain et al. (2009) is expressed as:

\[ f_{PET} = \frac{f_{PET}}{2B_c^* - f_{PET}} f_{AW}. \]  \hspace{1cm} (2.11)

The Hybrid or Blend Model presented by Hain et al. (2009) is expressed as:

\[ f_{AW} = \frac{f_{PET}}{B_c^*} \left( f_{PET} \right) + \frac{f_{PET}}{2B_c^* - f_{PET}} \left( 1 - f_{PET} \right). \]  \hspace{1cm} (2.12)

An evaluation of the performance of these four models to predict \( f_{AWC} \) is presented by Hain et al. (2007), for the timeframe years 2002 to 2004 and results were validated with SM observations from the Oklahoma Mesonet network. Based on the statistical analysis.
of the \( f_{AW} \) obtained, the BLEN D model showed itself to be the most representative of the four models, under the conditions of the network.

The Logarithmic Model presented by Anderson et al. (2007) is based on the logistic growth model applied to an agronomical simulation of crop growth in function of dry weight (W) (France & Thornley, 1984):

\[
\begin{align*}
    f_{PET} &= f_n[f_{AW}] = \frac{\ln W}{\ln W_f}.
\end{align*}
\]

(2.13)

Main limitations of these previous studies to estimate daily \( f_{AW} \) is the usage of a weighted averaged SM to represent the full column moisture, then missing the differences in the characterization of the dynamic between root zone and surface SM.

Several other models based on passive microwave remote sensing data are available for sensing SM dynamics at the global scale, but these studies are based on SM measurements at sampling depth of less than 5-10 cm, then they are just analyzing land-atmospheric coupling process using only the dynamics of the surface SM and overlooking the influence of SM at the root zone to the evapotranspiration process(Dong et al., 2022).

To evaluate the performance of the five models presented before, correlation functions \( f_{PET} \) and \( f_{AW} \), were developed based on point-based SM observations from the SCAN network, at site of observation denominated 2078 located in Southeast US, Figure 2.1, for the timeframe years 2006 to 2010 (V. Mishra & W. L. Ellenburg, personal communication, August 10, 2021). It is evident that predicted SM obtained from these models are still not closely accurate to real SM observations, suggesting that further research is needed to advance in the knowledge of soil water dynamics under
atmospheric requirements. Both fractions, evapotranspiration and available water, depend on multiple parameters, and the variability of these factors is not just be affected by the geographical scale (Lawrence & Hornberger, 2007).

![Figure 2.1](image)

**Figure 2.1** Relationships between fractional available water and fractional ET for a SCAN station (Mishra & Ellenburg, personal communication, 2021)

Consequently, the challenge to estimate regional SM with either LSM or remote sensing products, is based in the understanding of the influence on SM of factors as the soil properties, topography of the region, characteristics of vegetation/land cover/land use, and accurate climate data (Crow & Wood, 2002). Heterogeneity of soils profiles is considered to have a great influence on SM, and the effect of heterogeneity varies according to depth of layers, layering configuration, and land cover at the surface, especially for agricultural lands (Yetbarek et al., 2020). Famiglietti et al. (1998) concluded that under wet conditions, the dominant effects on the SM are the soil porosity and hydraulic conductivity of the soil, and in drier situation, SM is more affected by topography and clay content in the soil profile. Feng et al. (2013) concluded that the spatial variability of SM is directly affected by scale of the site investigated, for studies
made at watershed scales and smaller catchments. At smaller scales, land use type, slope, relative elevation, and vegetation cover are the dominant factors, in that order, on SM variability, while at larger scales, location on the slope, vegetation cover and relative slope, are more influential on spatial SM variability.

It is evident that SM estimation is affected by the influence of multiple factors and the very complex dynamics of water retained in the ground along the soil profile, from surface to root zone. Furthermore, is undeniable the importance of accurate prediction of SM at global level for areas as agricultural management, including drought prediction, climate or hydrological modeling and forecasting. Overcoming these challenges requires the development of advanced research, the use of accurate satellite or LSM products, with reliable sources of data, and the integration of ground-based measurements not just for calibration and validation, but also to provide meaningful information of the soil water – atmospheric interaction.

Gaps in the estimation of SM at plant root level by global and regional models has been remarked in this chapter, as well as the critical need to advance in the understanding of the dynamics of soil water and atmospheric demand at the depth of plant water intake for growth. This study advances further in the understanding of this relationship in the study region
Chapter 3. Methodology

The methodology and theoretical background of the techniques utilized is thoroughly recounted in this chapter. Three main processes are explained in this chapter: the evaluation of SCAN time-series SM at different layers and locations, that would later allow the calculation of the fraction of available water, $f_{AW}$, and the estimation of the PET, and the AET, with the purpose to estimate the fraction of potential evapotranspiration, $f_{PET}$.

The study area is introduced. SM quality control is described. PET is estimated based on the FAO-56 Penman-Monteith methodology (Allen et al., 1998) applying the agrometeorological SCAN data, and several other methodologies are also introduced and evaluated. Finally, the Soil Water Balance Model (SWBM) developed in this study to obtain daily values of daily AET at the 18 Alabama SCAN stations for their entire recorded time is presented.

3.1. Study Area

The region of study is located in the Southeast United States, the State of Alabama, where 18 SCAN stations are located (http://nrcs.usda.gov/). Figure 3.1. A map of soil areas of the Alabama State is presented in Figure 3.2, and shows eight main zones with similar soil characteristics: Limestone Valleys and Uplands, Appalachian Plateau, Piedmont Plateau, Coastal Plain, Blackland Prairie, Major Flood and Terraces,
and Costal Marshes and Beaches. Alabama soils can be categorized under the Ultisol group. Textures found in this study range from coarser granulometry in the south region, to finer graded soils in the north part of the state.

Alabama is characterized by a warm, humid climate resulting from its mid-latitude location and proximity to the Gulf of Mexico. The boundaries of the state extend from approximately 30° to 35° north latitude and 85° to 88.5° west longitude. It is located within the Humid Subtropical region in the Koppen classification system (Ojha & Dimov, 2017). Precipitation patterns tend to be higher in the southern half of the state averaging up to 65.9 inches per year, than in the northern half, area averaging 57.0 inches per year. Higher temperatures and precipitation patterns combine to produce a significant difference in the length of the growing season for agricultural production across the state, which varies from approximately 200 days per year in the north to approximately 250 days per year in the South (Kottek et al., 2006).

SCAN site locations and underlaying soil characteristics are presented in Table 3.1.
Figure 3.1 Location of SCAN stations in Alabama
Figure 3.2 Map of Alabama Soils (Department of Geography, The University of Alabama)
Table 3.1 Soil Characteristics in Station locations

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Depth (cm)</th>
<th>FC (cm^3/cm^3)</th>
<th>WP (cm^3/cm^3)</th>
<th>Θ_r (cm^3/cm^3)</th>
<th>Θ_s (cm^3/cm^3)</th>
<th>C (%)</th>
<th>Si (%)</th>
<th>S (%)</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAMU</td>
<td>0-5</td>
<td>0.36</td>
<td>0.12</td>
<td>0.05</td>
<td>0.49</td>
<td>22.9</td>
<td>47.9</td>
<td>29.2</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>5-20</td>
<td>0.36</td>
<td>0.19</td>
<td>0.07</td>
<td>0.45</td>
<td>32.3</td>
<td>43.4</td>
<td>24.3</td>
<td>CL</td>
</tr>
<tr>
<td>Bragg</td>
<td>0-5</td>
<td>0.34</td>
<td>0.16</td>
<td>0.09</td>
<td>0.47</td>
<td>31.1</td>
<td>56.2</td>
<td>12.7</td>
<td>SICL</td>
</tr>
<tr>
<td></td>
<td>5-20</td>
<td>0.37</td>
<td>0.20</td>
<td>0.09</td>
<td>0.48</td>
<td>36.7</td>
<td>50.2</td>
<td>13.1</td>
<td>SICL</td>
</tr>
<tr>
<td>Cullman</td>
<td>0-15</td>
<td>0.23</td>
<td>0.09</td>
<td>0.03</td>
<td>0.35</td>
<td>8.1</td>
<td>43.1</td>
<td>48.8</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>15-25</td>
<td>0.24</td>
<td>0.10</td>
<td>0.03</td>
<td>0.36</td>
<td>14.3</td>
<td>43.6</td>
<td>42.1</td>
<td>L</td>
</tr>
<tr>
<td>Hodges</td>
<td>0-15</td>
<td>0.48</td>
<td>0.12</td>
<td>0.10</td>
<td>0.50</td>
<td>16.4</td>
<td>59.6</td>
<td>24</td>
<td>SIL</td>
</tr>
<tr>
<td></td>
<td>15-28</td>
<td>0.36</td>
<td>0.12</td>
<td>0.06</td>
<td>0.44</td>
<td>26.1</td>
<td>56.3</td>
<td>17.6</td>
<td>SIL</td>
</tr>
<tr>
<td>Isbell</td>
<td>0-20</td>
<td>0.34</td>
<td>0.12</td>
<td>0.07</td>
<td>0.42</td>
<td>19.5</td>
<td>66</td>
<td>14.5</td>
<td>SIL</td>
</tr>
<tr>
<td>Koptis</td>
<td>0-28</td>
<td>0.17</td>
<td>0.08</td>
<td>0.04</td>
<td>0.33</td>
<td>10.1</td>
<td>20.5</td>
<td>69.4</td>
<td>FSL</td>
</tr>
<tr>
<td>Morris</td>
<td>0-25</td>
<td>0.16</td>
<td>0.07</td>
<td>0.04</td>
<td>0.41</td>
<td>13</td>
<td>17.1</td>
<td>69.9</td>
<td>FSL</td>
</tr>
<tr>
<td>Perdido</td>
<td>0-25</td>
<td>0.21</td>
<td>0.085</td>
<td>0.11</td>
<td>0.418</td>
<td>8.3</td>
<td>35.5</td>
<td>56.3</td>
<td>SL</td>
</tr>
<tr>
<td>Selma</td>
<td>0-28</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
<td>0.42</td>
<td>5.2</td>
<td>11.4</td>
<td>83.4</td>
<td>LS</td>
</tr>
<tr>
<td>Stanley</td>
<td>0-15</td>
<td>0.34</td>
<td>0.13</td>
<td>0.06</td>
<td>0.42</td>
<td>17.4</td>
<td>42.6</td>
<td>40</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>15-25</td>
<td>0.29</td>
<td>0.15</td>
<td>0.05</td>
<td>0.36</td>
<td>21.9</td>
<td>31.3</td>
<td>36.8</td>
<td>L</td>
</tr>
<tr>
<td>Sudduth</td>
<td>0-13</td>
<td>0.22</td>
<td>0.10</td>
<td>0.04</td>
<td>0.34</td>
<td>7.8</td>
<td>28.1</td>
<td>64.1</td>
<td>FSL</td>
</tr>
<tr>
<td></td>
<td>13-25</td>
<td>0.20</td>
<td>0.06</td>
<td>0.03</td>
<td>0.23</td>
<td>7.3</td>
<td>31.3</td>
<td>61.4</td>
<td>FSL</td>
</tr>
<tr>
<td>Tuskegee</td>
<td>0-15</td>
<td>0.10</td>
<td>0.02</td>
<td>0.02</td>
<td>0.38</td>
<td>3.2</td>
<td>11</td>
<td>85.8</td>
<td>LCOS</td>
</tr>
<tr>
<td></td>
<td>15-25</td>
<td>0.15</td>
<td>0.07</td>
<td>0.03</td>
<td>0.35</td>
<td>11.6</td>
<td>16.3</td>
<td>72.1</td>
<td>COSL</td>
</tr>
<tr>
<td>Wedowee</td>
<td>0-51</td>
<td>0.31</td>
<td>0.16</td>
<td>0.07</td>
<td>0.42</td>
<td>23.3</td>
<td>35.5</td>
<td>41.2</td>
<td>L</td>
</tr>
<tr>
<td>Wtars</td>
<td>0-10</td>
<td>0.37</td>
<td>0.21</td>
<td>0.07</td>
<td>0.44</td>
<td>31.5</td>
<td>61.5</td>
<td>7</td>
<td>SIL</td>
</tr>
<tr>
<td></td>
<td>10-23</td>
<td>0.33</td>
<td>0.16</td>
<td>0.03</td>
<td>0.41</td>
<td>26.3</td>
<td>67.9</td>
<td>5.8</td>
<td>SIL</td>
</tr>
</tbody>
</table>

The Soil Climate Analysis Network (SCAN) program focuses on agricultural areas of the U.S. (Schaefer et al., 2007) and is composed of 239 stations in the U.S. territory. In the state of Alabama there are 18 SCAN stations that have been collecting data as early as 2002, recording: air temperature, precipitation accumulation and increment, relative humidity, soil temperature, SM percent, solar radiation, vapor pressure, and wind speed. SCAN uses Hydaprobe Analog dielectric reflectometers (2.5
Volt), at depths of 2-in, 4-in, 8-in, 20-in and 40-in to record SM at instantaneous function interval. Location of the Alabama stations are presented in Figure 3.1 and Table 3.2. SCAN data retrieved from testing stations in the study area were downloaded from the USDA National Resources Conservation Service (NRCS) as csv files (https://www.wcc.nrcs.usda.gov/scan/). SCAN network is connected to the National Soil Moisture Network (NSMN) that monitors SM conditions in the contiguous US, and at global scale to the International Soil Moisture Network (ISMN).
Table 3.2 Location of SCAN stations in Alabama

