2004

An evaluation of reference evapotranspiration models in Louisiana

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AN EVALUATION OF REFERENCE EVAPOTRANSPIRATION MODELS IN LOUISIANA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Natural Sciences

In

The Interdepartmental Program of Natural Sciences

by
Royce Landon Fontenot
B.S., Louisiana State University and A&M College, 1999
August 2004

In Dedication

My Dearest Michelle

In Memoriam

Ralston Maurice Fontenot
September 8, 1974 – July 6, 2001
“O Fortuna”

Acknowledgments

I would like to thank the Southern Regional Climate Center for the fiscal and professional support over the last two and a half years while I have worked on this research. Dr. Kevin Robbins and Mr. Jay Grymes have both been professional guidance counselors of the highest regard, allowing me to prove under the highest levels of stress that my brain was not completely frozen in Alaska.

This work would also not be possible without the support of my major professor Dr. Robert Rohli. His guidance on research methods and incredible editing skills has made this task a significant degree less difficult than it could have been. I would also like to thank Dr. Barry Keim for his insightful comments along the way and Dr. S.A. Hsu for the constant humor he has brought into his classes over the years which made the load seem just a bit lighter. Finally, I offer thanks to my fellow graduate and undergraduate students who have made the last two years more interesting than it could have been!

I would like to thank my all of family, especially my Mom and Dad, for their undying support for my return to the world to complete this task. Their unwavering support in all of my endeavors continues to provide me with the confidence that I can complete the tasks ahead.

Finally, I would like to thank my fiancée Michelle, who always is there to support me and believe in me when it seems like I will never get “that paper” done. Just one more love…

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Abstract

Daily and monthly output from seven evapotranspiration models (FAO-24 Radiation, FAO-24 Blaney-Criddle, Hargreaves-Samani, Priestly-Taylor, Makkink, and Turc) have been tested against reference evapotranspiration data computed by the FAO-56 Penman-Monteith model to assess the accuracy of each model in estimating grass-reference evapotranspiration in Louisiana. Models were compared at eight stations of the Louisiana Agriclimate Information System using data from December 2002 to November 2003. Comparisons were also made using three composite regions: statewide, inland, and coastal. A pan evaporation to reference evapotranspiration model (FAO-24 Pan Evaporation) was also tested against daily grass reference evapotranspiration from the FAO-56 Penman-Monteith model using data from two pan evaporation sites.

Statewide and in the coastal region the Turc model was the most accurate daily model with a mean absolute error (MAE) of 0.26 mm day^{-1} and 0.27 mm day^{-1}, respectively. Inland the FAO-24 Blaney-Criddle performed best with a MAE of 0.31 mm day^{-1}. On a monthly basis, Turc again performed the best statewide and in the coastal region (MAE 0.17 and 0.27 mm day^{-1} respectively). Inland, FAO-24 Blaney-Criddle and Makkink tied for the most accurate model, although this may change with a longer dataset. Pan evaporation at both stations performed poorly with MAE values over 1.0 mm day^{-1}. It is possible that the equation for calculating the pan coefficient that is suggested by the FAO in the FAO-56 manual may not be a suitable equation for use in Louisiana. These results will assist agricultural and environmental planners in assessing the available water resources in Louisiana.

Chapter 1
Introduction

One of the most important factors in agriculture is water availability. Water is provided to the crops naturally through precipitation and subsurface moisture, but when these supplies prove to be inadequate for crop use, growers must resort to irrigation. Water availability is also a critical variable for virtually every other economic activity, including industry, the energy sector, and public use. In recent years, water availability has become an issue even in the relatively wet state of Louisiana as periods of prolonged drought have stressed both agriculture and non-agricultural sectors in Louisiana. As population in Louisiana increases, so does water demand. According to a recent report on Louisiana water use, in the 1960-2000 period the total withdrawal from ground water increased by 59 percent, with surface water usage increasing by 99 percent (Sargent 2002). Overall, Louisiana water demand has increased by 92 percent between 1960 and 2000, while the population of Louisiana increased by only 34 percent (Sargent 2002).

The result of this increase has been the drawdown of groundwater supplies, which increases during drought as industries who normally use surface water switch to sub-surface aquifers to provide water. A dramatic example is the Chicot Aquifer in the southwestern portion of Louisiana. Two-thirds of the drawdown from the aquifer is by the rice industry for field irrigation, with the remainder going to industry, public use, and other agricultural activities (Sargent 2002).

Before 1982, both agricultural and industrial interests were depleting the aquifer at alarming rates. In 1982, the Sabine River Diversion Canal was finished, allowing industry to use surface water instead of sub-surface supplies. As a result, the water level in the aquifer rose as much as 50 feet in about a two-year time period (Sargent 2002). Since that time, water levels in

the aquifer have been declining at a steady rate of 1-2 feet per year (Sargent 2002, Branch personal communication).

To schedule irrigation properly, a grower must know the environmental demand for surface water. For the grower, this surface water loss occurs primarily through evapotranspiration (ET). ET is simply the amount of water returned to the atmosphere through evaporation (moisture loss from the soil, standing water, *etc*.) and transpiration (biological use and release of water by vegetation) (Hansen *et al*. 1980). The ET rate is a function of factors such as temperature, solar radiation, humidity, wind, and characteristics of the specific vegetation that is transpiring, which may vary significantly between vegetation types (Allen *et al*. 1998). If the demand for water (ET) exceeds the availability to the plant through precipitation or stored in the soil, then transpiration may stop resulting in crop loss. Therefore, reliable estimates of ET, along with knowledge of precipitation totals and soil moisture storage capacity, can provide estimates of water need via irrigation.

Several methods are available to measure evapotranspiration directly. For instance, a lysimeter is used to measure ET by routinely measuring the change in soil moisture of known volume of soil that is covered with vegetation (Watson and Burnett 1995). Lysimetry can be expensive both economically and in time investments to install, check, and maintain the equipment. Evaporation pans measure the loss of a known quantity of water through evaporation, but they do not measure transpiration, and therefore they must be adjusted using coefficients to represent ET (Dingman 1994, Allen *et al*. 1998, Barnett *et al*. 1998). ET can also be measured by determining the flux of moisture from the vegetative surface to the atmosphere by using highly-sensitive sensors that detect the change in meteorological variables between the surface and a fixed level above the surface. The determination of ET through these flux-related methods, while highly accurate, can be difficult and are generally used only in research settings

(Allen *et al*. 1998, Geiger *et al*. 2003). In summary, the measurement of ET can be difficult, requiring methods that are either labor or financially-intensive or that are indirect proxies of evapotranspiration.

To simplify the process of determining ET, models have been developed to estimate ET for use in environments that lack direct ET measurements. Many of these have been derived empirically through field experiments; others have been derived through theoretical approaches. A major complication in modeling ET is the requirement for meteorological data that may not be easily available (*e.g*. solar radiation). This restriction at times prohibits use of more accurate models, and necessitates use of models that have less demanding data requirements.

A modification of the ET concept is reference evapotranspiration (ET_o) that provides a standard crop (a short, clipped grass) with an unlimited water supply so that a user can calculate maximum evaporative demand from that surface for a given day. This value, adjusted for a particular crop, is the consumptive use (or demand), and deficit represents that component of the consumptive use that goes unfilled, either by precipitation or by soil-moisture use, during the given time period. This deficit value is the amount of water that must be supplied through irrigation to meet the water demand of the crop (Dingman 1994, Allen *et al*. 1998).

It is important to provide the proper amount of water via irrigation. Too much or too little water at the wrong stage of crop development can damage the crop and reduce yield. Additionally, the economic value associated with irrigating with the proper amount of water at the right time is considerable. A 1 mm loss of water through ET across 1 ha is equivalent to 10 m^3 (268,000 gallons) of water (Allen *et al*. 1998). Thus, if the grower overestimates the actual ET value by 1 mm, the farmer will have to pay needlessly for 268,000 gallons of water, and the groundwater will have 268,000 gallons of water less than before (less the small amount that eventually percolates downward again). If a grower optimizes the use of irrigation scheduling,

the amount of money that can be saved in water purchase and or well operation is significant. Unfortunately, the number of growers in Louisiana that practice any scheduled or controlled irrigation is extremely low due to the traditional notion of Louisiana's "normal" abundance of water. The Louisiana State University AgCenter is attempting to educate growers of the advantages of scheduled irrigation (Branch, personal communication).

Successful irrigation scheduling, however, is dependent on an accurate assessment of ET (Hansen *et al*. 1980, Allen *et al*. 1998). Considering that the actual measurement of ET is difficult, it is vital that the estimate of ET used by growers is as accurate as possible. Thus, there is a definite need for the most accurate model available, for both economic and environmental purposes.

Many of the existing ET models were derived in arid and semi-arid environments with most of the comparisons of models in the United States focusing on the Great Plains of the Midwest or the West (Hatfield and Allen 1996, Hansen *et al*. 1980, Jensen *et al*. 1997). Others were developed on the east coast of the US (Thornthwaite 1948), Europe (Penman 1948, Makkink 1957, Turc 1961), or in Australia (Priestley and Taylor 1972, Linacre 1977). However, no major model has been specifically developed for use in the humid southern United States.

Furthermore, very few studies examine ET at all in Louisiana. Shah and Edling (2000) have specifically focused on rice and ET model performance in Louisiana, but they examined only one location for a relatively short time period. Other studies such as Sasser *et al.* (1998) and Ahmed (1991) examined ET in Louisiana, but in relation to a specific crop, not ET_o. McCabe (1989) examined the adjustment of the Thornthwaite (1948) model using pan-evaporation across the eastern United States, but the study used only one station from Louisiana and did not examine ET_o. No published studies have examined the spatial variability of ET models across Louisiana, a state with a great northwest to southeast gradient in temperature and precipitation.

This variety in climate allows several different crops to be farmed in Louisiana. Crops generally associated with drier climates (such as cotton) are grown in the north while semi-tropical crops, such as oranges, are grown in southern sections. Because of this gradient in precipitation climatology and agriculture, an assessment of the performance of ET models across space is required to allow proper monitoring of water usage in Louisiana's agricultural industry.

This project will compare several ET_o models to the reference ET model endorsed by the Food and Agriculture Organization of the United Nations (FAO 56 Penman-Monteith (56PM), Allen *et al.* 1998). The purpose is to assess the performance of these "simpler" models that require less readily available data against the standard model. While the 56PM model is used as the international standard model for calculating ET_o, it has the serious drawback of requiring meteorological data that are found only at a few weather stations in Louisiana. The models being examined, however, generally require data that is more readily available such as temperature, humidity, and wind. These elements can be measured by local farmers or derived from historical data. By evaluating the utility of a variety of models throughout the state, ET_o estimates may be calculated at additional weather stations more accurately, thus improving the spatial coverage of ET_o estimates over Louisiana. The accuracy of using evaporation pan data to assess ET_o will also be examined using the recommended methods of the FAO.

Therefore, this thesis has three primary objectives:

- To determine which evapotranspiration model best simulates the FAO reference evapotranspiration model (Penman-Monteith), taking into account the data requirement for each model;
- To determine the applicability and accuracy of the FAO-recommended model to convert evaporation pan data into reference evapotranspiration data;

- To determine whether spatial trends in model performance exist across space in Louisiana, focusing on inland versus coastal environments.

It is hoped that by answering these questions, agricultural and environmental scientists can better understand the water demands of agriculture in Louisiana.

Chapter 2 will review concepts in evapotranspiration (including reference evapotranspiration), its measurement, and its estimation as well as other relevant literature. Chapter 3 will provide further technical insight into the models themselves, providing the reader with a more substantial understanding of model design and limitations. Chapter 4 will detail the data and the methods used to perform the analysis. Chapter 5 will review the results, and Chapter 6 summarizes the major findings.

Chapter 2
Literature Review

This chapter will examine the concept of evapotranspiration (ET) in more detail and provide more details into the concept of reference evapotranspiration (ET_o) and of the measurement and estimation of ET_o. Studies of ET models usually involve the comparison of a single model in different climates, different model types in the same location, or model output to either lysimeteric measurements or a local evaporation pan. This chapter will examine the performance of ET models versus ET measured using lysimetery or pan evaporation and the performance of ET models when compared to a standard ET_o model. A review of the performance of pan evaporation to the standard ET_o model will also be performed. The findings of the relevant literature will be applied to the models used in this study and the possible performance of the models in Louisiana.

2.1 ET, Measurement, and The Development of the Reference ET Concept

2.1.1 Overview of ET

Water availability is a critical factor in agriculture. Water is provided to the crops naturally through precipitation and subsurface moisture, but when these supplies prove to be inadequate for crop use, growers must resort to irrigation. For efficient water use, the amount of water irrigated must not exceed the maximum amount that can be used by plants through evapotranspiration.

Evapotranspiration (ET), also known as consumptive use or actual evapotranspiration (AET) (Watson and Burnett 1995), is the sum of the amount of water returned to the atmosphere through the processes of evaporation and transpiration (Hansen *et al.*1980). The evaporation component of ET is comprised of the return of water back to the atmosphere through direct evaporative loss from the soil surface, standing water (depression storage), and water on surfaces

(intercepted water) such as leaves or roofs (Hansen *et al.*1980). Transpired water is that which is used by vegetation and subsequently lost to the atmosphere. This water enters the plant through the root zone, is used for various biological functions including photosynthesis, and then passes back out through the leaf stomates (Hansen *et al.*1980). Transpiration will stop if the vegetation becomes stressed to the wilting point, which is the point in which there is insufficient water left in the soil for a plant to transpire (Watson and Burnett 1995).

A related concept is that of potential evapotranspiration (PET), defined simply as the amount of water that would be lost from the surface to ET if the soil/vegetation mass had an unlimited supply of water available (Hansen *et al.*1980, Dingman 1994, Watson and Burnett 1995). Since PET assumes that water availability is not an issue, vegetation would never reach the wilting point (the point in which there is not enough water left in the soil for a plant to transpire). Therefore, the only limit to the transpiration rate of the plant is due to the physiology of the plant and not due to any atmospheric or soil moisture restrictions (Watson and Burnett 1995). Therefore, PET is considered the maximum ET rate possible with a given set of meteorological and physical parameters (Dingman 1994). Thus, any irrigation that supplies more water than PET can accommodate is simply wasted.

The process of ET in general (either AET or PET) is controlled by several variables. For example, meteorological variables such as solar radiation, temperature, humidity, and wind speed all have significant roles in determining ET (Dingman 1994, Allen *et al*. 1998, Geiger 2003). In addition, physical attributes of the vegetation and soil also are important to the ET process. For example, leaf shape, growth stage, crop height, and leaf albedo all are important factors in controlling transpiration functions (Allen *et al*. 1998). In addition, stomatal resistance is an important variable. Stomatal resistance refers to the restriction of the guard cells around the

opening of the stomata to the diffusion of water vapor back to the atmosphere (Geiger *et al*. 2003). Finally, soil characteristics such as heat capacity, albedo, and soil chemistry all can affect ET (Allen *et al.* 1998). These factors, combined with stomatal resistance, are combined into a single term called the bulk surface resistance (Allen *et al*. 1998).

2.1.2 Measurement of ET and the Development of ET Models

ET is very difficult to measure, but several methods have been developed for this purpose. First, a lysimeter can be used to measure ET. This instrument is embedded in a vegetated, known volume of soil that is constantly measured for changes in soil moisture throughout the growth cycle of the vegetation, giving an estimate of the water demand of the vegetation at different stages of growth. This can be done using either weighing or non-weighing techniques (Watson and Burnett 1995). A weighing lysimeter constantly weighs the soil/vegetation mass and estimates gains and losses in water by detecting changes in mass (Watson and Burnett 1995). The non-weighing lysimeter measures the amount of soil moisture using a neutron probe located within the mass or by measuring runoff from the lysimeter vessel. By knowing the change in water in the soil (through soil moisture change or runoff), any loss after accounting for water gain through precipitation or watering is attributed to ET (Watson and Burnett 1995, Allen *et al*. 1998). The weighing method is generally more accurate, but is more costly to install and operate (Watson and Burnett 1995). Lysimeters tend to be large and expensive, so few are available, but they are often used as primary measurements to calibrate ET models (Penman 1948, Blaney and Criddle 1950, Jensen and Haise 1963, Hargreaves 1974, Tyagi *et al*. 2000, Qiu *et al*. 2002, Lage *et al*. 2003). Currently, only one published study uses lysimetric data in Louisiana, and that study focused on rice in southwest Louisiana during 1985-1986 (Sasser *et al*. 1988). As of this writing, however, a lysimeter will shortly be under

construction at the Louisiana State University AgCenter research station in St. Joseph, Louisiana, to calculate cotton crop coefficients (Clawson, personal communication).

A second method of measuring ET is via energy budget methods. The heating and evaporation of water requires energy; therefore, the ET process is limited by the input of energy into the system (*i.e.* incoming radiation from the sun) (Allen *et al.* 1998, Geiger *et al.* 2003). ET is the one component that links the surface energy balance to the surface water balance, and by knowing the values of the remaining components in either system, ET can be computed (Allen *et al.* 1998). Allen *et al*. (1998) describes the energy balance as:

$$R_n - G - \lambda ET - H = 0 \tag{2.1}$$

where R_n is net radiation, G is soil heat flux, λET is the latent heat flux (i.e. ET) and H is the sensible heat flux. All terms are in units of W m^{-2} and may be positive (*i.e.*, R_n is received by the surface and the other fluxes are directed away from the surface) or negative (*i.e.*, R_n is lost from the surface and the other fluxes are directed toward the surface). In other words, a positive R_n term indicates an input of energy into the surface system (the typical daytime condition), and positive values for all other terms indicate a loss from the surface system (Dingman 1994, Allen *et al*. 1998, Geiger *et al*. 2003). The magnitude and sign of the energy balance terms depend on several factors, such as day of the year, time of day, and the condition of the atmosphere (Allen *et al*. 1998, Geiger *et al*. 2003). R_n, G, and H can all be measured directly, thus permitting the computation of the latent heat flux as a residual (ET). This technique is effectively the basis of the Priestley-Taylor equation that is described in Chapter 3. It should be noted that Equation 2.1 takes into account vertical flux gradients only, neglecting the horizontal and should be used in areas of generally homogeneous land cover (Allen *et al.* 1998).

