COMPARISON OF EVAPORATION ESTIMATION METHODS FOR A RIPARIAN AREA

FINAL REPORT

by


Sponsored by

U.S. Bureau of Reclamation

IIHR Technical Report No. 436

IIHR-Hydroscience & Engineering

College of Engineering
University of Iowa
Iowa City IA 52242-1585

April 2004
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COMPARISON OF EVAPORATION ESTIMATION METHODS FOR A RIPARIAN AREA

Final Report

by

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I. STATEMENT OF THE PROBLEM

Water use in the riparian areas of the Middle Rio Grande Basin in New Mexico is of growing concern. The Bureau of Reclamation has the responsibility to maintain the water level in the Rio Grande while ensuring that competing water demands are fulfilled and that the amount of water leaving New Mexico is sufficient to satisfy water obligations to Texas and Mexico. Accurate estimates of the evaporative water demand along the river, including the riparian areas, will enable more efficient use of available water. The field campaign described here is part of an effort to quantify the amount of evapotranspiration in salt cedar and cottonwood stands in the riparian areas of the Rio Grande.

This paper will compare evaporation estimates calculated using several well known methods and discuss their limitations.

II. BOSQUE DEL APACHE NATIONAL WILDLIFE REFUGE

The Bosque Del Apache National Wildlife Refuge (hereafter referred to as the Bosque) is located in the semiarid, south-central part of New Mexico. With an area of 57,000 acres, the Bosque is situated at the northern edge of the Chihuahuan desert. Straddling the Rio Grande,
approximately 20 miles south of Socorro, New Mexico, the Bosque is home to over 340 species of birds, as well as many species of reptiles, amphibians, fish and mammals including coyotes, mule deer and elk. Vegetation in the Bosque ranges from those associated with riparian areas to plants native to desert habitats. The site of two intensive campaigns along the west side of the Rio Grande consists almost entirely of a riparian area of uniformly dense salt cedar (*Tamarix ramosissima*) with a few mature cottonwood (*Polulus deltoides* ssp. *wislizenii*) sparsely mixed in. The salt cedar stand is bordered by the Rio Grande on the east and a road and levee to the west. West of the levee, the vegetation mainly consists of immature cottonwood trees approximately 4 m tall. Figure 1 shows the location of the Bosque relative to New Mexico and the study site in relation to the Bosque. Figure 2 is a panoramic view of the dense salt cedar patches near the site.

**A. Measurements at the Bosque.** The measurement concept was to make long term meteorological and energy flux measurements on the towers while measuring a wider range of atmospheric parameters during two short term, intensive campaigns. The sensors used for long term measurements were mounted on a meteorological tower, as seen in Figure 3. The tower

![Figure 1](image1.png)

**Figure 1.** Site map showing the location of the Bosque in relation to the Bosque. The right panel is a false color image showing the salt cedar, cottonwood stand, the drainage canal and the location of the micrometeorological towers and the lidar. The scan lines indicate the lines of sight used in the scanning series of the lidar.

![Figure 2](image2.png)

**Figure 2.** Panoramic view of the Bosque illustrating the dense patches of salt cedar.
used for the long term measurements is referred to as the North Tower in Figure 1. The area surrounding the North Tower is heavily overgrown by salt cedar, as seen from the path leading to the tower site (Figure 4). The instruments were capable of measuring all standard meteorological parameters as well as eddy correlation measurements of latent and sensible heat flux. The long term measurements were made from 15 April to 23 September, 1999 and from 15 March to 11 June, 2001.

Along with the long term measurements, two intensive field campaigns were conducted in September of 1998 and in June of 1999. During these intensive campaigns, additional instruments were fielded including the Los Alamos Raman lidar. The purpose of the intensive campaigns was to provide supporting information, such as vertical wind, humidity, and temperature profiles, from more sophisticated instruments, such as a radar RASS, a water vapor lidar, an elastic lidar, a sodar, and radiosondes.

**Figure 3.** A photograph of the instrumentation mounted on the North Tower. Flux instruments were mounted at two heights to measure the flux in the canopy and above it.

**Figure 4.** The path through the salt cedar to the North Tower. The salt cedar was heavily overgrown, preventing access to the interior of the stand.

**B. Instrumentation.** The instruments shown on the North Tower (Figure 3) comprise an energy/water budget and meteorological flux station. A list of instruments mounted on the North Tower and brief descriptions are detailed in Table 1. A description of available data sets for 1999 and 2001 is contained in Appendix 1. The water/energy budget is comprised of measurements of net radiation, storage in the canopy (available energy), turbulent fluxes of sensible and latent heat, and momentum flux. Available energy is estimated with measurements
from a net radiometer. Sensible, latent heat (evaporation) and momentum fluxes are measured by combining a sonic anemometer and a fast response hygrometer.

### Table 1. Instruments Mounted on the Meteorological Tower (North Tower) at the Bosque.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Height Above the Surface</th>
<th>Measures</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSAT3, Sonic Anemometer</td>
<td>7.96 m</td>
<td>Wind speed, direction, turbulent quantities</td>
<td>1%</td>
</tr>
<tr>
<td>KH20, Krypton Hygrometer</td>
<td>7.96 m</td>
<td>Water vapor concentration fluctuations</td>
<td>3%</td>
</tr>
<tr>
<td>HMP45C, Temp-Humidity Probe</td>
<td>9.1 m</td>
<td>Atmospheric temperature and humidity</td>
<td>±0.1°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±1% RH</td>
</tr>
<tr>
<td>Q6, Net Radiometer</td>
<td>8.5 m</td>
<td>Net long and short wave radiation</td>
<td>10% (est.)</td>
</tr>
<tr>
<td>MET ONE 34A-L, Cup Anemometer and Vane</td>
<td>8.95 m</td>
<td>Wind direction</td>
<td>10% (est.)</td>
</tr>
</tbody>
</table>

The sonic anemometer measures the three dimensional components of the wind flow (u, v, and w, the three components of the wind speed) at high rates, up to 20 Hz. The krypton hygrometer measures fluctuations of atmospheric water vapor concentration (q’) at the same rate as the sonic anemometer (20 Hz). Together, the fluctuations in vertical wind speed (w’) and water vapor concentration (q’) were used to calculate the vertical transport term of the eddy covariance fluxes, defined as $\overline{w'q'}$, where the overbar indicates time averaging. The covariance of these variables is the “standard” reference for the evaporative flux from the surface (subject to various corrections for instrument limitations [Webb et al., 1980; Massman, 2000; Massman and...
Lee, 2002). This method is accepted as the most physically based technique to measure evaporation and is used in this project as the “truth set”. The temperature/humidity probe, part of a standard meteorological station, is used as a data set for evaluating the utility of more advanced models for estimating evaporative flux from the surface. The cup anemometer and vane provide part of a one-propeller eddy correlation (OPEC) system, used as another method to calculate latent heat.

As indicated, the latent heat flux (LE) calculated using the sonic anemometer and krypton hygrometer is used as the “truth set”. Figures 5 and 6 illustrate daily eddy correlation estimates of evapotranspiration as measured from the North Tower during the long term measurement campaigns for 1999 and 2001. This data is used to compare the results from the evaporation estimation methods described in Section III.

For both 1999 and 2001, data flagged as being incomplete were deleted before taking the daily average. Data that was not flagged, yet with a latent heat flux value less than -50.0 W/m² were also deleted. In the 1999 data set, there are several periods where data is missing completely, causing the plot to appear “choppy”.

III. EVAPORATION ESTIMATION METHODS

A. Blaney-Criddle Method. The Blaney-Criddle Method was developed for estimating consumptive use of irrigated crops in the western United States. It is based on the assumptions that air temperature is correlated with the integrated effects of net radiation and other controls of evapotranspiration and that the available energy is shared in fixed proportion between heating the atmosphere and evapotranspiration [Dunne and Leopold, 1978]. The Blaney-Criddle Method is very similar to another evaporation estimation method, the Thornwaite Method, which is based on the same assumptions, but does not take into account differences in vegetation type as
the Blaney-Criddle method does. The major independent variables driving the Blaney-Criddle Method are temperature and day-length. The form of the equation used to estimate evaporation from the Bosque, as used by the U.S. Soil Conservation Service [1970] is:

\[ E_t = (0.142T_a + 1.095)(T_a + 17.8)kd \]  

(1)

where:

- \( E_t \) = potential evapotranspiration (cm/mo),
- \( T_a \) = average air temperature (°C) (when \( T_a \) is less than 3 °C , the first term in the parentheses is set equal to 1.38),
- \( k \) = empirical crop factor that varies with crop type and stage of growth (Appendix 2),
- \( d \) = monthly fraction of annual hours of daylight (Appendix 3).