<table>
<thead>
<tr>
<th>Name</th>
<th>ID</th>
<th>County</th>
<th>Elev. (ft)</th>
<th>Lat.</th>
<th>Long.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAMU-JTG</td>
<td>2057</td>
<td>Madison</td>
<td>860</td>
<td>34.78333</td>
<td>-86.55</td>
</tr>
<tr>
<td>Bragg Farm</td>
<td>2078</td>
<td>Madison</td>
<td>798</td>
<td>34.89375</td>
<td>-86.6024</td>
</tr>
<tr>
<td>Broad Acres</td>
<td>2177</td>
<td>Montgomery</td>
<td>269</td>
<td>32.28393</td>
<td>-86.0525</td>
</tr>
<tr>
<td>Cullman-NAHRC</td>
<td>2113</td>
<td>Cullman</td>
<td>799</td>
<td>34.19492</td>
<td>-86.799</td>
</tr>
<tr>
<td>Dee River Ranch</td>
<td>2174</td>
<td>Pickens</td>
<td>160</td>
<td>33.10768</td>
<td>-88.31</td>
</tr>
<tr>
<td>Hodges</td>
<td>2055</td>
<td>Marshall</td>
<td>730</td>
<td>34.4448</td>
<td>-86.1656</td>
</tr>
<tr>
<td>Isbell Farms</td>
<td>2173</td>
<td>Colbert</td>
<td>603</td>
<td>34.81982</td>
<td>-87.9869</td>
</tr>
<tr>
<td>Koptis Farms</td>
<td>2180</td>
<td>Baldwin</td>
<td>135</td>
<td>30.5238</td>
<td>-87.698</td>
</tr>
<tr>
<td>Livingston-UWA</td>
<td>2114</td>
<td>Sumter</td>
<td>144</td>
<td>32.608</td>
<td>-88.1974</td>
</tr>
<tr>
<td>Morris Farms</td>
<td>2178</td>
<td>Macon</td>
<td>220</td>
<td>32.41222</td>
<td>-85.9103</td>
</tr>
<tr>
<td>Perdido Riv Farms</td>
<td>2181</td>
<td>Escambia</td>
<td>299</td>
<td>31.10923</td>
<td>-87.5528</td>
</tr>
<tr>
<td>River Road Farms</td>
<td>2182</td>
<td>Houston</td>
<td>107</td>
<td>31.01912</td>
<td>-85.0369</td>
</tr>
<tr>
<td>Selma</td>
<td>2176</td>
<td>Dallas</td>
<td>140</td>
<td>32.40392</td>
<td>-86.8914</td>
</tr>
<tr>
<td>Stanley Farm</td>
<td>2056</td>
<td>Morgan</td>
<td>635</td>
<td>34.43333</td>
<td>-86.6833</td>
</tr>
<tr>
<td>Sudduth Farms</td>
<td>2179</td>
<td>Winston</td>
<td>772</td>
<td>34.17973</td>
<td>-87.4562</td>
</tr>
<tr>
<td>Tuskegee</td>
<td>2115</td>
<td>Macon</td>
<td>400</td>
<td>32.43455</td>
<td>-85.748</td>
</tr>
<tr>
<td>Wedowee</td>
<td>2175</td>
<td>Randolph</td>
<td>934</td>
<td>33.33168</td>
<td>-85.5182</td>
</tr>
<tr>
<td>Wtars</td>
<td>2053</td>
<td>Madison</td>
<td>625</td>
<td>34.9</td>
<td>-86.5333</td>
</tr>
</tbody>
</table>
3.2. Data Preparation

3.2.1. Quality control of SCAN stations data

The NSMN asserts that their data is harmonized, and quality controlled using Quality Control algorithms (Quiring et al., 2016), and the ISMN flags suspicions values such spikes, signal saturation, readings at frozen conditions and values exceeding determined physical ranges (Dorigo et al., 2010, 2011, 2013). Despite these efforts, some authors still report networks data inconsistencies in both networks (Ford & Quiring, 2019; Liao et al., 2019).

In this study quality control of SCAN SM values was developed in two phases. In the first instance, it was followed the basic procedure describe in Xia et al. (2015) and Liao et al. (2019) and consisted essentially in the following actions:

- Verify that measured SM is between the geophysical ranges of 0.0 and 0.6 m$^3$/m$^3$. Values outside this range were flagged as spurious data.
- Verify that Measured SM does not exceed the in-situ soil porosity. Values of measured SM larger than the soil porosity at the corresponding depth and site were flagged as spurious.

A second instance of quality control consisted in the observation of abnormal patterns in SM, not linked to seasonality but most probably to sensor errors. In this second instance, a Cumulative Distribution Function was utilized to correct the anomalies.
### 3.2.2. Cumulative Distribution Function for SM correction

Systematics bias differences in SM were also observed in several sensor datasets and locations. The Cumulative Distribution Function (CDF) statistical tool was used to rescale these differences (Liu et al., 2011; Reichle & Koster, 2004; Wang et al., 2018). The CDF represents the cumulative probability that a random variable $X$ will take a value less than or equal to $X$:

$$F_X(X) = P(X \leq X)$$ (3.1)

In this study, CDF was used as an observation operator to convert series that had irregular SM mean ranges to match reliable SM observations in the same dataset. To illustrate the approach used in this study, the correction process for the Bragg Station SM data series is presented. The CDF was formed by creating a ranking of reliable data points of the evaluated dataset and then assimilating this rank to a polynomial function. A second ranking is then developed of the unreliable values. This second ranking is then fitted to the polynomial function created for the reliable data. Once the unreliable data is fitted, the values of that range are rescaled following the polynomial function. In the particular case of the Bragg station, it is observed that SM timeseries at depth of 8-in present an irregular pattern in the period 2018-2021 (Figure 3.3). The procedure mentioned before was followed to obtain the CDF polynomial correction function, which is presented as the red-colored curve in Figure 3.4, while the gray-colored curve indicates the unadjusted rank of the 8-in SM in the period 2018-2021. Figure 3.5 presents the corrected 8-in SM after the CDF correction. Figure 3.6 presents the variation of mean values of SM before and after the correction, for layers 4-in and 8-in at Bragg Station.
Table 3.3 presents the percentage of data corrected by station and layer. It is observed that some stations required less data intervention (Bragg, Broad, Selma), while wider corrections were required in others (Wedowee, Tuskegee).

Figure 3.3 Bragg station Bias in SM at 8 in layer, for the range period 2018-2021
Figure 3.4 CDF for the SM 8 in layer at Bragg Station. The red line represents the polynomial function associated with the rank of reliable observations (2006 to 2017). The gray line represents the rank of the values that present strong biases (period 2018-2021).

Figure 3.5 Corrected value of SM 8 in layer after the CDF.
Figure 3.6 Adjusted 8-in and 4-in SM after CDF Bragg Station
Table 3.3 Percentage of data corrected after CDF function by Station.

<table>
<thead>
<tr>
<th>STATION</th>
<th>LAYER</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-in %</td>
<td>4-in %</td>
<td>8-in %</td>
<td>20-in %</td>
</tr>
<tr>
<td>AAMU</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Bragg</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Broad</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Cullman-</td>
<td>0</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Dee River</td>
<td>17</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Hodges</td>
<td>0</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Isbell Farms</td>
<td>11</td>
<td>0</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Koptis Farms</td>
<td>0</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Morris Farms</td>
<td>55</td>
<td>55</td>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td>Perdido Riv</td>
<td>9</td>
<td>23</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>River Road</td>
<td>0</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Selma</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Stanley Farm</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tuskegee</td>
<td>0</td>
<td>37</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>Wedowee</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>44</td>
</tr>
<tr>
<td>Wtars</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>18</td>
</tr>
</tbody>
</table>
3.3. PET Estimation

Daily PET was calculated following the FAO-56 Penman-Monteith methodology (Allen et al., 1998) for every location of the SCAN stations in Alabama. In this methodology PET estimations are expressed as:

\[ PET = \frac{0.408 \Delta (R_n - G) + \gamma u_2(e_s - e_a) \frac{900}{T + 273}}{\Delta + \gamma (1 + 0.34 u_2)} \]  

(3.2)

where PET (mm/d) is the reference evapotranspiration rate, \( T \) is the mean air temperature (°C), \( u_2 \) is the wind speed (m/s) at 2 m above the ground, \( R_n \) is the net radiation (MJm\(^{-2}\)h\(^{-1}\)) and \( G \) is the soil heat flux (MJm\(^{-2}\)h\(^{-1}\)). The Penman-Monteith methodology is widely accepted as a reliable methodology to estimate PET. Its disadvantage relies on the number of climatological variables needed for the estimation, that are not always available at local level. SCAN stations collect instantaneous, hourly and daily data of all the components of the Penman-Monteith equation.

To compare the values of PET obtained with the PM methodology, several other estimation methods were analyzed that require less amount of climate variables, including empirical methodologies. The objective of this comparison is to evaluate the performance of the estimations that require less climate information and their performance. The empirical methods included the Priestley-Taylor, the Hargreaves-Samani and the Blaney-Criddle estimations of PET.
The Priestley-Taylor PET (Priestley & Taylor, 1972) is a simplification of the Penman formulation. Vapor deficit and convection terms are reduced to an empirical constant $\alpha$, and the only observation required is the radiation, and is denoted as:

$$PET = \alpha \frac{\Delta (R_n - G)}{(\Delta + \gamma)}$$

(3.3)

where $R_n$ is net radiation (mm/d), $G$ is soil heat flux (mm/d), $\Delta$ is the gradient of saturated vapor pressure (kPa/$^\circ$C), and $\gamma$ is the psychometric factor (kPa/$^\circ$C). The $\alpha$ factor accounts for the aerodynamic component and has a typical value of 1.26 for humid areas.

Temperature based Hargreaves-Samani equation for PET (Droogers & Allen, n.d.-b) includes a component of solar radiation and Temperature:

$$PET = 0.408 \times 0.0025R (T_a + 16.8)(T_{max} - T_{min})^{0.5}$$

(3.4)

where $T_a$, $T_{max}$ and $T_{min}$ are the mean, maximum and minimum air temperatures, respectively ($^\circ$C), and $R$ is the extraterrestrial radiation (MJm$^{-2}$day$^{-1}$).

The Blaney Criddle equation requires just temperature datasets and is mainly used in stations with limited weather information:

$$PET = \rho \times (0.457 \times T_{mean} + 8.128)$$

(3.5)

where $\rho$ is the mean daily percentage of annual daytime hours, and $T_{mean}$ is the mean air temperature.

Penman-Monteith and Hargreaves methodologies had been compared in previous studies at global scale (Droogers & Allen, n.d.-a) displaying a statistical acceptable agreement among both methods. All the estimations methods presented above require less information than Penman-Monteith, then their usage is recommended when complete weather data is unavailable.
To further evaluate the Penman Monteith PET, the Moderate Resolution Imaging Spectroradiometer (MODIS) Evapotranspiration product was used for validation. MODIS is a spectral radiometer carried aboard NASA’s Terra and Aqua satellites. It collects data in 36 spectral bands (wavelengths) with each satellite offering two overpasses each day for any location on earth. The MOD16 (Mu et al., 2007) product uses an algorithm based on MODIS satellite imagery and global meteorology data to produce ET, latent energy (LE), potential ET and potential LE. The algorithm is constructed around the Penman-Monteith equation. The output is summed 8-day, monthly and annual ET at a 1 km² spatial resolution. MODIS AET and MODIS PET were compared to the calculated Penman Monteith PET in this study and the SWBM AET for validation of the estimations.

The root-mean square error (RMSE), and the coefficient of determination \( R^2 \) were used for the evaluation of the PET estimated by the models mentioned and the Penman-Monteith (FAO-56) methodology. The RMSE, and \( R^2 \) are defined as:

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}
\]  

\[R^2 = \frac{[\sum_{i=1}^{n}(P_i - \bar{P})(O_i - \bar{O})]^2}{[\sum_{i=1}^{n}(P_i - \bar{P})^2 \sum_{i=1}^{n}(O_i - \bar{O})^2]}\]

Where \( P_i \) and \( O_i \) are the predicted and observed values, respectively. \( \bar{P} \) and \( \bar{O} \) are the average of \( P_i \) and \( O_i \) and \( n \) is the total number of observations.

Table 3.4 summarizes the statistical performance of Priestley Taylor, Blaney-Criddle and Hargreaves-Samani PET compared to the Penman-Monteith PET estimation at every station, in terms of the coefficient of determination \( R^2 \).
The mean monthly Penman Monteith, Blaney Criddle, Priestley Taylor and Hargreaves-Samani PET estimation for every station is presented in Figure 3.7.

