Estimating Evaporation : Principles, Assumptions and Myths

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Evaporation… So what is it anyways?

Evaporation is the phenomenon by which a substance is converted from the liquid or solid phase into vapour.

In the case of solids, this is referred to as sublimation.

The vaporization of water through the stomata of living plants is called transpiration.

If you can’t see it… how important can it be?

An examination of the earth’s water budget indicates that annual evaporation from land surfaces is approximately 65% of the annual precipitation. (Brutsaert, 1982)

For whom is it important ?

Evaporation is a component of the Water Balance; hence it is of interest to Hydrologists.

Evaporation (latent heat) is a component of the Energy Balance; hence it is of interest to Meteorologists.

So where do we start?

For evaporation to occur these three conditions must be satisfied:

- a supply of water at the surface,
- a supply of energy to satisfy the requirement for the phase change, and
- a transport mechanism to carry the vapour away from the surface.

All methods for estimating evaporation are based on the observation or manifestation of one or more of these conditions:

- the supply of water at the surface,
- the supply of energy,
- the transport mechanism .

Some factors that may affect the supply of water at the surface:

- the soil’s capacity for infiltration and storage near the surface;
- subsurface discharge;
- the vegetative cover;
- the type and stage of vegetation.

Some factors that may affect the supply of energy:

- - the time of day, season;
- - latitude, slope and aspect;
- - cloud cover, type of cloud cover
- - the vegetative cover;
- - the type and stage of vegetation;
- - the presence and depth of open water.

Some factors that may affect the transport mechanism:

- the vegetative cover;
- atmospheric stability;
- the time step (hourly, daily);
- the slope of the surface relative to wind direction.

Estimating Evapotranpiration – Balance methods

“What if we measured absolutely everything… except what we’re really interested in?”

Mass Balance method

a) soil water depletion and seepage

for a surface: $E = P - R - I$

for a soil layer: $E = P - R - dS - q_d$

where P is precipitation, R is runoff, I is the infiltration, dS is the change in soil moisture and q_d is downward seepage

Mass Balance method

b) Hydrologic Catchments

for an extensive area:

$$E = P + [(R_i+G_i) – (R_o+G_o) - dS]/A$$

where ***P*** is precipitation, ***R*** is surface flow, ***G*** is groundwater flow, ***dS*** is the change in storage and ***A*** is the catchment's area. The subscript ***i*** refers to inflow and ***o*** to outflow.

Energy Balance method

a) for a bare soil surface:

$$LE = Rn - Qg - H$$

where ***Rn*** is the net allwave radiation, ***Qg*** is heat flow by conduction into the soil, ***H*** is the turbulent heat exchange to the atmosphere and ***L*** is the latent heat of vaporization.