Blaney-Criddle evaporation estimates were calculated for both 1999 and 2001. For both years, the half hour average temperature from the temperature/humidity probe was used in accordance with the rule specified above. Empirical crop values were used for salt cedar which covered the majority of the area near the tower. The values for the crop coefficients were obtained from the Middle Rio Grande Assessment, [1997] which determined the coefficients for a wide range of canopies found along the Rio Grande. The monthly fraction of annual hours of daylight is a function of latitude and time of year (Appendix 4). A record of the North Tower latitude is not available, however, the latitude of the South Met Tower, a few hundred meters to the south, is 33°48'15 sec or 33.80°N. This was used to calculate the monthly fraction of annual hours of daylight for the North Tower. Given the latitude of 33.80°N, fractional values were interpolated between 20°N and 40°N. The results of this interpolation are given in Appendix 4. Blaney-Criddle estimates were then calculated for the available data in 1999 and 2001. The half hour average results were then averaged over the day and converted to mm/day. The results

**Figure 7.** Daily averages of computed Blaney-Criddle evaporation estimates for 1999 in comparison to daily averaged measured evaporation rates.
from the Blaney-Criddle Method are plotted in Figures 7 and 8 against the daily averaged values of measured evaporation for ease of comparison. With the exception of the days surrounding day 300 in 2001, the Blaney-Criddle estimate of evapotranspiration is quite similar to the eddy correlation estimate for both years.

On inspection, between days 150 (May 30) and 225 (August 13) in 2001, the Blaney-Criddle method estimates the evapotranspiration rates particularly well and is plotted in Figure 9 for closer examination. As can be seen from the figure, the Blaney-Criddle method does a credible job of estimating the general trend of actual evapotranspiration, yet appears to overestimate evaporation by about 2 mm/day. Similarly, the method also overestimates the evapotranspiration in 1999, by a smaller amount. This method seems to approximate evapotranspiration for that particular span of the year during the summer when evaporation rates are at their peak. The root mean square error was calculated over the entire data period for both 1999 and 2001 and was found to be 1.53 mm/day and 1.16 mm/day, respectively.

**Blaney-Criddle Uncertainty Analysis:**

Fundamental to a conventional uncertainty analysis is the assumption that the method in question adequately captures the physics responsible for the parameter being estimated. The conventional analysis of
Evaporation is normally done from one of two perspectives. In the energy conservation perspective, the partitioning of solar energy between sensible heat flux and evaporation is a function primarily of the available energy, water availability, and the potential response of the plant canopy to heat and water stress. From an atmospheric transport perspective, evaporation is a function of the vapor deficit between the surface and the air above and the vertical flux of momentum. The Blaney-Criddle method does not explicitly account for any of the processes that govern the evaporation rate in either perspective. Because of this, evaporation rates predicted by this method will be correct only to the extent that the evaporation rate is similar from year to year. The only parameter in this method that changes from year to year is the monthly average temperature, $T_a$, a number that does not normally change more than 5 to 8 percent from year to year. That this is a problem is evident from efforts to measure the crop coefficient during different years. It is not uncommon for the crop coefficient to vary by more than a factor of two between years (see Figure 10). In Figure 8, the difference in estimated evaporation around day 300 of 2001 is likely due to the fact that the canopy senesced about a month earlier in 2001 than it did during the year for which the crop coefficients were measured. Ultimately, the variations in the measured crop coefficients are perhaps the best measure of the uncertainty of the method.

To illustrate the degree to which crop coefficients vary from year to year, a study done by the Soil Conservation Service is examined here. From 1962 to 1980, the Bureau of Reclamation cooperated with other interested federal agencies to conduct lysimeter studies on consumptive use of water by phreatophytes; plants with very long, extensive root systems which draw water from the water table or other permanent groundwater supplies, that are widely distributed along the Middle Rio Grande. Common phreatophytes in New Mexico include salt cedar, Russian Olive, and salt grass. This paper will address salt cedar only. Between 1962 and 1968, crop coefficients were calculated for salt cedar by the Soil Conservation Service using large evapotranspirometers situated along both sides of the Rio Grande from Bernado to San Acacia. Each evapotranspirometer was a 12-foot deep tank with a surface area of 1,000 square meters that was buried in the ground and used as a lysimeter. Six tanks were planted with salt cedar and using the measured monthly evapotranspiration data series from each tank, a monthly crop coefficient was calculated [Middle Rio Grande Water Assessment, Supporting Document No. 5]. Results from these seven years are seen in Figure 10, which illustrates the distribution of average crop coefficients from each of the six tanks. As seen from the figure, crop coefficients vary nearly by a factor of 3. When using an average crop coefficient, large degrees of uncertainty are
then introduced into the evaporation estimates.

Consider what will happen in a year with decreased water availability, leading to decreased evaporation. Decreased evaporation results in warmer temperatures (the sensible heat flux is increased by the amount of decrease in evapotranspiration). But with higher temperatures, the Blaney-Criddle method will predict higher evaporation, exactly the reverse of the real situation.

More significantly, the method relies on the sameness of the climate from year to year over a long averaging period (usually taken to be a month). Because of this, the method is particularly ill-suited for short term estimates of evapotranspiration that may be used to regulate the water level in the Rio Grande. Over short periods of time, the weather may be vastly different than the monthly average. As the averaging period becomes longer and if it approaches the climate average, the better the estimate. Because of this, the method has little value for short term estimates of evaporation and virtually no predictive capability.

**B. Penman Method.** The Penman method was developed to estimate evaporation from saturated surfaces. This is defined by Penman [1948] to be the condition that occurs after thoroughly wetting the soil by rain or irrigation, when soil type, crop type and root range are of little importance. The Penman method has been described as the recommended equation to estimate the potential evaporation rate from measured meteorological variables for an open

![Figure 10. Calculated Soil Conservation Service Blaney-Criddle Crop Coefficients for Salt Cedar between 1962 and 1968 [Middle Rio Grande Water Assessment, Supporting Document No. 5].](image)
water surface [Unland, 1998; Shuttleworth, 1993]. Based upon thermodynamic arguments for a water surface, Penman was able to write:

\[ A = \frac{\gamma + \Delta}{\Delta} E_t - \frac{\gamma}{\Delta} \left[ \frac{e_a^* - e_a}{e_s - e_a} \right] E_t \]  

(2)

where:

\( E_t \) = total evapotranspiration (W/m²),
\( \Delta \) = slope of the saturation vapor pressure vs temperature curve (kPa/°C),
\( A \) = total available energy, \((R_n - G)\) (W/m²),
\( \gamma \) = psychrometric constant (kPa/°C),
\( e_a^* \) = water vapor saturation pressure of the air (kPa),
\( e_a \) = water vapor pressure of the air (kPa),
\( e_s \) = water vapor pressure in the air right at the surface of the soil or the leaves of the canopy (kPa),

The problem with the practical use of this equation is that \( e_s \) is virtually impossible to measure since it is the water vapor pressure right at the surface of the soil or canopy leaves. Because of this, the equation is normally rewritten as:

\[ E_t = \frac{\Delta}{\gamma + \Delta} A + \frac{\gamma}{\Delta + \gamma} \left[ \frac{e_a^* - e_a}{e_s - e_a} \right] E_t \]

(3)

where:

\( D \) = water vapor deficit of the air at the reference height, \((e_a^* - e_a)\) (kPa).

It is well established that the evaporation rate, \( E_t \), is directly proportional to the vapor deficit between the surface and the air above, \((e_s - e_a)\). At the time Penman derived his equation, bulk transfer coefficient methods were in common use. These methods estimate evaporation as \( E_t = F(u) (e_s - e_a) \) where \( F(u) \) is some function of the wind speed, \( u \). As a result, the Penman equation is commonly expressed as:
\[ E_t = \Delta A + \frac{\gamma}{\Delta + \gamma} D \ F(u) \]  

(4)

The last two parts of the second term, D F(u), are sometimes called the “drying power of the air” and designated, \( E_a \). Ultimately, the practical use of the Penman equation requires the assumption of some form for the wind transfer function, F(u). Historically, most of these functions have been defined using bulk transfer methods. Penman himself used an expression for \( E_a = 0.35(1+9.8x10^{-3} \ u)(e_s - e_a) \). The Penman method as formulated by Federer et al. [1996] estimates total evaporation by:

\[ E_t = \frac{\Delta A + 2.6 \ c_t \ L_e \ \rho_w \ \gamma (1 + 0.54u) D}{\gamma + \Delta} \]  

(5)

where:

\( c_t = \) conversion constant, 0.01157 W m d MJ\(^{-1}\) mm\(^{-1}\),
\( L_e = \) latent heat of vaporization, 2448.0 MJ/Mg,
\( \rho_w = \) density of water, 1.0 Mg/m\(^3\),
\( u = \) wind speed, m/s.