**Table 3.4** Statistical Performance of PET Methods versus the Penman-Monteith model for estimating monthly PET during the study period (2002-2022)

<table>
<thead>
<tr>
<th>Station</th>
<th>PET Estimation Method</th>
<th>$R^2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTARS</td>
<td>Priestley Taylor</td>
<td>0.81</td>
<td>0.48</td>
</tr>
<tr>
<td>HODGES</td>
<td>Priestley Taylor</td>
<td>0.90</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.51</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.62</td>
<td>0.76</td>
</tr>
<tr>
<td>STANLEY</td>
<td>Priestley Taylor</td>
<td>0.84</td>
<td>0.41</td>
</tr>
<tr>
<td>AAMU</td>
<td>Priestley Taylor</td>
<td>0.90</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.51</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.62</td>
<td>0.76</td>
</tr>
<tr>
<td>BRAGG</td>
<td>Priestley Taylor</td>
<td>0.84</td>
<td>0.47</td>
</tr>
<tr>
<td>CULLMAN</td>
<td>Priestley Taylor</td>
<td>0.87</td>
<td>0.44</td>
</tr>
<tr>
<td>TUSKEGEE</td>
<td>Priestley Taylor</td>
<td>0.81</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.52</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>ISBELL</td>
<td>Priestley Taylor</td>
<td>0.81</td>
<td>0.52</td>
</tr>
<tr>
<td>DEE RIVER</td>
<td>Priestley Taylor</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>WEDOWEE</td>
<td>Priestley Taylor</td>
<td>0.86</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.51</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.59</td>
<td>0.74</td>
</tr>
<tr>
<td>SELMA</td>
<td>Priestley Taylor</td>
<td>0.88</td>
<td>0.40</td>
</tr>
<tr>
<td>BROAD</td>
<td>Priestley Taylor</td>
<td>0.81</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.52</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>MORRIS</td>
<td>Priestley Taylor</td>
<td>0.90</td>
<td>0.37</td>
</tr>
<tr>
<td>SUDDUTH</td>
<td>Priestley Taylor</td>
<td>0.87</td>
<td>0.43</td>
</tr>
<tr>
<td>KOPTIS</td>
<td>Priestley Taylor</td>
<td>0.88</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.20</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.58</td>
<td>0.71</td>
</tr>
<tr>
<td>PERDIDO</td>
<td>Priestley Taylor</td>
<td>0.86</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.43</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.73</td>
<td>0.63</td>
</tr>
<tr>
<td>RIVER ROAD</td>
<td>Priestley Taylor</td>
<td>0.80</td>
<td>0.51</td>
</tr>
</tbody>
</table>
Figure 3.7 Mean monthly PET calculated from the Penman Monteith, Priestley Taylor, Blaney Criddle, and Hargreaves-Samani estimations for SCAN stations in Alabama.

3.4. AET Determination

To obtain daily values of AET, a model was developed based on a soil-water balance concept, using the SCAN agrometeorological daily data as main inputs. The schematic method framework is presented in Figure 3.8.

The daily Soil Water Balance (SWBM) model created consists in one layer of SM reservoir defined by the root depth of the typical vegetation found in the SCAN stations, the Bermuda grass, which is located between 4-in and 8-in deep (Fuentealba et al., 2015). The SWBM is controlled by the inputs of daily values of precipitation incremental,
changes in water storage in the layer and the outputs of runoff, AET, and deep percolation (drainage) to the lower layers. Capillarity and horizontal water flux below surface are considered negligible. External irrigation was also neglected.

In the SWBM, water storage increases when inputs, as precipitation exceeds the outputs. If the outputs exceed the inputs, the soil water storage decreases.

The SWBM is then formulated as function of the daily fluctuation of the soil water storage, and is expressed as:

\[ \Delta S = P_i - DP_i - AET_i - RO_i \]  

(3.8)

\[ \Delta S = SM_i h - SM_{i-1} h \]  

(3.9)

where the sub-index \( i \) express days. A description of the parameters expressed in the SWBM is presented in Table 3.5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>Soil water content of the layer</td>
<td>mm/mm</td>
</tr>
<tr>
<td>h</td>
<td>Layer depth</td>
<td>mm</td>
</tr>
<tr>
<td>P</td>
<td>Precipitation increments</td>
<td>mm</td>
</tr>
<tr>
<td>DP</td>
<td>Deep Percolation</td>
<td>mm</td>
</tr>
<tr>
<td>AET</td>
<td>Actual Evapotranspiration</td>
<td>mm</td>
</tr>
<tr>
<td>RO</td>
<td>Surface Runoff.</td>
<td>mm</td>
</tr>
<tr>
<td>( \Delta S )</td>
<td>Soil water storage variation</td>
<td>mm</td>
</tr>
</tbody>
</table>
Figure 3.8 SWBM framework of AET daily estimation for SCAN stations in Alabama
Daily data of SM and P are obtained from the SCAN network. SCAN network has SM sensors at depths 2-in, 4-in, 8-in, 20-in and 40-in. Sensors display instantaneous readings. SM introduced in the model corresponds to the daily average SM at every layer.

Water storage is a function of soil pore space and pore size distribution determined by texture and structure of the soil. Finer soils as clays have smaller size particles and higher storage capacity, while loamy or coarser soils tend to have low water holding capacity. To obtain ΔS, daily average variations of SM reading in sensors 2-in, 4-in and 8-in were considered.

Deep Percolation (DP) is defined as the amount of water that moves out below the plant root zone. It is calculated in the SWBM as a positive daily increase in SM below the root zone. To estimate DP, daily variation of SM in layers 20-in and 40-in are considered.

Surface Runoff (RO) is referred to as flow of water that occurs when the soil is infiltrated to full capacity and the excess water from rainfall flows over the land surface. RO was calculated using an eight days antecedent rainfall (P₈) (Upreti & Ojha, 2020) on runoff prediction combined with the traditional Curve Number (CN) method developed by the Soil conservation Service (SCS) to estimate total runoff from agricultural watersheds (Lim et al., 2006; S. K. Mishra & Singh, 2003; Williams, 1989). Factors as land use, soil texture, agricultural management and hydrological conditions were considered in this methodology. The surface runoff (SR) is expressed as:

\[
RO = \frac{P(P + P₈)}{(P + P₈ + s)}, \text{ for } P > 0.2s
\]

(3.10)
where \( P \) (mm) is precipitation incremental, \( P_8 \) is the previous 8 days rainfall (mm), and \( s \) (mm) is the potential maximum retention at the initial time of the storm, and is a function of the CN number calculated according to the expression:

\[
s = 2.54 \left( \frac{100}{CN} - 1 \right)
\]  

(3.11)

CN is the curve number obtained from tables at the Technical Release 55 (TR-55) of the Soil Conservation Service (*Urban Hydrology for Small Watersheds*, 1986) that categorizes four types of soil hydrological groups, based on soil texture, slope and land cover.

The SWMD simulates the AET as the water lost to the atmosphere by direct evaporation from the soil and water lost through transpiration of the vegetation. To account for either surplus (AET>PET) or negative (AET<0) values in AET calculation, two buffers are created in the model. In the first instance, the daily DP is extended to the variations in SM storage in the layer 40-in, to account for the excess. In the second situation, it is evaluated the daily \( \Delta P \) (precipitation increment). If there is an increment of precipitation from the previous day (\( \Delta P > 0 \)), thus is considered that excess moisture in the soil has still not been account by the sensors, and the AET reaches PET. If \( \Delta P \leq 0 \), AET is considered null.

Daily AET was estimated from this soil water model for every SCAN station in Alabama. It is observed in Figure 3.9 the components of the SWBM for the Bragg station, year 2008. There is a good correspondence of fluctuations of precipitation increments with the variation patterns of \( \Delta S \), RO and DP. It is also observed that precipitation increment is the main driver for AET fluctuations. A representation of the water balance for colder months (December, January and February) is presented in Figure
3.10, and for warmer months (June, July, August) is presented in Figure 3.11, both at Bragg Station. During the winter months, PET and AET are lower than the warmer months, due to colder temperatures and reduced solar radiation, in addition to that vegetation go dormant, with reduced transpiration rates. Another characteristic in the wintertime are higher precipitation rates, and increased soil water storage. In the other hand, vegetation growth and evapotranspiration demand, added to less significant precipitations increment, are greatly influencing the water storage availability in the ground during the warmer season. The values of PET and AET are also higher in the warmer months. A timeseries of Penman Monteith PET and SWBM AET is presented in Figure 3.12, for the period 2004-2022. Missing AET values are due to gaps in source climate information as observed in the figure. The seasonality observed in PET is followed as well in the AET pattern, with peaks of PET and AET during the warmer seasons, and lows during the colder weather, Figure 3.9.

![Figure 3.9 Daily SWBM with cumulative components of the daily model. Bragg Station, year 2008.](image)
Figure 3.10 SBM parameters – Bragg Station time series Dec 2009 to Feb 2010

Figure 3.11 SBM parameters – Bragg Station time series Jun-to-Aug 2017
Among the limitations of the present SBWM, can be mentioned: assumptions of soil-water dynamics mentioned before and the quality of climatological data.

![PET vs. AET Bragg Station](image)

**Figure 3.12** Penman Monteith PET and SWBN AET time series for Bragg Station

### 3.5. Determination of $f_{AW}$ and $f_{PET}$

Fractional $f_{PET}$ obtained as a ratio of AET and PET for every station, according to the relationship:

$$f_{PET} = \frac{AET}{PET} \tag{3.12}$$

Likewise, the fraction of available water content, $f_{AW}$ was obtained based on SM parameters at layers 2-in, 4-in, and 8-in and soil matric potential indexes (FC and WP) for the same layers at every station.
\[ f_{AW} = \frac{\theta - \theta_{wp}}{\theta_{fc} - \theta_{wp}} \]  

(3.13)

The selection of layers for \( f_{AW} \) evaluation was based on the interest of this study to clarify the effects of the AET on the SM at root-zone of the vegetation, where the rate of water uptake by plants is influenced by the soil water availability and the evaporative demand of the atmosphere.
Chapter 4. Analysis of Results

4.1. PET Data Analysis

Accurate estimation of PET is a critical step before the quantification of $f_{\text{PET}}$. Five PET estimates methodologies were examined to summarize the variability of PET in the humid climate of Alabama. Each dataset estimates PET differently, from energy balance approaches, combination methodologies, and satellite observations (MODIS). A performance evaluation to compare monthly estimations of the Penman-Monteith to the Priestley Taylor, the Hargreaves – Samani, and the Blaney Criddle PET is presented in Table 3.4. Figure 4.1 presents the time series of the mentioned methodologies. Description of every one of these methodologies were presented in Chapter 2 and Chapter 3. It is observed that time patterns exhibited by each estimation are consistent with seasonality, with warmer months exhibiting higher PET values, while colder months have low values of PET. Another interesting observation is after comparing empirical estimations and the Penman Monteith, the Priestley Taylor presents a better statistical fitting based on the total least squares linear regression, with $R^2$ between 0.90 and 0.90, followed by the Hargreaves-Samani estimation, with $R^2$ between 0.59 and 0.73. Blaney-Criddle presented the lower fitting estimations, with $R^2$ in the order of 0.40 to 0.50. These findings are consistent with other studies developed for regions with humid climates (Y. Feng et al., 2016; J. Lu et al., 2005; Song et al., 2019). This study valued these methodologies with the aim to recommend an empirical estimation that require less
climate variables than the Penman Monteith equation, particularly for regions with similar climatology, where complete climate information is not available. Considering that the Hargreaves-Samani requires only temperature information and a radiation component, it could represent a valid option for PET estimations in humid climate regions when limited data is available.

To add further evaluation to the Penman Monteith PET performance, it was compared to the satellite MODIS PET products, which has temporal resolution of 8-day aggregate. Summary of the statistical correlations MODIS and Penman Monteith PET-8-day are presented in Table 4.3. Figure 4.2 presents time series of the two estimations for the Wtars station, and Figure 4.3 present the plot of least squares linear regression for the two PET estimations along all the stations of this study. It is observed that time series patterns exhibited by both estimations are consistent with seasonality, with warmer months exhibiting higher PET values, while colder months have low values of PET. It is also observed that the MOD16 PET exhibit higher estimates than the Penman Monteith, and the tendency seems higher in warmer months. Statical comparison of both estimations based on the total least squares linear regression (Table 4.3), shows $R^2$ between 0.68 and 0.97, which indicate a good statistical fitting among both estimations of PET. These findings are consisting with previous PET studies for the South Eastern US ((Ellenburg, n.d.), and provide reliability to further calculations of the fractional potential evapotranspiration, based on the Penman Monteith PET estimations calculated un this study.
Finally, a summary of Penman Monteith PET monthly average estimations is presented in Table 4.2 for stations in Alabama, where is again observed the seasonal variability of the PET estimations.
Figure 4.1 PET empirical estimations time series for WTAR Station
Table 4.1 Statistical Performance of Priestley Taylor, Blaney-Criddle, and Hargreaves-Samani PET estimations versus the Penman-Monteith PET estimation for every station.