The mass transfer method of computing ET examines the movement of air parcels above a generally homogenous surface (Allen *et al.* 1998). These parcels, also known as eddies, transport water vapor, heat, and momentum to and from an evaporating surface (Dingman 1994, Allen *et al.* 1998, Geiger *et al.* 2003). Assuming that the transport coefficients for heat and momentum are the same as those for water vapor, the evaporation rate can be computed by calculating the positive vertical flux of water vapor from the evaporating surface (Dingman 1994, Allen *et al.* 1998, Geiger *et al.* 2003). This assessment is typically done using the Bowen Ratio equation (Allen *et al.* 1998). The details of the Bowen Ratio are beyond the scope of this text and the reader should consult other texts for a complete explanation (*e.g.*, Knapp 1985, Geiger *et al.* 2003). Aside from lysimeters and mass transfer techniques, several other methods exist for measuring ET directly, such as eddy covariance (Massman and Grantz 1995, Scott *et al*. 2004, Testi *et al*. 2004) and scintillometric techniques (Daoo *et al*. 2004). However, these methods require very high-resolution equipment that is generally cost-prohibitive and labor-intensive. Therefore such use is typically for research only (Qiu *et al.* 2002, Brotzge and Crawford 2003, Payero *et al.* 2003, Peacock and Hess 2004).

Finally, a less complicated but indirect technique for measuring ET is through the use of a metal evaporation pan, typically about 1 meter in diameter. Evaporation pans measure the loss of a known quantity of water through evaporation using a vernier caliper to identify changes in the precise water level, but they do not measure transpiration. To compensate, pan evaporation data must be adjusted downward using a pan coefficient. Pan evaporation data typically overestimates ET due to the nature of the pan. Evaporation pans often will still evaporate at night due to the residual heat that is stored in the water of the pan. Additionally, there are differences in temperature, atmospheric turbulence, and humidity above the water in the pan that

make evaporation rates different from that over a leaf surface. Finally, the stomata of a plant control the return of loss of water back to the atmosphere and act as a regulator. The water in an evaporation pan has no such limiting factor and is free to evaporate as much as the atmospheric conditions will allow (Allen *et al.* 1998, Barnett *et al.*1998). Pan coefficients can be derived experimentally or through various equations (Eagleman 1967, Doorenbos and Pruitt 1977, Jensen *et al.* 1990, Barnett *et al.*1998, Grismer *et al.* 2002, Irmak *et al.* 2002). Some limitations to evaporation pans include the cost of the pan and equipment (approximately $1000 to $2000) and the amount of water required, which can be critical in arid locations or locations where running water is not available (Hansen *et al.*1980). Another substantial cost in the operation of evaporation pan stations is that for personnel to take daily measurements at the site. Despite these costs, however, pan measurement was still more cost-effective than an automated weather station until recently, but as the costs of automated weather stations have decreased over the years, the option of computing ET_o based on meteorological data has become more cost effective due to the elimination of recurring costs.

As seen above, direct measurement of ET can be a difficult task. Basic measurements of the atmosphere, such as temperature, humidity, rainfall, wind, and solar radiation tend to be relatively easy to collect and are available at numerous locations. As a result, a wide range of models have been developed for the estimation of ET for use in environments that lack either sufficient radiometric, meteorological, or lysimetric data to measure or calculate ET using the above methods. Many of these have been derived empirically through field experiments (*e.g.*, Thornthwaite 1948, Blaney and Criddle 1950, Jensen and Haise 1963), while others (*e.g.*, Penman 1948, Hargreaves 1974, Hargreaves and Samani 1985) have been derived through

theoretical approaches that involve a combination of the energy budget and mass transfer methods.

ET models tend to be categorized into three basic types: temperature, radiation, and combination (Jensen *et al.* 1990, Dingman 1994, Watson and Burnett 1995). Temperature models only generally require only measurements of air temperature as the sole meteorological input to the model (*e.g.*, Thornthwaite 1948, Doorenbos and Pruitt 1977) (Jensen *et al.* 1990). Radiation models (*e.g.*, Turc 1962, Doorenbos and Pruitt 1977, Hargreaves and Samani 1985) are typically designed to use some component of the energy budget concept and usually require some form of radiation measurement. Finally, combination models (*e.g.*, Penman 1948) combine elements from both the energy budget and mass transfer models to give very accurate results (Jensen *et al.* 1990). The Penman family of models is by far the most common combination model in use today (Jensen *et al.* 1990, Allen *et al.* 1998).

2.1.3 Development of Reference ET

As discussed previously, PET is the ET from a vegetated surface that has a limitless supply of water. However, as PET still depends on vegetation-specific characteristics (as mentioned above) and not solely meteorological variables, there was a determined need for a reference surface that was independent of vegetation and soil characteristics (Jensen *et al.* 1990, Allen *et al.* 1998). This reference surface would allow for the analysis of the "evaporative demand of the atmosphere", thus leaving only meteorological factors to be considered (Jensen *et al.* 1990, Allen *et al.* 1998). This simplifies the calculation of ET by creating a single surface against which other surfaces (*i.e.* different vegetation types) can be compared. Furthermore, use of such an ET term would also eliminate the requirement to vary the ET equation at different stages of vegetative growth (Allen *et al.* 1998). This new form of ET, known as reference

evapotranspiration (ET_o), simply "expresses the evaporating power of the atmosphere at a specific location and time of year" (Allen *et al.* 1998). ET_o can also be thought of as a specific form of PET where the transpirating vegetation has been specifically defined.

Two surfaces have been used commonly as a reference surface: short clipped grass and alfalfa (Penman 1948, Blaney and Criddle 1950, Jensen and Haise 1963, Hargreaves 1974, Doorenbos and Pruitt 1977, Linacre 1977, Jensen *et al.* 1990, Allen *et al.* 1994, Allen *et al.* 1998, Pereira *et al.* 1999). Researchers have tended to choose the reference surface (grass or alfalfa) based on the availability of relevant data. Alfalfa has bulk stomatal resistance and exchange values that are similar to many agricultural crops, but more experimental data exist on short clipped grass. Therefore, grass was selected as the primary reference surface by the FAO for international use (Pereira *et al.* 1999). Also in question was which model should be used as the standard model for computing ET_o. Doorenbos and Pruitt (1977) had suggested four methods (FAO-24 Blaney-Criddle, FAO-24 Penman, FAO 24 Radiation, and FAO-24 Pan Evaporation). Smith *et al.* (1991) first recommended the use of Penman-Monteith as the primary model for computing ET_o. This recommendation was based on past performance of the model and the model's incorporation of plant physiological and aerodynamic micrometeorological factors (Allen *et al.* 1989, Jensen *et al.* 1990, Allen *et al.* 1998, Pereira *et al.* 1999). The Penman-Monteith equation was officially adapted as the FAO-recommended model with the publication of FAO-56 in 1998 (Allen *et al.* 1998). Details of this model will be provided in Chapter 3.

With the selection of Penman-Monteith as the ET_o equation, it was necessary to choose the physical, physiological, and aerodynamic parameters for the reference grass. The FAO adopted a set of parameters for a hypothetical grass with a crop height of 0.12 m, an albedo of 0.23, and a fixed surface resistance value of 70 s m^{-1} (Allen *et al.* 1998). These parameters are

very similar to the parameters of clipped Alta fescue grass that is found in the weighing lysimeters in Davis, California -- a site that has been used in much ET research (Hargreaves and Allen 2003).

The selection of the Penman-Monteith model as the standard for ET_o and the fixed hypothetical parameters for the grass reference crop has standardized the calculation of reference evapotranspiration. Thus, the plant physiological and soil factors are neglected in the calculation of ET_o. Furthermore, a baseline value of ET_o is created which allows for the objective comparison of ET_o across different climates. The development of ET_o also allows simplified calculation of crop coefficients for different varieties of crops, which are used to adjust ET_o to a value specific to a particular crop at a certain time in the growth of the crop (Allen *et al.* 1998).

2.2 Model Performance

2.2.1 General Model Performance in Practice

Qiu *et al.* (2002) compared the relatively new Three-Temperature (3T) model (Qiu 1996, Qiu *et al.* 1996) against the Penman-Monteith, the Bowen Ratio, Temperature Difference (Idso *et al*. 1977, Monteith 1965, Hatfield 1985), and ENWATBAL (Evett and Lascano 1993) models for use in Japan. Results suggested that the Penman-Monteith model compared well to the lysimeteric standard with MAE value of 0.42 mm day^{-1} (Qiu *et al*. 2002). This research supports the use of the Penman-Monteith equation as an accurate model and as the model of choice of the FAO for computing ET_o. The performance of the Penman-Monteith model here serves to reinforce the selection of the Penman-Monteith equation as the international standard from calculating ET_o by the FAO. Other studies that use the 56PM model as the standard include Utset *et al*. (2004), Gavin and Agnew (2004), and Irmak *et al*. (2003a, 2003b)

Barnett *et al.* (1998) examined five commonly used models (Modified Penman (Hansen *et al*. 1980), Jensen-Haise (Jensen and Haise 1963), and the SCS (Blaney and Criddle 1950) and FAO versions of the Blaney-Criddle model (Doorenbos and Pruitt 1977) and one Canada-specific model, Baier-Robertson (Baier and Robertson 1965)) for use in Quebec (Barnett *et al.*1998). Model outputs were compared to an evaporation pan located about 20 km from the meteorological station on a monthly and seasonal scale for 1995 and 1996 (Barnett *et al.*1998). Results suggested that the best-fit model on the seasonal scale was that of Baier-Haise, which was not found to differ significantly from the corrected pan value. The most relevant finding from Barnett *et al.* (1998) to this study was that the remaining models (including the FAO Blaney-Criddle and the Modified Penman) would perform better than the pan data if each model were properly calibrated to the local climate (Hansen *et al.*1998). This finding was corroborated by Xu and Singh (2000), who examined several models (including Priestley-Taylor, Makkink, and Turc) against pan evaporation data in Switzerland. These findings support the possibility that each parameter of a model may need to be properly adjusted for the local climate, particularly if the model is not designed explicitly for that climate. One potential flaw in the studies by Barnett *et al.* (1998) and Xu and Singh (2000) is the use of pan evaporation data as a reliable standard of measurement for ET_o, especially with the known errors in converting pan evaporation to ET_o (see Allen *et al.* 1998). Therefore, the calibration of relatively simple models against a more reliable reference (such as ET_o) may provide a useful means of estimating ET for agricultural and environmental applications.

The Linacre model (Linacre 1977) is another model that was designed to simulate ET_o by using the basic concepts of the Penman (1948) model while utilizing minimal climate data such as temperature and dew point. Two significant studies assessed the performance of the Linacre

model (Linacre 1977) relative to two standards. Linacre (1977) showed in his initial paper introducing the model that the model provided accurate results when compared to lysimetric data in Idaho, Africa, and Denmark, and differences of less than 1.0 mm day^{-1} when compared to Penman (1948) at the same sites. Linacre (1977) also found that the accuracy of his model increased as the temporal scale increased. Anyadike (1987) compared the monthly Linacre ET model with the Thornthwaite and Penman methods in four different West African climates utilizing data from 1931-1960. The Linacre and Thornthwaite models were then compared against the Penman model for 34 stations (where no evaporation pan data existed), and all three models were compared against evaporation pan data for ten stations (Anyadike 1987). When compared to evaporation data and the Penman model, the Linacre model returned a higher correlation coefficient than the Thornthwaite method (Anyadike 1987).

Most relevant geographically to this study is research by Shah and Edling (2000), who predicted daily ET in a flooded rice field near Crowley, Louisiana. Shah and Edling (2000) compared three forms of the Penman equation (Penman-Monteith, FAO-Penman (Doorenbos and Pruitt 1977), and 1963 Penman (Penman 1963)) to ET data derived from the water balance method (Shah and Edling 2000) for May-July 1995. Shah and Edling (2000) found that the results from the Penman models were comparable to the water balance method, with the Penman-Monteith (daily) being slightly better than the others. The Penman-Monteith (daily) underreported ET by 3.7%, which was found acceptable for irrigation purposes (Shah and Edling 2000).

While the work of Shah and Edling (2000) provides insight into how accurate the Penman family of models will perform in Louisiana, it has several drawbacks. First, while rice is a vital Louisiana crop, it certainly does not represent of all of Louisiana agriculture, and a

flooded field is not typical for most farmland in the state. Furthermore, measurements of runoff and seepage are difficult. Also, Shah and Edling (2000) only examined a two-month period, which does not provide data on longer-term trends. Finally, the technique implemented requires extensive instrumentation in the study area to measure not only the meteorological variables but also hydrologic variables such as flow into the soil. Therefore, simpler techniques would be more ideal.

2.2.2 Model Performance versus FAO 56 Penman-Monteith (56PM)

As the 56PM model has become more accepted as the standard ET_o equation, many studies are examining how other grass-reference models, particularly those with fewer data requirements, perform against 56PM. Research by Amatya *et al.* (1995) is quite similar to this study. Amatya *et al.* (1995) compared Hargreaves-Samani (1985), Priestley-Taylor (1972), Makkink (1957), and Turc (1961) to 56PM at three sites in North Carolina using data collected intermittently over the period from 1982 to 1994. In general, Amatya *et al.* (1995) found that Turc was the best model to simulate 56PM ET_o on the annual and monthly time scales. On the daily scale, Turc performed the best at one site while Priestley-Taylor and Makkink were the best at the remaining two sites. It was also found that the Makkink generally underestimated ET_o during peak months, while temperature-based methods (including Hargreaves-Samani) tended to overpredict ET_o (Amatya *et al.* 1995).

ET models tend to perform the best in the climates in which they were designed. The study by Amayta *et al.* (1995) showed that the while the Makkink model generally performed well in North Carolina, the model underestimated ET_o in the peak months of summer. Yet, the Makkink model shows excellent results in western Europe where it was designed, both in comparisons to 56PM and measured ET_o data (de Bruin and Lablans 1998, Xu and Singh 1998,

de Bruin and Stricker 2000). Research by Barnett *et al.* (1998) and Irmak *et al.* (2003b) supports this observation as well. The implication is that some models, like Makkink, may not perform satisfactorily in the humid climate of Louisiana. This may not be true in all situations, however. Several authors (Amayta *et al.* 1995, George *et al.* 2002, Irmak *et al.* 2003b) showed that the Turc model, another model designed in western Europe (Jensen *et al.* 1990), performs well in warm, humid climates such as those found in North Carolina (Amatya *et al*. 1995), India (George *et al*. 2002), and Florida (Irmak *et al*. 2003b).

The best model to simulate 56PM often depends on data availability. George *et al.* (2002) researched a decision support system that selected the best ET_o model, depending on data availability and the climate of the location in question. They found that certain models, such as Hargreaves-Samani, perform best in situations where only maximum and minimum air temperature data are available. George *et al.* (2002) also examined ET_o estimation at three sites, with daily and monthly comparisons in India and Davis, California, and an additional site in India used for monthly data only. Both sites in India are in humid climates while Davis is an arid site (George *et al.* 2002). Of the radiation models used, the FAO 24 Radiation model overestimated ET_o for Davis when compared to the 56PM model, with Priestley-Taylor and Turc both underestimating ET_o. Of the temperature models, the results of George *et al*. (2002) show that the FAO 24 Blaney-Criddle model overestimated 56PM, while the Hargreaves-Samani model fell within 1 percent of 56PM. This is not surprising as Hargreaves-Samani was initially designed using Davis data (George *et al.* 2002). At the Indian sites, Priestley-Taylor and Turc tended to underestimate ET_o, with the behavior of the remaining models site-dependent (George *et al.* 2002). The Georges *et al*. (2002) study is similar to that of Irmak *et al.* (2003b), which examines the performance of ET_o models in Gainesville, Florida. The conclusions were similar,

with the recommendation that most temperature models require local calibration if they were not designed of the climate in which they were being used. Irmak *et al.* (2003b) also noted that model choice is highly dependent on the availability and quality of meteorological data. It should also be noted that while Irmak *et al.* (2003b) provides a valuable study of ET_o models in a humid climate, the study only uses data from one location. Louisiana has a varying climate, with a humid coastal climate in the southern portion of the state and a relatively drier and warmer climate in the northwest portion of the state (NOAA 2002). The resulting model behavior in a humid environment from both George *et al.* (2002) and Irmak *et al.* (2003b) may not be completely applicable to Louisiana as a whole.

2.3 FAO 24 Pan Evaporation (24PAN) versus 56PM

Irmak *et al.* (2002) examined the techniques of Frevert *et al.* (1983) and Snyder (1992) to convert pan evaporation to 56PM-derived ET_o in the humid subtropical climate of Gainesville, Florida. Results of Irmak *et al.* (2002) show that the Frevert *et al.* (1983) methods produce estimates that are within approximately 5 percent of 56PM, depending on the temporal scale of the data (*i.e.* daily, monthly, etc). The Snyder (1992) method tended to overestimate 56PM, especially in summer (Irmak *et al.* 2002). The Frevert *et al.* (1983) method is not the one recommended by the FAO in the FAO 56 text (Allen *et al.* 1998), although it is based upon the original data from FAO 24 (Doorenbos and Pruitt 1977). This thesis uses the FAO 56 recommended method, which is based on work by Allen and Pruitt (1991) (Allen *et al.* 1998).