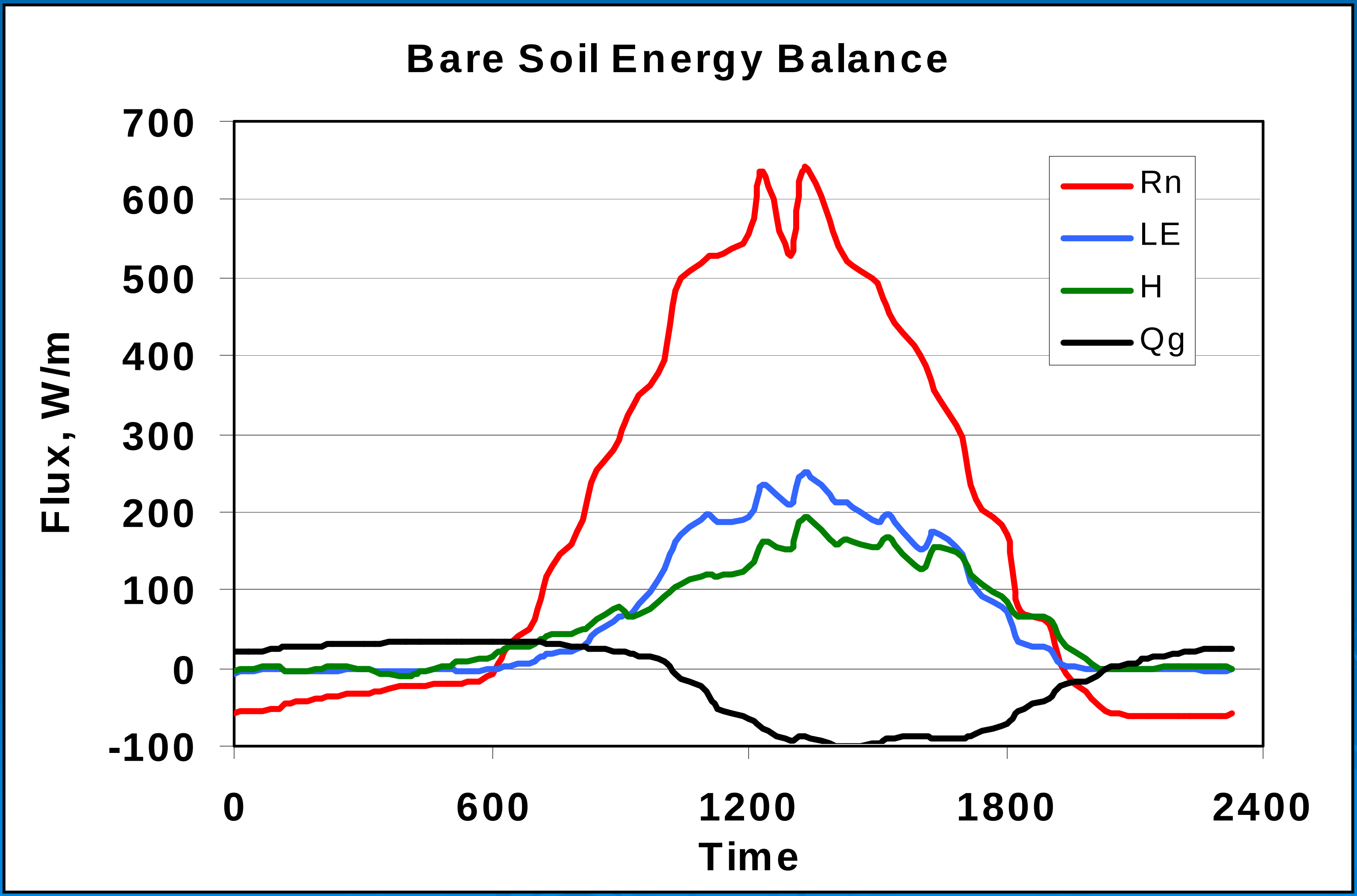
Energy Balance method

b) for a surface with a vegetative cover:

$$LE = Rn - dQs - Qg - H$$

where ***dQs*** is the rate of change of energy stored in the vegetation. Other terms are as before.

Energy Balance



Indirect Energy Balance

c) Bowen Ratio:

$$B = \frac{H}{LE} = \frac{C_p (T_1 - T_2)}{L(q_1 - q_2)}$$

where ***Cp*** the specific heat of air, ***T*** is air temperature and ***q*** is the specific humidity of the air. The subscripts refer to measurements at different heights.

From the energy balance:

$$E = \frac{Rn - Qg}{L(1 + B)}$$

Bowen Ratio:

$$E = \frac{Rn - Qg}{L(1 + B)}$$

Advantages: no need for wind speed measurement.

Disadvantage: does require accurate measure of temperature and humidity at 2 heights.

Estimating Evapotranpiration Profile method

“Why do we need so many sensors on this tower anyways?”

Profile method

The vapour flux can be related to the vertical humidity gradient:

$$E = -rK_e \frac{\partial q}{\partial z}$$

where: ***ρ*** is air density
q is the specific humidity
z is the height, and
Ke is the eddy diffusivity for water vapour.

Profile method

The eddy diffusivity for water (*Ke*) can be related to that for momentum (*Km*):

$$K_m = k^2 z^2 \frac{\partial u}{\partial z}$$

where **k** is the von Karman constant = 0.4 **u** is the wind speed, and **z** is the measurement height.