<table>
<thead>
<tr>
<th>Station</th>
<th>PET Estimation Method</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTARS</td>
<td>Priestley Taylor</td>
<td>0.81</td>
</tr>
<tr>
<td>HODGES</td>
<td>Priestley Taylor</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.62</td>
</tr>
<tr>
<td>STANLEY</td>
<td>Priestley Taylor</td>
<td>0.84</td>
</tr>
<tr>
<td>AAMU</td>
<td>Priestley Taylor</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Hargreaves - Samani</td>
<td>0.62</td>
</tr>
<tr>
<td>BRAGG</td>
<td>Priestley Taylor</td>
<td>0.84</td>
</tr>
<tr>
<td>CULLMAN</td>
<td>Priestley Taylor</td>
<td>0.87</td>
</tr>
<tr>
<td>TUSKEGEE</td>
<td>Priestley Taylor</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Hargreaves - Samani</td>
<td>0.73</td>
</tr>
<tr>
<td>ISBELL</td>
<td>Priestley Taylor</td>
<td>0.81</td>
</tr>
<tr>
<td>WEDOWEE</td>
<td>Priestley Taylor</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Hargreaves - Samani</td>
<td>0.59</td>
</tr>
<tr>
<td>SELMA</td>
<td>Priestley Taylor</td>
<td>0.88</td>
</tr>
<tr>
<td>BROAD</td>
<td>Priestley Taylor</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Hargreaves - Samani</td>
<td>0.73</td>
</tr>
<tr>
<td>MORRIS</td>
<td>Priestley Taylor</td>
<td>0.90</td>
</tr>
<tr>
<td>SUDDUTH</td>
<td>Priestley Taylor</td>
<td>0.87</td>
</tr>
<tr>
<td>KOPTIS</td>
<td>Priestley Taylor</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Hargreaves - Samani</td>
<td>0.58</td>
</tr>
<tr>
<td>PERDIDO</td>
<td>Priestley Taylor</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Blaney Criddle</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Hargreaves-Samani</td>
<td>0.73</td>
</tr>
<tr>
<td>RIVER ROAD</td>
<td>Priestley Taylor</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Figure 4.2 Mod16 PET and Penman Monteith PET time series for WTARS Station
Table 4.2 Averaged Monthly Penman Monteith PET (mm) for SCAN Stations

<table>
<thead>
<tr>
<th>Station/Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAMU</td>
<td>22.17</td>
<td>29.41</td>
<td>49.67</td>
<td>66.11</td>
<td>87.64</td>
<td>98.44</td>
<td>101.52</td>
<td>87.99</td>
<td>58.12</td>
<td>41.15</td>
<td>26.53</td>
<td>19.70</td>
</tr>
<tr>
<td>BRAGG</td>
<td>33.05</td>
<td>41.18</td>
<td>70.99</td>
<td>89.99</td>
<td>104.09</td>
<td>115.81</td>
<td>124.14</td>
<td>114.89</td>
<td>93.78</td>
<td>65.66</td>
<td>43.40</td>
<td>32.14</td>
</tr>
<tr>
<td>ISBELL</td>
<td>35.55</td>
<td>44.90</td>
<td>70.39</td>
<td>87.12</td>
<td>103.26</td>
<td>115.86</td>
<td>103.90</td>
<td>78.31</td>
<td>57.20</td>
<td>36.83</td>
<td>31.57</td>
<td>25.33</td>
</tr>
<tr>
<td>MORRIS</td>
<td>29.09</td>
<td>36.28</td>
<td>63.68</td>
<td>76.98</td>
<td>103.38</td>
<td>97.71</td>
<td>114.60</td>
<td>107.32</td>
<td>80.18</td>
<td>51.88</td>
<td>31.01</td>
<td>25.33</td>
</tr>
<tr>
<td>RIVERROAD</td>
<td>41.64</td>
<td>50.35</td>
<td>84.30</td>
<td>90.60</td>
<td>103.51</td>
<td>86.13</td>
<td>92.25</td>
<td>79.36</td>
<td>64.08</td>
<td>56.96</td>
<td>41.12</td>
<td>34.38</td>
</tr>
<tr>
<td>PERDIDO</td>
<td>35.90</td>
<td>42.40</td>
<td>64.63</td>
<td>72.22</td>
<td>91.90</td>
<td>92.60</td>
<td>102.25</td>
<td>87.66</td>
<td>69.94</td>
<td>55.32</td>
<td>36.41</td>
<td>30.37</td>
</tr>
<tr>
<td>STANLEY</td>
<td>28.30</td>
<td>33.71</td>
<td>54.78</td>
<td>65.61</td>
<td>80.11</td>
<td>87.85</td>
<td>92.48</td>
<td>88.39</td>
<td>66.80</td>
<td>45.30</td>
<td>32.46</td>
<td>27.68</td>
</tr>
<tr>
<td>SUDDUTH</td>
<td>29.08</td>
<td>37.17</td>
<td>64.22</td>
<td>80.33</td>
<td>96.57</td>
<td>101.82</td>
<td>108.62</td>
<td>91.77</td>
<td>76.02</td>
<td>54.00</td>
<td>30.91</td>
<td>25.10</td>
</tr>
<tr>
<td>WEDOWEE</td>
<td>34.64</td>
<td>40.28</td>
<td>63.27</td>
<td>77.38</td>
<td>92.22</td>
<td>90.75</td>
<td>101.70</td>
<td>98.32</td>
<td>82.24</td>
<td>59.41</td>
<td>38.88</td>
<td>28.76</td>
</tr>
<tr>
<td>WTARS</td>
<td>35.05</td>
<td>42.46</td>
<td>72.80</td>
<td>90.28</td>
<td>105.51</td>
<td>112.28</td>
<td>102.98</td>
<td>105.47</td>
<td>84.73</td>
<td>60.60</td>
<td>41.57</td>
<td>32.28</td>
</tr>
<tr>
<td>HODGES</td>
<td>24.55</td>
<td>31.99</td>
<td>54.32</td>
<td>72.56</td>
<td>95.86</td>
<td>106.84</td>
<td>109.41</td>
<td>95.75</td>
<td>64.98</td>
<td>47.88</td>
<td>31.25</td>
<td>22.24</td>
</tr>
<tr>
<td>CULLMAN</td>
<td>35.88</td>
<td>45.83</td>
<td>75.51</td>
<td>95.64</td>
<td>109.34</td>
<td>127.74</td>
<td>132.93</td>
<td>119.64</td>
<td>91.01</td>
<td>65.75</td>
<td>43.32</td>
<td>33.43</td>
</tr>
<tr>
<td>BROAD</td>
<td>40.43</td>
<td>48.20</td>
<td>77.13</td>
<td>89.60</td>
<td>103.92</td>
<td>104.94</td>
<td>119.40</td>
<td>109.59</td>
<td>88.98</td>
<td>74.95</td>
<td>49.04</td>
<td>38.52</td>
</tr>
<tr>
<td>TUSKEGEE</td>
<td>42.69</td>
<td>53.21</td>
<td>84.26</td>
<td>101.79</td>
<td>117.12</td>
<td>127.89</td>
<td>136.31</td>
<td>124.75</td>
<td>100.07</td>
<td>70.35</td>
<td>47.78</td>
<td>38.17</td>
</tr>
<tr>
<td>KOPTIS</td>
<td>32.79</td>
<td>42.48</td>
<td>65.70</td>
<td>83.82</td>
<td>105.88</td>
<td>98.12</td>
<td>105.36</td>
<td>84.60</td>
<td>79.12</td>
<td>64.56</td>
<td>41.51</td>
<td>32.26</td>
</tr>
<tr>
<td>DEERIVER</td>
<td>28.72</td>
<td>30.20</td>
<td>49.20</td>
<td>56.21</td>
<td>71.13</td>
<td>68.96</td>
<td>74.03</td>
<td>70.83</td>
<td>62.70</td>
<td>55.16</td>
<td>35.29</td>
<td>27.73</td>
</tr>
<tr>
<td>SELMA</td>
<td>27.32</td>
<td>35.65</td>
<td>57.92</td>
<td>73.05</td>
<td>101.90</td>
<td>102.78</td>
<td>113.56</td>
<td>98.09</td>
<td>81.97</td>
<td>52.27</td>
<td>28.70</td>
<td>22.81</td>
</tr>
</tbody>
</table>
Figure 4.3 Linear Regression MODIS PET – Penman Monteith PET 8-day aggregation by Station
Table 4.3 Evaluation of $R^2$ for Penman Monteith PET and MOD16 PET for Scan Stations

<table>
<thead>
<tr>
<th>STATION</th>
<th>MODIS PET – PM PET $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAMU</td>
<td>0.87</td>
</tr>
<tr>
<td>BRAGG</td>
<td>0.84</td>
</tr>
<tr>
<td>ISBELL</td>
<td>0.77</td>
</tr>
<tr>
<td>MORRIS</td>
<td>0.81</td>
</tr>
<tr>
<td>RIVERROAD</td>
<td>0.77</td>
</tr>
<tr>
<td>PERDIDO</td>
<td>0.73</td>
</tr>
<tr>
<td>STANLEY</td>
<td>0.79</td>
</tr>
<tr>
<td>SUDDUTH</td>
<td>0.79</td>
</tr>
<tr>
<td>WEDOWEE</td>
<td>0.81</td>
</tr>
<tr>
<td>WTARS</td>
<td>0.78</td>
</tr>
<tr>
<td>HODGES</td>
<td>0.86</td>
</tr>
<tr>
<td>CULLMAN</td>
<td>0.86</td>
</tr>
<tr>
<td>BROAD</td>
<td>0.80</td>
</tr>
<tr>
<td>TUSKEGEE</td>
<td>0.85</td>
</tr>
<tr>
<td>KOPTIS</td>
<td>0.73</td>
</tr>
<tr>
<td>DEERIVER</td>
<td>0.68</td>
</tr>
<tr>
<td>SELMA</td>
<td>0.75</td>
</tr>
</tbody>
</table>

4.2. AET Data Analysis

AET calculated after the SWBM, presented in Chapter 3, is evaluated in this section. Daily AET for every station was obtained with a Soil Water Balance Model (SWBM). A time series plot of Penman- Monteith PET and SWBM AET calculated for Wtars Station (medium fine soil) is shown in Figure 4.5, and for Selma Station (coarse soil) in Figure 4.6, where the seasonal effect is observed. Information about characteristic of the underlying soils for stations was presented in Table 3.1.

Monthly AET variations by station are presented in Table 4.4. Lower values of monthly mean AET for the stations are observed in November, December, and January,
while higher values are observed from May through August, with July being the month with highest average AET for the state. Generally, obtained SWBM AET datasets are validated by the annual cycle of AET in the Southeastern United States, where in winter time AET values are the lowest and summer values highest in average (J. Lu et al., 2003).
Figure 4.4 SM and Components of the SWBM - Bragg Station considering inputs: Precipitation Increment, and outputs Soil-Water Storage, Deep Percolation, AET and Runoff
Figure 4.5 Time series Penman Monteith PET and SWBM AET for Wtars Station, with underlying finer soils
Figure 4.6 Time series Penman Monteith PET and SWBM AET Selma Station, with underlying coarse soils
<table>
<thead>
<tr>
<th>Station/Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRAGG</td>
<td>15.27</td>
<td>19.22</td>
<td>32.66</td>
<td>39.58</td>
<td>29.81</td>
<td>34.47</td>
<td>34.18</td>
<td>29.64</td>
<td>23.92</td>
<td>18.06</td>
<td>17.02</td>
<td>17.34</td>
</tr>
<tr>
<td>ISBELL</td>
<td>18.26</td>
<td>25.60</td>
<td>35.30</td>
<td>42.92</td>
<td>32.66</td>
<td>30.16</td>
<td>28.38</td>
<td>23.66</td>
<td>20.03</td>
<td>22.10</td>
<td>16.53</td>
<td>17.06</td>
</tr>
<tr>
<td>RIVER R</td>
<td>17.44</td>
<td>18.71</td>
<td>26.73</td>
<td>27.00</td>
<td>23.09</td>
<td>27.00</td>
<td>20.16</td>
<td>17.77</td>
<td>11.81</td>
<td>12.51</td>
<td>11.11</td>
<td>13.55</td>
</tr>
<tr>
<td>STANLEY</td>
<td>12.72</td>
<td>18.30</td>
<td>28.62</td>
<td>38.87</td>
<td>40.29</td>
<td>40.65</td>
<td>47.26</td>
<td>33.90</td>
<td>21.48</td>
<td>18.46</td>
<td>17.21</td>
<td>15.08</td>
</tr>
<tr>
<td>SUDDUTH</td>
<td>13.38</td>
<td>17.46</td>
<td>26.53</td>
<td>35.89</td>
<td>41.37</td>
<td>35.45</td>
<td>36.03</td>
<td>39.75</td>
<td>28.35</td>
<td>21.26</td>
<td>11.94</td>
<td>12.91</td>
</tr>
<tr>
<td>WEDOWEE</td>
<td>13.47</td>
<td>17.39</td>
<td>29.99</td>
<td>29.49</td>
<td>24.08</td>
<td>21.64</td>
<td>24.85</td>
<td>23.87</td>
<td>23.91</td>
<td>15.89</td>
<td>10.21</td>
<td>12.88</td>
</tr>
<tr>
<td>WTARS</td>
<td>15.63</td>
<td>18.69</td>
<td>28.78</td>
<td>35.28</td>
<td>33.00</td>
<td>31.18</td>
<td>26.63</td>
<td>25.74</td>
<td>17.21</td>
<td>16.97</td>
<td>16.83</td>
<td>16.50</td>
</tr>
<tr>
<td>CULLMAN</td>
<td>11.65</td>
<td>15.25</td>
<td>24.87</td>
<td>30.59</td>
<td>25.25</td>
<td>21.85</td>
<td>25.05</td>
<td>24.76</td>
<td>18.65</td>
<td>11.63</td>
<td>10.00</td>
<td>12.58</td>
</tr>
<tr>
<td>BROAD</td>
<td>22.04</td>
<td>22.40</td>
<td>32.75</td>
<td>31.10</td>
<td>34.17</td>
<td>31.52</td>
<td>33.90</td>
<td>34.15</td>
<td>25.67</td>
<td>25.14</td>
<td>17.56</td>
<td>17.65</td>
</tr>
<tr>
<td>TUSKEGEE</td>
<td>24.87</td>
<td>31.56</td>
<td>39.50</td>
<td>40.23</td>
<td>33.75</td>
<td>36.03</td>
<td>43.69</td>
<td>40.24</td>
<td>27.15</td>
<td>24.16</td>
<td>18.62</td>
<td>20.85</td>
</tr>
<tr>
<td>DEE RIV</td>
<td>12.54</td>
<td>13.28</td>
<td>18.59</td>
<td>22.96</td>
<td>19.54</td>
<td>21.23</td>
<td>28.63</td>
<td>25.06</td>
<td>22.37</td>
<td>16.78</td>
<td>10.74</td>
<td>12.31</td>
</tr>
<tr>
<td>SELMA</td>
<td>12.60</td>
<td>16.28</td>
<td>22.11</td>
<td>16.08</td>
<td>22.98</td>
<td>18.51</td>
<td>25.65</td>
<td>19.59</td>
<td>16.52</td>
<td>10.57</td>
<td>7.32</td>
<td>10.25</td>
</tr>
</tbody>
</table>