Grismer *et al.* (2002) also examined the accuracy of pan evaporation conversion methods at eight sites in California using ET_o computed by the California Irrigation Management and Information System (CIMIS). CIMIS uses versions of the Modified-Penman or Penman-Monteith equations (Grismer *et al.* 2002). The stations varied in location and climate, with some

stations located on the coast and others in dry inland locations. Six different conversion models were used, including the Allen and Pruitt (1991) method that is used in this study. Grismer *et al*. (2002) found that the accuracy of the Allen and Pruitt (1991) method meets or exceeds that from the use of a manual table from FAO 24 (Doorenbos and Pruitt 1977) and is "consistently nearer to the measured (CIMIS) values than that estimated by any other equation". The Irmak *et al.* (2003b) study discussed previously also examined ET_o estimation from evaporation pans using the FAO (Frevert *et al.* 1983) equation and the Christiansen (Christiansen and Hargreaves 1969) models. Both models performed poorly, with errors of 1.18 and 1.19 mm day^{-1} respectively. This finding is important, as one of the two evaporation stations used in this study (Ben Hur) is in a climate very similar to that of Gainesville and the Irmak *et al.* (2003b) study may give a good indication of how accurate pan evaporation to ET_o models may be in Louisiana. Neither of the equation sets used by Irmak *et al.* (2003b) are used in this study; instead the suggested international FAO standard equation as presented in by Allen *et al*. (1998) has been used. The reason behind this decision is to determine the accuracy of the recommended standard equation before examining other methods that are not recognized as by the FAO as standard equations.

All of the studies in Sections 2.2 and 2.3 show valuable insight into the performance of ET models, both compared to measured ET values and to FAO 56 ET_o values. However, few studies have examined ET in Louisiana and no detailed study has focused on the performance of ET_o models when compared to the reference 56PM model. As water demand increases throughout Louisiana, a greater expectation will be placed on the agricultural industry to make the most efficient use of water possible. Therefore, an improved understanding of ET_o model performance will provide the agricultural community with better information for irrigation

scheduling. The next chapter will focus on the individual models, providing a technical insight into each model.

Chapter 3
Reference Evapotranspiration Models

This chapter provides an overview of the various methods of estimating evapotranspiration. These models span the spectrum from purely physically-based to purely empirically-based. An evaluation of the utility of the models described in this chapter in Louisiana will be conducted in this thesis. Therefore, it is important to understand the input requirements of the models so that these requirements can be considered against the accuracy when determining the optimal model(s) for use in Louisiana.

3.1 FAO Penman-Monteith (56PM)

The ET_o model that will be used as the reference standard for this study is the United Nations Food and Agriculture Organization's (FAO) Penman-Monteith model (Allen *et al.* 1998). The Penman family of models is generally considered among the most accurate ET models in virtually any climate (Anyadike 1987, Barnett *et al.* 1998, Qiu *et al.* 2002). The FAO version of the Penman-Monteith model (hereafter referred to as 56PM) is so accurate that it is recommended as the sole method of calculating ET_o, if data are available (Allen *et al.* 1998). The major limitation to the Penman family of models is that they require many meteorological inputs, thereby limiting their utility in data-sparse areas (Hansen *et al.* 1980, Dingman 1994).

Several major versions of the Penman model exist, each with its own variations for specific climates, crops, *etc*. The 56PM model is a variant of the original 1948 Penman model, but the 56PM model accounts for aerodynamic (r_a) and bulk surface resistance (r_s) (Allen *et al.* 1998). These terms modify the original equation to take into account the increasing resistances involved in transporting moisture from the evaporating surface upward and to the atmosphere under increasingly dry surface conditions. Specifically, r_a describes the physical resistance in transporting moisture from the evaporating surface (plant leaf) into the atmosphere (Allen *et al.*

1998) by modeling stomatal resistance of the vegetation and r_s models resistance from the soil surface (Allen *et al.* 1998). The addition of these two terms allows the original Penman model to better approximate the actual processes of evapotranspiration from a vegetated surface. It also allows the adaptation of the equation to a specific type of vegetation, such as a particular crop. The basic form of the PM equation is given as (Allen *et al.* 1998):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad 3.1$$

where λ is the latent heat of vaporization (J kg^{-1}), ET is evapotranspiration (J m^{-2} s^{-1}), Δ is the slope of the saturation vapor pressure-temperature curve (Pa K^{-1}), γ is the psychrometric constant (Pa K^{-1}), R_n is the net radiation(J m^{-2} s^{-1}), G is the soil heat flux (J m^{-2} s^{-1}), $(e_s - e_a)$ is the difference between the saturation vapor pressure e_s (Pa) and the actual vapor pressure e_a (Pa), ρ_a is the mean air density (kg m^{-3}), c_p is the specific heat of air (J kg^{-1} k^{-1}), and r_a and r_s are the aerodynamic and surface resistances (s^{-1} m) (Allen *et al.* 1998). The formulas for calculation of the individual components are beyond the scope of this text and can be found in the FAO 56 manual by Allen *et al.* (1998). Further explanation of the units in Equation 3.1 can be found in FAO-56 (Allen *et al.* 1998).

As the reference grass surface concept was introduced and its parameters were defined, Allen *et al.* (1998) modified the basic form of PM to incorporate these variables and to produce a simplified PM equation (56PM). The final form of the 56PM equation is described by Equation 3.2:

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad 3.2$$

where ET_o is grass reference evapotranspiration (mm day^{-1}), R_n is net radiation (MJ m^{-2} day^{-1}), G is soil heat flux (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa °C^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), and Δ is the slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}), T is the average daily air temperature (°C), and u_2 is the mean daily wind speed at 2 m (m s^{-1}) (Allen *et al.* 1998).

On a daily scale, the nature of the climate system allows for the soil heat flux term, G, to be ignored as soil heat flux on a daily scale is essentially zero (Allen *et al.* 1998). The term cannot be ignored for longer time scales, such as monthly data. In this study, daily soil heat flux is assumed to be zero and is ignored; monthly soil heat flux is computed as specified by Allen *et al.* (1998).

3.2 FAO 24 Radiation (24RD)

The FAO 24 Radiation method was first introduced by Doorenbos and Pruitt (1977) as a modification of the Makkink (1957) method (Doorenbos and Pruitt 1977, Jensen *et al.* 1990). It was originally suggested that this model be used over a Penman method when measured air temperature and solar radiation were available but wind and humidity data were unavailable or were of questionable quality (Doorenbos and Pruitt 1977, Jensen *et al.* 1990). However, the 24RD model performs much better with measured data (Jensen *et al.* 1990). The form of 24RD given by Jensen *et al.* (1990) is described in Equation 3.3:

$$ET_O = a + b\left[\frac{\Delta}{\Delta+\gamma}R_s\right] \qquad 3.3$$

where ET_o is grass-reference evapotranspiration (mm day^{-1}), $\Delta$and γ are the same variables defined for Equation 3.1, R_s is solar radiation (mm day^{-1}) (see Allen *et al.* 1998 for conversion factors), and a = -0.3 mm day^{-1}. Furthermore, in Equation 2.3,

$$b = 1.066 - 0.13 \times 10^{-2} RH_{mean} + 0.045 U_d - 0.20 \times 10^{-3} RH_{mean} U_d - 0.315 \times 10^{-4} RH_{mean}{}^2 - 0.11 \times 10^{-2} U_d{}^2 \quad 3.4$$

where RH_{mean} is the daily mean relative humidity (percent) and U_d is the mean daytime wind speed (m s^{-1}) (Jensen *et al.* 1990).

3.3 FAO 24 Blaney-Criddle (24BC)

The Blaney-Criddle model is one of the older models available to calculate evapotranspiration. Blaney and Criddle (1950) developed their model for use in arid farmlands of the western U.S. while working as engineers for the Soil Conservation Service (SCS) (Hansen *et al.* 1980). The model's relationships were derived from experimental data for a variety of crops over the western U.S (Blaney and Criddle 1950). The original model is similar to the classic Thornthwaite model, requiring only temperature and a function of sunlight hours as data input. The original model as described by Blaney and Criddle (1950) is:

$$ET = kf \quad .5$$

where PET is in mm per unit time, k is a crop-specific coefficient and f is a is a consumptive use factor given by:

$$f = \frac{T \times P}{100} \quad 3.6$$

with T being the mean monthly temperature (°F) and P the monthly percentage of the annual daytime hours (Blaney and Criddle 1950).

Several revisions of the Blaney-Criddle model have been proposed, but the one used in this study was originally described in the FAO 24 manual (Doorenbos and Pruitt 1977) and modified by Jensen *et al.* (1990). The FAO 24 version introduces the grass reference elements into the equation, allowing the later use of crop coefficients (Doorenbos and Pruitt 1977, Jensen *et al*. 1990). The model as described by Jensen *et al.* (1990) is as follows:

$$ET_O = a + bf \quad 3.7$$

$$f = p(0.46T + 8.13) \quad 3.8$$

$$a = 0.0043RH_{\min} - \frac{n}{N} - 1.41 \quad 3.9$$

$$\begin{aligned} b = {} & 0.908 - 0.00483RH_{\min} + 0.7949\frac{n}{N} + 0.768[\ln(U_d + 1)]^2 \\ & - 0.0038RH_{\min}\frac{n}{N} - 0.000443RH_{\min}U_d + 0.281\left[\ln\left(\frac{n}{N} + 1\right)\right] \\ & - 0.00975[\ln(U_d + 1)]\,[\ln(RH_{\min} + 1)]^2\left[\ln\left(\frac{n}{N} + 1\right)\right] \end{aligned} \quad 3.10$$

where ET_o is reference evapotranspiration (mm day^{-1}), p is the mean percentage of annual daytime hours (defined as the percentage of the total annual daylight hours that occur in the time period being examined, such as daily or monthly (Doorenbos and Pruitt 1977)), T is the mean air temperature (°C), RH_{min} is the minimum relative humidity (percent), n/N is the ratio of possible to actual sunshine hours, and U_d is the daytime wind speed at 2 m (m s^{-1}). The original Blaney-Criddle model was designed to use monthly values only and was known to produce erroneous results for any period shorter than one month (Hansen *et al.* 1980). This limitation was due to the use of temperature as the sole climatic variable (Hansen *et al.* 1980). The 24BC version of the model, however, uses humidity and wind speed, thus minimizing this limitation.

3.4 Hargreaves-Samani 1985 (H/S)

The Hargreaves-Samani 1985 model is one of the more represent versions of one of the older evapotranspiration models (Hargreaves and Allen 2003). The H/S model used in this study has conceptually similar versions (Hargreaves 1974, Hargreaves and Samani 1982), which intended to be computationally simple and applicable to a variety of climates using only commonly available meteorological data. The creation of the H/S model used in this study was

intended to simplify the previous versions further by reducing the amount of measured meteorological data to air temperature and by using extraterrestrial radiation (R_a) as a substitute for measured sunshine or radiation data (Hargreaves and Allen 2003). The H/S model was later adopted for used by the FAO for areas where air temperature alone is the only available variable (Allen *et al.* 1998, Hargreaves and Allen 2003). The form of the H/S equation presented in FAO 56 by Allen *et al.* (1998) is:

$$ET_O = 0.0023(T_{mean} + 17.8)(T_{\max} - T_{\min})^{0.5} R_a \qquad 3.11$$

where ET_o is the reference evapotranspiration (mm day^{-1}), T_{mean} is the mean air temperature (°C), T_{max} is the daily maximum temperature (°C), T_{min} is the daily minimum temperature (°C), and R_a is the daily extraterrestrial radiation (mm day^{-1}). Equation 3.11 does not account for any local factors such relative humidity as the previous Hargreaves models do, which may be a limitation. This equation, however, is computationally simple and can be used over a variety of climates with a minimal amount of climate data required (Hargreaves and Allen 2003).

3.5 Priestley-Taylor (P/T)

The Priestley-Taylor model is essentially a shortened version of the original 1948 Penman combination equation (Priestley and Taylor 1972, Jensen *et al.* 1990). The original intent of the model was for use in large-scale numerical modeling where it is assumed that advection is small, thus allowing the aerodynamic component of the original Penman equation to be reduced to a coefficient that modifies the remaining equation (Priestley and Taylor 1972, Jensen *et al.* 1990, McAneney and Itier 1996). The P/T model was designed to be used in humid areas where surfaces were usually wet (Priestley and Taylor 1972; Jensen *et al.* 1990). The form of the P/T used in this study was described by Jensen *et al.* (1990) as:

$$ET = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G) \qquad 3.12$$

where ET is evapotranspiration (mm day^{-1}), $\alpha = 1.26$, and all other terms are identical to those defined previously. The coefficient term may be modified for different wind and humidity regimes, but it has been found that the current value of 1.26 is reasonable across most climates (McAneney and Itier 1996).

3.6 Makkink (Makk)

The Makkink model was designed in 1957 in the Netherlands as a modification of Penman after comparing the Penman model to lysimetric data (Allen 2003, Makkink 1957). Currently, Makkink is popular in western Europe (Allen 2003) and has been used successfully in the U.S (see Amatya *et al.* 1995). Allen (2003) gives the operational form of the Makkink model as:

$$ET_O = 0.61\frac{\Delta}{\Delta+\gamma}\frac{R_S}{2.45} - 0.12 \qquad 3.13$$

where ET_o is evapotranspiration (mm day^{-1}), R_s is solar radiation (MJ m^{-2} day^{-1}), and Δ and γ are the same variables defined for Equation 3.1.

3.7 Turc

The Turc (1961) model was also designed for use in western Europe and was a simplification of an older equation (Jensen *et al.* 1990). Turc has been used to some extent in the United States (*e.g.*, Amatya *et al.* 1995). As defined for operational use by Allen (2003):

$$ET_O = a_T 0.013\frac{T_{mean}}{T_{mean}+15}\frac{23.8856R_S+50}{\lambda} \qquad 3.14$$

where ET_o is evapotranspiration (mm day^{-1}), T_{mean} is the mean daily air temperature (°C), R_s is solar radiation (MJ m^{-2} day^{-1}), and λ is the latent heat of vaporization (MJ kg^{-1}). The coefficient a_T is a humidity-based value. If the mean daily relative humidity (RH_{mean}) is greater than or

equal to 50 percent, then $a_T = 1.0$. If the mean daily relative humidity is less than 50 percent, then a_T has the value of:

$$a_T = 1 + \frac{50 - RH_{mean}}{70} \quad 3.15$$

3.8 Linacre (Lina)

A method that is similar in concept to the original Penman is the Linacre model (Linacre 1977). This model was designed to calculate lake evaporation and evapotranspiration in areas with limited climatic data while still using the physical concepts that enable the Penman family of models to be generally regarded as the most accurate (Linacre 1977). Linacre's model requires slightly more data than that required by other limited data models such as H/S, but significantly less than is needed by the Penman models (Linacre 1977). The initial equation derived by Linacre (1977) for grass-reference evapotranspiration is:

$$ET_O = \frac{\left(\frac{500T_m}{100 - A}\right) + 15(T - T_d)}{(80 - T)} \quad 3.16$$

$$T_m = T + 0.006h \quad 3.17$$

where T is the mean temperature (°C), T_d is the mean dew point (°C), A is the latitude of the station in degrees, and T_m (Equation 2.17) is an elevation adjustment with h as the station elevation (m). Equation 3.16 is actually one of two, with the second equation used for calculating lake evaporation. The equations only differ in a value of a single coefficient (Linacre 1977).

While the Linacre equation requires less data than required for the Penman, some areas may still only have temperature and precipitation data available, with humidity or dew point data not being available in the data record. Linacre recognized this limitation and developed a substitute for the mean dew point depression ($T - T_d$) element in Equation 3.16:

$$\left(T - T_d\right) = 0.0023h + 0.37T + 0.53R + 0.35R_{ann} - 10.9 \qquad 3.18$$

where R is the mean daily range of temperature (°C) and R_{ann} is the difference between the mean temperatures of the warmest and coldest month (°C) (Linacre 1977). In Equation 3.18, Linacre made the substitution of temperature range for dew point on the assumption that the drier a given air mass is, the greater the temperature range will be (Linacre 1977). The caveat to using Equation 3.18 is that the station must have at least 5 mm of precipitation per month and that the mean dew point depression ($T - T_d$) must be at least 4 °C (Linacre 1977).

This latter limitation of Equation 3.18 could present a problem in humid climates. An examination of monthly mean temperature and dew point data from Baton Rouge (Table 3.1) indicates that this limitation would probably not be problematic over most of Louisiana, most of the time, assuming that Baton Rouge is generally representative of the climate Louisiana as a whole (Table 3.1). As all of the meteorological stations used in this study have dew point information, the substitution of Equation 3.18 is not required.

Table 3.1: Differences in monthly mean temperature and dew point for Baton Rouge, LA (From NOAA 2002)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temperature (C°)	10.6	12.4	15.9	20	23.8	26.9	27.8	27.7	25.4	20.2	15.1	11.7
Mean Dew Point (C°)	5.6	6.6	9.6	13.8	17.9	21.1	22.4	22.2	19.9	14.2	9.8	6.6
Difference (C°)	5	5.8	6.3	6.2	5.9	5.9	5.4	5.4	5.5	6	5.3	5.1

One additional limitation of the Linacre model is that its utility is limited to locations where monthly mean temperature ranges from 8 – 36 °C (Linacre 1977). This probably would not be a limitation in Louisiana, except for possibly stations in northern Louisiana during the winter months when the mean temperature is approximately 8 °C.