It should be noted here that the total available energy, \( A \), is defined as \( (R_n-G) \). The storage in the canopy is commonly estimated as ten percent of the net radiation, making the available energy:

\[ A = R_n - 0.1 \ R_n \]

Examining the energy balance using the eddy correlation measurements of sensible and latent heat fluxes, it was found that a better approximation for the available energy in the salt cedar canopy is:

\[ A = R_n - 0.2 \ R_n \]

Using this version of the Penman method, the evaporation rates were estimated for 1999 and
2001 using the meteorological data measured at the North Tower. These estimates are compared to measured evaporation and plotted in Figures 11 and 12, respectively. As seen in the figures, the Penman method of evaporation estimation overestimates the measured evaporation (LE) in 1999 throughout the entire data set. The 1999 data spans the summer months, April 23rd through September 29th, where evaporation rates are high and water demand is greatest. Since the data in 1999 is missing many records, the plot appears irregular, or “choppy”. Although the Penman method follows the pattern of the measured evaporation relatively well, it either overestimates or underestimates evaporation rates by nearly 4 mm/day. During 2001, a larger data set allowed Penman evaporation estimation to be examined over a longer range.

As seen in Figure 12, the Penman method of estimating evaporation seems to do a relatively good job of estimating evaporation during the summer months but fails to follow the decrease in the spring and fall. For example in the spring, the Penman method overestimates the measured evaporation by four to five mm/day. Figure 13 gives a closer look at the Penman method versus measured evaporation during the summer months of 2001, May 30 to September 7. From this plot it can be seen that in the summer of 2001 the Penman method does a much better job of estimating evaporation than it did in 1999.

One reason for this is the lack of consistent data during 1999. The root mean square error for 1999 and 2001 is 2.15 and 2.35, respectively, with a root mean square error of
0.76 mm/day during the summer months of 2001. The main cause of the difference between the Penman method and measured values is that the Penman method assumes that water is freely available. One would not expect the Penman method to work at all in a severely water limited, desert environment. However, during those months when the salt cedar canopy is well-developed, the system acts as if it were well-watered, regardless of rain rate or surface water availability. This is because the deep-rooted salt cedars can tap into the deep water supply near the river and evaporate the water through their leaves. When the canopy has senesced, there is little or no evaporation through the leaves and the surface acts as if it were bare soil. Since there is little surface moisture along the Rio Grande, the actual evaporation rate is much less than the Penman method would predict. Thus practical use of the Penman method will have to include some means of dealing with those times of the year when the surface is moisture limited.

A more modern approach to the problem of a wind function, would be to use Monin-Obukhov theory (see below) to obtain an expression for the wind transfer function [Brutsaert, 1982; Katul and Parlange, 1992]. Using equation 27 below, the Penman equation can be rewritten as:

$$
E_t = \frac{\Delta}{\gamma + \Delta} A + \frac{\gamma}{\Delta + \gamma} D \frac{0.622 L_e \rho_{air} u^* k}{P \ln \left( \frac{z - d_0}{z_0} \right)}
$$

(6)

where:

- $L_e$ = latent heat of evapotranspiration (J/kg),
- $u^*$ = vertical momentum flux / unit mass (m/s),
- $k$ = Von Karman constant, taken to be 0.40,
- $P$ = atmospheric pressure (kPa),
- $z$ = height above ground that the air temperature measurements are made (m),
\[ z_0 = \text{roughness height (m)}, \]
\[ d_0 = \text{displacement height, taken to be 2/3 canopy height (m)}, \]

An estimate for the roughness height was be obtained from the Monin-Obukhov similarity form of the wind profile [Brutsaert, 1982]:

\[ \bar{u} = \frac{u^*}{k} \ln \left( \frac{z - d_0}{z_0} \right) \]

where:
\[ \bar{u} = \text{mean wind speed, m/s}. \]

The displacement height for the Bosque is found to be 3.13 m, based on the height of the salt cedar canopy. With the measured \( u^* \) values and the known height of wind measurements, an average roughness height, \( z_0 \), is found to be 0.806 m. The Penman method using a similarity form for the wind function was applied to the data sets in 2001, giving the evaporation estimates as seen in Figure 14. From the figure, it can be seen that this modified Penman method appears to be very similar to the original Penman method. The root square mean error for this method is 2.71 mm/day, greater than the original Penman method by 0.36 mm/day. A closer examination of the evaporation estimation during the summer months, May 30 to September 7, 2001 appears in Figure 15. This modified method continues to follow the original method. While appearing to be a close approximation, the root mean square error over the summer months is 0.87 mm/day, an error greater than the original method by 0.11 mm/day.

The ET Toolbox uses a daily average Penman formulation. In terms of the variables used in this analysis, the ET Toolbox

![Image](image.png)

**Figure 14.** Daily averages of the modified Penman method, using Monin-Obukhov theory, evaporation estimates for 2001 in comparison to the daily averaged, measured evaporation.
Figure 15. A closer examination of the 2001 daily averaged, modified Penman method, using Monin-Obukhov theory, evaporation estimates in comparison to the measured evaporation rates.

The ET-toolbox modified Penman method was used to estimate evaporation during 2001, and is plotted in Figure 16. This method predicts the summer months of high evaporation to be later than in actuality, by nearly one month. Days 150-250 are plotted in Figure 17 to illustrate what happens during the summer months. In this figure, it can be seen that the ET toolbox method captures some instances of

\[
E_t = \frac{10}{L_e} \left[ \frac{\Delta R_n}{\gamma + \Delta} + \frac{2 \gamma}{\Delta + \gamma} D F(u) \right] \quad \text{mm/day} \tag{7}
\]

\[
R_n = 0.95 \left[ \frac{(1 - R)}{0.041868} S_{\text{downwelling}} \right] - 64 \quad \text{cal/(cm}^2\text{day)} \tag{8}
\]

where:
\[
S = \text{downwelling solar radiation (MJ/m}^2\text{-day)},
\]
\[
D = \text{water vapor deficit, defined in the ET Toolbox as}
\]
\[
= (e_{\text{sat}}(T_{\text{max}}) + e_{\text{sat}}(T_{\text{min}}) - r_{\text{min}} e_{\text{sat}}(T_{\text{max}}) - r_{\text{max}} e_{\text{sat}}(T_{\text{min}}))/2 \quad \text{(mbar)},
\]
\[
r_{\text{min}} = \text{minimum relative humidity during the day,}
\]
\[
r_{\text{max}} = \text{maximum relative humidity during the day,}
\]
\[
T_{\text{min}} = \text{minimum temperature during the day,}
\]
\[
T_{\text{max}} = \text{maximum temperature during the day,}
\]
\[
R = \text{albedo of the earth’s surface, taken in the Toolbox as 0.21,}
\]
\[
F(u) = \text{wind function, defined in the ET Toolbox as}
\]
\[
= 15.36 (1.0 + 0.0062*3.6*24* u(2m)) \quad \text{(km/day)},
\]
\[
u(2m) = \text{wind speed at an altitude of 2 m (m/s),}
\]
the rise and fall of the measured latent heat flux, but in other instances not at all.

**Penman Uncertainty Analysis:**

Using a conventional uncertainty analysis [Coleman and Steele, 1989; Taylor, 1982], the maximum likely uncertainty of the method can be estimated. Data from the intensive campaigns will be used to verify the theoretical prediction. Using equation 4 as the basic equation defining the evaporation estimate for the method, standard error propagation methods, assuming the measurements are independent (although the relative humidity measurement is not independent of the temperature), and that the fractional uncertainty in air density is equal to the fractional uncertainty in temperature, the fractional uncertainty in the evaporation rates is obtained by summing the contributions in quadrature:

\[
\frac{\delta E}{E} = \sqrt{\left(\frac{\Delta \delta A}{\Delta A} + \frac{(2.6c_\gamma L_\rho \rho_w \rho F(u) \delta D)^2 + (2.6c_\gamma L_\rho \rho_w \rho D \delta F(u))^2 + \left(\frac{A \gamma \delta \Delta}{\gamma + \Delta}\right)^2}{\Delta A + 2.6c_\gamma L_\rho \rho_w \rho F(u) D}}
\]  

(9)
where the $\delta$ indicates the uncertainty in the value that follows the symbol.