Table 4.4: Aggregated Monthly SWBM AET (mm) for SCAN Stations
The SWBM is based on the conceptualization of the law of conservation of mass: any change in a soil water content over a given period of time must be equal to the amount of water that was withdrawn from it. Analyzing the five components of the SWBM and fluctuations of SM for the same time period, in a station with underlying fine soils, Bragg station located in North Alabama, it is interesting to see the dynamics of the soil reservoir under variations of the water availability (Figure 4.4). In the time frame observed of 90 days, there is an interesting regime of precipitation ranging from 20 mm to more than 100 mm increment. With the incremental of Precipitation (Input) a response variation in the other components of the model is noted (outputs), deep percolation increments once the FC of the layer is achieved. Runoff is also very related to the precipitation regime and given the 8-day period analyzed for the antecedent moisture conditions it is expected to have runoff situations, especially after several days of rain. The other two components: soil water storage and AET show a particular interrelation. Soil water storage increases with precipitation, but decreases rapidly in between periods of rain, particularly in warm stations, up to situation where the storage is negative in between rain occurrence. AET fluctuations have seemingly a time gap difference with soil water storage increments and decrements, and this might be related to the stomatal control of the plants and the mechanism that the vegetation exerts in controlling the transpiration process in situation of water stress. This characteristic is consistent with observations of previous research (Dong et al., 2022). It is important to mention.

To add further evaluation to the SWBM AET performance, datasets were compared to the satellite MODIS AET product, which has temporal resolution of 8-day
aggregate and produced at 500 m spatial resolution. Summary of the statistical
correlations MODIS and SWBM AET 8-day are presented in Table 4.5. Plot of least
squares linear regression for the two AET estimations along all the stations of this study
is presented in Figure 4.7. It is observed that the MOD16 AET exhibits greater estimates
than the SWBM AET, and this tendency seems more elevated in warmer months.
Statistical comparison of both estimations based on the total least squares linear
regression, shows $R^2$ between 0.06 and 0.41 among all the stations, which indicates a low
to fair statistical fitting among both estimations of AET.

Pearson's Correlation coefficient ($r$) was also evaluated among the two AET
estimates. Pearson's correlation coefficient is obtaining dividing the covariance of the two
variables by the product of their standard deviations, and is expressed as:

$$
\rho_{x,y} = \frac{COV(X,Y)}{\sqrt{\bar{X}\bar{Y}}}
$$

(4.1)

where the covariance is a measure of interdependence of two data sets. Pearson
correlation among monthly averages of both estimations show values between 0.71 to
0.95, which indicates a strong positive linear relationship among the MOD16 AET and
SWBM AET estimates.

MOD16 reports mean absolute errors of 24% for AET measurements, and 10-30% range of the accuracy of the AET observations (Mu et al., 2007, 2011; Velpuri et al.,
2013). Similar research employing soil water balance model at field scale report errors in
the order of 16% for seasonal AET (J. L. Chopart, 1990). To determine the actual error of
the SWBM AET estimations it is required real AET measurements that are not available
for the study area. Thus, comparison to the MOD16 AET offer a reasonable evaluation of
the performance of this study model.
A summary of SWBM AET monthly average estimations is presented in Table 4.4 for stations in Alabama, where is observed the seasonal variability of the AET.

**Table 4.5 Evaluation of R² for SWBM AET and MOD16 AET for Scan Stations**

<table>
<thead>
<tr>
<th>STATION</th>
<th>MODIS AET – SWBM AET R²</th>
<th>MODIS AET – SWBM AET Pearson correlation r</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAMU</td>
<td>0.20</td>
<td>0.85</td>
</tr>
<tr>
<td>BRAGG</td>
<td>0.24</td>
<td>0.85</td>
</tr>
<tr>
<td>ISBELL</td>
<td>0.09</td>
<td>0.71</td>
</tr>
<tr>
<td>MORRIS</td>
<td>0.30</td>
<td>0.93</td>
</tr>
<tr>
<td>RIVERROAD</td>
<td>0.09</td>
<td>0.53</td>
</tr>
<tr>
<td>PERDIDO</td>
<td>0.31</td>
<td>0.94</td>
</tr>
<tr>
<td>STANLEY</td>
<td>0.37</td>
<td>0.91</td>
</tr>
<tr>
<td>SUDDUTH</td>
<td>0.41</td>
<td>0.95</td>
</tr>
<tr>
<td>WEDOWEE</td>
<td>0.22</td>
<td>0.74</td>
</tr>
<tr>
<td>WTARS</td>
<td>0.27</td>
<td>0.76</td>
</tr>
<tr>
<td>HODGES</td>
<td>0.19</td>
<td>0.75</td>
</tr>
<tr>
<td>CULLMAN</td>
<td>0.25</td>
<td>0.84</td>
</tr>
<tr>
<td>BROAD</td>
<td>0.17</td>
<td>0.85</td>
</tr>
<tr>
<td>TUSKEGEE</td>
<td>0.29</td>
<td>0.75</td>
</tr>
<tr>
<td>KOPTIS</td>
<td>0.29</td>
<td>0.86</td>
</tr>
<tr>
<td>DEERIVER</td>
<td>0.06</td>
<td>0.92</td>
</tr>
<tr>
<td>SELMA</td>
<td>0.27</td>
<td>0.79</td>
</tr>
</tbody>
</table>
Figure 4.7 Linear Regression MODIS AET and SWBM AET by station
4.3. SWBM strength and limitations

The SWBM was able to simulate AET in all SCAN sites throughout the study period. The depths of the analysis were chosen to represent different soil layers and root zones at the station sites. The model was able to reproduce seasonal variations in the AET for different soil types. To further evaluate the performance of the model in simulating AET-SM dynamics, it was compared with MOD16 AET for every station and different periods. The two models showed strong statistical correlation (Pearson’s correlation). Analysis of the SWBM also confirmed that deep-root plants have control of the recharge, but that the degree of control is modified by the AET and the prevailing weather conditions (dry and wet).

As limitations of the model must be mentioned two main factors. First, the amount and quality of data requirements. To evaluate every component of the model, a significant amount of data is required, that was not always available. Uninterrupted determination of AET in the time series was not always possible, particularly when there was not enough information to determine the daily soil water storage variability, and that information is determined through daily readings of SM at the different layers of sensors locations. Second, the assumptions and parametrizations of the model. Physical dynamics that were not considered as capillarity, horizontal water movement, or interception loss, and simplifications as the runoff determination must be mentioned as potential limitations and source of errors of the model.
4.4. $f_{\text{PET}} - f_{\text{AW}}$ Analysis

One main goal of this study is to find correlation between the evaporative fraction and the available water fraction in the soil. The previous sections described and discussed the obtention of the components of the evaporative fraction $f_{\text{PET}}$, PET and AET. The available water fraction $f_{\text{AW}}$ is obtained through daily sensor SM ($\theta$) readings and physical characteristics of the soil.

During periods of rainfall, AET can reach PET rates as plants and soils actively take up and transpire water. In contrast, during dry periods, SM levels decrease, and AET rates can significantly decline (J. Lu et al., 2003). Hence, to identify the dynamics between the SM and the evapotranspiration is the goal for this section of the analysis. Other factors that may take part in this correlation will also be evaluated.

The relationship function $f_{\text{PET}}/f_{\text{AW}}$ was evaluated for 14 stations of the Alabama SCAN network at layers 2-in, 4-in and 8-in. As mentioned earlier, selection of layers is determined by the root system depth in the stations, where the dynamics of the AET and soil water storage -plant interaction takes place. Particularly, vegetation in the stations consist in Bermuda grass year around, with rooting system between 4-in and 8-in depth (Fuentealba et al., 2015). For the analysis, each point of the variable dataset corresponds to a rolling-mean of the 7-past days to facilitate the findings of long-term trends. Stations with unavailable soil physical properties characterization were not considered in this evaluation.

Initially, several polynomial regression analyses were performed among the two variables, with uneven results along the different stations. Subsequently, the analysis was focused on linear and piecewise regressions. Table 4.6 and Table 4.7 summarize soil
characteristics by layer for every station, and the results of the regression analysis. Three regression models were evaluated by layers 2-in, 4-in and 8-in, for every station. Regressions are noted as Linear, Linear Best Fit and Piecewise.

The Linear Best Fit is a linear regression model that evaluates portions of the $f_{PE}$-$f_{AW}$ dataset to find the value of the independent variable $f_{AW}$, hereafter denominated $\Omega$, at which the best coefficient of determination ($R^2$) between both variables is obtained. It adopts the form of $mx+b$, where m is the slope of the line and b is the y-interception. It is also recorded the $f_{PET}$ at which the $\Omega$ value is detected, and the percentage of the whole dataset that is included in this regression.

Once $\Omega$ is determined, the Piecewise (two-step) regression is built, where the first step adopts the geometric factors of the best Linear Best Fit calculated before (m and b). This first step goes from the lower values of the dataset until it reaches the $\Omega$ point. After that, the second step follows, where is assumed a no-slope linear fit until the end of the dataset.

The third regression model presented is a full linear regression for the whole dataset. In practical terms, the $\Omega$ value is related to the critical SM or boundary of the transition between the water-limited regime to the energy-limited. The reason of the construction of the piecewise regression is to determine if this study datasets show water limitations for the evapotranspiration process, as observed in previous research (Anderson et al., 2007a; Dong et al., 2022; Hain et al., 2009). Every regression model was evaluated using the mean absolute error (MAE), the p-value, and the coefficient of determination ($R^2$), to assess the robustness of the outputs.
\[ MAE = \frac{\sum_{i=1}^{n} |P_i - O_i|}{n} \]  

(4.2)

Here \( P_i \) is the modeled value, \( O_i \) is the observed value, and \( n \) is the size of the sample.

**4.5. Linear and Piecewise Approximations**

**4.5.1. Analysis at 4-in depth**

At the 4-in depth layer, where much of the root system of the vegetation is located, most of the stations exhibit a better Best-Fit regression performance (in terms of \( R^2 \)) compared to the Piecewise and the Linear Regression models. MAE has slight difference between regression models. Similarly, the Best Fit model presents in range \( p \)-values, indicating statistically significant evidence of correlation between the two variables. \( \Omega \) values range between 0.40 and 1.90 (Table 4.6), where values \( \Omega < 1.0 \) indicate SM critical is below the FC of the soil at that layer. The best linear fit model shows evidence of water limitations in the yearly cycle, as is observed for stations AAMU, Bragg, Cullman, Hodges, Selma, Stanley, Sudduth and Wedowee, with \( \Omega \) values ranging from 0.4 to 0.8. Bermuda grass feels water stress when the available water in the soil reaches 0.55 to 0.60 of the total capacity (Allen et al., 1998), thus the vegetation in these stations experiences water stress during their annual cycle. Interestingly, in stations Bragg, Cullman, Selma, Hodges, Stanley, and Wedowee, approximately 50% or more of their dataset is situated in this regime, meaning than more than half a year, between the months of April and September, the soil will experience a water deficit condition at that depth. For the piecewise regression model, Stations Hodges, Selma, and Tuskegee show higher \( p \)-values than the level of significance of 0.05 for the independent variable (\( f_{AW} \),
indicating a low statistical significance of the piecewise coefficients to explain the association \( f_{\text{PET}} \) and \( f_{\text{AW}} \). Considering that the second step of piecewise function was built forcing a no-slope linear function after the inflexion \( \Omega \), it would be expected to be a low overall fit. This is also apparent in Figure 4.11 b, Figure 4.16 b, and Figure 4.19 b. In these stations, the linear model displays a better fit for the \( f_{\text{AW}}-f_{\text{PET}} \) variable association.