3.9 FAO 24 Pan Evaporation (24PAN)

Doorenbos and Pruitt (1977) described a method to convert pan evaporation to ET_o. This method, known as FAO 24 Pan Evaporation (24PAN), adjusts the measured pan evaporation by a coefficient to estimate ET_o. The basic form of the 24PAN model, as described by Allen *et al.* (1998) is:

$$ET_O = K_P E_{pan} \tag{3.19}$$

where ET_o is in mm day^{-1}, K_P is the pan coefficient, and E_{pan} is the pan evaporation (mm day^{-1}). The coefficient, K_P, is dependent on several factors, including pan type (Class "A" pan or a "Colorado" pan), the upwind fetch, humidity, and wind speed (Allen *et al.* 1998, Doorenbos and Pruitt 1977, Jensen *et al.* 1990). The original 24PAN method relied on a series of tables to determine the appropriate coefficient based upon mean relative humidity, fetch, and wind speed. These tables have been replaced by regression equations developed by Allen and Pruitt (1989) for green and dry crops. Their regression for green crops, as described by Allen *et al.* (1998) is:

$$\begin{aligned} K_P &= 0.108 - 0.0286 u_2 + 0.0422 \ln(FET) + 0.1434 \ln(RH_{mean}) \\ &- 0.000631 \left[\ln(FET)\right]^2 \ln(RH_{mean}) \end{aligned} \tag{3.20}$$

where K_P is the pan coefficient, u_2 is the average daily wind speed at 2 m (m s^{-1}), FET is the fetch distance of the green crop (m), and RH_{mean} is mean daily relative humidity (percent). The limits for Equation 3.20 are wind speeds must be between 1-8 m s^{-1}, RH_{mean} must be between 30 and 84 percent, and the fetch distance must be between 1-1000 m (Allen *et al.* 1998). Due to the variable nature of the environment around the evaporation pans used in this study, a fetch distance of 1000 m has been assumed as suggested by Allen (2003).

FAO Penman-Monteith (56PM) was selected to be the ET_o model because of its physical basis and broad range of acceptable performance. The eight other models described above all have advantages and disadvantages in terms of input data requirements and quality of results. A

primary goal of this study is to identify the model that most closely approximates 56PM while considering the input data required. Chapter 4 will identify the methods and data involved to address this question, and Chapter 5 will present the results of the tests implemented to answer the question.

Chapter 4
Data and Methods

4.1 Data Sources

Each of the eight ET_o models used in this study has different input data requirements (Table 4.1). Most of the models require some measurement of temperature (usually daily maximum and minimum temperatures that are converted into a daily average) and a radiation variable. Some of the models can use estimated clear-sky radiation (R_{so}) in place of measured solar radiation (Allen *et al*. 1998, Linacre 1977). Other models, such as the 56PM, 24RD, 24BC, Turc, and Linacre require a humidity variable. Many of the models, such as Linacre, have substitution equations for humidity when those data are not available.

Table 4.1 Meteorological Data Requirements. Source: Allen *et al*. 1998, Doorenbos and Pruitt 1977, Jensen *et al*. 1989, Linacre 1977, Makk 1957

Model	Meteorological Data Requirements
56PM (1998)	Air Temperature, Solar/Net Radiation, Humidity, Wind Speed
24RD (1977)	Air Temperature, Solar Radiation, Humidity, Wind Speed
24BC (1977)	Air Temperature, Sunshine, Humidity, Wind Speed
H/S (1985)	Air Temperature, Extraterrestrial Radiation
P/T (1972)	Air Temperature, Solar/Net Radiation
MAKK (1957)	Air Temperature, Solar Radiation
TURC (1961)	Air Temperature, Solar Radiation, Humidity
LINA (1977)	Air Temperature, Humidity
24PAN (1977)	Pan Evaporation, Humidity, Wind Speed

4.2 LAIS Overview and Data Elements

Several of the meteorological measurements required for input into the ET_o estimation equations, such as solar radiation and humidity, are not collected at many official weather

stations. Therefore, ET_o is estimated instead for stations with available data from the Louisiana Agriclimate Information System (LAIS). The LAIS is a statewide network of 25 automated weather stations operated by the Louisiana State University Agricultural Center (Figure 4.1)

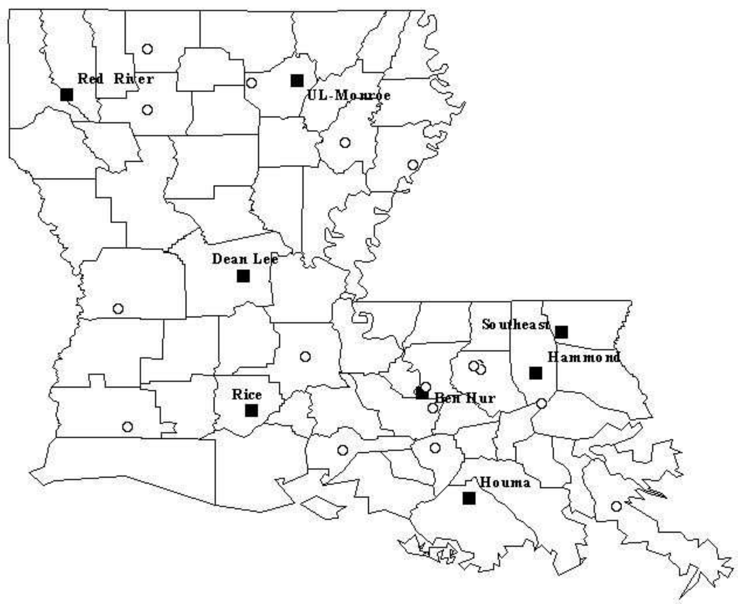

Figure 4.1 LAIS Stations. Stations marked with a box are included in this study

The LAIS is primarily dedicated to collecting meteorological data for use in agriculture and is perfectly suited for use in this study. In all, 19 of the sites are at LSU Agricultural Center research stations with the remaining sites located at other state universities, private sites, and a USDA research facility. Although the network has been in operation for nearly 20 years, data quality has always been an issue and only the last one to two years can be used with confidence for ET_o modeling.

Each LAIS station in the network samples all meteorological elements at three-second intervals and records the data as 1-minute, 1-hour, and 24-hour averages. Data for the 24-hour time scale are available at two intervals: midnight to midnight (which are used in this study) and 7:00am to 7:00am. All observations are recorded in Central Standard Time. Data are retrieved

at a real-time basis for 23 of the 25 LAIS stations, with two sites polled in the morning only. Of the 25 stations, 8 were selected for use in this study (study stations). These stations were selected because of the completeness of their data records and spatial coverage.

The meteorological data are recorded at each site by a Campbell Scientific CR-23X datalogger. Temperature and relative humidity are measured using a combination of Vaisala HMP-35 or HMP-45 thermoelectric sensors located at heights of approximately 1.5 meters. Wind speed and direction (in degrees) is measured at both 3 and 10 meters, and the midnight-to-midnight average at 10 meters is utilized for input. A RM Young Wind Monitor measures the 10-meter wind speed and direction. Although the 3-meter wind measurements are close to the 2-meter standard for agricultural use, the 10-meter wind is used for this study because of the greater accuracy and reliability of the data from the 10-meter sensor when compared to the 3-meter wind data. The 10-meter wind data was converted to 2-meter height by the REF-ET software (the software which was used to run the models) using standard formulas as found in Allen *et al.* (1998). The formula described by Allen *et al.* (1998) is a form of the logarithmic wind profile and assumes the ground coverage is grass and that the atmospheric stability is neutral. All stations used in this study are located over clipped grass and it can be assumed that on average atmospheric stability is not significantly different from neutral. Further explanation of the logarithmic wind profile can be found in Oke (1987) and Geiger *et al.* (2003). Finally, solar radiation is measured at each station using a LiCor LI-200S pyranometer. The sensor measures incoming shortwave (*i.e.*, solar) radiation (R_s). The value used for the ET_o models is the average daily value (calculated as the average of each 1-minute observation during the day), as specified by Allen *et al*. (1998) as the FAO standard. This 1-minute sample interval should reduce potential errors in the calculation of ET_o as suggested by Hupet and Vanclooster (2001).

Pan evaporation data were collected from the Ben Hur and Red River Research Farms. Each site is equipped with a NWS Class "A" evaporation pan. The pan level is sampled daily at 8:00am. The pan evaporation data were obtained from the unedited NWS B-91 forms archived at the Southern Regional Climate Center.

4.3 Data Quality Control

The daily LAIS data were subjected to several data quality control (QC) procedures. All elements were examined using methods similar to those suggested by Allen *et al*. (1998) and Allen (1996). Few automated routines were used and the data were corrected manually for extreme values. If a value was missing, the value from the previous day or a nearby station was substituted for use by the REF-ET software, if possible. This allowed 365 days of data at all stations except Houma, where not all data elements were available for substitution for 14 May 2003 due the lack of a complete data record at the nearby FAA weather station. The exception was the pan evaporation data, because of the extreme importance of having an accurate value of this variable. If a pan level value was missing, no estimation or substitution was made and the day was omitted. This resulted in a total of 336 observations for Ben Hur and 344 observations for Red River out of a possible 365 observations.

Relative humidity is one of the most difficult parameters on which to perform QC procedures because it varies greatly both spatially and temporally. In addition, the reliability of the sensors on the LAIS platforms is questionable. In some cases, spuriously high maximum and minimum values were found, perhaps in part because of poor instrument calibration. To mitigate this problem, each site was compared to the nearest NWS or FAA automated station and the data were corrected subjectively by taking into account the time of day, general weather conditions,

and station location. Missing data were substituted by the data from the nearest NWS or FAA station.

Daily temperatures were also compared to the nearest NWS or FAA station. Daily temperature data for the LAIS was in much better condition and only those values that were erroneous due to sensor failure or missing were corrected by substituting the value from the nearest NWS or FAA station.

The QC of solar radiation data is a very difficult task. Unlike humidity and temperature, no other network in Louisiana records solar radiation data. Therefore, the only method available for QC purposes is a comparison to the estimated clear-sky solar radiation (R_{so}). R_{so} is the amount of solar radiation that would strike the local surface on a clear, cloudless day given the sun angle and day length for that day (Allen *et al*. 1998). A coefficient is used to reduce the extraterrestrial radiation (R_a) to R_{so}. The value of this coefficient is dependent on several atmospheric variables, including the amount of moisture in the atmosphere, station elevation, and the amount of atmospheric pollution (Allen *et al.*1998). This makes a true estimation of R_{so} difficult at best. There are several equations that can used to estimate R_{so}, but most require data not easily obtained (such as a turbidity factor) or require the use of humidity data (which itself must be run through QC) (Allen *et al*. 1998). For simplicity and uniformity throughout the year, a fixed value of 0.75 was used. This value is reported to work well at most humid locations and is the baseline value for most of the equations mentioned above (Allen *et al.* 1998).

R_s data were examined for relative fit to the R_{so} curve. Four stations (Hammond, Houma, Red River, and Southeast) had Rs data that required adjustment. Three sites (Houma, Red River and Southeast) had R_s values that were significantly below the R_{so} values. The R_s values at Hammond typically were in excess of the R_a curve. Data for the three underestimating sites were

corrected to approximate the R_{so} curve by adding a percentage of the daily R_{so} value to the measured R_s values (Table 4.2).

Table 4.2 R_s Correction Values for Houma, Red River, and Southeast

Station	Amount R_s Adjustment
Houma	Added 20% of daily R_{so} value to R_s
Red River	Added 30% of daily R_{so} value to R_s
Southeast	Added 20% of daily R_{so} value to R_s

Data for Hammond were corrected by adjusting those days with values over the calculated R_{so} value downward by 20 percent of the R_{so} values calculated for that day. Values that did not exceed the calculated R_{so} values were not adjusted. Figures 4.2 and 4.3 demonstrate the radiation data before and after adjustment. It should be noted in Figure 4.2 of the measured values meeting or exceeding the daily R_a value around Day 33.

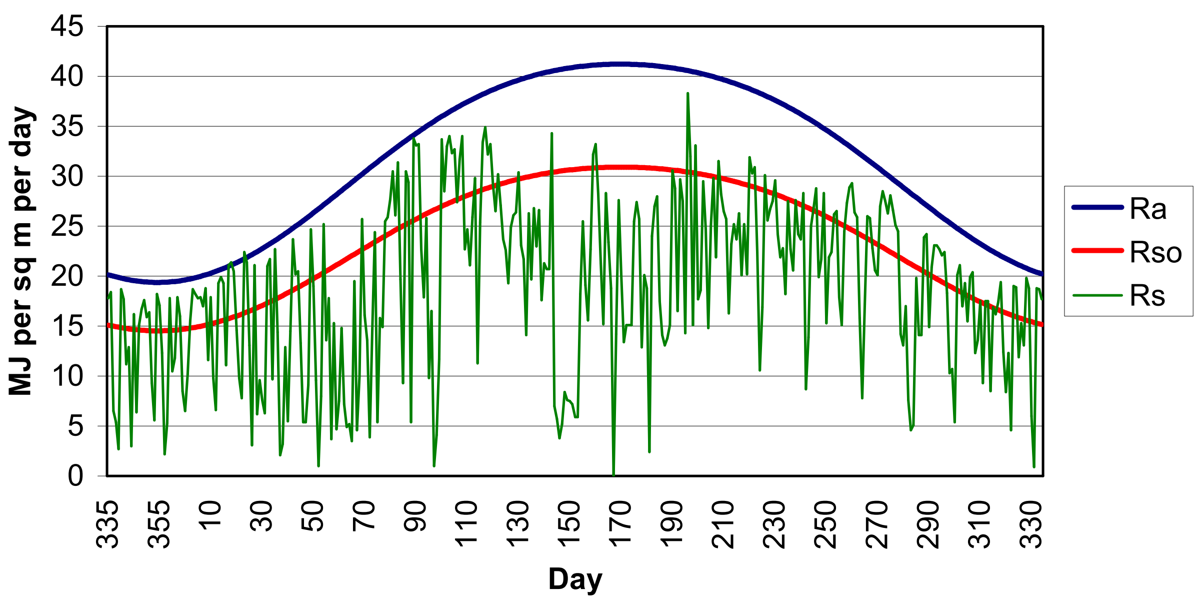

Figure 4.2 Hammond R_s values before correction. R_{so} values are calculated using a 0.75 coefficient.

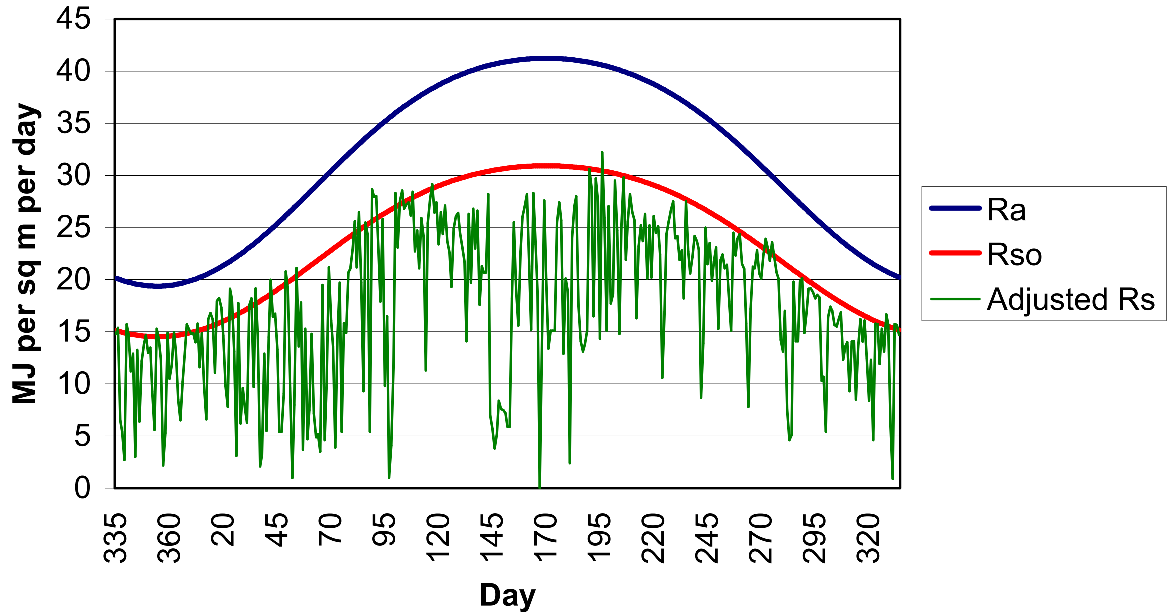

Figure 4.3 Hammond R_s values after downward correction.

4.4 Methods

Once data from the LAIS and pan evaporation sites were edited and quality controlled, they were input for the ET_o models. REF-ET software obtained from the University of Idaho was used for most of the models. Written by R.G Allen (the primary author of the FAO 56 guide), REF-ET computes hourly, daily, and monthly ET_o values using a wide array of models. REF-ET is a very flexible program that can convert various input parameters (such as relative humidity) into usable parameters (such as vapor pressure) for use by the ET_o models. This is accomplished using standard equations that can be found in FAO-56 (see Allen *et al.*1998) (University of Idaho 2001). Data that were loaded into REF-ET for each site consisted of daily maximum/minimum air temperature and relative humidity, average daily wind speed, daily solar radiation, and pan evaporation (for Red River and Ben Hur). Information for each station (such as location, elevation, and anemometer height) was also entered into REF-ET, which was then run for each of the stations. The output included daily ET_o values as well as all intermediate

values used in calculating the various ET_o models and the original input values. The only model not calculated using REF-ET was Linacre, which was computed using the output data from REF-ET.

4.4 Analysis Procedures and Methods

4.4.1 Statistics

Several statistical routines could be used to analyze the relationship of the ET_o models to 56PM. Two areas are of concern: difference and model fit. The difference statistic measures the deviation of the test model (models other than 56PM) to 56PM. Several tests to analyze the difference statistic exist, including mean bias error (MBE), root mean square error (RMSE), and mean absolute error (MAE) (Willmott 1982):

$$MBE = N^{-1}\sum_{i=1}^{N}(P_i - O_i) \tag{4.1}$$

$$RMSE = [N^{-1}\sum_{i=1}^{N}(P_i - O_i)^2]^{0.5} \tag{4.2}$$

$$MAE = N^{-1}\sum_{i=1}^{N}(|P_i - O_i|) \tag{4.3}$$

where N is the overall number of points (in this study, days of valid data), P is the test model ET_o value, and O is the 56PM value. MBE is a good measure of model bias and is simply the average of all differences in the set. This provides a measure of general bias, but not of average error that could be expected (Willmott 1982). By contrast, RSME and MAE are measures of average difference. RSME involves the square of the departures and therefore becomes sensitive to extreme values (Willmott 1982). If RSME is used, anomalous values could significantly change the evaluation of a model when compared to 56PM. MAE uses the absolute difference, thus reducing the sensitivity to extreme differences. While RSME has been used in other similar

studies (Amatya *et al*. 1995), it was decided to use MAE as suggested by Willmott (1982) and used in practice by Qiu *et al.* (2002).