Profile method

The vapour flux is then given by:

$$E = -r\,b\,k^2 z^2 \frac{\partial u}{\partial z}\frac{\partial q}{\partial z}$$

$$E = -r\,b\,k^2 \frac{(u_b - u_a)(q_b - q_a)}{\ln^2(b/a)}$$

where ***β*** is the ratio of eddy diffusivities ***Ke/Km***
a and ***b*** are the measurement heights.

Profile method

The ratio of eddy diffusivities, β, is affected by the stability of the atmospheric boundary layer:

β = 1 for neutral conditions,
β increases with increasing instability
(temperature decreasing with height),
β decreases with increasing stability.
(temperature increasing with height),

Profile method

Advantages:

No need for energy and water availability considerations.

Disadvantages:

Requires two or more levels of wind speed and humidity measurements;

Stability corrections require an estimate of the sensible heat flux.

Estimating Evapotranpiration

Evaporation models

“Beware the magician!”

Evaporation models

Most evaporation models are based on the Penman (1948) method.

This is essentially a combination of the energy balance and aerodynamic (profile) methods for the special case of a saturated surface.

Penman, working with daily time steps, used a Dalton form of the aerodynamic expression, giving evaporation as:

$$E = f(u)\left(e_s - e_a\right)$$

where:

e_s is the vapour pressure at the evaporating surface,

e_a is the vapour pressure in the atmosphere above, and

f(u) is a linear function of the horizontal wind velocity

$f(u) = a + bU$

Penman introduced the Drying Power of the air.

The "Drying Power", $E_{a,}$ is obtained by putting e_a* , the saturated vapour pressure at air temperature, instead of e_s :

$$E_a = f(u)\left(e_a^{\,*} - e_a\right)$$

By combining the energy balance and aerodynamic approaches, Penman developed the following general evaporation equation for saturated surfaces:

$$E_p = \frac{\Delta Q_a + gE_a}{\Delta + g}$$

where:

Qa is the available energy = Rn-Qg;

Ea is the drying power of the air;

γ is the psychrometric constant;

Δ is the slope of the saturated VP vs Temperature curve

Assumptions inherent to Penman's development:

$$E_p = \frac{\Delta Q_a + gE_a}{\Delta + g}$$

- Net available energy ***(Q$_a$)*** is <u>positive</u> (daily average);

- Partitioning of energy occurs <u>at the surface</u>;

- <u>Steady state</u> conditions are present (fluctuations masked by daily time step);

- The transfer coefficient is a function of wind speed only.

Data Requirements for applying the Penman Equation:

$$E_p = \frac{\Delta Q_a + gE_a}{\Delta + g}$$

Net radiation ***(Rn)*** can be either measured or calculated;

Soil heat flux ***(Qg)*** can be measured, calculated as a fraction of Rn, or (all too often) ignored;

Wind speed at a height of 2m;

Temperature and humidity at a height of 1.5m.

“It only needs measurements from one height!”

Limitations of the Penman Equation:

$$E_p = \frac{\Delta Q_a + g E_a}{\Delta + g}$$

Applicable to situations with positive energy input. Does not apply to nighttime or winter situations (condensation).

Adjustments required when applied to time steps shorter than daily.

Applies only to wet surfaces, but not to open water surfaces.

Myths associated with the Penman Equation:

$$E_p = \frac{\Delta Q_a + gE_a}{\Delta + g}$$

\# Penman = Potential **X**

\# There is a direct relationship between actual evaporation and the Penman evaporation **X**

(Qa – direct; Ea – generally inverse)

\# If it applies to wet surfaces; it therefore applies to open water **X**

Evaporation models:

Extending the Penman equation to the non-saturated case

“Fitting a square peg into a round hole.”

Penman expected a direct relationship between his reference evaporation

$$E_p = \frac{\Delta Q_a + gE_a}{\Delta + g}$$

and the actual evaporation from a non-saturated land surface.

E = c* Ep ??

