# REPORT ON METHODS OF CALCULATING POTENTIAL EVAPOTRANSPIRATION FOR THE CLIMATE INDICE TOOL

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# 1. Background

The Climate Indice Tool (CIT) was developed to compute various agroclimatic indices which could be used in the Land Suitability Rating System (LSRS) for Canada (Agronomic Interpretations Working Group, 1995). Available heat units and aridity or moisture are the primary factors considered for the rating system. Indices related to aridity or moisture deficit are calculated using precipitation (P) and potential evapotranspiration (PE) during the growing season. Thus PE is an important factor in the calculation of various indices in the CIT. This report focuses on a brief review of the concept of PE, reviews some of the literature and describes in detail various methods of calculating PE that will be made available in the CIT. Some of the advantages and disadvantages of each method are presented.

# 2. Literature review

## *2.1. Terminology*

Penman (1948) defined PE as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile". Thus PE is essentially a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming that water supply is not limiting. Unlike actual evapotranspiration (AE), PE is not directly related to soil and crop conditions, although both of these can influence the climatic conditions which determine it.

Baier and Robertson (1965) introduced the term "latent" evaporation (LE), which they defined as the amount of water being evaporated from a black porous disk atmometer. They developed a series of eight regression-type models which estimated daily latent evaporation from simple meteorological observations and astronomical data. The simplest of these models ($BR_1$) required only maximum and minimum air temperature and solar radiation at the top of the atmosphere ($R_a$) as estimator variables. The more complex equations could include up to three additional factors, namely incoming sky and solar energy at the surface (estimated from solar radiation at the top of the atmosphere, daylength and sunshine duration), wind speed and vapor pressure deficit. In general, models with most variables produced the best fit to the data. Baier (1971) later compared LE estimates to PE estimates using the Penman method and established a conversion factor of 0.0094 $cm/cm^3$. However, based on reviews from the literature they recommended a conversion factor of 0.0086 $cm/cm^3$ for irrigation scheduling and water budgeting, The Baier and Robertson $BR_1$ model with a conversion factor of 0.086 $mm/cm^3$ is presently used as the default method for calculating PE in the CIT as it requires minimal input variables and is the model that is used in the LSRS.

More recently, the concept of "reference evapotranspiration" (ETo) has been introduced to replace PE. The American Society of Civil Engineers (ASCE, 2005) defined ETo as *"the ET rate from a uniform surface of dense, actively growing vegetation having* *specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation"*. They recommended using an ETo for a short crop with an approximate height of 0.12 m (similar to clipped, cool-season grass) and a tall crop with an approximate height of 0.50 m (similar to full-cover alfalfa). Thus, unlike PE, ETo is dependent on the type of crop for which it is defined. . Measurements of ETo are relatively difficult, and thus it has become common to estimate ETo based the ASCE Standardized Reference Evapotranspiration Equation (ASCE, 2005) which uses a modified version of the Penman-Monteith model. This model requires air temperature, humidity, solar radiation at the surface and wind speed as input variables. Since these are generally not all available, this model is not incorporated into the CIT. Many studies reported in the literature use the ASCE equation as the standard against which to compare other models of estimating evapotranspiration, since measured values using lysimeters or other micrometeorological techniques are usually not available.

### *2.2. Some examples of applications of PE*

There are numerous examples in the literature of applications where PE is required. Estimates of PE are commonly used, for example, in soil moisture evaluations (Baier and Robertson, 1966), irrigation planning and scheduling (Boisvert et al., 1990), crop yield predictions (Akinremi and McGinn, 1996), decision support systems for agriculture (Jones et al., 2003), hydrologic models for simulating water sheds and ground-water flow (Lu et at., 2005; Soylu et al., 2011) and global scale water balance models (Vörösmarty et al., 1998).