Table 2. Conditions Taken as Typical for the Uncertainty Analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>27°C</td>
<td>±0.1°C</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>30%</td>
<td>±3% RH</td>
</tr>
<tr>
<td>Vapor Deficit</td>
<td>2.49 kPa</td>
<td>4%</td>
</tr>
<tr>
<td>Wind Speed at 3 m</td>
<td>2.5 m/s</td>
<td>±5%</td>
</tr>
<tr>
<td>Net Radiation $Rn - G = A$</td>
<td>420 W/m²</td>
<td>15%</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.059</td>
<td>0.1%</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>0.210</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

A mid-morning day in June is taken as a typical day. For this day the air temperature is assumed to be 27°C, the relative humidity 30% over the canopy, and the wind speed is 2.5 m/s at a measurement height of 3 m. The manufacturer’s estimates for the uncertainty of the instruments is used. As will be seen below, the uncertainty for the available energy and the wind function dominate the uncertainty in evaporation. The uncertainty in the net radiation is on the order of ten percent for most inexpensive net radiometers, especially those without corrections for the case temperature. The other part of the uncertainty is the amount of energy storage in the soil and canopy. While the energy storage in the soil can be measured, it is difficult to do so in a plant canopy, particularly one as complex as salt cedar. Storage in the canopy is often estimated to be ten percent of the net radiation. The amount of storage in the salt cedar, estimated from the measurements of net radiation, latent and sensible heats is highly variable and on the order of twenty percent for the summer months. This value is expected to be seasonal, varying with the amount of foliage. The uncertainty in the value of the wind function is difficult to estimate. This function should be different for each canopy type, and should vary with the ability of the wind to penetrate the canopy. Thus one would expect this function to vary with time of year. With these estimates of the uncertainty in the measured values, the following estimate for the fractional uncertainty in the evaporation rate can be obtained:

$$\frac{\delta E}{E} = \sqrt{(0.210 \times 0.059)^2 + (2.6 \times 0.01157 \times 0.059 \times 2448 \times 2.35 \times 0.1)^2 + (2.6 \times 0.01157 \times 0.059 \times 2448 \times 2.49 \times 0.12)^2 + \left(\frac{350 \times 0.59 \times 0.001}{0.059 \times 0.210}\right)^2}$$ (10)
This estimate of the uncertainty is deceptive. It assumes that the theory completely and perfectly describes the phenomena and situation under examination. The most important disconnect is the theory assumption that water is freely available at the surface. In fact there are three distinct water availability conditions that are found. The first is found in the summer months when the salt cedar has fully developed leaves. At this time, the deep roots of the salt cedar move water from deep in the soil to the surface where it evaporates through the leaves. The system acts as if water is freely available at the surface because of the root system of the canopy. During this time, the Penman equation approximates the system quite well (days 150 to 250). The opposite condition is found during the winter months. At this time the salt cedar has senesced and is essentially dormant. The only water that is available is that which is in the uppermost soil layers. The system is water limited and the evaporation rate is about one-sixth of what it would be were water freely available (days 75 to 110 and 300 to 365). The third condition is the period between the first two, when the canopy is developing or senescing, and only a part of the fully developed canopy is available for evaporation. During these times, the system is water limited, but limited by the ability of the canopy to move and evaporate water. During the winter period, the estimates of evaporation could be improved by including a soil moisture probe as part of the instrument suite. The expected uncertainty of 13% should be expected only during the summer months when a full canopy is present. This analysis demonstrates that the single most important factor in increasing the reliability of this estimate of the potential rate is a better estimate of the available energy.

**ET Toolbox Comments:**

In most respects, the ET Toolbox version of the Penman equation will have the same limitations as a conventional Penman analysis. As with the Penman equation, the largest source of uncertainty will be the estimate of the available energy. The ET Toolbox uses a measurement of the total downwelling shortwave radiation over the course of a day. The albedo is estimated
to be a constant value of 0.21 for all canopies and all times. The net long wave radiation is
estimated as -64 cal/cm²-day (-31 W/m²) for all days of the year. The available energy is taken
to be the net long wave radiation and 95% of the net solar radiation. As can be seen from figure
18, the ET toolbox method systematically overestimates the measured values by nearly 45 W/m²
with the difference being slightly higher in the summer months than in the winter. The problem
is likely to be two assumptions that work in opposite directions. In the summer, the net long
wave radiation is probably much larger than 31 W/m² outgoing, making the available energy
estimate too large. The albedo is likely to be larger in the summer than 0.21 which makes the
estimate too small. Conversely, during the winter, the net longwave radiation is likely to be on
the order of or smaller than 31 W/m², but the albedo will be less. Because these two errors
partially compensate for each other, the net error is smaller than if just one was present.

The use of a crop coefficient based on growing degree days is not effective in predicting the
evaporation for 2001. As with any crop coefficient, the degree to which it performs well is
dependent upon how similar the year in question is to the year(s) in which the coefficients were
determined. Since the evaporation rate is dependent on the state of the canopy, which is a
function of a number of variables, a measurement of this state or some surrogate (like leaf area
index, LAI) would be preferable to the use of a crop coefficient.

C. Priestley Taylor Method. Based on a large number of measurements of evaporation
over water surfaces, Priestley and Taylor [1972] suggested a modification to the Penman
equation that requires less extensive measurements. The method is largely driven by the amount
of available energy and estimates evapotranspiration by the following:
$E_t = \frac{\Delta A}{\gamma + \Delta}$

where:

$E_t =$ total evapotranspiration (W/m$^2$),

$\alpha =$ Priestley-Taylor coefficient.

The Priestley-Taylor coefficient, $\alpha$, was originally postulated to be a constant equal to 1.26 by Priestley and Taylor for freely evaporating surfaces. A large number of papers have been published which report measurements of evaporation from wet or well-watered surfaces that are consistent with the value of 1.26 [Davies and Allen, 1973; Stewart and Rouse, 1976; Mukammal and Neumann, 1977; Stewart and Rouse, 1977; Brutsaert, 1982;]

### Table 3. Measured values of the Priestley-Taylor coefficient, $\alpha$ [Flint and Childs, 1991].

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>Surface Conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.57</td>
<td>Strongly advective conditions</td>
<td>Jury and Tanner, 1975</td>
</tr>
<tr>
<td>1.29</td>
<td>Grass(soil at field capacity)</td>
<td>Mukammal and Neumann, 1977</td>
</tr>
<tr>
<td>1.27</td>
<td>Irrigated ryegrass</td>
<td>Davies and Allen, 1973</td>
</tr>
<tr>
<td>1.26</td>
<td>Saturated surface</td>
<td>Priestley and Taylor, 1972</td>
</tr>
<tr>
<td>1.26</td>
<td>Open-water surface</td>
<td>Priestley and Taylor, 1972</td>
</tr>
<tr>
<td>1.26</td>
<td>Wet meadow</td>
<td>Stewart and Rouse, 1977</td>
</tr>
<tr>
<td>1.18</td>
<td>Wet Douglas-fir forest</td>
<td>McNaughton and Black, 1973</td>
</tr>
<tr>
<td>1.12</td>
<td>Short grass</td>
<td>De Bruin and Holtslag, 1982</td>
</tr>
<tr>
<td>1.05</td>
<td>Douglas-fir forest</td>
<td>McNaughton and Black, 1973</td>
</tr>
<tr>
<td>1.04</td>
<td>Bare soil surface</td>
<td>Barton, 1979</td>
</tr>
<tr>
<td>0.84</td>
<td>Douglas-fir forest (unthinned)</td>
<td>Black, 1979</td>
</tr>
<tr>
<td>0.8</td>
<td>Douglas-fir forest (thinned)</td>
<td>Black, 1979</td>
</tr>
<tr>
<td>0.73</td>
<td>Douglas-fir forest (daytime)</td>
<td>Giles et al., 1984</td>
</tr>
<tr>
<td>0.72</td>
<td>Spruce forest (daytime)</td>
<td>Shuttleworth and Calder, 1979</td>
</tr>
</tbody>
</table>
Parlange and Katul, 1992]. Not surprisingly, when applied to surfaces with complex vegetation and in situations where water is not freely available, the constant has been found to range from 0.72 to 1.57 (Table 2) [Flint and Childs, 1991; McNaughton and Black, 1973; Barton, 1979; Shuttleworth and Calder, 1979]. There is also some data to indicate that there may be systematic variations in the value of $\alpha$ with time of day and season of the year [de Bruin and Keijman, 1979]. This coefficient is generally interpreted as the ratio between the actual evaporation rate and the equilibrium evaporation rate. Given that salt cedar is a deep rooting plant and is rarely water starved, the value of 1.26 was used for the Priestley-Taylor coefficient.