Unsuccessful because, for non-saturated surfaces, ***E*** responds directly to ***Qa***, and inversely to ***Ea***.

The concept of Potential Evaporation (PE) or Potential Evapotranspiration (PET).

Webster! Where were you when we needed you?

Potential Evaporation

This is generally a reference evaporation which we hope can be related to the actual evaporation through some defined relationship.

But…

There are so many different definitions and calculation schemes for “Potential Evaporation”, and these are all too often used indiscriminately and interchangeably, so as to render the concept dangerous!

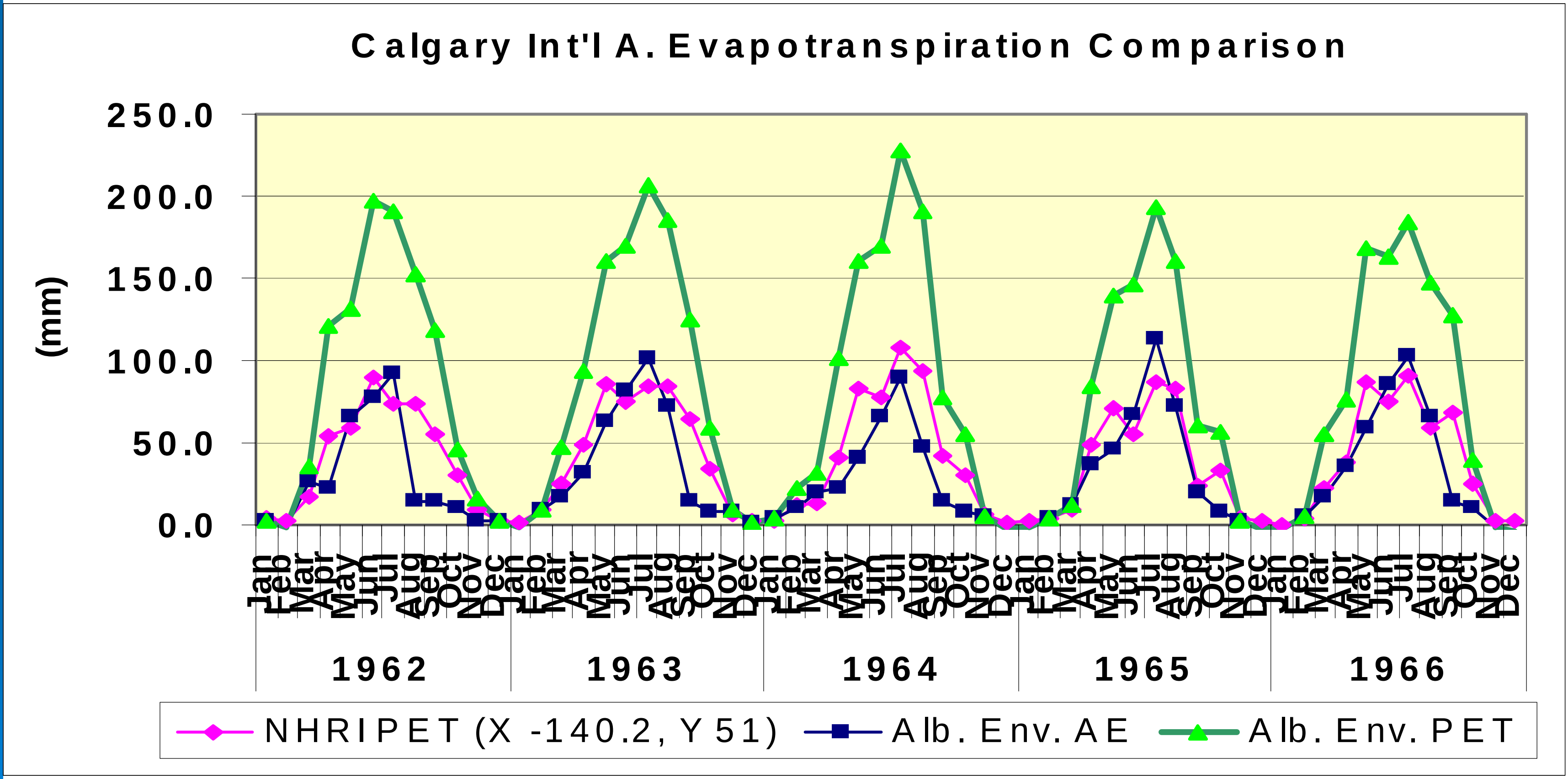
Potential Evaporation

Hargreaves PET

Used within a distributed streamflow model that requires only temperature and precipitation as inputs. Hargreaves uses a definition of PET consistent with the Penman approach... But the calculation scheme is inconsistent with the definition.