Estimates of PE have been used in various applications of the Versatile Soil Moisture Budget (VSMB) (Baier and Robertson, 1996) or modifications of it. These include estimates of field workdays available in spring (Baier et al., 1978) and fall (Dyer and Baier, 1979), estimating seeding dates of the prairies (Bootsma and De Jong, 1988), characterizing long term soil moisture variability on the prairies (Sly and Coligado, 1974; Sly, 1982; De Jong and Bootsma, 1988; De Jong et al., 1992), estimating moisture conserved by summerfallowing (Bootsma et al., 1992) and estimating evaporation from prairie grassland (Hayashi et al, 2010). Early versions of the VSMB used the Baier-Robertson method of estimating PE, although other estimates of PE could be used as input into the program (Baier et al., 1979). Bootsma et al. (2004) examined the potential impact of climate change on various indices that included PE based on $BR_1$ for southern regions of Ontario and Quebec. The $BR_1$ model for estimating PE is used to determine the moisture factor (P-PE) for crop suitability ratings in the LSRS (Agronomic Interpretations Working Group, 1995). This model must presently be used in the LSRS as crop ratings were calibrated using this method. The $BR_1$ model is presently also used to calculate PE in the historical daily climate data archived by Agriculture and Agri-Food Canada, Eastern Cereal and Oilseed Research Centre, for stations all across Canada. More recently, some researchers modified the VSMB to include other methods for calculating PE such as Priestley-Taylor (Akinremi et al., 1996) and Penman-Monteith (Ojo, 2012), although these methods required more than the basic inputs of temperature and solar radiation at the top of the atmosphere.

### *2.3 Comparisons of models estimating PE or ETo*

There have been numerous investigations reported in the literature on relationships between various empirical or semi-empirical models and estimated ETo in many regions of the world. Studies have indicated that such models can often be reasonably applied when the use of the full equation based on the Penman-Monteith model for estimating ETo recommended by the ASCE (2005) cannot be used due to limited availability of input climatic variables. However, it is generally recommended that regional evaluation and/or calibration of empirical models be carried out prior to their use (Droogers and Allen, 2002; Xu and Singh, 2002; Martínez-Cob and Tejero-Juste, 2004; Xystrakis and Matzarakis, 2011) particularly if models are used under substantially different climate conditions than under which they were developed, or used in areas with high heat advection (Berengena and Gavilán, 2005). Without calibration, models can exhibit high degree of variability (Federer et al., 1996; Vörösmarty et al., 1998; Gavilán et al., 2006).

Hargreaves and Samani (1985) developed an empirical model based on temperature only (and $R_a$). Their model was developed using actual measurements of ETo using lysimeter data in California, whereas other models are often based on calibration with estimates from the ASCE Standardized Reference Evapotranspiration equation or similar method. Temesgen et al. (2005) found that the Hargreaves model performed well in most parts of California even without calibration. Wang et al. (2009) found that the Hargreaves temperature-based model overestimated ETo in the semiarid zone of Africa, and were able to construct a better temperature-based model using an artificial neural network. Some other studies that compare models of ETo with measured values rather than another model include Grace and Quick (1988), Kashyap and Panda (2001), Berengena and Gavilán (2005) and Yoder, et al. (2005).

There are also examples of studies that have compared the performance of various empirical models against reference evapotranspiration (ETo) or potential evapotranspiration (PE) in Canada. Grace and Quick (1988) compared estimates of PE from eight different models to Class A Pan evaporation in the Chinook-dominated semi-arid climate of southern Alberta. Estimates differed widely when accumulated over a 21-day period. Apparently heat advection under dry windy conditions experienced in southern Alberta was not properly accounted for in many of the PE models.

Maulé et al. (2006) compared estimates of ETo based the ASCE 2005 standardized reference model for a well-watered short crop surface to various available empirical models of PE and developed additional regression-based models of their own. Their study was based on data from the agricultural regions of the Canadian prairies. They concluded that the Baier-Robertson model was not accurate for estimating ETo for the prairie region and recommended using models they developed instead. This has led to some concerns about the validity of using the $BR_1$ model for estimating PE for the LSRS. However, their results indicate that the Coefficients of Determination ($r^2$ values) are not all that much different for the temperature-based models. The main problem seemed to be a constant bias such that the $BR_1$ model consistently underestimated ETo values. It's possible that such biases could be accounted for by adjusting the calibrations used for crop ratings in the LSRS .

Comparisons of PE estimates from various empirical models, including several developed by Maulé et al. (2006), with ASCE standardized reference ETo were undertaken by Armstrong (2011). Armstrong used ETo's for both a short and a tall reference crop and included data from other regions in Canada besides the prairies. He also compared estimates based on shorter growing periods than April to October, such as to first cut of alfalfa and to spring wheat maturity, although this was only done for three locations, namely Abbotsford, Saskatoon and Ottawa. Unlike Maulé, Armstrong found a reasonably good relationship between $BR_1$ and ETo for a short reference crop using data accumulated from April to October for 19 stations across Canada. In fact, when PE was accumulated over the whole season, the $BR_1$ model produced better estimates than several of the other models tested. The $BR_1$ model (as well as other models) consistently estimated values lower than the ETo for a tall reference crop when accumulated over the full season. Most of the models tended to estimate values higher than ETo for a short reference crop when values were accumulated over the shorter growth periods for alfalfa and spring wheat. However, model values for the shorter growth periods were often considerably lower than ETo for a tall reference crop, except under the cooler climate at Abbotsford, where the models tended to produce estimates quite a bit higher than ETo.