Evaporation was estimated using the Priestley-Taylor method for the 1999 and 2001 data sets and compared to the measured evaporation in Figures 19 and 20, respectively. The Priestley-Taylor method provides a good approximation to the measured evaporation values during the summer months of both 1999 and 2001. During the summer months, the Priestley-Taylor method follows the curve of the measured evaporation, however, it underestimates the measured evaporation by about one mm/day as estimated by the root mean square error. A closer examination of the 2001 summer months is plotted in Figure 21. The underestimation is to be expected. The Priestly-Taylor equation obtained the value of 1.26 from measurements over the ocean and in

![Figure 19. Daily averages of computed Priestley-Taylor evaporation estimates for 1999 in comparison to the daily averaged measured evaporation.](image)

![Figure 20. Daily averages of computed Priestley-Taylor evaporation estimates for 2001 in comparison to the daily averaged measured evaporation.](image)
well-watered areas. It assumes that the second term in the Penman equation is, on average, 26 percent of the first term. The kinds of areas for which it was developed have relative humidities on the order of 80 to 90 percent. In contrast, the relative humidity in New Mexico rarely rises above 20 percent, and thus the vapor pressure deficit in New Mexico will be much larger.

During the non-summer months, the Priestley-Taylor method greatly overestimates the evaporation for the same reasons that the Penman method, failed. The surface is water limited during those periods when the salt cedar canopy is not fully developed.

With these differences from the measured evaporation, the Priestley-Taylor method of estimating evaporation the root mean square difference is 1.64 mm/day in 1999 and 1.70 mm/day in 2001 for the periods in which data is available and during the summer months, a root mean square error of 1.64 mm/day in 1999 and 1.70 mm/day in 2001.

A more sophisticated treatment of the thermodynamics of the Penman equation allows an expression for the Priestley-Taylor parameter to be derived that corrects for the low relative humidity found in New Mexico [Eichinger et al., 1996]. This expression permits calculation of the parameter values based on ambient meteorological conditions:

\[
\alpha = \frac{1 + \left[ \frac{\gamma}{\Delta + \gamma} \right]}{1 - \left[ \frac{\gamma}{\Delta + \gamma} \right]^2}
\]  

(12)

where

\[
C = \frac{(e_a^* - e_a)}{(e_s^* - e_a)}.
\]  

(13)
The saturation vapor pressure for the air or at the surface, is calculated using the expression [Alduchov and Eskridge, 1996]:

\[ e^* = 0.6108 \exp\left(\frac{17.27}{T}(T+273.3)\right) \]  \hspace{1cm} (14)

where \( T \) is the temperature in K.

Unfortunately, in neither 1999 and 2000, was the surface temperature measured at the Bosque north tower. Surface temperature is required to determine the saturation vapor pressure at the surface. A more representative value for \( \alpha \) could therefore not be obtained. In tests in an arid area in California, the method did predict the correct value for \( \alpha \) under strongly advective conditions in an irrigated field in the midst of an arid area.

**Priestley-Taylor Uncertainty Analysis:**

An uncertainty estimate for the Priestley-Taylor method was developed from equation 11 using standard error propagation methods. The fractional uncertainty in the evaporation rate can be estimated from:

\[
\frac{\delta E}{E} = \sqrt{\left(\frac{\delta \alpha}{\alpha}\right)^2 + \left(\frac{\delta (R_n-G)}{R_n-G}\right)^2 + \left(\frac{\delta \gamma}{\gamma}\right)^2 + \left(\frac{\delta \Delta}{\Delta} - \frac{\delta \Delta}{\gamma+\Delta}\right)^2}
\]  \hspace{1cm} (15)

To evaluate the expected uncertainty, the conditions outlined in table 2 were used as typical conditions. In addition, an estimate of the fractional uncertainty in the Priestley-Taylor coefficient is required. The Bosque region is a narrow, wet area in the middle of an arid region, far from the conditions envisioned by the method developers. The influence of advection (hot dry air from areas outside the Bosque) on the local evaporation rate cannot be discounted. This is especially true depending on from what direction the wind is blowing, particularly winds with easterly or westerly components. If a constant coefficient value is used, the uncertainty at any time could be 15% or more. If the coefficient is calculated based on existing conditions (for example, using equations 12 and 13), the uncertainty would be less than 5%. We take 10% as an intermediate value.
\[
\frac{\delta E}{E} = \sqrt{(0.10)^2 + (0.15)^2 + (0.01)^2 + (0.01 - 0.05)^2} = 0.18
\] (16)

The expected uncertainty of 18% is primarily due to uncertainty in net radiation.

**D. McNaughton Black Method.** This method estimates total evaporation using the following [McNaughton and Black, 1973]:

\[
E_t = \frac{c_p \rho D}{\gamma r_c}
\] (17)

where

- \(E_t\) = total evapotranspiration (W/m²),
- \(c_p\) = specific heat at constant pressure (1005 J/kg/°C),
- \(\rho\) = air density (kg/m³),
- \(D\) = vapor pressure deficit (kPa),
- \(r_c\) = surface or canopy resistance (s/m).

All of the variables in the McNaughton Black equation are readily available except \(r_c\), the surface or canopy resistance. An estimate of this value is performed recognizing that \(r_c\) can be defined as:

\[
r_c = \frac{c_p \rho D}{\gamma E_t}
\] (18)

Canopy resistance for 2001 can then be estimated using the measured evaporation rate from 1999 as:

\[
r_c(2001) = \frac{c_p \rho D}{\gamma LE_{1999}}
\] (19)

Since the 1999 measured evaporation was used to estimate canopy resistance, the McNaughton Black method can only be used to estimate evaporation rates for 2001. Given
the smaller data record and missing values in 1999, evaporation could only be estimated for 2001 data corresponding to existing 1999 records. This is required since the canopy resistance required for the method is limited by the amount of data available for 1999. This estimate is compared to the 2001 measured evaporation rates (Fig 22). Given the shorter data record and missing values, the McNaughton Black method does not appear to make a good approximation of the measured evaporation from 2001. From days 175 to 225, however, the estimated evaporation follows the general pattern of the measured evaporation, with a general trend that overestimates evaporation by about 3 mm/day.

**McNaughton Black Uncertainty Analysis:**

An estimate of uncertainty for the McNaughton-Black method was developed from equation 17 using standard error propagation methods. The fractional uncertainty in the evaporation rate can be found from:

\[
\frac{\delta E_t}{E_t} = \sqrt{\left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta D}{D}\right)^2 + \left(\frac{\delta \gamma}{\gamma}\right)^2 + \left(\frac{\delta R_{cs}}{R_{cs}}\right)^2}
\]  

(20)

To evaluate the expected uncertainty, the conditions outlined in table 2 were used as typical. An estimate of the fractional uncertainty for the canopy resistance values is required. In principle, this parameter could be measured. In practice, only an rough estimate of the value can be obtained. It is a complex function of the ability of a plant to move water from deep underground up to the leaves, the availability of groundwater, and the current state of the stomates (which is a function of both the existing and antecedent conditions). Obtaining the resistances as was done here, using values determined for a
previous year, is equivalent to using a multiplicative crop coefficient, and is subject to the same limitations. The most important limitation is that coefficients vary from year to year, depending on the conditions. The accuracy of the resulting evaporation estimate depends on how similar the year in question is to the base year used to calculate resistances. Using an estimate of 20% for the fractional uncertainty in the resistances (a value too high for the summer months, but too small for the canopy transition periods), an estimate of the fractional uncertainty in the evaporation rate can be made:

\[
\frac{\delta E_t}{E_t} = \sqrt{(0.01)^2 + (0.04)^2 + (0.001)^2 + (0.02)^2} = 20.4\%
\]

This uncertainty estimate must be used with great care. Though consistent with the 2001 estimates, this equation is completely empirical. It includes little of the physics that control or limit the evaporation rate. The availability of energy and water are perhaps the most important limiting factors that are not included. This is a serious deficiency in an arid region where the availability of water limits evaporation in all cases except when the canopy is fully developed.

**E. Penman-Monteith Method.** This method estimates total evaporation using the following [Montieth, 1965]:

\[
E_t = \left( \Delta A + \rho c_p D / r_a \right) / \left( \Delta + \gamma (1 + r_c / r_a) \right)
\]  

(21)

where:

- \(E_t\) = total evapotranspiration (W/m²),
- \(\Delta\) = slope of the saturation vapor pressure vs temperature curve (kPa/°C),
- \(A\) = total available energy, \((R_n - G)\) (W/m²),
- \(\rho\) = air density (Kg/m³),
- \(c_p\) = specific heat at constant pressure (1005 J/kg/°C),
- \(D\) = vapor pressure deficit (kPa),
- \(\gamma\) = psychrometric constant (kPa/°C),
- \(r_a\) = aerodynamic resistance (s/m),
- \(r_s\) = surface or canopy resistance (s/m).
Aerodynamic resistance is defined by [McNaughton and Black, 1973]:

\[ r_a = \left( \frac{u_2}{u} \right)^{-1} \]

Canopy resistance, \( r_s \), is estimated using the 1999 measured evaporation as with the McNaughton Black method. The aerodynamic resistance is estimated using the same data. Given that these parameters are estimated from 1999 data, the evaporation estimate using the Penman Montieth method can only be made for corresponding 2001 data values. Results of these evaporation estimates are plotted in Figure 23 against corresponding daily averages of the measured evaporation. This method gives credible evaporation estimates for the summer months. There is considerable error in the estimates during the non-summer months. The root mean square error during 2001 is 1.93 mm/day. This is the smallest root mean square error value of any of the methods investigated in this paper, despite the haphazard nature of the data set.