CRAE PET as used by Alberta Environment
Employs a Penman formulation with climatological inputs of monthly dew point temperature, air temperature and monthly sunshine as a percentage of possible sunshine. This is also based on the Penman approach.

Comparison of PET schemes



Evaporation models:

Extending the Penman equation to the non-saturated case

Introducing the concept of resistance.

Monteith (1965) characterized evaporation using an aerodynamic resistance, r_a:

$$E = r\left(q_s - q_a\right)/r_a$$

where, q_s is the specific humidity at the surface, q_a that in air. r_a is an aerodynamic resistance.

He defined a "surface resistance", r_s, as that giving the evaporation across a gradient defined by the saturated specific humidity, q_s^*, at the surface:

$$E = r\left(q_s^* - q_s\right)/r_s$$

Converting specific heat to vapour pressure, and combining with the Penman equation yields the **Penman-Monteith equation:**

$$E = \frac{\Delta Q_a + r c_p \left(e_a^* - e_a\right) / r_a}{\Delta + g\left(1 + r_s / r_a\right)}$$

Introducing the surface resistance term extends the Penman equation to the non-saturated case.

Penman-Monteith equation:

$$E = \frac{\Delta Q_a + r c_p \left(e_a^* - e_a\right) / r_a}{\Delta + g\left(1 + r_s / r_a\right)}$$

Advantages:

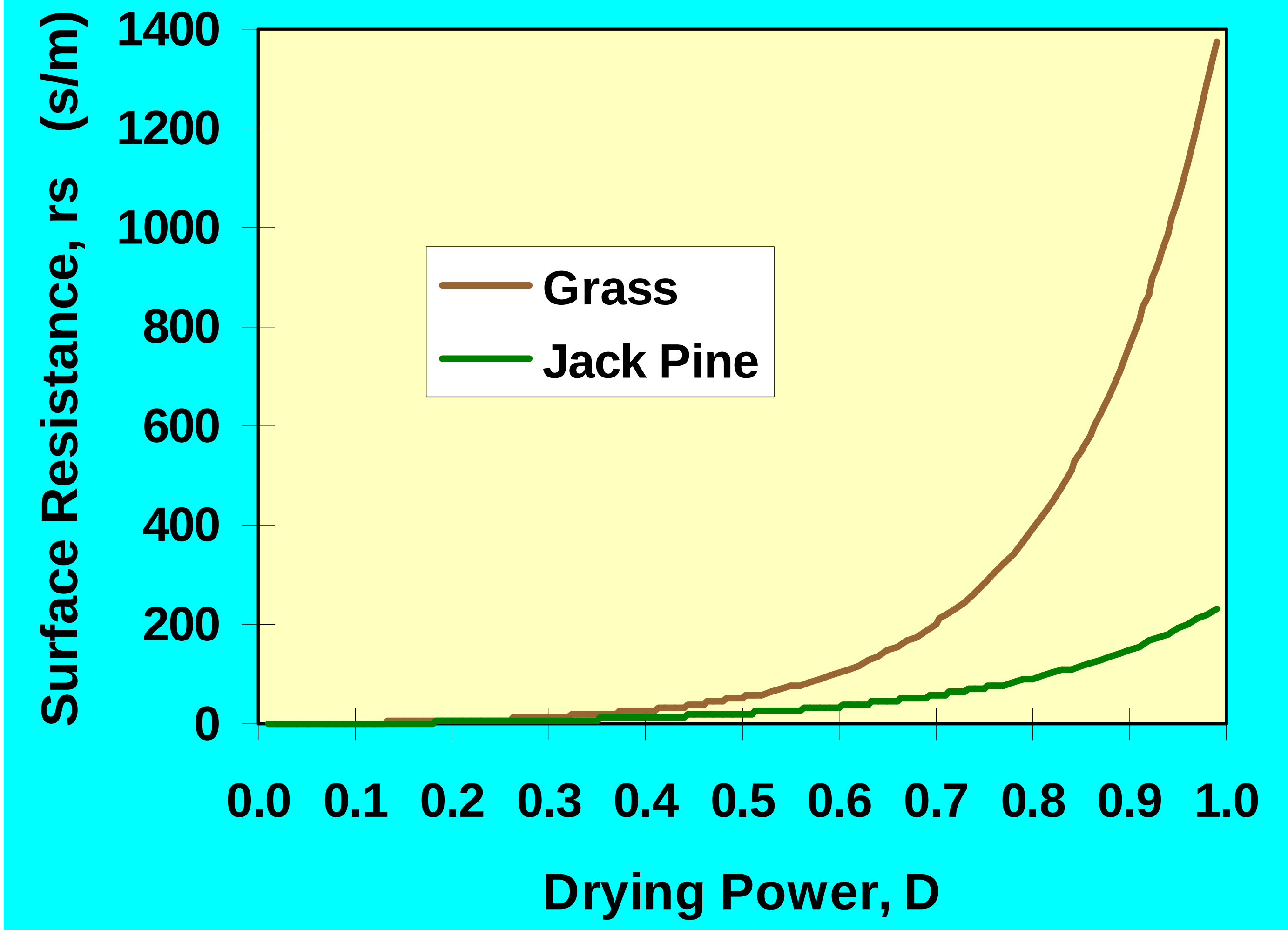
Requires basically the same input parameters as does the Penman equation, plus an estimate of surface resistance.