In the case of the Hodges Station, the 2-in layer is seemingly where the main soil evaporation and canopy transpiration takes place, and the transition of regimes is more evident. Isbell and Morris Station data could not be fitted to a piecewise regression function for this layer, and the linear regression shows also weak association among variables. For the stations of Perdido, Koptis, and Tuskegee the threshold is closer to their FC, with \( \Omega \) value ranging from 1.0 to 1.9, indicating that energy limited regime takes place after the soil-plant system has reached the soil FC. The critical SM at which the threshold between regimens takes place can be derived from the \( f_{\text{AW}} \) function for every station, as presented in Table 4.7, Table 4.8, Table 4.9, and Table 4.10.

Another element to analyze is the slope of the best fit linear regression at different layers. In general, the slope of the water limited regime is an indication of the water use efficiency of the plant and can vary depending on factors such as vegetation type, climatic conditions, and soil type. Plants that are well-adapted to dry conditions will have a shallower slope, indicating that they are less sensitive to changes in water availability and are able to continue growing even when water is scarce. Conversely, plants that are adapted to wetter conditions will have a steeper slope, indicating that they are more sensitive to changes in water availability and are more likely to experience growth reductions when water is limited (Fernandez-Illescas et al., 2001; Hatfield & Dold, 2019).
Stations with coarser textures such as Koptis, Morris, Perdido, Selma, Sudduth, and Tuskegee exhibit consistent behavior with the previous description as they present shallower slopes than stations with finer texture.

The $f_{\text{PET}}$ values ranged between 0.47 and 0.65, indicating that the AET in these conditions never reached more than 65% of the PET value.

4.5.2. Analysis at 2-in depth

At the 2-in depth layer, stations AAMU, Bragg, Koptis, Perdido, Tuskegee, and Wtars exhibit SM critical values that are lower than of those at 4-in layers, which is expected considering the proximity to the surface and direct exposition to energy flux dynamics (Table 4.7). This finding is also consistent with previous researches (Dong et al., 2022). However, the SM critical at evapotranspiration regimes threshold is higher at this depth than the 4-in deep layer at stations Cullman, Hodges, Isbell, and Sudduth.

Interestingly, these stations exhibit a higher content of the clay fraction at deeper layers (Cullman, Isbell and Hodges), or the silt fraction (Sudduth), thus these finer fractions are causing slower changes in threshold transition due to the higher water retention capacity of underlying soils. For stations Selma and Stanley, the threshold remains the same at the 4-in depth, but lower than the 8-in layer. Generally, there is not and unique pattern of threshold transition from surface to deeper layers, and this is expected considering great variability of soil texture in depth, that have an impact on soil water retention capabilities at different layers. Furthermore, other factors that are not evaluated in this study, such as capillarity, sub-surface lateral movement of soil water moisture, different canopy presence, might affect the threshold occurrence and location.
The \( f_{\text{PET}} \) values ranged between 0.37 and 0.65, indicating that the AET in these conditions never reached more than 65% of the PET value.

At the 8-in layer most of the stations exhibit \( \Theta \) values that are higher than the 4-in layer, which is similarly expected considering that most of the root system is leaning above this layer (Table 4.7).

### Table 4.6 Soil Characteristics by Station

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Depth (cm)</th>
<th>FC (cm(^3)/cm(^3))</th>
<th>WP (cm(^3)/cm(^3))</th>
<th>( \Theta_t ) (cm(^3)/cm(^3))</th>
<th>( \Theta_s ) (cm(^3)/cm(^3))</th>
<th>C (%)</th>
<th>Si (%)</th>
<th>S (%)</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAMU</td>
<td>0-5</td>
<td>0.36</td>
<td>0.12</td>
<td>0.05</td>
<td>0.49</td>
<td>22.9</td>
<td>47.9</td>
<td>29.2</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>5-20</td>
<td>0.36</td>
<td>0.19</td>
<td>0.07</td>
<td>0.45</td>
<td>32.3</td>
<td>43.4</td>
<td>24.3</td>
<td>CL</td>
</tr>
<tr>
<td>Bragg</td>
<td>0-5</td>
<td>0.34</td>
<td>0.16</td>
<td>0.09</td>
<td>0.47</td>
<td>31.1</td>
<td>56.2</td>
<td>12.7</td>
<td>SICL</td>
</tr>
<tr>
<td></td>
<td>5-20</td>
<td>0.37</td>
<td>0.20</td>
<td>0.09</td>
<td>0.48</td>
<td>36.7</td>
<td>50.2</td>
<td>13.1</td>
<td>SICL</td>
</tr>
<tr>
<td>Cullman</td>
<td>0-15</td>
<td>0.23</td>
<td>0.09</td>
<td>0.03</td>
<td>0.35</td>
<td>8.1</td>
<td>43.1</td>
<td>48.8</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>15-25</td>
<td>0.24</td>
<td>0.10</td>
<td>0.03</td>
<td>0.36</td>
<td>14.3</td>
<td>43.6</td>
<td>42.1</td>
<td>L</td>
</tr>
<tr>
<td>Hodges</td>
<td>0-15</td>
<td>0.48</td>
<td>0.12</td>
<td>0.10</td>
<td>0.50</td>
<td>16.4</td>
<td>59.6</td>
<td>24</td>
<td>SIL</td>
</tr>
<tr>
<td></td>
<td>15-28</td>
<td>0.36</td>
<td>0.12</td>
<td>0.06</td>
<td>0.44</td>
<td>26.1</td>
<td>56.3</td>
<td>17.6</td>
<td>SIL</td>
</tr>
<tr>
<td>Isbell</td>
<td>0-20</td>
<td>0.34</td>
<td>0.12</td>
<td>0.07</td>
<td>0.42</td>
<td>19.5</td>
<td>66</td>
<td>14.5</td>
<td>SIL</td>
</tr>
<tr>
<td>Koptis</td>
<td>0-28</td>
<td>0.17</td>
<td>0.08</td>
<td>0.0368</td>
<td>0.331</td>
<td>10.1</td>
<td>20.5</td>
<td>69.4</td>
<td>FSL</td>
</tr>
<tr>
<td>Morris</td>
<td>0-25</td>
<td>0.16</td>
<td>0.07</td>
<td>0.04</td>
<td>0.41</td>
<td>13</td>
<td>17.1</td>
<td>69.9</td>
<td>FSL</td>
</tr>
<tr>
<td>Perdido</td>
<td>0-25</td>
<td>0.21</td>
<td>0.085</td>
<td>0.107</td>
<td>0.418</td>
<td>8.3</td>
<td>35.5</td>
<td>56.3</td>
<td>SL</td>
</tr>
<tr>
<td>Selma</td>
<td>0-28</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
<td>0.42</td>
<td>5.2</td>
<td>11.4</td>
<td>83.4</td>
<td>LS</td>
</tr>
<tr>
<td>Stanley</td>
<td>0-15</td>
<td>0.34</td>
<td>0.13</td>
<td>0.06</td>
<td>0.42</td>
<td>17.4</td>
<td>42.6</td>
<td>40</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>15-25</td>
<td>0.29</td>
<td>0.15</td>
<td>0.05</td>
<td>0.36</td>
<td>21.9</td>
<td>31.3</td>
<td>36.8</td>
<td>L</td>
</tr>
<tr>
<td>Sudduth</td>
<td>0-13</td>
<td>0.22</td>
<td>0.10</td>
<td>0.0407</td>
<td>0.341</td>
<td>7.8</td>
<td>28.1</td>
<td>64.1</td>
<td>FSL</td>
</tr>
<tr>
<td></td>
<td>13-25</td>
<td>0.20</td>
<td>0.06</td>
<td>0.0282</td>
<td>0.298</td>
<td>7.3</td>
<td>31.3</td>
<td>61.4</td>
<td>FSL</td>
</tr>
<tr>
<td>Tuskegee</td>
<td>0-15</td>
<td>0.10</td>
<td>0.02</td>
<td>0.02</td>
<td>0.38</td>
<td>3.2</td>
<td>11</td>
<td>85.8</td>
<td>LCOS</td>
</tr>
<tr>
<td></td>
<td>15-25</td>
<td>0.15</td>
<td>0.07</td>
<td>0.03</td>
<td>0.35</td>
<td>11.6</td>
<td>16.3</td>
<td>72.1</td>
<td>COSL</td>
</tr>
<tr>
<td>Wedowee</td>
<td>0-51</td>
<td>0.31</td>
<td>0.16</td>
<td>0.07</td>
<td>0.42</td>
<td>23.3</td>
<td>35.5</td>
<td>41.2</td>
<td>L</td>
</tr>
<tr>
<td>Wtars</td>
<td>0-10</td>
<td>0.37</td>
<td>0.21</td>
<td>0.07</td>
<td>0.44</td>
<td>31.5</td>
<td>61.5</td>
<td>7</td>
<td>SICL</td>
</tr>
<tr>
<td></td>
<td>10-23</td>
<td>0.33</td>
<td>0.16</td>
<td>0.03</td>
<td>0.41</td>
<td>26.3</td>
<td>67.9</td>
<td>5.8</td>
<td>SIL</td>
</tr>
</tbody>
</table>
### Table 4.7 Regression Analysis by Station for layer 2-in depth

<table>
<thead>
<tr>
<th>Station Name</th>
<th>2-in Best Linear Fit</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>2-in Piecewise</th>
<th></th>
<th></th>
<th></th>
<th>2-in Linear</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ω</td>
<td>%</td>
<td>R²</td>
<td>p</td>
<td>MAE</td>
<td>m</td>
<td>b</td>
<td>fPET</td>
<td>R²</td>
<td>p</td>
<td>MAE</td>
<td>R²</td>
<td>p</td>
</tr>
<tr>
<td>AAMU</td>
<td>0.70</td>
<td>64.00</td>
<td>0.29</td>
<td>&lt;0.05</td>
<td>0.11</td>
<td>0.42</td>
<td>0.25</td>
<td>0.54</td>
<td>0.20</td>
<td>&lt;0.05</td>
<td>0.12</td>
<td>0.19</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Bragg</td>
<td>0.80</td>
<td>67.00</td>
<td>0.30</td>
<td>&lt;0.05</td>
<td>0.11</td>
<td>0.45</td>
<td>0.16</td>
<td>0.52</td>
<td>0.30</td>
<td>0.01</td>
<td>0.17</td>
<td>0.30</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Cullman</td>
<td>1.30</td>
<td>60.00</td>
<td>0.53</td>
<td>&lt;0.05</td>
<td>0.10</td>
<td>0.25</td>
<td>0.32</td>
<td>0.65</td>
<td>0.40</td>
<td>&lt;0.05</td>
<td>0.12</td>
<td>0.40</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Hodges</td>
<td>0.60</td>
<td>86.00</td>
<td>0.41</td>
<td>&lt;0.05</td>
<td>0.13</td>
<td>1.19</td>
<td>-0.29</td>
<td>0.42</td>
<td>0.34</td>
<td>&lt;0.05</td>
<td>0.13</td>
<td>0.32</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Isbell</td>
<td>0.70</td>
<td>58.00</td>
<td>0.16</td>
<td>&lt;0.05</td>
<td>0.14</td>
<td>0.33</td>
<td>0.25</td>
<td>0.48</td>
<td>0.12</td>
<td>&lt;0.05</td>
<td>0.15</td>
<td>0.19</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Koptis</td>
<td>1.00</td>
<td>92.00</td>
<td>0.38</td>
<td>&lt;0.05</td>
<td>0.13</td>
<td>0.35</td>
<td>0.28</td>
<td>0.63</td>
<td>0.31</td>
<td>&lt;0.05</td>
<td>0.13</td>
<td>0.37</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Morris</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.01</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Perdido</td>
<td>0.90</td>
<td>32.00</td>
<td>0.53</td>
<td>&lt;0.05</td>
<td>0.09</td>
<td>0.41</td>
<td>0.06</td>
<td>0.42</td>
<td>0.47</td>
<td>0.42</td>
<td>0.11</td>
<td>0.45</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Selma</td>
<td>0.50</td>
<td>94.00</td>
<td>0.21</td>
<td>&lt;0.05</td>
<td>0.15</td>
<td>0.49</td>
<td>0.29</td>
<td>0.53</td>
<td>0.21</td>
<td>0.69</td>
<td>0.14</td>
<td>0.20</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Stanley</td>
<td>0.60</td>
<td>54.00</td>
<td>0.37</td>
<td>&lt;0.05</td>
<td>0.19</td>
<td>0.38</td>
<td>0.14</td>
<td>0.37</td>
<td>0.25</td>
<td>&lt;0.05</td>
<td>0.15</td>
<td>0.21</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Sudduth</td>
<td>1.10</td>
<td>68.00</td>
<td>0.38</td>
<td>&lt;0.05</td>
<td>0.14</td>
<td>0.25</td>
<td>0.36</td>
<td>0.63</td>
<td>0.18</td>
<td>&lt;0.05</td>
<td>0.13</td>
<td>0.22</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Tuskegee</td>
<td>1.20</td>
<td>85.00</td>
<td>0.46</td>
<td>&lt;0.05</td>
<td>0.12</td>
<td>0.32</td>
<td>0.12</td>
<td>0.50</td>
<td>0.45</td>
<td>0.16</td>
<td>0.10</td>
<td>0.41</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Wedowee</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.27</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Wtars</td>
<td>0.60</td>
<td>45.00</td>
<td>0.27</td>
<td>&lt;0.05</td>
<td>0.12</td>
<td>0.27</td>
<td>0.35</td>
<td>0.51</td>
<td>&lt;0</td>
<td>&lt;0.05</td>
<td>0.14</td>
<td>0.08</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