**Penman-Montieth Uncertainty Analysis:**

An uncertainty estimate for the Penman-Monteith method was developed from equation 21 using standard error propagation methods. The fractional uncertainty in the evaporation rate can be determined from:

\[
\frac{\delta E}{E} = \sqrt{\left( \frac{\delta A}{\Delta A} \right)^2 + \left( \frac{\delta D}{\rho C_P} \right)^2 + \left( \frac{\gamma r_c \delta r_a}{E_i} \right)^2 + \left( \frac{\delta r_c}{\rho C_P D / r_a} \right)^2} \tag{22}
\]

To evaluate the expected uncertainty, the conditions outlined in table 2 were used as

![Penman Montieth 2001 Daily Averages](image)

**Figure 23.** Daily averages of computed Penman Montieth evaporation estimates for 2001 in comparison to the daily averaged measured evaporation.
typical. An estimate of the fractional uncertainty of the canopy resistance values is required.

\[
\frac{\delta E}{E} = \sqrt{(0.210 \times 60)^2 + (1005 \times 0.1/(40 \times 890))^2 + (275 \times 0.059 \times 25 \times 10/40^2)^2 + (275 \times 0.059 \times 8)^2} \]

\[
= \frac{0.210 \times 350 + 1005 \times 2.49/40}{136.0} = 9.8%
\]

With the result that:

\[
\frac{\delta E}{E} = \frac{\sqrt{(12.6)^2 + (0.03)^2 + (2.53)^2 + (3.25)^2}}{136.0} = 9.8%
\]

This level of uncertainty is consistent with the comparison for the summer months of 2001. During these months, water is available from the canopy. In other months, the system is water-limited. Because some canopy effects are included, the system does better than straight potential evaporation methods at estimating evaporation during canopy transition periods. This method is conceptually midway between models that estimate potential evaporation modified by crop coefficients and those models that measure the parameters necessary to “measure” evaporation. However, the model should be used with caution because it assumes water is freely available at the surface, an assumption not often the case in arid environments, particularly during the winter and canopy transition periods.

**F. Monin-Obukhov Method.** Over ideal homogeneous surfaces, Monin-Obukhov Similarity (MOS) Theory relates changes of vertical gradients in wind speed, temperature, and water vapor concentration. According to MOS, the relationship between the temperature and water vapor concentration at the surface, \(T_s\) and \(q_s\), and the wind speed, \(u(z)\), temperature, \(T(z)\), or water vapor concentration, \(q(z)\), at any height, \(z\), within the inner region (the first few meters of atmosphere above the surface) of the boundary layer is expressed as

\[
u(z) = \frac{u^*}{k} \left[ \ln \left( \frac{z}{z_0} \right) - \Psi_m \left( \frac{z}{L} \right) \right]
\]

\[
T_s - T(z) = \frac{H}{\rho u^* k C_p} \left[ \ln \left( \frac{z}{z_0} \right) - \Psi_h \left( \frac{z}{L} \right) \right]
\]

\[
q_s - q(z) = \frac{LE}{\rho u^* k L_e} \left[ \ln \left( \frac{z}{z_0} \right) - \Psi_v \left( \frac{z}{L} \right) \right]
\]
Where the Monin-Obukhov length, $L$, is a stability parameter, defined as:

$$L = \frac{-\rho u^3}{k g \left[ \frac{H}{T c_p} - 0.61 LE \right]} \quad (29)$$

Where:
- $z_o$ is the roughness length (assumed uniform for all variables),
- $H$ is the sensible heat flux,
- $LE$ is the latent energy flux,
- $\rho$ is the air density,
- $L_e$ is the latent heat of evaporation for water,
- $c_p$ is the specific heat for air,
- $k$ is the von Karman constant (taken to be 0.40),
- $u_*$ is the friction velocity,
- $g$ is acceleration due to gravity,
- $\Psi_m$, $\Psi_h$, and $\Psi_v$ are the Monin-Obukhov stability functions for momentum, temperature, and water vapor.

Simply, the MOS method assumes that vertical fluxes of scalars and mass are proportional to the difference between values at the surface and some height, $z$, and scaled by a term that quantifies the turbulent transport, the friction velocity, $u_*$. The method is simple, requiring only a measurement of wind speed, temperature and humidity at some height and the temperature at the surface. The air immediately above the surface is assumed to be saturated. At the surface, the wind speed is zero.

Unfortunately, long term measurements of canopy temperature were not made, so a comparison cannot be made for an extended period.

**Monin-Obukhov Uncertainty Analysis:**

An estimate of the uncertainty of the Monin-Obukhov method is developed below from equations 28 using standard error propagation methods. We first develop the basic equation defining the evaporation estimate. Combining equations 2a and 2c above and
rearranging,

\[
LE = \frac{\left[ q_s - q(z) \right] \rho u(z) k^2 L_e}{\ln \left( \frac{z}{z_0} \right) - \Psi_m \left( \frac{z}{L} \right)} \cdot \ln \left( \frac{z}{z_0} \right) - \Psi_v \left( \frac{z}{L} \right) \]  

(30)

where all variables are as defined above. To simplify the analysis, the atmosphere is assumed to be neutral, i.e. \( \Psi_m \) and \( \Psi_v \), the stability corrections functions are zero. This greatly simplifies the analysis without loss of generality. The evaporation estimate becomes

\[
LE = \frac{\left[ q_s - q(z) \right] \rho u(z) k^2 L_e}{\ln \left( \frac{z}{z_0} \right)^2} 
\]

(31)

Using error propagation methods, assuming the measurements are independent, although the relative humidity measurement is dependent on temperature, and assuming the fractional uncertainty in air density is equal to that temperature, the fractional uncertainty in the evaporation rate is obtained by summing the contributions in quadrature:

\[
\frac{\delta LE}{LE} = \left( \frac{\delta \left[ q_s - q(z) \right]}{\left[ q_s - q(z) \right]} \right)^2 + \left( \frac{\delta T}{T} \right)^2 + \left( \frac{\delta u(z)}{u(z)} \right)^2 + \left( \frac{\delta \ln \left( \frac{z}{z_0} \right)}{\ln \left( \frac{z}{z_0} \right)} \right)^2
\]

(32)

where the \( \delta \) indicates the uncertainty in the value following the symbol.

To evaluate the expected uncertainty, the conditions outlined in table 2 were used as typical. An estimate of the fractional uncertainty in the \( z_0 \) value is required. This is estimated to be 25\%. An estimate for the fractional uncertainty can be obtained as:

\[
\frac{\delta LE}{LE} = \left( \frac{0.00042}{0.0205} \right)^2 + \left( \frac{0.2}{300} \right)^2 + \left( \frac{0.2}{2.5} \right)^2 + \left( \frac{0.0334}{8.60} \right)^2 \right)^{1/2} = 8.3\%
\]

(33)

This uncertainty estimate is somewhat deceptive. It assumes a perfect surface and ideal conditions. It assumes that the theory completely and perfectly describes the phenomena. The Bosque region is a narrow, wet area in the middle of an arid region, far from ideal. The
influence of advection of warm, dry air on the local evaporation rate cannot be discounted.
This is especially true depending on from which direction the wind is blowing, particularly
winds with easterly or westerly components. This method is far more reliable than the other
methods because it does not assume that water is available at the surface. It should be able to
accurately estimate evaporation during winter and canopy transition periods when the other
methods fail.

VI. CONCLUSIONS
There are two general classes of evaporation estimates. The first estimates the potential
evaporation rate (the rate at which water would evaporate from a surface where water is freely
available) along with some method of estimating the effect that the canopy has on moderating
the flux. The other class attempts to measure the evaporative flux by measuring appropriate
atmospheric variables.