Disadvantages:

Resistance term is difficult to estimate; it varies with vegetation type and condition, with ambient conditions, and with soil moisture availability.

Does not apply to condensation.

Surface Resistance



Evaporation models:

Extending the Penman equation to the non-saturated case

Introducing the concept of a Complementary Relationship.

Bouchet (1963)

Postulated that as a wet surface dries, the decrease in E was matched by an equivalent increase the the potential Ep:

$$dE = -dE_p$$

If Epw is the condition when E = Ep, then

$$E = E_{pw} - dE$$

$$E_p = E_{pw} + dE$$

$$and$$

$$E + E_p = 2E_{pw}$$

Morton (1983) developed a Complementary Relationship Areal Evapotranspiration model (CRAE) using this concept.

Morton uses a precisely-worded set of definitions, with a calculation scheme corresponding to the definition, such that the model does work.

Evaporation models:

Extending the Penman equation to the non-saturated case

Introducing the concept of a dimensionless Relative Evaporation.

Granger - Gray

Using a consistent set of definitions, showed that the Penman and Bouchet approaches are not contradictory.

By introducing the concept of a dimensionless Relative Evaporation, they showed that the Penman and Bouchet approaches both result in the same general equation for non-saturated surfaces.

Relative Evaporation, G

is defined as the ratio of actual evaporation to that which would occur if the surface were saturated at the same temperature. This is then expressed as:

$$G = \frac{f(u)(e_s - e_a)}{f(u)(e_s^* - e_a)}$$

where e_a is the vapour pressure in the air
e_s is the actual vapour pressure at the surface,
e_s^* is the saturated vapour pressure at the surface temperature.