71
<table>
<thead>
<tr>
<th>Station Name</th>
<th>4-in Best Linear Fit</th>
<th>4-in Piecewise</th>
<th>4-in Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ω</td>
<td>%</td>
<td>$R^2$</td>
</tr>
<tr>
<td>AAMU</td>
<td>0.70</td>
<td>35.00</td>
<td>0.32</td>
</tr>
<tr>
<td>Bragg</td>
<td>0.60</td>
<td>48.00</td>
<td>0.38</td>
</tr>
<tr>
<td>Cullman</td>
<td>0.60</td>
<td>52.00</td>
<td>0.40</td>
</tr>
<tr>
<td>Hodges</td>
<td>0.40</td>
<td>88.00</td>
<td>0.35</td>
</tr>
<tr>
<td>Isbell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koptis</td>
<td>1.30</td>
<td>95.00</td>
<td>0.44</td>
</tr>
<tr>
<td>Morris</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perdido</td>
<td>1.20</td>
<td>70.32</td>
<td>0.51</td>
</tr>
<tr>
<td>Selma</td>
<td>0.50</td>
<td>60.00</td>
<td>0.38</td>
</tr>
<tr>
<td>Stanley</td>
<td>0.60</td>
<td>66.00</td>
<td>0.26</td>
</tr>
<tr>
<td>Sudduth</td>
<td>0.70</td>
<td>52.00</td>
<td>0.51</td>
</tr>
<tr>
<td>Tuskegee</td>
<td>1.90</td>
<td>94.00</td>
<td>0.35</td>
</tr>
<tr>
<td>Wedowee</td>
<td>0.70</td>
<td>92.00</td>
<td>0.22</td>
</tr>
<tr>
<td>Wtars</td>
<td>0.80</td>
<td>48.00</td>
<td>0.30</td>
</tr>
</tbody>
</table>
### Table 4.9 Regression Analysis by Station for layer 8-in

<table>
<thead>
<tr>
<th>Station Name</th>
<th>8-in Best Linear Fit</th>
<th>8-in Piecewise</th>
<th>8-in Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ω</td>
<td>%</td>
<td>$R^2$</td>
</tr>
<tr>
<td>AAMU</td>
<td>0.90</td>
<td>36.00</td>
<td>0.10</td>
</tr>
<tr>
<td>Bragg</td>
<td>1.00</td>
<td>82.00</td>
<td>0.30</td>
</tr>
<tr>
<td>Cullman</td>
<td>0.90</td>
<td>59.00</td>
<td>0.40</td>
</tr>
<tr>
<td>Hodges</td>
<td>0.80</td>
<td>92.00</td>
<td>0.41</td>
</tr>
<tr>
<td>Isbell</td>
<td>0.02</td>
<td>&lt;0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Koptis</td>
<td>1.40</td>
<td>90.00</td>
<td>0.28</td>
</tr>
<tr>
<td>Morris</td>
<td>0.00</td>
<td>0.26</td>
<td>0.15</td>
</tr>
<tr>
<td>Perdido</td>
<td>1.00</td>
<td>32.00</td>
<td>0.41</td>
</tr>
<tr>
<td>Selma</td>
<td>0.60</td>
<td>98.00</td>
<td>0.35</td>
</tr>
<tr>
<td>Stanley</td>
<td>1.30</td>
<td>73.00</td>
<td>0.24</td>
</tr>
<tr>
<td>Sudduth</td>
<td>1.20</td>
<td>80.00</td>
<td>0.45</td>
</tr>
<tr>
<td>Tuskegee</td>
<td>1.10</td>
<td>96.00</td>
<td>0.23</td>
</tr>
<tr>
<td>Wedowee</td>
<td>1.30</td>
<td>93.00</td>
<td>0.16</td>
</tr>
<tr>
<td>Wtars</td>
<td>0.60</td>
<td>47.00</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Table 4.10 SM critical at the 2-in, 4-in, and 8-in layer. Values in () indicate FC of the soil at the specific layer.

<table>
<thead>
<tr>
<th>Station</th>
<th>2-in layer</th>
<th>4-in layer</th>
<th>8-in layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ω</td>
<td>SM critical (cm³/cm³)</td>
<td>Ω</td>
</tr>
<tr>
<td>AAMU</td>
<td>0.7</td>
<td>0.29 (0.36)</td>
<td>0.7</td>
</tr>
<tr>
<td>Bragg</td>
<td>0.8</td>
<td>0.30 (0.34)</td>
<td>0.7</td>
</tr>
<tr>
<td>Cullman</td>
<td>1.3</td>
<td>0.27 (0.23)</td>
<td>0.6</td>
</tr>
<tr>
<td>Hodges</td>
<td>0.6</td>
<td>0.34 (0.48)</td>
<td>0.4</td>
</tr>
<tr>
<td>Isbell</td>
<td>0.7</td>
<td>0.27(0.34)</td>
<td>(0.34)</td>
</tr>
<tr>
<td>Koptis</td>
<td>1.0</td>
<td>0.17 (0.17)</td>
<td>1.3</td>
</tr>
<tr>
<td>Morris</td>
<td></td>
<td>(0.16)</td>
<td>(0.16)</td>
</tr>
<tr>
<td>Perdido</td>
<td>0.9</td>
<td>0.20 (0.21)</td>
<td>1.0</td>
</tr>
<tr>
<td>Selma</td>
<td>0.5</td>
<td>0.1 (0.17)</td>
<td>0.5</td>
</tr>
<tr>
<td>Stanley</td>
<td>0.6</td>
<td>0.26 (0.34)</td>
<td>0.6</td>
</tr>
<tr>
<td>Sudduth</td>
<td>1.1</td>
<td>0.23 (0.22)</td>
<td>0.7</td>
</tr>
<tr>
<td>Tuskegee</td>
<td>1.2</td>
<td>0.12 (0.10)</td>
<td>1.9</td>
</tr>
<tr>
<td>Wedowee</td>
<td></td>
<td>(0.31)</td>
<td>0.7</td>
</tr>
<tr>
<td>WtarS</td>
<td>0.6</td>
<td>0.31 (0.37)</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Figure 4.8 AAMU Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.

Figure 4.9 Bragg Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.
**Figure 4.10** Cullman Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.

**Figure 4.11** Hodges Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.
Figure 4.12 Isbell Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.

Figure 4.13 Koptis Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.
**Figure 4.14** Morris Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.

**Figure 4.15** Perdido Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.
Figure 4.16 Selma Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.

Figure 4.17 Stanley Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.
Figure 4.18 Sudduth Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.

Figure 4.19 Tuskegee Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.
Figure 4.20 Wedowee Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.

Figure 4.21 WTARS Station $f_{AW}$ versus $f_{PET}$ at layers a) 2-in, b) 4-in, and c) 8-in.
An analysis to evaluate the influence of soil texture in the relation \( f_{\text{PET}} - f_{\text{AW}} \) is thereafter presented. Stations were grouped by soil texture according to USDA Texture Triangle, in three main groups: Stations with Fine Soil texture (Broad, Isbell and Dee River Stations). In this category are included clay, clay loam, sandy clay, silty clay, and silty clay loam textures. Stations with Medium Soil texture (Wtars, Hodges, Stanley, AAMU, Cullman, Bragg, Morris, Perdido, Sudduth, and Koptis). In this category are included loam, sandy clay loam, silt loam, silt, and silty clay. Finally, Coarse Soil texture (Tuskegee, Selma, and River Road). In this category, loamy sand, sand, and sandy loam soils are included (Figure 4.22).
Figure 4.22 USDA Soil Texture and location of Stations according to three main groups: fine, medium, and coarse soils.

Stations with predominant Coarse Texture Soils are Sudduth, Tuskegee, Selma, River Road, Koptis, and Morris. An important characteristic of the soil profile in this group is the high sand content, in the order of 65% and greater. Soil water retention parameters and texture are summarized in Table 4.6. At the 2-in layer, the threshold value $\Omega$ varies in the range of 0.50 to 1.20, with an average of 0.94. At the 4-in layer, $\Omega$ ranges between 0.50 and 1.90 (the wider range among the three layers), with an average of 1.12. At the 8-in layer, between 0.60 and 1.40, with an average of 1.06. Another interesting characteristic is the amount of data in water-limited regime, which is an average of 74.2% for both 4-in and 2-in layer. This findings are consistent with previous study for sandy
soils (Denissen et al., 2020; Muñoz et al., 2022; Rubert et al., 2018). Soils with less content of fines are staying for prolonged periods in the water limited regime during the yearly cycle. Average AW for these stations is 0.15 m$^3$/m$^3$. Comparatively, the superficial layer shows an average $\Omega$ value smaller than those at the root-zone.

Station with predominant Medium Texture soils are Wtars, Hodges, Stanley, Cullman, Isbell, Perdido, and Wedowee. Physical properties of soil at these stations are summarized in Table 4.6. Main feature of soil profile is the silt content ranges between 31 and 68%. At the 2-in layer, the threshold value $\Omega$ varies in the range of 0.6 to 1.3 (average of 0.76). At the 4-in layer, $\Omega$ ranges between 0.6 and 0.8 (average of 0.62) and at the 8-in layer, between 0.60 and 1.30 (average of 0.98). Another interesting characteristic is the amount of data in the water-limited regime zone is similar in both 2-in layer and 4-in layer in the order of 60 to 80% (except for Cullman Station). The average SM for layers 2-in and 4-in is 0.16 m$^3$/m$^3$, which is slightly higher than the SM in the coarser soil texture group. Water holding retention capacity of these types of soils are better than the coarser soils, as the amount of clay increases.

Comparatively, the superficial layer shows an average $\Omega$ value greater than at the root-zone.

Stations with predominant Fine Texture soils are AAMU and Bragg. Physical properties of stations with predominant Fine Texture Soils are summarized in Table 4.6. The average AW for layers 2-in and 4-in is 0.19 m$^3$/m$^3$, which is higher than the average of the two previous soil texture groups of stations, which is expected as the clay fraction increases. $\Omega$ values for the 2-in layer average 0.75, while for the 4-in layer has an average of 0.65. The amount of data in the water limited regime is 65.5% and 41.5% respectively.
for layers 2-in and 4-in. For layer 8-in, the $\Omega$ average is 0.95, and the percentage of the dataset in the water limited regime for a year cycle is 59%. Comparatively, the superficial layer shows an average $\Omega$ value greater than at the root-zone.

4.5.3. Variability with Soil Texture

Table 4.11 presents a summary of the averaged critical SM at which the regimen transition take place, according to soil texture at the 14 stations evaluated. The first observation is that the critical SM for coarser soils is the lowest of the three groups. Another finding is that superficial (2-in layer) critical SM is smaller than deeper layers, and this indicates that transitions of evapotranspiration regime occur at lower value of SM than the root zone. This finding is consistent with energy transition regimes in drier areas. Another finding is that the threshold between evapotranspiration regimes is in average occurring at a value of SM lower than the average FC of the soils in this group (FC average at 2-in layer and 4-in layer is 0.22 cm$^3$/cm$^3$, and 0.20 cm$^3$/cm$^3$ for the 8-in layer).

For medium texture soils, it is observed that the surface SM critical is greater than SM at 4-in layer, and the transition between water limited and energy limited is taking place very close to the average FC of these soils (FC average is 0.30 cm$^3$/cm$^3$ for layers 2-in and 4-in, and 0.29 cm$^3$/cm$^3$ for the 8-in layer). For layer 4-in, the transition between regimes takes place at SM critical lower than the average FC for the layer.

For fine textured soils, it is observed that the surface SM critical is lower than the SM critical at 4-in layer, and the transition between water limited and energy limited for
layers 2-in, 4-in and 8-in is taking place at a fraction of the average FC of these soils (FC average is 0.35 cm³/cm³ for layer 2-in, and 0.37 cm³/cm³ for layers 4-in and 8-in).

SM critical values obtained for the medium coarse soils in this study are consisting with a previous study that describes SM critical for continental US (Dong et al., 2022).

Summarizing, the critical value of SM for layer 2-in is lower than critical values at layers 4-in and 8-in, for coarse and fine soils. For soils in the transition of both textures, or medium textured soils, the SM critical at 2-in is higher than the SM critical at 4-in.