Ojo (2012) compared the Priestley-Taylor method on a daily basis with ETo values based on the FAO-56 equation (Allen, 1998) for seven site-years in Manitoba and found that the Priestley-Taylor equation tended to underestimate ETo overall. Ojo also found that the Hargreaves method (Hargreaves and Samani, 1985) of estimating solar radiation from daily temperature range and extraterrestrial radiation resulted in overestimates at low observed values and underestimates at higher values. It is interesting to note, however, that for the most part Ojo did not get significantly different soil moisture estimated from his version of the Versatile Soil Moisture Budget when using the FAO-56 equation in comparison to the Priestley-Taylor method to estimate ETo.

## 3. PE models for the Climate Indice Tool

The variations among models present some concerns and dilemmas when applying estimates of PE to the LSRS as the differences can affect the land suitability ratings. There may also be difficulties in selecting an appropriate reference crop when using the concept of 'reference evapotranspiration'. Armstrong (2011) noted that since most crops progress from short to tall over the growing season, neither short nor tall reference surfaces may be ideal. Many of the model comparisons in the literature involved using the standard reference model as an estimate of ETo rather than measured values, and this adds additional uncertainty. Different 'standard' reference models may be used which result in different ETo values (Wright et al., 2000; Lopez-Urrea et al., 2006; Gavilán et al., 2008; Bakhtiari et al., 2011). It is suggested that, rather than attempting to come up with improved models of PE for use in LSRS, it would be better to stay with the existing Baier-Robertson model and calibrate the P-PE deduction curves for the aridity factor for different regions of Canada and cropping systems as may be required.

Since there is no mechanism to define the crop type in the CIT, estimates of PE rather than ETo will continue to be the main variable available for determining aridity factors. The PE methods are limited to those which require only maximum and minimum air temperature and extraterrestrial solar radiation ($R_a$) or for which other required variables can be modeled from these inputs. The selection of the PE method will be up to the user. However, the default method is the Baier-Robertson model ($BR_1$) since it must presently be used for the LSRS.

Based on the literature reviewed, it is recommended that procedures for estimating PE using the five methods listed in Table 1 be available in the CIT. Some advantages and disadvantages are listed for each method, which are mostly based on the studies reported by Maulé et al. (2006) and by Armstrong (2011). Complete instructions on the calculation procedures for each method are provided in Appendix 1.

Table 1. Summary of empirical models available for calculating Potential Evapotranspiration in the Climate Indice Tool.

| Method | Reference | Variables needed | Advantages | Disadvantages |
|---|---|---|---|---|
| $BR_1$ | Bair and Robertson Formula I (Baier and Robertson, 1965; Baier, 1971) | Tmax; Tmin; $R_a$ | - minimal input variables needed.<br>- used in LSRS calibrations.<br>- good correlation and small bias with ETo for short crop over full season across Canada.<br>- developed using data from across Canada. | - underestimates ETo for tall crops,<br>- full season across Canada.<br>- relatively low coefficient of efficiency for prairie region, full season, short crop.<br>- variable results for shorter season.<br>- tested only at 3 locations for short seasons. |
| HG | Hargreaves and Samani temperature model (Hargreaves and Samani, 1985) | Tmax; Tmin; $R_a$ | - minimal input variables needed.<br>- model developed using lysimeter data.<br>- good correlation and small bias with ETo for short crop over full season across Canada.<br>- reasonably good coefficient of efficiency (*E*) with ETo for prairie region,<br>- full season, short crop. | - model developed from California data.<br>- lysimeter calibration data only for one specific crop (fescue grass).<br>- underestimates ETo for tall crops, full season across Canada.<br>- variable results for shorter season.<br>- tested only at 3 locations for short seasons. |
| $M_{HG}$ | Hargreaves and Samani temperature model modified by Maulé et al., 2006 | Tmax; Tmin; Ra | - minimal input variables needed.<br>- reasonably good *E* values with ETo for prairie region, full season, short crop. | - model developed using estimates of ETo as ‘observed’.<br>- developed using only prairie data.<br>- calibrated only for ‘short crop surface’.<br>- underestimates ETo for tall crops, full season across Canada.<br>- not tested for shorter seasons. |

Table 1 (cont'd). Summary of empirical models available for calculating Potential Evapotranspiration in the Climate Indice Tool.