Granger-Gray General Equation

$$E = \frac{\Delta G Q_a + g G E_a}{\Delta G + g}$$

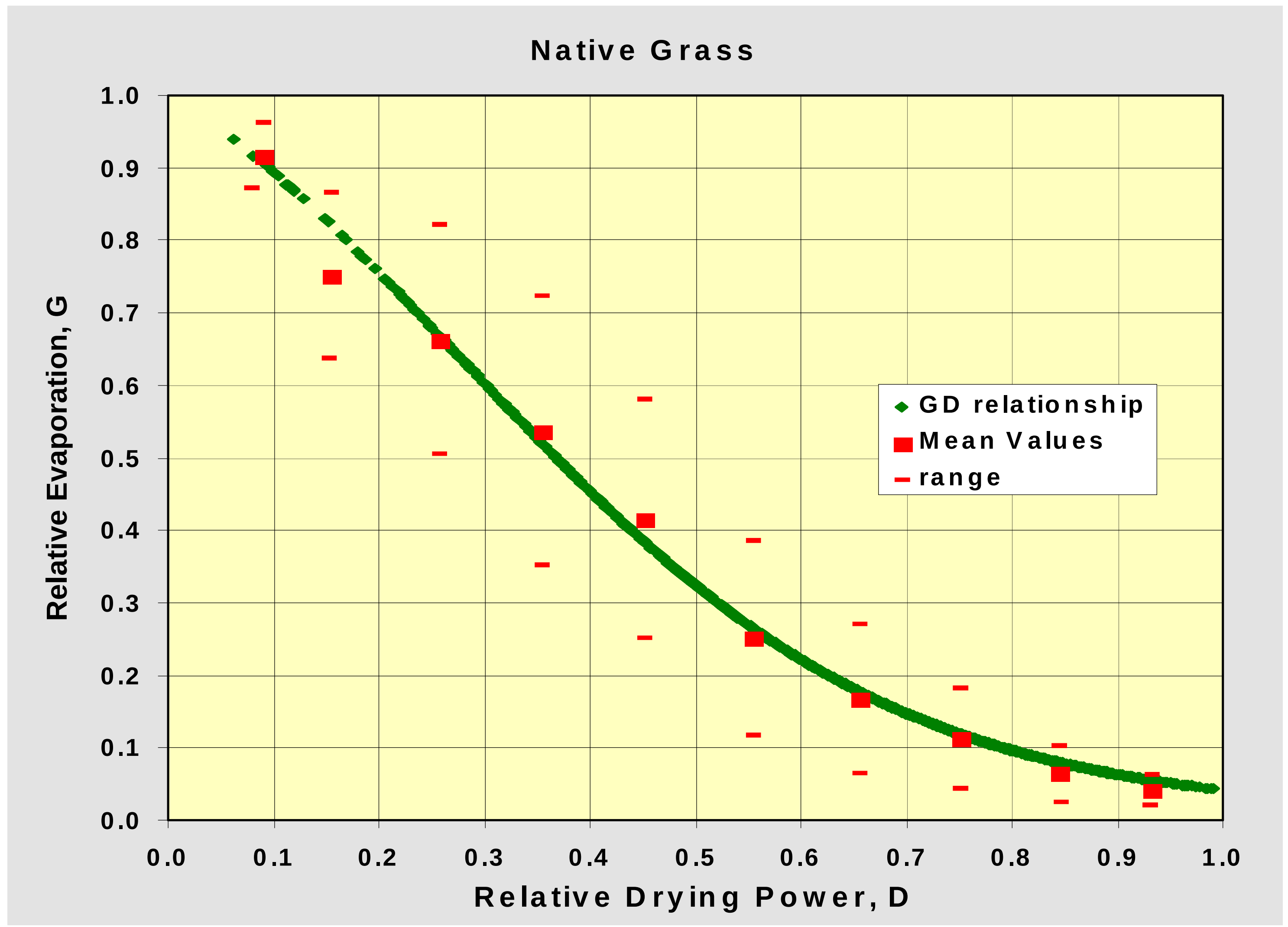
G = relative evaporation (dimensionless)

G is related to the Relative Drying power, D;

D = $E_a/(E_a + Q_a)$ (dimensionless)

$$\boxed{G = 1/\left(0.793 + 0.2\exp(4.902D)\right) + 0.006D}$$

The G-D Relationship



Granger - Gray

Advantages:

Same inputs as for Penman.

G-D relationship is universal.

No need to estimate resistance terms.