### Table 4.11 Averages \( \Omega \) value and SM critical by layer and soil group.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Coarse Soils</th>
<th>Medium Soils</th>
<th>Fine Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Omega_{\text{avg}} )</td>
<td>SM_{\text{avg critical}} (cm³/cm³)</td>
<td>( \Omega_{\text{avg}} )</td>
</tr>
<tr>
<td>2-in</td>
<td>0.94</td>
<td>0.16</td>
<td>0.76</td>
</tr>
<tr>
<td>4-in</td>
<td>0.90</td>
<td>0.17</td>
<td>0.52</td>
</tr>
<tr>
<td>8-in</td>
<td>1.06</td>
<td>0.18</td>
<td>0.98</td>
</tr>
</tbody>
</table>

### 4.5.4. SM Variability with Location and Average Annual Precipitation

Since SM is greatly dependent on precipitation increments, an analysis of average \( \Omega \) value and average critical SM by station precipitation zone location is presented in this section. Stations are located in three main precipitation areas, which have high correspondence with groups of similar soil texture types. Stations at the south of the state have higher average annual precipitation ranges, in the order of \( P>60 \text{-in/year} \). In this
region are located Koptis and Perdido Stations. Underlying soils in these areas are of coarse texture. In the center region of the state (black belt area), soils are predominantly medium loamy texture, and the annual average precipitation regime is the lower in the state, with P<52-in/year. Stations located in this region are Morris, Selma, Tuskegee, Broad, Livingston and Dee River Farms. The intermediate region of precipitation in the state has finer to medium texture soils, with average annual precipitation in the order 52-in/year to 56-in/year. Stations located in this area are AAMU, Bragg, Cullman, Isbell, Hodges, River Road, Stanley, Sudduth, Wedowee and Wtars.

Table 4.12 Averages $\Omega$ value and SM critical by layer and zones of precipitation

<table>
<thead>
<tr>
<th>Layer</th>
<th>Avg. Precipitation $\geq$60-in</th>
<th>Avg. Precipitation 52 to 56-in</th>
<th>Avg. Precipitation $\leq$52-in</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{avg}$</td>
<td>$\text{SM}_{avg}$ critical (cm$^3$/cm$^3$)</td>
<td>$\Omega_{avg}$</td>
</tr>
<tr>
<td>2-in</td>
<td>0.95</td>
<td>0.18</td>
<td>0.80</td>
</tr>
<tr>
<td>4-in</td>
<td>1.15</td>
<td>0.20</td>
<td>0.58</td>
</tr>
<tr>
<td>8-in</td>
<td>1.20</td>
<td>0.21</td>
<td>1.00</td>
</tr>
</tbody>
</table>

A summary of the averaged critical SM at which the regimen transition take place for regions of precipitation is presented in Table 4.12. The first observation is that the lowest $\Omega$ value is in the root-zone (4-in), in the region of intermediate annual average precipitation. Another finding is that superficial $\Omega$-value is smaller than in deeper layers on the region with highest precipitation rates, and the transition of evapotranspiration...
occurs near the FC of plants in this region. This finding is consistent with energy transition regimes in dry climate regions (N. Lu et al., 2011).

For regions with intermediate precipitation annual ranges and lower precipitation ranges, it is observed that the surface $\Omega$ value is greater than the $\Omega$ value at the 4-in layer. Then the transition of evapotranspiration regimes is taking place at a lower value of critical SM in the root-zone than in the surface. In this region, transition of regimes take place when the soil reaches almost 60% of the available water, thus the vegetation experiments water stress. Similar behavior is observed in the region with lower precipitation regimes, where the $\Omega$ value is again smaller at root-zone than at surface.

Summarizing, $\Omega$ value at 4-in is observed to have lower than superficial $\Omega$ value in regions with medium and low average annual precipitation. These regions are characterized with medium to fine soil textures, and plants might experiment water stress along the year. For the region with the highest annual precipitation range, the $\Omega$ value is lower at surface than at deeper layers. Soils in this region are of coarse texture, and regime transition take place at near field capacity of the soils.
4.6. Discussion

A great challenge in the soil water balance at regional and global level is to determine SM at the root-zone, with most large-scale models can estimate well SM at surface level, but there are many uncertainties at the zone where the plant-water intake for vegetation growth takes place. Evapotranspiration is very affected by availability of water in the soil. During drier and warmer seasons, AET is constrained by the water-limitation in the soil, as observed in arid and semiarid ecosystems, or draught conditions between rains. When the SM is past a critical value, and the plants can transpire freely, the evapotranspiration weakly depends on SM. This regime is associated with humid ecosystems. (Budyko: Climate and Life - Google Scholar, n.d.; Gan et al., 2021).
To evaluate the interaction of the evapotranspiration and the SM at the root zone of the plants, and the transition between energy-limited to water-limited regimes in Alabama, several approaches were tested between the fraction of potential evapotranspiration ($f_{PET}$) and the fraction of available water ($f_{AW}$).

The Penman Monteith daily PET calculated in this study presented good statistical correspondence with a satellite PET estimation. Further, other empirical estimations were evaluated with the conclusion that the Hargreaves-Samani methodology present reasonable values and could be used for PET estimations in data-limited situations.

The SWBM developed in this study, allowed the obtention of daily AET estimations. It was built based on the principle of mass balance equation considering the precipitation increment as input, and AET, soil water storage, runoff, and deep percolation as outputs. Main variables of the SWBM were obtained from the SCAN stations daily data collection. The SWBM AET calculated showed good correspondence with Penman Monteith PET estimates in terms of seasonality. The SWBM also presented good Pearson's correlation with MOD16 AET at the different stations evaluated. Limitations of the SWBM are related to the parametrization of factors that are not directly measured by the stations, the quality and quantity of the SCAN measurements, and the assumptions of the model.

The SWBM allowed the construction of the fraction of potential evapotranspiration $f_{PET}$ and to study different situations for the correlation with the fraction of available water in the soil. Several models of correlation were evaluated, and two of these models presented valuable information about the dynamics and complex
nature of the relationship between the two variables. Linear and piecewise regression functions presented the most promising results. The functions were evaluated at layers of 2-in, 4-in and 8-in deep from the surface. It is estimated that the root system is located between 4-in and 8-in depth for the prevalent vegetation in the stations, the *Cynodon dactylon* or Bermuda Grass (Fuentealba et al., 2015). The evaluation included several statistical metrics to validate the findings.

Previous researchers (Anderson et al., 2007b; Dong et al., 2022) have defined functions of the fraction of potential evapotranspiration and the fraction of available water were the boundary between water-limitations and energy-limited evapotranspiration regime is distinctly apparent, as it is observed in drier regions of the world. In the humid region of Alabama, this distinction was not very apparent.

The best linear fit model shows evidence of water limitations in the yearly cycle, in some stations with $\Omega$ values ranging from 0.4 to 0.8. Bermuda grass experiences water stress when the available water in the soil reaches 0.55 to 0.60 of the total capacity (Allen et al., 1998), thus the vegetation in these stations experiences water stress during their annual cycle. For some stations approximately 50% or more of their dataset indicates situation of water stress, meaning than more than half a year, between the months warmer months the soil will experience a water deficit condition at root zone. Another finding is that the AET in those conditions reaches up to 65% of the PET.

Considering the soil texture, it was observed that in medium and fine textured soils, the $\Omega$ values were lower at root-zone than at surface. Thus, models that are based on conditions of surface SM to model the root-zone AET-AW interactions are overpredicting the critical conditions of the root-zone.
Considering the geographical regions, in terms of annual average precipitation distribution, it was observed that zones with low and intermediate precipitation present the same behavior in terms of $\Omega$ value as the zones with medium and fine soil texture. The root zone presented $\Omega$ values lower than those observed at surface level.

Future directions to advance in the knowledge of SM and interaction with atmosphere demand in humid regions should include a more comprehensive monitoring and modeling approaches, the incorporation of the findings of this study in large scale models. The study provided valuable insights into the assessment of AET and SM relationships and it is expected to have contributed to the development of more sustainable water resources management strategies in the region.
Chapter 5. Conclusions and Contributions

This dissertation examined the effect of the Actual Evapotranspiration (AET) on SM at surface and root-zone in several locations Alabama, Southeastern (SE) region of the United States. The goal of the analysis was to determine functions among these variables at local scale, that provide meaningful information for estimations on a greater scale. Below are the conclusions of this study:

1. It is possible to estimate reliable daily PET at local scale using SCAN network data set. Penman Monteith PET estimated with local data presented a good correlation with regional scale MODIS PET aggregated at 8-day scale. This result was expected considering that both estimates are based on the same energy balance model.

2. Several other empirical methods were also evaluated, to assess the feasibility of obtaining PET when limited weather information is available. Although all the empirical methods showed similar temporal variability, the Priestly Taylor PET was more consisted with the Penman Monteith methodology, followed by the Hargreaves-Samani assessment, for the different data sets. The Hargreaves-Samani calculation only require daily weather information of maximum and minimum temperatures, thus simplifying the obtention of PET in data-limited situations.
3. Unreliable SM values were modified effectively using the CDF methodology. This procedure allowed to have larger datasets to accomplish the analysis.

4. The estimation of daily local AET based on a soil water-based model developed in this study, was accomplished. The model accuracy of AET estimations relies strongly in high quality daily data, as Precipitation and SM. To correctly determine one of the essential factors of the soil water balance model, the soil water storage, is key to have available good quality and quantity SM data at several depths along the root of the vegetation. Another important component of the SWBM model that is not directly measured is the Runoff event. To account for the effect of infiltrated water after periods of rainfall, an 8-day period of water precipitation is considered in the runoff estimation. Deep percolation was considered as SM excess after FC is reached. Interception losses, horizontal water movement and Capillarity were neglected.

5. Penman Monteith PET and SWBM AET estimates show evidence of seasonality, with higher values of Pet and AET in warmer months.

6. It was observed that a fair correlation between regional AET MOD16 and the SWBM AET. The differences can be related to several factors including that the MOD16 uses superficial SM for the estimation of energy transfer between the surface and the atmosphere, the scale factor of the MODIS measurements (500 m grid), and canopy estimation. The SWBM evaluates the impact of the root-zone SM in the estimation of available water since direct real SM readings are available.
7. The SWBM allowed the construction of the fraction of potential evapotranspiration $f_{PET}$ and to study correlations with the soil $f_{AW}$. Several models of correlation were evaluated. The best fit linear and piecewise regression functions provided a good insight in the relationship of the two functions.

8. Fractions were evaluated at layers of 2-in, 4-in and 8-in deep from the surface. It is estimated that the root system is located between 4-in and 8-in depth for the prevalent vegetation in the stations, the *Cynodon dactylon* or Bermuda Grass (Fuentealba et al., 2015).

9. Previous researchers (Anderson et al., 2007b; Dong et al., 2022) have defined functions of the fraction of potential evapotranspiration and the fraction of available water were the boundary between water-limitations and energy-limited evapotranspiration regime is distinctly apparent, as it is observed in drier regions of the world. In the humid region of Alabama, this distinction was not very apparent.

10. The best linear fit model shows evidence of water limitation in some stations annual cycle, with $\Omega$ values ranging from 0.4 to 0.8. Bermuda grass experiences water stress when the available water in the soil reaches 0.55 to 0.60 of the total capacity (Allen et al., 1998), thus the vegetation in these stations experiences water stress during their annual cycle. For some stations approximately 50% or more of their dataset indicates a situation of water stress, in the warmer months of the year. Another finding is that the AET in those conditions reaches up to 65% of the PET.
11. Medium and fine textured soils, have $\Omega$ values lower at root-zone than at surface. Thus, models that are based on conditions of surface SM to model the root-zone AET-AW interactions are overpredicting the critical conditions of the root-zone. This can lead to underestimations, especially in events of rapid droughts.

12. In terms of geographical annual average precipitation distribution in Alabama, it was observed that root-zone $\Omega$ value in zones with low and intermediate precipitation present the similar behavior as the regions with medium and fine soil texture. The root zone presented $\Omega$ values in the order of 0.4 to 0.8.

13. It was possible to develop evaluate $f_{AW}$ and $f_{PET}$ for 17 different locations in the State of Alabama, with different climatology and soils. Results are location specific, but the methodology can be extended to other locations given that climatological data is available.

Implications of the findings: under atmospheric demand there is a real distinction between the behavior of the fraction of available water at surface and at root-level. It was found that that at surface level transitions take place at higher values of SM, while for the root zone same transition occurs with lower values of SM, particularly in medium and fine texture soils.

As recommendations for future research, it is advised to extend the methodology to the whole Southeastern United States, to obtain more information about influence of SM in root zone and correlations water/energy balance. In addition, the SWBM should be improved with more stations and longer periods of quality data recorded.
The study provided valuable insights into the assessment of AET and SM relationships and it is expected to have contributed to the development of better estimations of SM to enhance water resources management strategies in the region.
References


https://doi.org/10.2136/vzj2012.0170


https://doi.org/10.1175/2008JHM1024.1


Mishra, V., & Ellenburg, W. L. (2021, August 10). *Soil Moisture Variability* [Personal communication].


http://epicapex.tamu.edu/files/2015/05/EpicModelDocumentation.pdf


https://doi.org/10.1029/2000WR900325