To test the model fit between each test model and 56PM, a series of simple linear regressions (SLR) was performed for each of the test models and 56PM. The SLR gives an estimate of the fit of an unadjusted test model to the values calculated by 56PM (Amatya *et al*. 1995). SLR output statistics are reported to index the quality of the fit.

4.4.2 Daily Model Analysis Procedures

The daily model analysis procedure consists of two major components: the creation and analysis of the daily-individual station dataset and of the daily-composite dataset. First, the daily-individual station dataset was created. Meteorological data from each station were loaded into REF-ET and ET_o for all models (with the exception of Linacre) was calculated. Data were then imported into a MS-Excel spreadsheet and the Linacre model was added. The model evaluation statistics (MAE and SLR) were then calculated for each individual station. After the daily-individual station dataset was created, the daily ET_o values were averaged into three composite datasets: a statewide dataset, an inland dataset, and a coastal dataset (Table 4.2).

Table 4.3 Stations by composite region

Region	Stations
Statewide	All eight study stations
Inland	Dean Lee, Red River, UL-Monroe
Coastal	Ben Hur, Hammond, Houma, Rice, Southeast

ET_o values from each of the stations were averaged together by model to create an average model value across the state and each region. Statistical analysis procedures for the composite datasets were identical to those used in the daily-individual dataset analysis.

4.4.3 Daily-Seasonal Cumulative ET_o Analysis

The daily-seasonal cumulative dataset was created from the individual station and composite datasets. ET_o values for each day were added to those from the previous day to create a running daily total of ET_o to date, creating an annual ET_o total at the end of the data year. Seasonal cumulative totals for each station and region were also calculated. Departures of each test model from 56PM were computed for each season and annually. These deviations were calculated as an absolute difference as well as a percentage of 56PM. Finally, graphs of cumulative ET_o were created for the composite regions only.

4.4.4 Monthly ET_o Analysis

The process for creating and analyzing the monthly dataset was analogous to that of the daily. The monthly dataset was created by averaging the daily meteorological data into monthly averages of maximum/minimum temperature and relative humidity, daily average wind speed, and solar radiation for each station. Data were then loaded into REF-ET for calculation of the monthly ET_o values. As with the daily data, the Linacre model was calculated in a MS-Excel spreadsheet. Monthly composite regions were also calculated in the same fashion. Likewise, the statistical analysis procedure for the monthly dataset is identical to that of the daily data. With one year of available data, only 12 pairs of data are used in the statistical analysis and therefore, caution should be exercised in the interpretation of results.

4.4.5 Pan Evaporation ET_o Analysis

As stated in Section 4.2, daily totals of pan evaporation were obtained directly from copies of the original observation form. Days with missing values were coded as –999 and were not used in the final analysis. These data were then paired with meteorological data from the LAIS station co-located at Ben Hur and Red River. The 24-hour midnight-midnight observation

totals for the meteorological data rather than the 7:00am-7:00am totals were used, for consistency in the 56PM values throughout all datasets. The paired data were then loaded into REF-ET and only 56PM and the 24RD models were calculated.

The analysis for the 24 Pan Evaporation (24PAN) model examined three relationships: 56PM to an uncorrected pan value, 56PM to the 24PAN method using a coefficient calculated on a daily basis, and finally a fixed coefficient that was the overall average of the daily coefficients. The average value calculated from the daily 24PAN coefficients was 0.82. The statistical methods used to analyze the pan data were identical to the daily and monthly dataset using MAE and a SLR.

4.5 Summary

Eight models that have been cited prominently in the literature were used to estimate daily and monthly ET_o for eight sites in Louisiana over a one-year period from December 2002 to November 2003. Results from each of the eight models were compared quantitatively to the calculated values using the more complicated, data-demanding, physically-based Penman-Monteith equation (56PM), which is taken as the reference value. These methods will reveal the model that performs optimally both across space and across seasons in Louisiana and evaluate the accuracy of the FAO recommended pan evaporation to ET_o model. Chapter 5 reveals the results of these analyses.

Chapter 5
Results and Discussion

5.1 Daily Results

Daily ET_o values were computed for all eight LAIS stations as described in Chapter 4. These daily values were averaged into three region-wide daily means: statewide, an inland region, and a coastal region. For each station and region, each test model was compared to the 56PM model using MAE and regression. The best model for each station or region was selected first based on the lowest MAE, then the highest r^2 value, and finally the lowest cumulative departure for the 2002-2003 data year.

5.1.1 Composite Regions

For all three regions, all models had a MAE of less than 1.0 mm day^{-1}, suggesting that all models provide fairly good approximations of 56PM. However, even an error of only 1.0 mm day^{-1} of evapotranspiration on a 1 ha field amounts to approximately 268,000 gallons of water per day, or over 97 million gallons per year. The greatest departure in MAE for any region was for H/S in the Coastal region. All 21 regressions were significant with F values significant at $\alpha < 0.01$.

For the statewide dataset (Table 5.1), the Turc model showed the lowest MAE at 0.26 mm day^{-1} and a r^2 value of 0.94. The 24BC model followed with a MAE of 0.29 and a r^2 value of 0.97. The least effective model for statewide use is the 24RD model with a MAE of 0.67 mm day^{-1} and a r^2 value of 0.95. Linacre had the lowest r^2 with a value of 0.84, but the Linacre MAE displays better model fit, at 0.58 mm day^{-1}.

Table 5.1 Statewide Daily MAE and Regression Results

Model (n=365)	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.67	0.95	Y= 0.78x + 0.27

(Table 5.1 continued)

FAO 24 Blaney-Criddle	0.29	0.97	Y= 0.88x + 0.26
Hargreaves-Samani (1985)	0.56	0.89	Y= 0.94x – 0.23
Priestley-Taylor	0.45	0.95	Y= 0.78x + 0.62
Makkink	0.51	0.95	Y= 1.11x + 0.13
Turc	0.26	0.94	Y= 0.93x + 0.16
Linacre	0.58	0.84	Y= 1.03x – 0.53

On the whole, the Turc model was closest to 56PM with the cumulative annual deviation of only 1.69 percent of 56PM (Table 5.2, Figure 5.1). Turc, P/T, and 24BC all had overall deviations of less than 5 percent of 56PM. Turc outperformed all other models in three of four seasons, with P/T doing slightly better in autumn. H/S is next with a total deviation of 12.86 percent statewide and this value falls within the 15 percent range of acceptability as suggested by Hargreaves and Allen (2003) and Allen (1996). The greatest overall deviation was a 16.85 percent overestimation by 24RD, with Makkink following with a 13.94 percent underestimation of 56PM.

Table 5.2 Cumulative Difference between Modeled Results and 56PM ET_o Values by Region: Dec 2002 –Nov 2003. Differences in mm, Percent is of 56PM ET_o.

Statewide										
Model	Dec-Jan-Feb		Mar-Apr-May		Jun-Jul-Aug		Sep-Oct-Nov		Overall	
	Diff	Percent	Diff	Percent	Diff	Percent	Diff	Percent	Diff	Percent
24RD	23.27	16.49	67.40	18.62	61.00	13.54	56.60	20.16	208.27	16.85
24BC	-11.18	7.92	7.49	2.07	24.48	5.43	35.50	12.58	56.29	4.56
H/S	28.48	20.18	41.57	11.48	52.48	11.65	36.35	12.89	158.89	12.86
P/T	-26.40	18.71	22.38	6.18	68.19	15.14	-11.85	4.20	52.32	4.23
MAKK	-17.10	12.12	-53.37	14.74	-67.07	14.89	-34.70	12.30	-172.24	13.94
TURC	-6.37	4.52	2.14	0.59	6.63	1.47	18.52	6.56	20.91	1.69
LINA	42.99	30.46	-5.62	1.55	26.25	5.83	84.14	29.82	147.75	11.96
Inland										
Model	Dec-Jan-Feb		Mar-Apr-May		Jun-Jul-Aug		Sep-Oct-Nov		Overall	
	Diff	Percent	Diff	Percent	Diff	Percent	Diff	Percent	Diff	Percent
24RD	26.68	19.31	90.55	23.32	92.77	18.08	72.46	23.96	282.46	21.05
24BC	-21.16	15.32	-5.50	1.42	26.54	5.17	26.16	8.65	26.03	1.94
H/S	11.77	8.52	7.86	2.02	2.34	0.46	7.73	2.56	29.69	2.21
P/T	-22.96	16.62	34.84	8.97	85.35	16.63	-5.75	1.90	91.47	6.82
MAKK	-14.26	10.32	-46.30	11.93	-65.31	12.73	-31.09	10.28	-156.96	11.70
TURC	-11.81	8.55	7.93	2.04	12.31	2.40	22.00	7.27	30.42	2.27
LINA	27.16	19.66	-40.17	10.35	-18.26	3.55	64.74	21.41	33.54	2.50

(Table 5.2 continued)

Coastal										
Model	Dec-Jan-Feb		Mar-Apr-May		Jun-Jul-Aug		Sep-Oct-Nov		Overall	
	Diff	Percent	Diff	Percent	Diff	Percent	Diff	Percent	Diff	Percent
24RD	21.23	14.85	53.51	15.45	41.93	10.16	47.10	17.46	163.77	13.97
24BC	-5.19	3.63	15.28	4.41	23.24	5.63	41.14	15.25	74.47	6.35
H/S	38.51	26.95	61.80	17.84	82.57	20.00	53.60	19.86	236.48	20.18
P/T	-28.46	19.92	14.91	4.30	57.89	14.02	-15.47	5.73	28.86	2.46
MAKK	-18.81	13.16	-51.61	16.63	-68.12	16.50	-36.82	13.64	-181.36	15.48
TURC	-1.67	1.17	-1.33	0.38	3.22	0.78	16.47	6.10	16.69	1.42
LINA	52.48	36.73	15.10	4.36	52.92	12.82	95.82	35.51	216.32	18.46

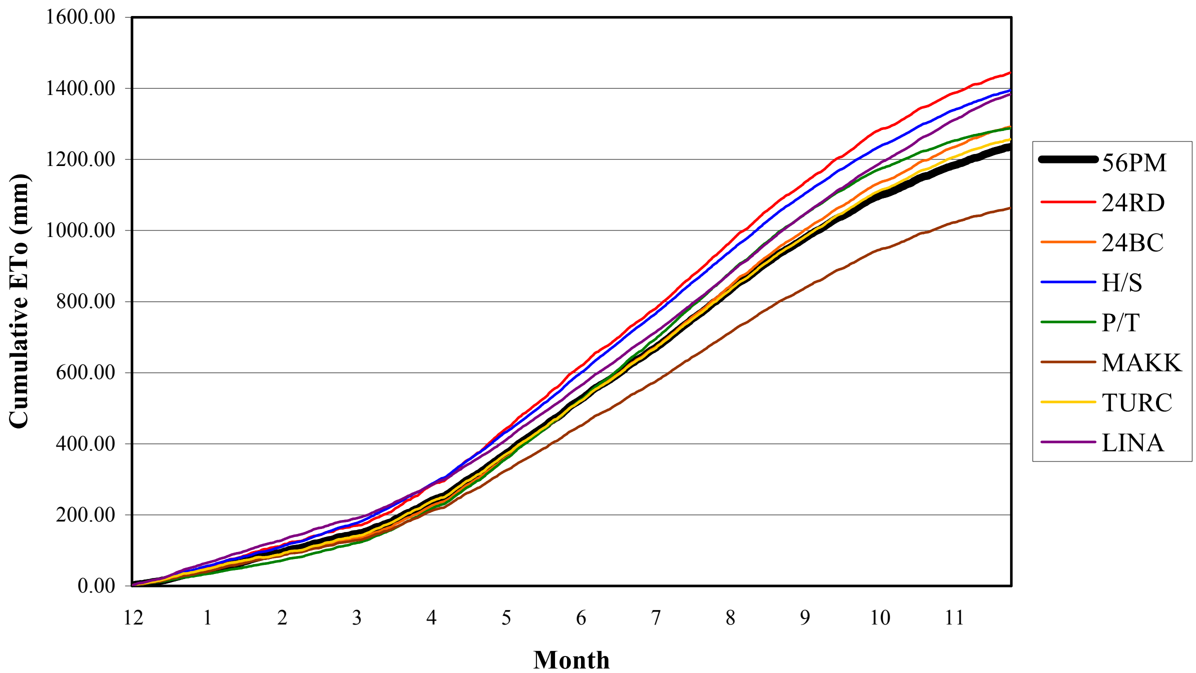

Figure 5.1 Statewide Cumulative ET_o: December 2002-November 2003

Seasonally, Turc does well in all seasons with no cumulative deviation more than 6.56 percent. Overall, Turc provides a slight overestimation of 56PM (20.91 mm). Autumn and winter appear to be the seasons during which the models have their highest deviation, with Linacre having the highest statewide of 30.46 percent in the Dec-Jan-Feb time frame.

Statewide, Turc is the most effective ET_o model. Turc has the lowest MAE, and while the r^2 value is exceeded by 24BC, the low cumulative departure and the lowest departure in three of four seasons more than compensate. The Turc model also has fewer data requirements,

requiring only R_s, temperature, and daily average humidity, whereas the next closest models (24BC and P/T) require wind data (24BC) or calculations for net radiation and soil heat flux (P/T) (see Chapter 2).

Results for the Inland region were slightly different. 24BC and Turc both reported a MAE of 0.31 mm day^{-1}, but 24BC had a slightly higher r^2 value of 0.97 compared to Turc's of 0.95 (Table 5.3, Figure 5.2). 24BC also had a slightly smaller overall deviation of 1.94 percent to that of 2.27 for Turc (Table 5.2). Turc was not the most accurate model in any of the four three-month seasons, but it did maintain a deviation of less than 10 percent throughout all seasons. The least effective model was 24RD, with a MAE of 0.86, and an overall cumulative deviation of 21.05 percent (282.46 mm). Overall, 24BC is the recommended model for inland use. However, if wind data are not available, Turc should be the model of choice.

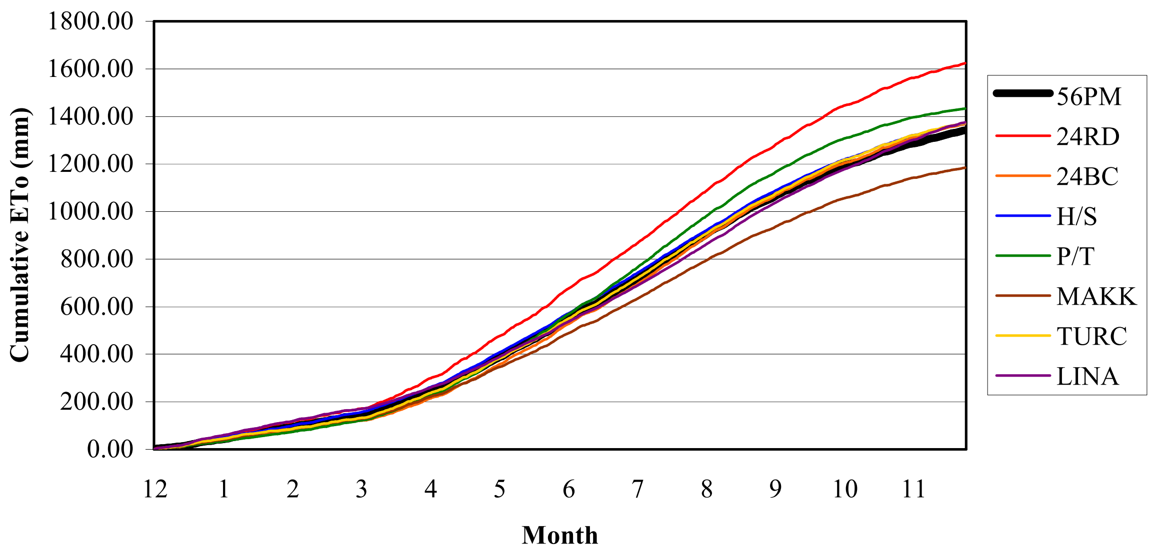

Figure 5.2 Inland Cumulative ET_o: December 2002 - November 2003

Table 5.3 Inland Daily MAE and Regression Results

Model (n=365)	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.86	0.96	Y= 0.77x + 0.24
FAO 24 Blaney-Criddle	0.31	0.97	Y= 0.89x + 0.33
Hargreaves-Samani (1985)	0.51	0.89	Y= 1.05x – 0.28

(Table 5.3 continued)

Priestley-Taylor	0.56	0.95	Y= 0.79x + 0.56
Makkink	0.48	0.96	Y= 1.10x + 0.09
Turc	0.31	0.95	Y= 0.92x + 0.19
Linacre	0.63	0.83	Y= 1.10x – 0.47

Results for the Coastal region are similar to those of the statewide results (Table 5.2, Table 5.4, Figure 5.3). Turc (MAE 0.27 mm day^{-1}) had the lowest daily MAE, with 24BC slightly more (MAE 0.32 mm day^{-1}). 24BC had a better r^2 (0.96) than Turc (0.93). The least