The Penman and Priestley-Taylor methods are methods that attempt to estimate the
potential evaporation. Both of these methods do well during those times when the salt cedar
makes deep water available for evaporation. During the summer months the salt cedar canopy
is sufficiently developed so that the surface acts as if water were freely available at the
surface. All of the method variants attempted did reasonably well during the summer months,
but all could benefit from some adjustment of the parameters. However, there are two other
periods during the year. The first is the winter months when the canopy is senesced and the
only water available for evaporation is that near the surface in the topsoil. During this time of
the year, the evaporation rate is limited by the ability of the soil to transport water vertically.
If the soil properties were known, and measurements of soil water content were made, it
would be possible to estimate the evaporation rates. At the experimental site, the only soil
water measurement available is the depth to the water table, which is not relevant for surface
moisture availability. The last period is the time during which the canopy is only partially
active, during late April and May, and September. At these times, the canopy is only partially
able to transport deep water and evaporate it from the foliage and the evaporation rates are
between the water-limited case and the potential rate. The method used by the ET Toolbox
applies a crop coefficient that is determined by the number of degree-days. As shown in
figure 17 for the only year in which we can test the method, this works poorly. Since the state
of the canopy during these transitional periods is a function of more than growing degree-
days, this method is not likely to produce a crop coefficient that works well from year to year.
Some method of quantifying the state of the canopy is needed during this period.

There are several methods (for example, the Penman-Monteith or McNaughton-Black methods) of adjusting the potential evaporation for the effects of the canopy that do not use a crop coefficient. They use one or more resistances that attempt to model the ability of the plant to transport water from the soil and transpire. These resistances are a function of soil water availability, the depth of the root system, the maturity level of the plant and its condition (which implies antecedent conditions can play a role), and the existing atmospheric conditions. In principle, all of this information can be measured and the resistances determined from either direct measurements or derived from indirect measurements. In practice, this is difficult, if not impossible, to accomplish. What is done more often is to measure the relevant parameters and evaporation rate, then invert the evaporation equations to estimate the resistances. For example, this report uses the estimates of resistance obtained from 1999 data to estimate evaporation during 2001. If this is done over a period of time in which all of the relevant parameters are similar to those in the period of time over which the resistances will be used, the method may work quite well. However, as with crop coefficients, one is always limited to the degree to which the conditions this year match those in the reference year or years.

Fundamentally, these methods that are based upon potential evaporation, including those that modify the potential evaporation for canopy effects, should not be used in arid environments. All of these methods assume that water is freely available at the surface. For the case of salt cedar, this is nearly never true (flood periods being an obvious exception). For the summer months, salt cedar acts like water is available, but only because of its deep root system and when the canopy is developed enough to take advantage of it. What is really present is a system where water availability in the topsoil limits evaporation except during those periods when the salt cedar can transport deep soil water. None of these methods will correctly estimate the evaporation rates during the winter months when the canopy has no effect. They will correctly estimate evaporation rates during the canopy transition periods (during the spring and fall months) only to the degree that the canopy coefficients or resistances are similar to the those in the reference year. During the summer months, no canopy effects are required at all, the surface evaporates at the potential rate.

Should these methods continue to be used, it is recommended that some measure of the state of the canopy be made so that the crop coefficients or resistances can be accurately estimated. One possible method would be to obtain a satellite measurement of leaf area index
(LAI) in mid-April and mid-May. While these measurements of LAI have limitations for this purpose, it would allow a more realistic assessment of the canopy state than the use of growing degree-days. Further, it could be done over and extended area and for many different crops at one time. Timely availability and processing of the data is an issue for consideration. For the winter months, some measure of the surface soil water content must be made. With these additional measurements, better estimates could be obtained than are currently available.

The second class of methods is a more direct method of estimating evaporation. In this study, it includes only the Monin-Obukhov similarity method, although it could include the Bowen Ratio method as well. These methods require measurements of enough atmospheric parameters to determine the evaporation rate. Unfortunately, these parameters were not measured except for the intensive campaigns, so that an extended comparison cannot be made to evaluate the potential of these methods. While these methods require more individual measurements in order to be used, they neither make nor need assumptions about water availability or the state of the canopy. A measurement of the surface roughness length is needed, but is a relatively simple parameter to estimate and is a one-time requirement.

For most of the meteorologic stations, only an additional measure of the canopy top temperature is needed to use the Monin-Obukhov method. In addition, special care must be taken to ensure the accuracy of the temperature, humidity, and wind speed measurements. The accuracy of the evaporation estimates depends on the accurate measurement of small temperature and humidity differences. The uncertainty of the individual measurements must be as small as possible to minimize the uncertainty in the evaporation estimates. Despite this, these methods are far more robust and reliable than any of the potential evaporation methods.
VII. BIBLIOGRAPHY


# Appendix 1: North Tower Data Set Description

Table 4. Description of parameters given in the data sets from the North Tower at the Bosque for both 1999 and 2001.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td></td>
<td>Day of year</td>
</tr>
<tr>
<td>Hour</td>
<td></td>
<td>Data averaged every half hour</td>
</tr>
<tr>
<td>Flag</td>
<td></td>
<td>Indicates a problem in the data</td>
</tr>
<tr>
<td>LE</td>
<td>W/m²</td>
<td>Computed using combination of sonic anemometer and krypton hygrometer</td>
</tr>
<tr>
<td>H</td>
<td>W/m²</td>
<td>Computed using combination of sonic anemometer and krypton hygrometer</td>
</tr>
<tr>
<td>G</td>
<td>W/m²</td>
<td>Computed using combination of sonic anemometer and krypton hygrometer</td>
</tr>
<tr>
<td>uₓ (avg)</td>
<td>m/s</td>
<td>Wind speed in the x-direction (sonic anemometer)</td>
</tr>
<tr>
<td>uᵧ (avg)</td>
<td>m/s</td>
<td>Wind speed in the y-direction (sonic anemometer)</td>
</tr>
<tr>
<td>U - magnitude</td>
<td>m/s</td>
<td>Magnitude of the wind speed (sonic anemometer).</td>
</tr>
<tr>
<td>U - direction</td>
<td>degrees</td>
<td>Wind direction (degrees)</td>
</tr>
<tr>
<td>u*</td>
<td>m/s</td>
<td>Friction velocity (sonic anemometer)</td>
</tr>
<tr>
<td>T (avg)</td>
<td>°C</td>
<td>Average temperature measured by the temperature/humidity probe.</td>
</tr>
<tr>
<td>e (avg)</td>
<td>kPa</td>
<td>Vapor pressure (temperature/humidity probe)</td>
</tr>
<tr>
<td>WS</td>
<td>m/s</td>
<td>Wind speed (cup anemometer and vane)</td>
</tr>
<tr>
<td>Wdir</td>
<td>degrees</td>
<td>Wind direction (cup anemometer and vane)</td>
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</table>
Available Data Sets

99 flux summary.xls
   Excel file containing 1999 tower data and eddy covariance calculations for days 113-272.

Bosque 2001 flux summary.xls
   Excel file containing 2001 tower data and eddy covariance for days 74-365.

Flux Data 2001 Day 74 to 163.xls
   Excel File containing flux data for days 74 to 163, 2001.

IRT Data Intensive Period.wb3
   Quattro file containing one minute averaged IRT data from the North Tower for days 169 to 171, 1999.

NetRadiation_Bosque_2001.xls

North Bosque tower 2001.xls
   Excel file containing 2001 tower data for days 74-162 for the North Tower.

North Tower data 2001 Day 74 to 94.xls
   Excel file containing flux data for days 74 to 94, 2001 for the North Tower.

North Tower Fluxes day173 to 272.xls
   Excel file containing flux data for days 173 to 272, 1999 from the North Tower.

NSC3D_02.xls
   Excel file containing 2001 tower data for days 74-162.

NSC3DR_2001.xls
Minimal Data for days 101 and 110, 2001.

South Bosque Met Station Data 1999.xls
   Excel file containing 1999, daily and hourly met tower data from the north and south towers for the entire year.

South Bosque Met Station Data 2001.xls
   Excel file containing 2001, hourly met data from the South Met Station for the entire year.

South Bosque Met Station Data 2002.xls
   Excel file containing 2002, hourly met data from the South Met Station for the entire year.

South Bosque Met Station Data 2003.xls
   Excel file containing 2003, hourly met data from the South Met Station for days 1 through 60.
### Table 5: Empirical crop factors for salt cedar as determined by the Soil Conservation Service (SCS), Middle Rio Grande (MRG) and New Mexico State University (NMSU) [Middle Rio Grande Assessment, 1997].

**SALTCEDAR**

Crop number 4 (XCONRIP)  
Beginning Date January 1  
Ending Date December 31  
Growing Season 365 Days  
Earliest growth rate 45 degrees mean temperature  
Latest growth rate 45 degrees mean temperature

<table>
<thead>
<tr>
<th>Month</th>
<th>Day</th>
<th>Date</th>
<th>SCS K</th>
<th>MRG K</th>
<th>NMSU K</th>
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<td>Jan 15</td>
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<td>Jan</td>
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Figure 24: Saltcedar crop growth stage coefficient curve with values given by the Middle Rio Grande (MRG) and New Mexico State University (NMSU).
Appendix 3. Monthly Fraction of Annual Daylight Hours
(for use with the Blaney-Criddle Method)

Table 6: Monthly fraction of annual hours of daylight (for use in the Blaney-Criddle Equation) [Dunne and Leopold, 1978].