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|---|---|---|---|---|
| $M_t$ | Temperature model by Maulé et al., 2006 | Tmax; Tmin; $R_a$ | - minimal input variables needed.<br>- good correlation with ETo for short crop over full season across Canada.<br>- reasonably good *E* values with ETo for prairie region, full season, short crop. | - model developed using estimates of ETo as 'observed'.<br>- developed using only prairie data. calibrated only for 'short crop surface'.<br>- overestimated ETo for short crop over full season across Canada.<br>- underestimates ETo for tall crops, full season across Canada.<br>- variable results for shorter season.<br>- tested only at 3 locations for short seasons. |
| $M_{tr}$ | Temperature and humidity model by Maulé et al., 2006 | Tmax; Tmin; $R_a$ | - minimal input variables needed.<br>- good correlation and small bias with ETo for short crop over full season across Canada.<br>- best correlation with ETo for tall crop over full season across Canada of the 5 models.<br>- highest *E* values with ETo of the 5 models for prairie region, full season, short crop.<br>- most consistent of the 5 models for shorter growth period of alfalfa and spring wheat. | - model developed using estimates of ETo as 'observed'.<br>- developed using only prairie data.<br>- dew point temperature estimated using model developed on only northern Great Plains data in USA.<br>- calibrated only for short crop surface.<br>- underestimates ETo for tall crops, full season across Canada.<br>- vapour pressure must be estimated. |

Tmax = daily maximum air temperature; Tmin = daily minimum air temperature; $R_a$ = Incoming global solar radiation at the top of the atmosphere. The coefficient of efficiency, *E*, is defined as $E = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}$ where *O* and *P* are observed and predicted values, respectively. Larger values of *E* indicate better agreement between observed and predicted values (Maulé et al., 2006).

## 4. Conclusions

Based in studies reported in the literature, it is apparent that estimates of PE can vary considerably from one method to another. These variations are not always consistent from one climatic region to another. Nevertheless, it is difficult at this stage to recommend models of PE for the LSRS that require only temperature and $R_a$ that would be a significant improvement overall to the Baier-Robertson method. The temperature-relative humidity model proposed by Maulé et al. (2006) probably performs the best of all the models for the prairie region of Canada, but does not seem to offer significant improvement over the Baier-Robertson model ($BR_1$) on a Canada-wide basis when PE values are accumulated over the entire season.

Models tend to perform more erratically when accumulations are for shorter growing periods such as to the first cut of alfalfa or to maturity of spring wheat, and if such periods are to be used for land suitability ratings, then further investigations into model performances and their impacts on the ratings may be needed.

Overall, it is suggested that variations in model performances can be best accommodated within the LSRS system at this stage by adjustments in the P-PE deduction curves when required for different climatic zones and/or different cropping systems. At present, only calibrations based on the $BR_1$ model are available for use in the LSRS.

The inclusion of alternate methods of calculating PE in the Climate Indice Tool does not mean that one is recommended over another. Users should be aware of the limitations and advantages that each method may offer. Further investigations into the impact that these models have on the various indices computed by the CIT would be of value once they are incorporated into the software.

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**Appendix 1.** Methods of calculating Potential Evapotranspiration (PE).

**1. BR1: Baier and Robertson Method (Equation I)** (Baier and Robertson, 1965; Baier, 1971).

(This method must be used when deriving LSRS crop ratings, since the P-PE deduction curves contained within the LSRS calculator have been calibrated for "Baier Robertson P-PE" values.)

$PE_{BR1} = 0.086 * (0.928 * Tmaxf + 0.933 * Trangef + 0.0486 * RStop - 87.03);$
if $PE_{BR1}$ #0 then $PE_{BR1} = 0.0;$

where Tmaxf = Tmax * 9 / 5 + 32
Tminf = Tmin * 9 / 5 + 32
Trangef = Tmaxf – Tminf
RStop = 23.89* $R_a$

Tmax and Tmin are the mean daily maximum and minimum temperatures in EC; Tmaxf and Tminf are the mean daily maximum and minimum temperatures in EF.
$R_a$ is the extra terrestrial radiation in $MJ/m^2$/day.
RStop is extra terrestrial radiation in $cal/cm^2$/day.
(1 $cal/cm^2$/day = 0.041868 $MJ/m^2$/day; 1 $MJ/m^2$/day = 23.89 $cal/cm^2$/day)