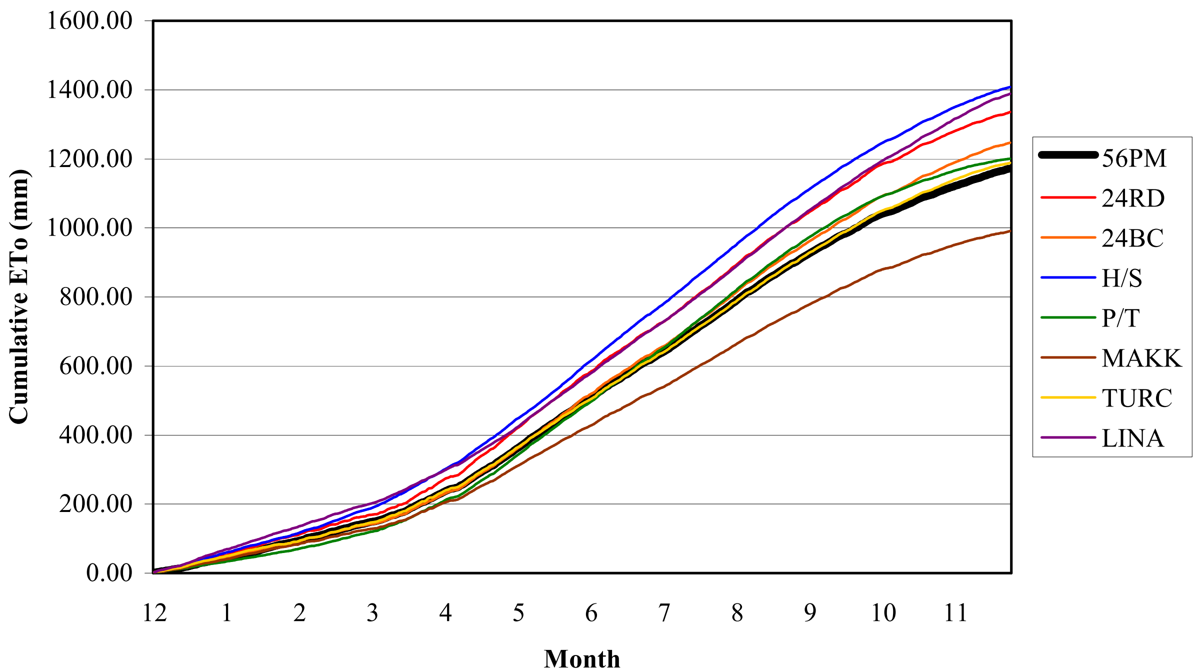

Figure 5.3 Coastal Cumulative ET_o: December 2002 - November 2003

effective model was H/S with a MAE of 0.73 and a r^2 value of 0.86. Cumulative results for the Coastal region were also very similar to those of the statewide with Turc showing the least overall deviation of 1.42 percent. Turc was the best model again in three of four seasons, with P/T performing better in autumn. P/T and 24BC also have overall cumulative totals with less than 10 percent deviation from 56PM. Makkink again underestimated 56PM by 15.48 percent

(181.36 mm), and Linacre overestimated 56PM overall by 18.46 percent (216.32 mm). Overall, Turc is the apparent best model for use in coastal areas.

Table 5.4 Coastal Daily MAE and Regression Results

Model (n=365)	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.59	0.92	Y= 0.78x + 0.34
FAO 24 Blaney-Criddle	0.32	0.96	Y= 0.86x + 0.25
Hargreaves-Samani (1985)	0.73	0.86	Y= 0.87x – 0.17
Priestley-Taylor	0.41	0.94	Y= 0.77x + 0.64
Makkink	0.54	0.93	Y= 1.10x + 0.20
Turc	0.27	0.93	Y= 0.93x + 0.15
Linacre	0.68	0.83	Y= 0.98x – 0.52

5.1.2 Individual Stations

Results at individual stations varied spatially. Overall, Turc and 24BC were the best models, with the Turc model leading at five stations (Dean Lee, Houma, Red River, Rice, and UL-Monroe) and 24BC leading at the remaining three stations (Ben Hur, Hammond, and Southeast). The least accurate model for each station was more difficult to ascertain than the best model. The 24RD and H/S models tended to generate the highest MAE values at most stations. The Linacre and Makkink models tended to perform moderately to poorly, often with relatively high MAE values and/or low r^2 values (Table 5.5).

Table 5.5 Daily Results for Individual LAIS Stations: December 2002 - November 2003

Ben Hur			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.64	0.88	Y= 0.73x + 0.70
FAO 24 Blaney-Criddle	0.45	0.95	Y= 0.82x + 0.35
Hargreaves-Samani (1985)	0.54	0.74	Y= 0.89x – 0.07
Priestley-Taylor	0.50	0.87	Y= 0.82x + 0.81
Makkink	0.87	0.85	Y= 1.08x + 0.57
Turc	0.46	0.86	Y= 0.95x + 0.42
Linacre	0.80	0.77	Y= 0.97x – 0.55
Dean Lee			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.87	0.95	Y= 0.76x + 0.28
FAO 24 Blaney-Criddle	0.37	0.95	Y= 0.98x + 0.28
Hargreaves-Samani (1985)	0.67	0.82	Y= 1.07x - 0.44
Priestley-Taylor	0.66	0.96	Y= 0.76x + 0.46

(Table 5.5 continued)

Makkink	0.43	0.96	Y= 1.05x + 0.15
Turc	0.35	0.96	Y= 0.92x + 0.11
Linacre	0.76	0.77	Y= 1.20x – 0.52
Hammond			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.67	0.92	Y= 0.79x + 0.16
FAO 24 Blaney-Criddle	0.27	0.94	Y= 0.93x + 0.19
Hargreaves-Samani (1985)	0.85	0.89	Y= 0.88x – 0.38
Priestley-Taylor	0.52	0.95	Y= 0.75x + 0.49
Makkink	0.40	0.93	Y= 1.08x + 0.03
Turc	0.37	0.94	Y= 0.92x + 0.01
Linacre	0.63	0.82	Y= 1.06x – 0.73
Houma			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.62	0.91	Y= 0.77x + 0.33
FAO 24 Blaney-Criddle	0.38	0.95	Y= 0.84x + 0.26
Hargreaves-Samani (1985)	0.76	0.75	Y= 0.87x – 0.10
Priestley-Taylor	0.46	0.90	Y= 0.76x + 0.66
Makkink	0.55	0.90	Y= 1.10x + 0.18
Turc	0.33	0.91	Y= 0.94x + 0.07
Linacre	0.81	0.71	Y= 0.92x – 0.39
Red River			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.78	0.95	Y= 0.79x + 0.16
FAO 24 Blaney-Criddle	0.45	0.97	Y= 0.81x + 0.47
Hargreaves-Samani (1985)	0.48	0.89	Y= 0.96x + 0.01
Priestley-Taylor	0.56	0.89	Y= 0.80x + 0.73
Makkink	0.58	0.92	Y= 1.16x + 0.01
Turc	0.38	0.91	Y= 0.94x + 0.23
Linacre	0.57	0.84	Y= 0.98x – 0.14
Rice			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.58	0.91	Y= 0.73x + 0.62
FAO 24 Blaney-Criddle	0.38	0.95	Y= 0.82x + 0.33
Hargreaves-Samani (1985)	0.67	0.80	Y= 0.88x – 0.08
Priestley-Taylor	0.44	0.91	Y= 0.78x + 0.72
Makkink	0.66	0.91	Y= 1.05x + 0.49
Turc	0.33	0.91	Y= 0.91x + 0.35
Linacre	0.74	0.77	Y= 0.94x – 0.39
Southeast			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.67	0.92	Y= 0.79x + 0.16
FAO 24 Blaney-Criddle	0.27	0.94	Y= 0.93x + 0.19
Hargreaves-Samani (1985)	0.85	0.89	Y= 0.88x – 0.38
Priestley-Taylor	0.52	0.95	Y= 0.75x + 0.49
Makkink	0.40	0.93	Y= 1.08x + 0.03
Turc	0.37	0.94	Y= 0.92x + 0.01
Linacre	0.63	0.82	Y= 1.06x – 0.73
UL-Monroe			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	1.02	0.95	Y= 0.73x + 0.36
FAO 24 Blaney-Criddle	0.42	0.95	Y= 0.87 + 0.30
Hargreaves-Samani (1985)	0.64	0.85	Y= 1.11x – 0.40
Priestley-Taylor	0.54	0.96	Y= 0.80x + 0.51

(Table 5.5 continued)

Makkink	0.48	0.96	Y= 1.07x + 0.16
Turc	0.34	0.95	Y= 0.91x + 0.25
Linacre	0.80	0.79	Y= 1.09x – 0.61

5.2 Monthly Results

Monthly ET_o values were computed for all eight LAIS stations as described in Chapter 4. As with the daily dataset, these monthly values were averaged into three regions: Statewide, Inland, and Coastal. For each station and region, each test model was compared to the 56PM model using MAE and regression. The best model for each station or region was selected first based on the lowest MAE, then on the highest r^2 value, and finally on the lowest cumulative departure for the 2002-2003 data year. Results from the monthly dataset should be viewed with caution because the dataset only used data from December 2002 through November 2003, thus limiting the *n* value to 12. The low number of data points may result in inaccurate results. For example, because of the limited number of observations, all monthly r^2 values are above 0.90. Because the output of regression analysis is of very limited utility, more emphasis will be placed on the MAE value as an indicator of model performance. As higher-quality LAIS data become available, a larger dataset will be available for further analysis.

5.2.1 Composite Regions

Results for the statewide monthly dataset were similar to that of the daily model dataset (Table 5.6, Figure 5.4). As with the daily models, the Turc model is the apparent best

Table 5.6 Statewide Monthly MAE and Regression Results

Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.53	0.99	Y= 0.85x + 0.03
FAO 24 Blaney-Criddle	0.23	0.99	Y= 0.87x + 0.26
Hargreaves-Samani (1985)	0.48	0.98	Y= 0.90x – 0.13
Priestley-Taylor	0.34	0.98	Y= 0.75x + 0.74
Makkink	0.41	0.99	Y= 1.16x – 0.03
Turc	0.17	0.98	Y= 0.99x – 0.13
Linacre	0.22	0.95	Y= 1.08x – 0.43

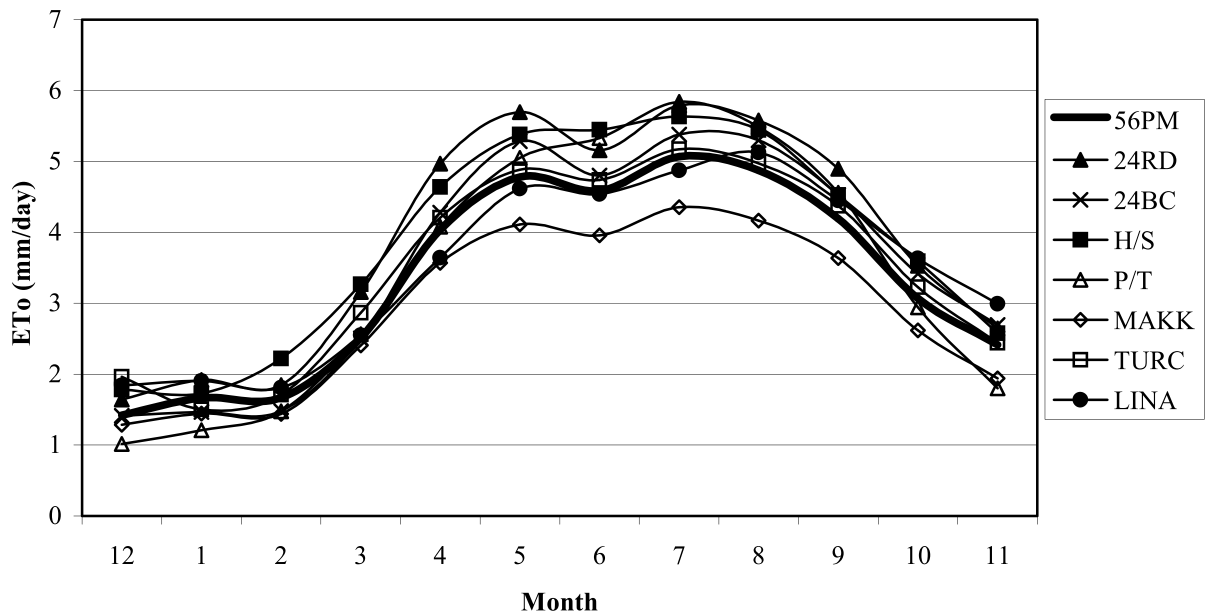

Figure 5.4 Statewide Monthly Composite ET_o: December 2002 - November 2003

model with a MAE value of 0.17 mm day^{-1} and a r^2 of 0.98. The Turc model followed very closely to 56PM. Linacre and 24BC were also acceptable, with MAE values of 0.22 and 0.23 mm day^{-1} respectively. The least accurate model was 24RD with a MAE of 0.53 mm day^{-1}. In examining Figure 5.4, the trends in model performance are fairly clear. Makkink, for example, is almost always underestimating 56PM ET_o, although it follows the seasonal trends fairly well. Other models, such as 24RD, follow the seasonal patterns well but almost always overestimate 56PM ET_o.

Results in the Inland region are slightly different (Table 5.7, Figure 5.5). 24BC and the Makkink models surpass the Turc model, which was the leading model statewide. 24BC and Makkink tie with MAE values of 0.30 mm day^{-1} and r^2 values of 0.99. Ordinarily, the best model would be decided by which regression equation is closest to unity (Y = 1x + 0) (see Amatya *et al.* 1995). However, with such a small sample (*n*=12), this would not be advisable.

The least accurate model on the monthly timescale for the Inland region is 24RD with a MAE of 0.79 mm day^{-1}. The inland monthly pattern also shows some evidence of the bimodal peak that appears in the statewide dataset (Figure 5.4), but the peak in July is much more pronounced by the models (Figure 5.5). As with the statewide dataset, 24RD always overestimates 56PM ET_o, where as Makkink underestimates it. Other models perform with intermediate degrees of success, with most slightly overestimating 56PM ET_o.

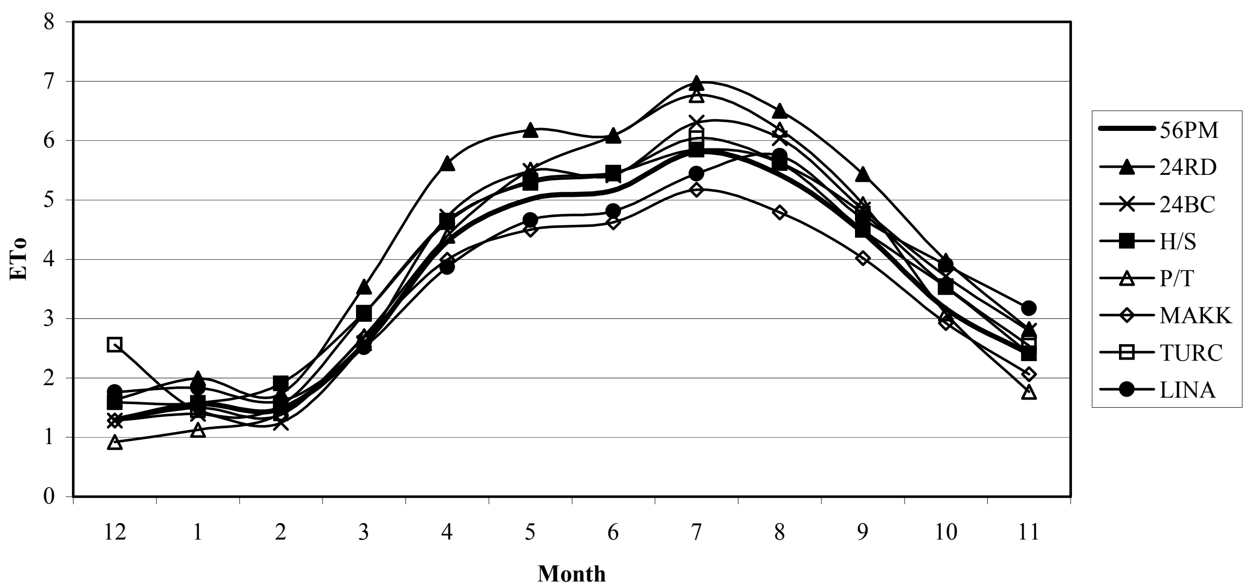

Figure 5.5 Inland Monthly Composite ET_o: December 2002 - November 2003

Table 5.7 Inland Monthly MAE and Regression Results

Model	*MAE (mm day^{-1})*	*r^2*	*Regression*
FAO 24 Radiation	0.79	0.99	Y= 0.83x – 0.08
FAO 24 Blaney-Criddle	0.30	0.99	Y= 0.87x + 0.22
Hargreaves-Samani (1985)	0.44	0.98	Y= 1.00x – 0.26
Priestley-Taylor	0.40	0.98	Y= 0.76x + 0.68
Makkink	0.30	0.99	Y= 1.14x – 0.17
Turc	0.33	0.95	Y= 1.00x – 0.32
Linacre	0.31	0.94	Y= 1.10x – 0.48

As with the daily Coastal dataset, the Turc model proved to be the most accurate with a MAE of 0.08 mm day^{-1} and a r^2 value of 0.99 (Table 5.8, Figure 5.6). 24BC was the second

most accurate model with a MAE of 0.19 and an r^2 value of 0.99. The least effective model is H/S with a MAE of 0.63 and a r^2 value of 0.97. As with previous datasets, some models perform in a consistent way. Makkink underestimates 56PM ET_o in the Coastal region, as 24RD overestimates it. The Coastal region shows a bimodal distribution as well, with the peak in the late spring and early summer.