<table>
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<tr>
<th>LATITUDE</th>
<th>JAN.</th>
<th>FEB.</th>
<th>MAR.</th>
<th>APR.</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUG.</th>
<th>SEPT.</th>
<th>OCT.</th>
<th>NOV.</th>
<th>DEC.</th>
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<tbody>
<tr>
<td>60°N</td>
<td>0.047</td>
<td>0.057</td>
<td>0.081</td>
<td>0.096</td>
<td>0.117</td>
<td>0.124</td>
<td>0.123</td>
<td>0.107</td>
<td>0.086</td>
<td>0.070</td>
<td>0.050</td>
<td>0.042</td>
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<tr>
<td>50°N</td>
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<td>0.063</td>
<td>0.082</td>
<td>0.092</td>
<td>0.107</td>
<td>0.109</td>
<td>0.110</td>
<td>0.100</td>
<td>0.085</td>
<td>0.075</td>
<td>0.061</td>
<td>0.056</td>
</tr>
<tr>
<td>40°N</td>
<td>0.067</td>
<td>0.066</td>
<td>0.082</td>
<td>0.089</td>
<td>0.099</td>
<td>0.100</td>
<td>0.101</td>
<td>0.094</td>
<td>0.083</td>
<td>0.077</td>
<td>0.067</td>
<td>0.075</td>
</tr>
<tr>
<td>20°N</td>
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<td>0.070</td>
<td>0.084</td>
<td>0.087</td>
<td>0.095</td>
<td>0.095</td>
<td>0.097</td>
<td>0.092</td>
<td>0.083</td>
<td>0.080</td>
<td>0.072</td>
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<td>0.082</td>
<td>0.085</td>
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<td>0.081</td>
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<td>20°S</td>
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<td>30°S</td>
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<tr>
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<td>0.074</td>
<td>0.080</td>
<td>0.092</td>
<td>0.097</td>
<td>0.105</td>
</tr>
</tbody>
</table>
Appendix 4: Bosque South Met Tower Monthly Fraction of Annual Hours of Daylight

Table 7. Bosque South Met Tower Blaney-Criddle d Through Interpolation [Dunne and Leopold, 1978]

Bosque South Met Tower Latitude = 33°48'15sec = 33.80°N

<table>
<thead>
<tr>
<th>Month</th>
<th>20°N Latitude</th>
<th>40°N Latitude</th>
<th>33.80°N Latitude</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.073</td>
<td>0.067</td>
<td>0.071</td>
</tr>
<tr>
<td>2</td>
<td>0.070</td>
<td>0.066</td>
<td>0.069</td>
</tr>
<tr>
<td>3</td>
<td>0.084</td>
<td>0.082</td>
<td>0.083</td>
</tr>
<tr>
<td>4</td>
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<td>0.088</td>
</tr>
<tr>
<td>5</td>
<td>0.095</td>
<td>0.099</td>
<td>0.096</td>
</tr>
<tr>
<td>6</td>
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<td>0.097</td>
<td>0.101</td>
<td>0.098</td>
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<tr>
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<td>0.094</td>
<td>0.093</td>
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<td>10</td>
<td>0.080</td>
<td>0.077</td>
<td>0.079</td>
</tr>
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</tr>
<tr>
<td>12</td>
<td>0.072</td>
<td>0.075</td>
<td>0.073</td>
</tr>
</tbody>
</table>

Figure 25. Blaney-Criddle ‘d’ for the South Met Tower through interpolation between 20°N and 40°N.
Appendix 5: List of Variables/Parameters

\[ A = \text{Total available energy (Rn - G) (W/m}^2) \]

\[ A_s = \text{Available energy at the soil surface (W/m}^2) \]

\[ c_p = \text{Specific heat of air (1.005 kJ/(kg - °C) for dry air)) MJ/(kg - °C)} \]

\[ C_{cs}, C_s = \text{Resistance combination equations} \]

\[ d_0 = \text{Displacement height (m)} \]

\[ D = \text{Vapor pressure deficit in the air at the reference height (kPa)} \]

\[ D = e_{sat} (1 - \frac{RH}{100}) \quad (kPa) \]  \hspace{1cm} (A-9)

\[ D_0 = \text{Vapor pressure deficit in the canopy (kPa)} \]

\[ D_0 = D \ + \frac{\Delta A - E_c (\Delta + \gamma) r_{aa}}{\rho \ c_p} \]  \hspace{1cm} (A-11)

\[ e_{sat} = \text{Saturated water vapor pressure at the air temperature (kPa)} \]

\[ e_{sat}(T) = 0.6108 \exp\left[\frac{17.27 \ T_{air}}{T_{air} + 237.3}\right] \quad (kPa) \]  \hspace{1cm} (A-3)

\[ E_c = \text{Evaporation from the closed canopy (W/m}^2) \]

\[ E_s = \text{Evaporation from the bare substrate (W/m}^2) \]

\[ E_t = \text{Total evaporation (W/m}^2) \]

\[ G = \text{Soil heat flux (W/m}^2) \]

\[ \text{LAI} = \text{Leaf Area Index} \]

\[ \text{LAI} = 24 \ \text{height of the canopy for clipped grass} \]  \hspace{1cm} (A-8)

\[ \text{LAI} = 5.5 + 1.5 \ln(\text{height of the canopy}) \quad \text{for alfalfa} \]

\[ P = \text{Atmospheric pressure (sea level 101.4 kPa)} \]

\[ P = 101.3 \left[\frac{293 - 0.0065z}{293}\right]^{5.256} \]  \hspace{1cm} (A-8)
\[ r_{sa} = \text{Aerodynamic resistance (s/m)} \]

\[ r_{sa} = \frac{\ln[(z-d_0)/z_{om}] \ln[(z-d_0)/z_{ov}]}{0.40^2 u} \] (A-8)

\[ r_{ss} = \text{Surface resistance of the land cover (s/m) (69 s/m for clipped grass 0.12 m high)} \]

\[ r_{ss} = \frac{200}{LAI} \] (A-8)

\[ R = \text{Ideal Gas constant, 287 J/(kg - K)} \]

\[ RH = \text{Relative Humidity (no units)} \]

\[ RH = \text{relative humidity} = 100 \frac{e}{e_{sat}} \% \] (A-8)

\[ Rn = \text{Net long and short wave radiation (W/m}^2) \]

\[ T_{air} = \text{Air temperature (°C)} \]

\[ T_{air\ absolute} = \text{Absolute air temperature (K)} \]

\[ u = \text{wind speed (m/s)} \]

\[ z_{om} = \text{Roughness height for momentum (m)} \]

\[ z_{ov} = \text{Roughness height for water vapor transport (m)} \]

\[ \alpha = \text{Priestley-Taylor coefficient, a constant often taken to be 1.26} \]

\[ \gamma = \text{Psychrometric constant (mbar/°C)} \]

\[ \gamma = \frac{c_p \ P}{0.622 \ \lambda} = 0.0016286 \frac{P}{\lambda} \text{ (kPa/°C)} \] (A-4)

\[ \Delta = \text{Slope of the saturated water vapor pressure curve versus temperature (kPa/°C)} \]

\[ \Delta = \text{slope of } e_{sat}(T) = \frac{4098 \ e_{sat}}{(T_{air} + 237.3)^2} \text{ (kPa/°C)} \] (A-2)
\[ \lambda = \text{Latent heat of vaporization (MJ/kg)} \]

\[ \lambda = 2.501 - 0.002361 T_{air} \quad (MJ/kg) \quad (A-5) \]

\[ \rho = \text{Air density (kg/m}^3) \]

\[ \rho = \frac{P}{R \ T_{air \ absolute}} \approx 3.486 \frac{P}{275+T_{air}} \quad (kg/m^3) \quad (A-10) \]

\[ \rho_w = \text{water density (1000.0 kg/m}^3) \]

2. Priestley-Taylor Model

\[ E_t = \alpha \ \frac{\Delta A}{\Delta + \gamma} \quad (A-1) \]

3. McNaughton-Black Model

\[ E_t = \frac{c_p \rho \ D}{\gamma \ r_{cs}} \quad (A-6) \]

4. Penman Model

\[ E_t = \frac{\Delta A}{\Delta + \gamma} + \frac{73.64 \ \rho_w \ \gamma \ (1 + 0.54u) \ D}{\Delta + \gamma} \quad (A-11) \]

5. Penman-Monteith Model

\[ E_s = \frac{\Delta A + \rho \ c_p \ D_{0}/r_{sa}}{\Delta + \gamma(1+r_{ss}/r_{sa})} \quad (A-11) \]