**2. HG: Hargreaves and Samani** (Hargreaves and Samani, 1985; Hargreaves et al., 1985)

$PE_{HG} = 0.0023 * (Tmax - Tmin)$^0.5 * (Tmean + 17.8) * ($R_a$ / Lv)
If ($PE_{HG} < 0.0$), then $PE_{HG} = 0$
Tmean = mean air temperature (°C)
Tmax = maximum air temperature (°C)
Tmin = minimum air temperature (°C)
$R_a$ = extra terrestrial radiation ($MJ/m^2$/day)
(1 $cal/cm^2$/day = 0.041868 $MJ/m^2$/day; 1 $MJ/m^2$/day = 23.89 $cal/cm^2$/day)
Lv = latent heat of vaporization (MJ/kg)
= 2.45 MJ/kg (Allen et al., 1998**)**

**3. $M_{HG}$: Modified Hargreaves temperature model by** Maulé et al., 2006

$PE_{MH} = 0.002 * ((Tmax - Tmin)$^0.5) * (Tmean + 24.4) * ($R_a$ / Lv)
if $PE_{MH}$ #0 then $PE_{MH} = 0.0;$

Tmean = mean air temperature (°C)
Tmax = maximum air temperature (°C)
Tmin = minimum air temperature (°C)
$R_a$ = extra terrestrial radiation ($MJ/m^2$/day)
(1 $cal/cm^2$/day = 0.041868 $MJ/m^2$/day; 1 $MJ/m^2$/day = 23.89 $cal/cm^2$/day)
Lv = latent heat of vaporization (MJ/kg)
= 2.45 MJ/kg (Allen et al., 1998**)**

## 4. $M_t$ : Temperature model by Maulé et al., 2006

$PE_t$ = 0.0109 * Tmean + 0.134 * (Tmax - Tmin) + 0.708 * Δ * $R_a$ - 0.669
If ($PE_t$ < 0.0), then $PE_t$ = 0

Tmean = mean air temperature (°C)
Tmax = maximum air temperature (°C)
Tmin = minimum air temperature (°C)
Δ = slope of the saturation temperature pressure curve (kPa/°C)

$$= \frac{2503 \exp\left[\dfrac{17.27T}{T+237.3}\right]}{(T+237.3)^2}$$ where $T$ = Tmean (Allen et al. 1998)

$R_a$ = extra terrestrial radiation (MJ/$m^2$/day)
(1 cal/$cm^2$/day = 0.041868 MJ/$m^2$/day; 1 MJ/$m^2$/day = 23.89 cal/$cm^2$/day)

## 5. $M_{tr}$ : Temperature and humidity model by Maulé et al., 2006

$PE_{tr}$ = 0.131 * Tmean + 0.0515 * (Tmax - Tmin) - 3.18 * $e_a$ + 0.846 * Δ * $R_a$ + 1.28
If ($PE_{tr}$ < 0.0), then $PE_{tr}$ = 0

Tmean = mean air temperature (°C)
Tmax = maximum air temperature (°C)
Tmin = minimum air temperature (°C)
$e_a$ = actual vapour pressure (kPa)
Δ = slope of the saturation temperature pressure curve (kPa/°C)

$$= \frac{2503 \exp\left[\dfrac{17.27T}{T+237.3}\right]}{(T+237.3)^2}$$ where $T$ = Tmean (Allen et al. 1998)

$R_a$ = extra terrestrial radiation (MJ/$m^2$/day)
(1 cal/$cm^2$/day = 0.041868 MJ/$m^2$/day; 1 MJ/$m^2$/day = 23.89 cal/$cm^2$/day)

Actual vapour pressure ($e_a$) can be estimated from dew point temperature ($T_{dew}$) as follows:

$$e_a = e^{\circ}(T_{dew}) = 0.6108 \exp\left[\frac{17.27\,T_{dew}}{T_{dew}+237.3}\right]$$

where $e^o$ is the saturation vapour pressure at the dewpoint temperature ($T_{dew}$) [°C] (Allen et al., 1998)
Dew point temperature can be estimated from air temperature (Hubbard et al., 2003) as follows:
$T_{dew}$ = -0.036 * Tmean + 0.9679 * Tmin + 0.0072 * (Tmax – Tmin) + 1.0119
where $T_{dew}$ = dew point temperature (°C)