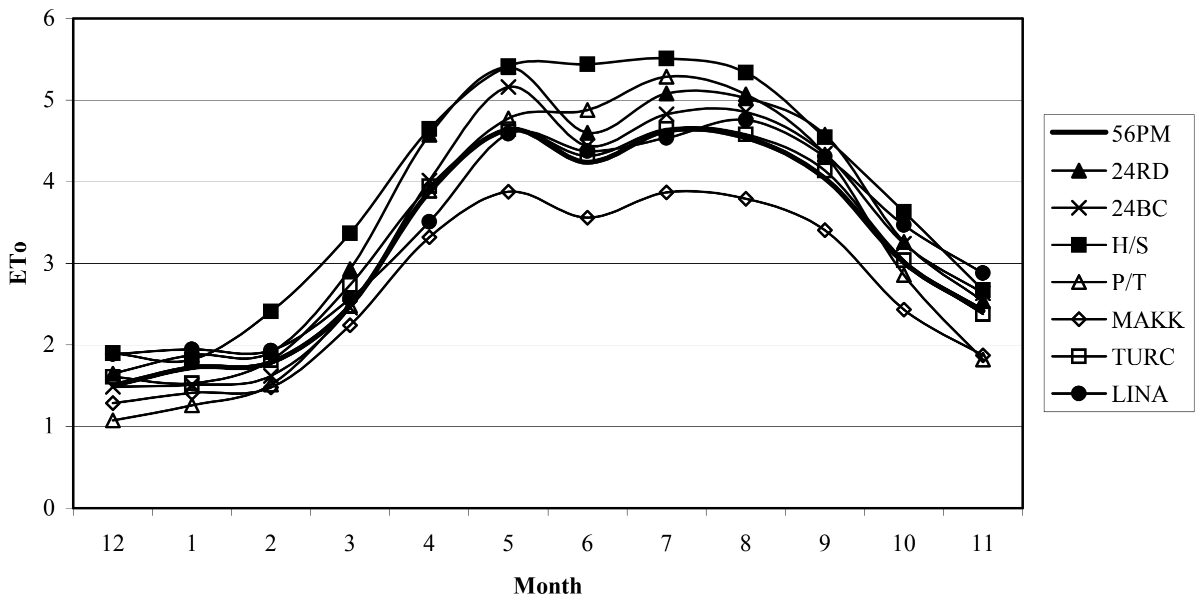

Figure 5.6 Coastal Monthly Composite ET_o: Dec 2002 - Nov 2003

Table 5.8 Coastal Monthly MAE and Regression Results

Model	*MAE (mm day^{-1})*	*r^2*	*Regression*
FAO 24 Radiation	0.59	0.92	Y= 0.78x + 0.34
FAO 24 Blaney-Criddle	0.32	0.96	Y= 0.86x + 0.25
Hargreaves-Samani (1985)	0.73	0.86	Y= 0.87x – 0.17
Priestley-Taylor	0.41	0.94	Y= 0.77x + 0.64
Makkink	0.54	0.93	Y= 1.10x + 0.20
Turc	0.27	0.93	Y= 0.93x + 0.15
Linacre	0.68	0.83	Y= 0.98x – 0.52

5.2.2 Individual Stations

As with the daily dataset, model performance at individual stations was similar to the region (Inland or Coastal) in which the station is located (Table 5.9, Figures 5.7 – 5.14). Some

common trends in model performance throughout the stations are apparent. For example, the 24BC was the most common "best model" on the monthly scale, as the leading model at six of the eight sites. The H/S model was the best model at one site, and P/T was the top model at the remaining site. Makkink was the least accurate model at all sites on the monthly scale. Turc also performed very well at the monthly time scale, being in the top three models at many sites.

Table 5.9 Monthly Results for Individual LAIS Stations: December 2002 – November 2003

Ben Hur			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.25	0.99	Y= 0.83x + 0.45
FAO 24 Blaney-Criddle	0.15	0.99	Y= 0.79x + 0.56
Hargreaves-Samani (1985)	0.36	0.94	Y= 0.82x + 0.26
Priestley-Taylor	0.50	0.95	Y= 0.77x + 1.04
Makkink	1.01	0.98	Y= 1.20x + 0.34
Turc	0.44	0.98	Y= 0.99x + 0.30
Linacre	0.80	0.77	Y= 0.97x – 0.55
Dean Lee			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.85	0.98	Y= 0.85x – 0.23
FAO 24 Blaney-Criddle	0.80	0.98	Y= 0.95x + 0.10
Hargreaves-Samani (1985)	0.55	0.97	Y= 1.01x – 0.41
Priestley-Taylor	0.55	0.98	Y= 0.73x + 0.61
Makkink	1.04	0.99	Y= 1.14x – 0.29
Turc	0.55	0.95	Y= 1.10x – 0.50
Linacre	0.95	0.95	Y= 1.21x –0.61
Hammond			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.58	0.98	Y= 0.88x – 0.13
FAO 24 Blaney-Criddle	0.45	0.99	Y= 0.97x + 0.07
Hargreaves-Samani (1985)	0.39	0.97	Y= 0.86x – 0.30
Priestley-Taylor	0.45	0.99	Y= 0.74x + 0.56
Makkink	0.87	0.98	Y= 1.15x – 0.17
Turc	0.31	0.98	Y= 0.96x – 0.17
Linacre	0.40	0.97	Y= 1.09x – 0.77
Houma			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.39	0.97	Y= 0.83x + 0.21
FAO 24 Blaney-Criddle	0.23	0.99	Y= 0.86x + 0.24
Hargreaves-Samani (1985)	0.24	0.96	Y= 0.90x – 0.22
Priestley-Taylor	0.45	0.97	Y= 0.74x + 0.79
Makkink	0.92	0.98	Y= 1.15x + 0.10
Turc	0.33	0.98	Y= 0.98x
Linacre	0.47	0.95	Y= 1.02x – 0.67
Red River			
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.70	0.98	Y= 0.83x + 0.01
FAO 24 Blaney-Criddle	0.44	0.99	Y= 0.83x + 0.36
Hargreaves-Samani (1985)	0.50	0.99	Y= 0.95x – 0.01

(Table 5.9 continued)

Priestley-Taylor	0.73	0.97	Y= 0.78x + 0.81
Makkink	1.18	0.98	Y= 1.17x – 0.07
Turc	0.71	0.95	Y= 1.05x – 0.18
Linacre	0.69	0.93	Y= 1.00x – 0.17
	Rice		
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.25	0.99	Y= 0.84x + 0.32
FAO 24 Blaney-Criddle	0.13	0.99	Y= 0.82x + 0.42
Hargreaves-Samani (1985)	0.29	0.96	Y= 0.82x + 0.17
Priestley-Taylor	0.38	0.96	Y= 0.74x + 0.89
Makkink	0.87	0.98	Y= 1.16x + 0.26
Turc	0.30	0.98	Y= 0.96x + 0.20
Linacre	0.42	0.93	Y= 0.91x – 0.18
	Southeast		
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.56	0.98	Y= 0.88x – 0.13
FAO 24 Blaney-Criddle	0.57	0.99	Y= 0.97x + 0.07
Hargreaves-Samani (1985)	0.27	0.97	Y= 0.86x – 0.30
Priestley-Taylor	0.41	0.99	Y= 0.74x + 0.56
Makkink	0.83	0.98	Y= 1.15x – 0.17
Turc	0.28	0.98	Y= 0.96x – 0.17
Linacre	0.36	0.97	Y= 1.09x – 0.77
	UL-Monroe		
Model	MAE (mm day^{-1})	r^2	Regression
FAO 24 Radiation	0.90	0.99	Y= 0.80x – 0.02
FAO 24 Blaney-Criddle	0.46	0.98	Y= 0.83x + 0.22
Hargreaves-Samani (1985)	0.79	0.99	Y= 1.05x –0.36
Priestley-Taylor	0.71	0.99	Y= 0.77x + 0.64
Makkink	1.16	0.99	Y= 1.12x – 0.15
Turc	0.69	0.96	Y= 0.97x – 0.27
Linacre	0.83	0.92	Y= 1.09x – 0.65

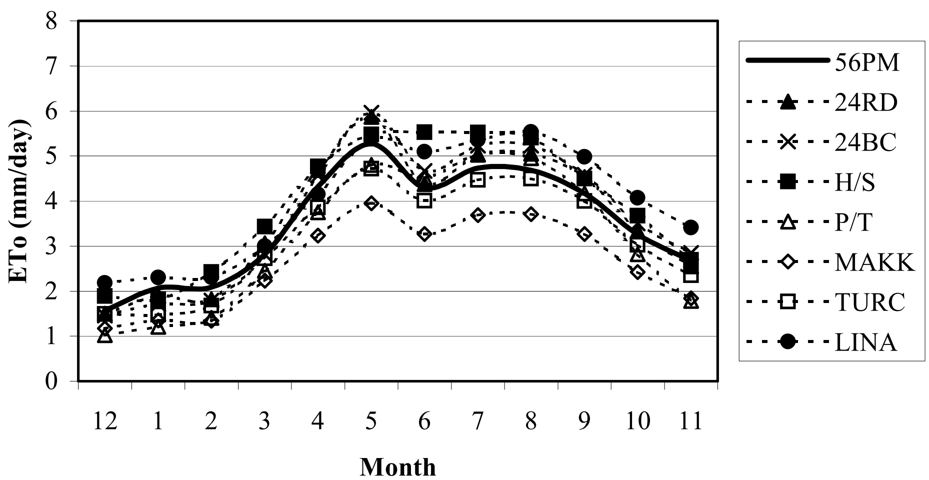

Figure 5.7 Monthly ET_o- Ben Hur RS: December 2002 - November 2003

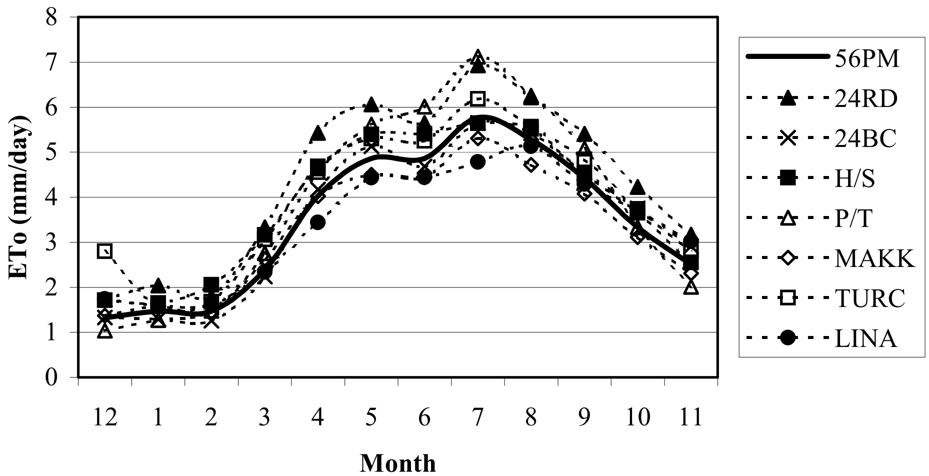

Figure 5.8 Monthly ET_o- Dean Lee RS: December 2002 - November 2003

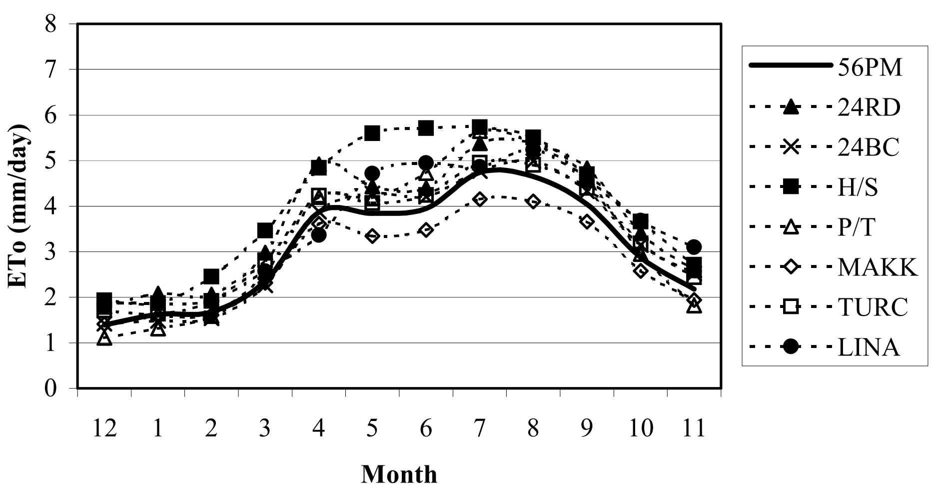

Figure 5.11 Monthly ET_o- Hammond RS: December 2002 - November 2003

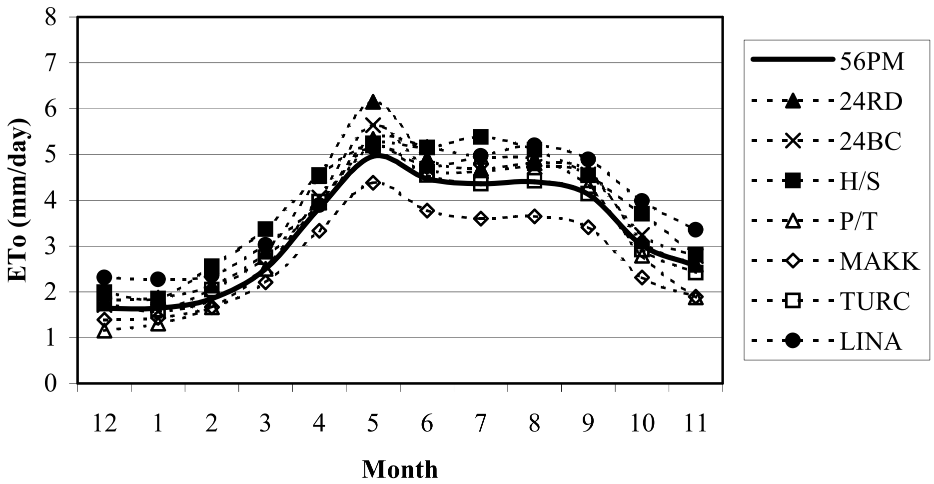

Figure 5.9 Monthly ET_o- Houma: December 2002 - November 2003

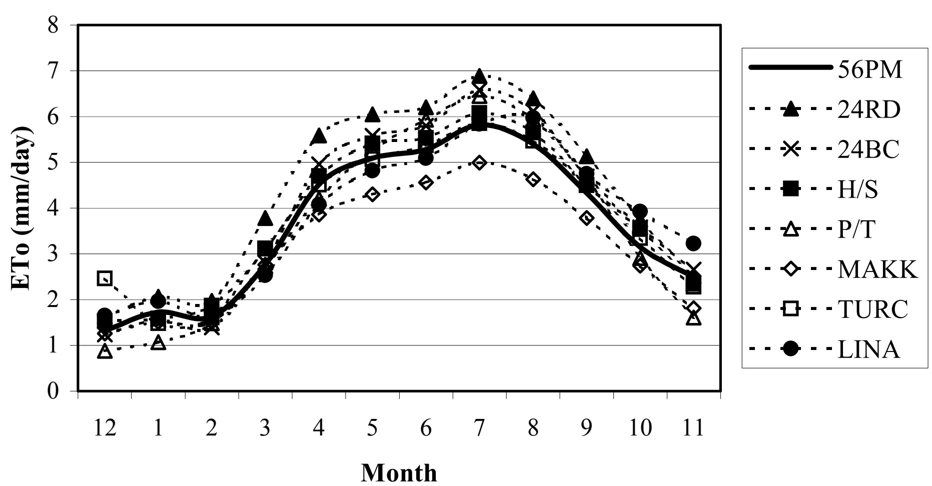

Figure 5.10 Monthly ET_o- Red River RS: December 2002 - November 2003

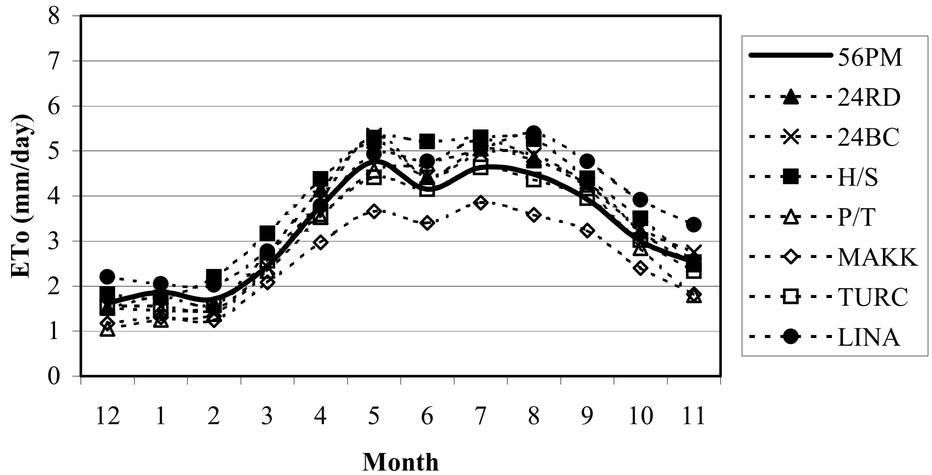

Figure 5.11 Monthly ET_o- Rice RS: December 2002 - November 2003

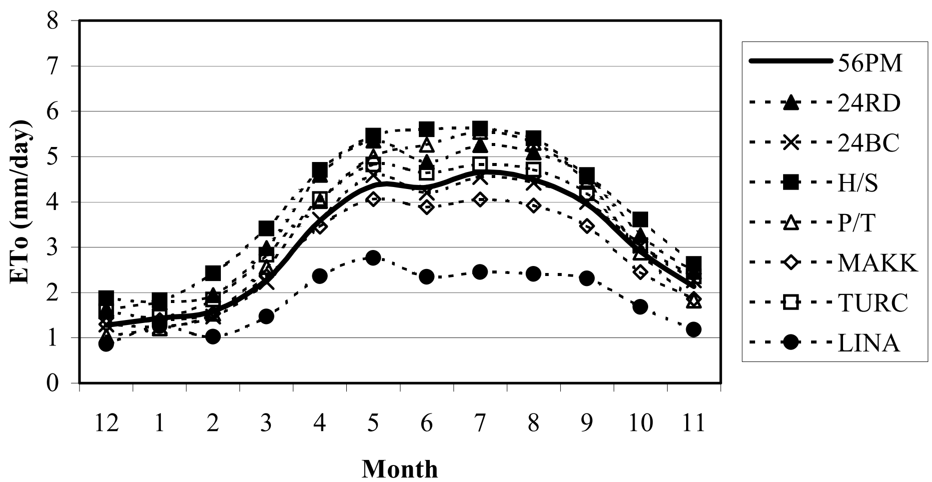

Figure 5.12 Monthly ET_o- Rice RS: December 2002 - November 2003

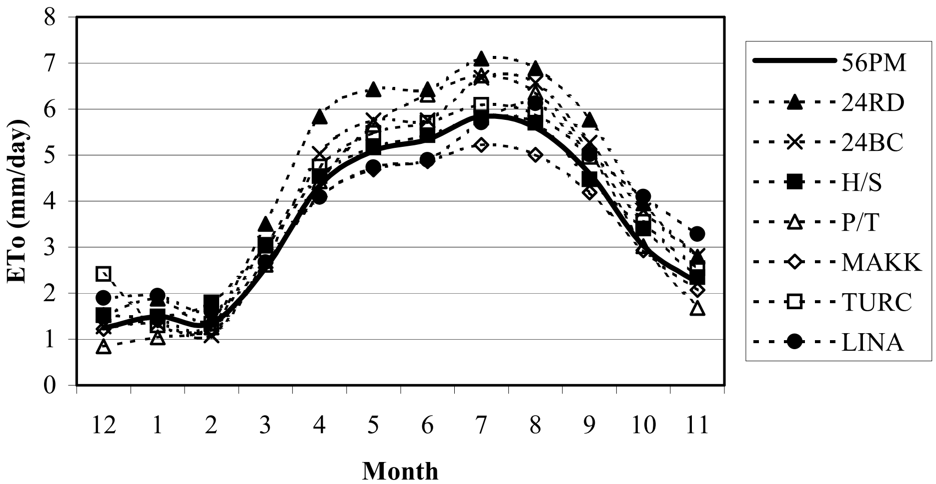

Figure 5.13 Monthly ET_o- UL-Monroe: December 2002 - November 2003

5.3 Pan Evaporation

ET_o derived from pan evaporation was also examined. Pan evaporation data from Ben Hur and Red River were compared to 56PM ET_o using a coefficient derived from the 24PAN model. Overall, results of using evaporation pan data to calculate ETo were disappointing. At Red River, the lowest MAE of 1.07 mm day^{-1} was obtained (Table 5.10). The lowest MAE at Ben Hur was 1.19 mm day^{-1}, which was the MAE for both the 24PAN method and the fixed coefficient. Although the fit of all models was significant at $\alpha < 0.01$, the r^2 values for the regressions were disappointing. Ben Hur had a r^2 value of 0.34 across all methods.

Table 5.10 Pan Evaporation to ET_o Results: December 2002 - November 2003

Ben Hur (*n*=336)			
Model	MAE (mm day^{-1})	r^2	Regression
No Adjustment	1.52	0.34	Y= 0.39x + 1.84
FAO 24 Pan Evaporation	1.19	0.34	Y= 0.47x + 1.82
Fixed FAO 24 Average	1.19	0.34	Y= 0.48x + 1.81
Red River (*n*=344)			
Model	MAE (mm day^{-1})	r^2	Regression
No Adjustment	1.42	0.51	Y= 13.25x + 0.37
FAO 24 Pan Evaporation	1.07	0.52	Y= 0.64x + 1.37
Fixed FAO 24 Average	1.09	0.51	Y= 0.63x + 1.41

The r^2 value for Red River was 0.51 for the fixed coefficient and no coefficient methods and this was only increased to 0.52 for the 24PAN method. Based on these results, even the least accurate model examined in previous sections would be preferable to using the 24PAN model, under the specified parameters, to estimate ET_o in Louisiana.

5.4 Discussion

Overall, MAE values for all daily models and most monthly models were all below 1.0 mm day^{-1}. The Turc model overall is the suggested model for statewide and coastal daily use. 24BC is the best model for use on the monthly time scale as well as for daily inland use. Pan evaporation methods to calculate ET_o are not recommended.

Model performance appears to be more dependent on individual model characteristics rather than model type (*i.e.*, radiation- or temperature-based). Specifically, 24BC (a temperature model) and Turc (a radiation model) both performed admirably and Makkink (radiation) and Linacre (temperature) showed less encouraging model fits. In the statewide datasets, the coastal stations tended to determine the success of individual models, for two major reasons: 1) the coastal dataset has one more station, thus weighing the data more toward the coastal trends; and 2) in the humid coastal environments seem to favor models that require radiation and humidity inputs.

One reason that the 24PAN method produced poor results may be the nature of pan evaporation. The 56PM equation by nature assumes that most of the ET_o will occur during daytime hours due to the solar radiation input required (Allen *et al*. 1998). Evaporation pans, however, can encourage evaporation at night due to heat storage in the pan. Other differences may be caused by heat transfer around the pan, differences in the albedo of the water compared to the reference grass crop, and the physical characteristics of the atmosphere around the pan and water surface (Allen *et al.* 1998). Another possible explanation is that the relationship between

ET_o and pan evaporation may not be quite linear, as assumed by 24PAN. The non-linearity of the 24PAN coefficient was also noted by Irmak *et al*. (2002) and Grismer *et al*. (2002). It is possible that the some of the specified parameters for the 24PAN model may not be correct. The 24PAN model had specified parameters of wind speed, fetch, and humidity (Allen *et al.* 1998). It is possible that the assumption of the 1000 m fetch may be incorrect. It is also very likely that the requirement for a mean relative humidity in the range of 30-84 percent have been violated, especially at the upper end. These results suggest that the use of the 24PAN model, in the conditions specified in this study, for calculating ET_o is not recommended over other models in this study. Other errors could include observational and equipment errors such as the pan water level, which could result in errors of up to 15 percent (Allen *et al.* 1998). However, the 24PAN model may be more accurate on weekly or monthly time scales than on daily scales. Finally, it is possible that the equation specified in FAO 56 by Allen *et al.* (1998) is not the best fit for Louisiana, with the possibility that other equations may be more useful (see Irmak *et al.* 2002, 2003b). Further research using all five pan evaporation stations and a longer data record would provide more insight into the potential applicability of pan evaporation data for ET_o estimation.

It was interesting to discover the poor performance of H/S in the coastal region, with an overall cumulative deviation of 20.18 percent (236.48 mm). This deviation falls outside of the suggested 15 percent deviation noted by Allen (1996) and Hargreaves and Allen (2003) even though it performs within the expected 15 percent in the inland region. Several possible reasons may explain the relatively poor performance in the coastal region. For example, H/S was designed for weekly or longer time steps (Hargreaves and Allen 2003). However, the more likely reason is the structure of the H/S equation. H/S uses R_a rather than R_s for radiation data. This means that H/S is using the maximum possible radiation value and not taking into account atmospheric transmissivity. In coastal Louisiana, transmissivity would be affected by several

variables, including atmospheric moisture, which tends to be higher in the coastal areas, thus increasing the attenuation of solar radiation at the surface. Likewise, a second variable that H/S does not account for is humidity. Humidity is positively correlated with vapor pressure. Given the same temperature (and therefore the same saturation vapor pressure), an inland location with less humidity will be able to evaporate more moisture than a coastal location with a higher humidity. Ultimately, the performance of H/S in the coastal region is not terribly surprising, as Allen *et al*. (1998) noted that H/S tends to overpredict in areas of high humidity.

Another interesting pattern to emerge is the bimodal distribution of ET_o in Louisiana (Figures 5.4-5.6). Statewide, double peaks of near the same magnitude are shown in Figure 5.4, with one peak in May and the second in July. The Inland dataset (Figure 5.5) shows the primary peak in July, while the Coastal dataset shows the primary ET_o peak in May. The probable explanation for the discrepancy is related to the precipitation patterns of Louisiana. Figure 5.15 shows the monthly 30-year normal precipitation for NWS cooperative stations located near LAIS stations in coastal Louisiana. Precipitation in late spring is decreased as frontal activity in the

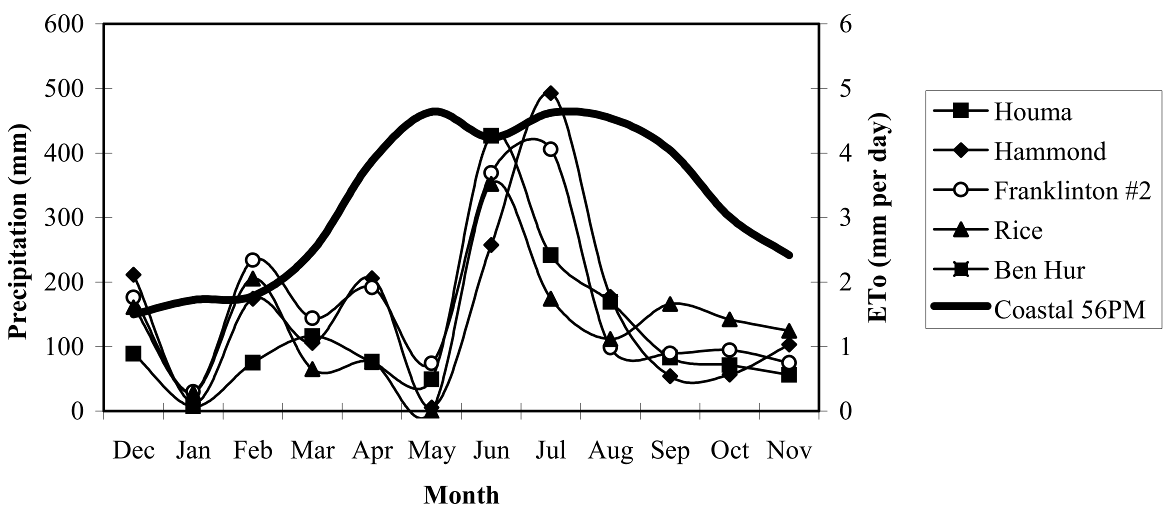

Figure 5.14 Precipitation versus 56PM ET_o (December 2002 - November 2003) for Coastal Louisiana

coastal areas decreases, and rises in the summer due to the change to the summer precipitation regime. If precipitation were used as a proxy for cloud cover, late spring would see on average lower R_s values, thus decreasing the amount of energy available for evapotranspiration. By contrast, Inland sections of Louisiana are receiving more frontal precipitation than coastal sites in spring. This would lead to the increase in ET_o in late June and early July as solar input reaches its maximum. This pattern is similar to the one found by McCabe and Muller (1987) in which the amount of pan evaporation varied with the synoptic weather type. Interestingly, P/T and H/S are the only models that do not show the bimodal distribution. This would make sense with H/S as it uses R_a rather than R_s for an input and is immune to any local meteorological/climatological patterns. By contrast, P/T uses net radiation, which does include R_s, but also includes calculations and estimations for other components of the net radiation equation. P/T also incorporates soil heat flux, which unless measured is calculated using equations from FAO 56. Soil heat flux would peak in the late summer months, thus helping to contribute to the single peak that P/T shows.

Chapter 6
Summary of Research

Three research objectives were stated in Chapter 1:

1. To determine which evapotranspiration model best simulates the FAO reference evapotranspiration model (Penman-Monteith) in Louisiana, taking into account data availability;
2. To determine the applicability and accuracy of the FAO-recommended model to convert evaporation pan data into reference evapotranspiration data in Louisiana;
3. To determine whether spatial trends in model performance exist in Louisiana, focusing on inland versus coastal environments.

Each of these three objectives has been explored according to the procedures detailed in Chapter 4. Results were reported in Chapter 5. A summary of each of these findings will be reported this chapter.

6.1 Daily and Monthly Model Performance

6.1.1 Daily Model Performance

On a statewide (Table 5.1-5.2, Figure 5.1) basis, Turc (MAE 0.26 mm day^{-1}, annual cumulative departure +1.69 percent) was the best overall model for estimating daily 56PM ET_o, followed by the 24BC model. The least accurate model statewide was the 24RD model (MAE 0.67 mm day^{-1}, cumulative Departure +16.85 percent). Both the Turc and 24BC models performed well, and the selection of one model over the other should be dependent upon the available meteorological data.

In the inland part of Louisiana (Table 5.2-5.3, Figure 5.2), the most accurate model for estimating 56PM is the 24BC model (MAE 0.31 mm day^{-1}, annual cumulative departure 1.94 percent). The MAE for 24BC tied with that of Turc, but 24BC had a higher R^2 value and a lower

annual cumulative departure. As with the statewide dataset, selection of either model should be based upon data availability. The least accurate model was again 24RD (MAE 0.86 mm day^{-1}, annual cumulative departure +21.05 percent).

Finally, Turc (MAE 0.27 mm day^{-1}, annual cumulative departure +1.42 percent) was the most accurate model in the Coastal region (Table 5.2, 5.4, Figure 5.3). 24BC again was the second most accurate model. H/S (MAE 0.73 mm day^{-1}, annual cumulative departure +20.18 percent) was the least accurate in the Coastal region. The H/S model appears to overestimate ET_o in the coastal region because of its lack of a humidity variable and the use of extraterrestrial radiation, which does not account for attenuation due to cloud cover, atmospheric moisture, and atmospheric particulates.

Performance of the models at individual stations varied from station to station (Table 5.5). Overall, Turc was the most accurate model at five stations (Dean Lee, Houma, Red River, Rice, and UL-Monroe) with 24BC leading at the three remaining stations (Ben Hur, Hammond, and Southeast). The least accurate models tended to be 24RD and the H/S models.

6.1.2 Monthly Model Performance

Results of the monthly dataset are similar to those of the daily. On a statewide basis (Table 5.6, Figure 5.4), Turc (MAE 0.17 mm day^{-1}) is the most accurate model in approximating monthly 56PM ET_o. Closely following is Linacre and 24BC. Selection of any of the three models should be based upon data availability, but use of Turc is encouraged. The Makkink model tended to consistently underestimate ET_o. The least accurate model in estimating statewide 56PM ET_o is the 24RD model (MAE 0.53 mm day^{-1}). In the inland part of the state (Table 5.7, Figure 5.5), the most accurate models are 24BC and Makkink (MAE 0.30 mm day^{-1}). Each model had the same r^2 value and the regression models differed little. As the monthly

dataset has a low sample size, the best model cannot be recommended from these data and selection of a model for monthly use inland should be based upon data availability. It should be noted, however, that in other datasets in this thesis, the 24BC model has a pattern of being one of the most accurate models, where as Makkink has a tendency to underestimate ET_o and has generally a higher MAE than 24BC. The least accurate model is again 24RD (MAE 0.79 mm day^{-1})

In the Coastal region (Table 5.8, Figure 5.6), Turc once again is the most accurate estimator of 56PM ET_o (MAE 0.27 mm day-1), with 24BC following as the next most accurate model. As with other regions, selection of a model should be based upon data availability. As with the daily Coastal dataset, the H/S model was the least accurate model for similar reasons.

Individual station results (Table 5.9, Figures 5.7-5.14) varied from site to site, as with the daily results. 24BC was the most accurate model at six of the eight sites, with H/S and P/T being the "best model" at one site each. Makkink was the least accurate at all stations on the monthly scale.

Results of the monthly dataset may not be completely representative of the true behavior of the models in Louisiana because of the low sample number (n=12). Future research should use more than one year of data (increasing the sample size) for improved assessment of model performance on a monthly scale.

6.2 Pan Evaporation

Overall, performance of the 24PAN model in estimating daily 56PM ET_o was disappointing (Table 5.10). MAE values at each site exceeded all of the meteorologically-based models used to estimate 56PM, suggesting that even use of the least accurate meteorologically-based model would be more accurate than the 24PAN method. Reasons for this result could be

related to the nature of pan evaporation, inaccuracy of measured variables in the equation, violation of model assumptions, or the daily time scale used in this thesis. However, another, more probable, explanation is that equation used to compute the pan coefficient (the method recommended as the international standard in FAO 56 by Allen *et al*. (1998)) is simply inappropriate for Louisiana's climate. Other methods to compute the coefficient (*e.g.* Irmak *et al*. 2003b) may prove more accurate and should be researched using all available data in Louisiana.

6.3 Spatial Trends

The spatial trends in model performance vary from model to model, depending on the design and the input variables required of the model. The H/S model does not take into account humidity and uses extraterrestrial radiation, thereby causing poor model performance in coastal Louisiana where humidity can modify the amount of solar radiation striking the surface as well as the ability of the atmosphere to evaporate water. Not surprisingly, the P/T model tended to perform slightly better in the humid regions, because that model was designed for humid environments (Priestley and Taylor 1977). The Turc model generally performed well statewide, with a slight improvement in accuracy in the coastal areas, particularly at the monthly time scale.

The most interesting spatial trend discovered was the bimodal distribution in ET_o across Louisiana. Two distinct peaks in ET_o were observed: one in late-April to May and a second peak in July (Figures 5.4-5.6). The likely cause is the seasonal change of precipitation regimes in Louisiana and their timing, with summer ET_o being in an inverse relationship with precipitation. Further research could verify this hypothesis by studying the relationships between cloud cover, incoming shortwave radiation, precipitation, and ET_o.

Overall, the research presented in this thesis should be viewed as an exploratory view of the performance of ET_o models in Louisiana. It provides insight into the general performance of ET_o models in the state to provide a starting point for further research. The research presented in this thesis also provides basic guidance to the agricultural community in Louisiana as to which models will give a better estimate of ET_o, in light of data availability, for use in irrigation scheduling. These results may help the agricultural industry to maximize the impact of its water resources by reducing stress on the water supply, thereby potentially increasing productivity, profit, and environmental impact.

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