Disadvantages:

Same as for Penman: better for daily time steps; not applicable to condensation.

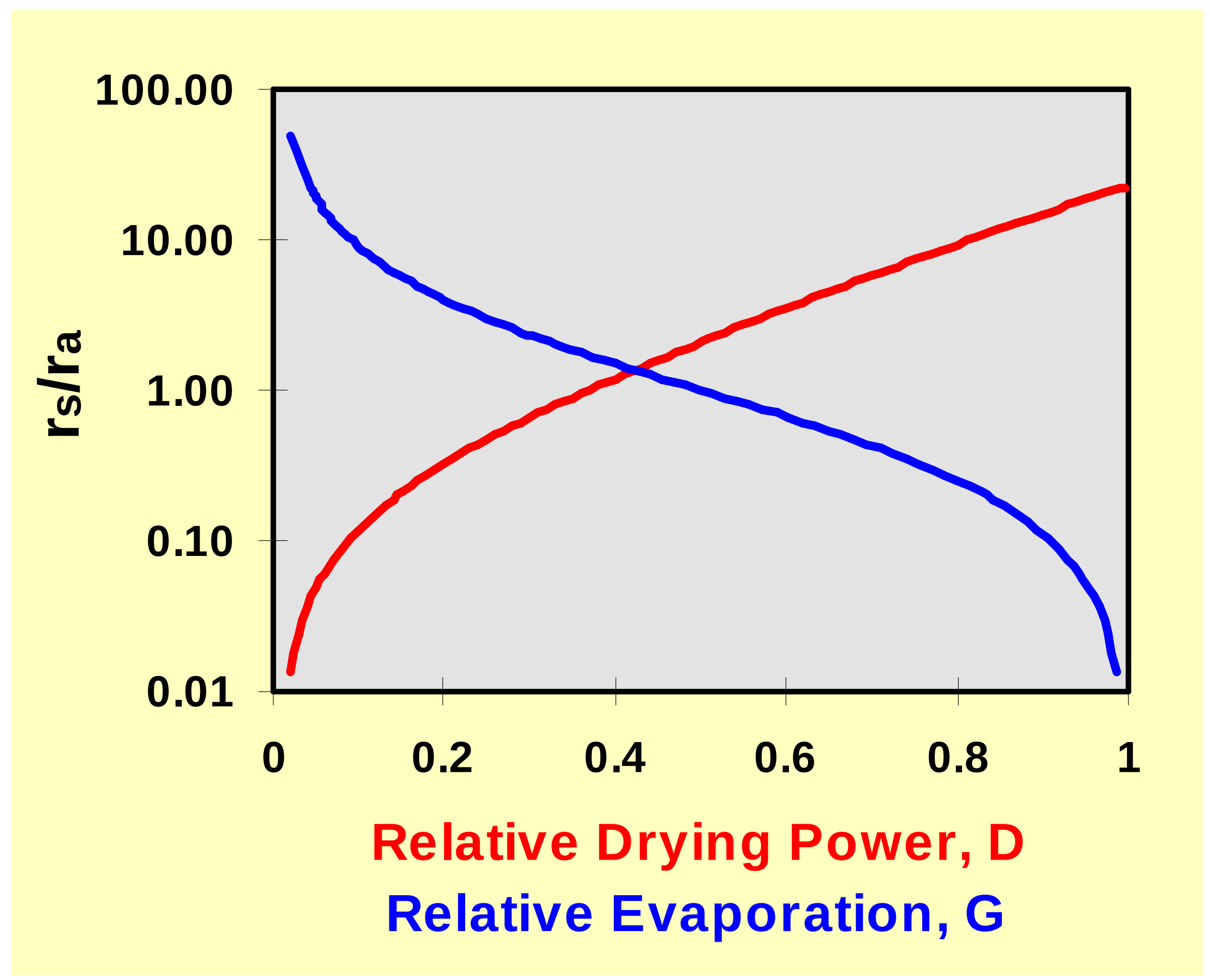
Relationship between G and r_s/r_a

Combining the Penman-Monteith and the Granger-Gray equations yields:

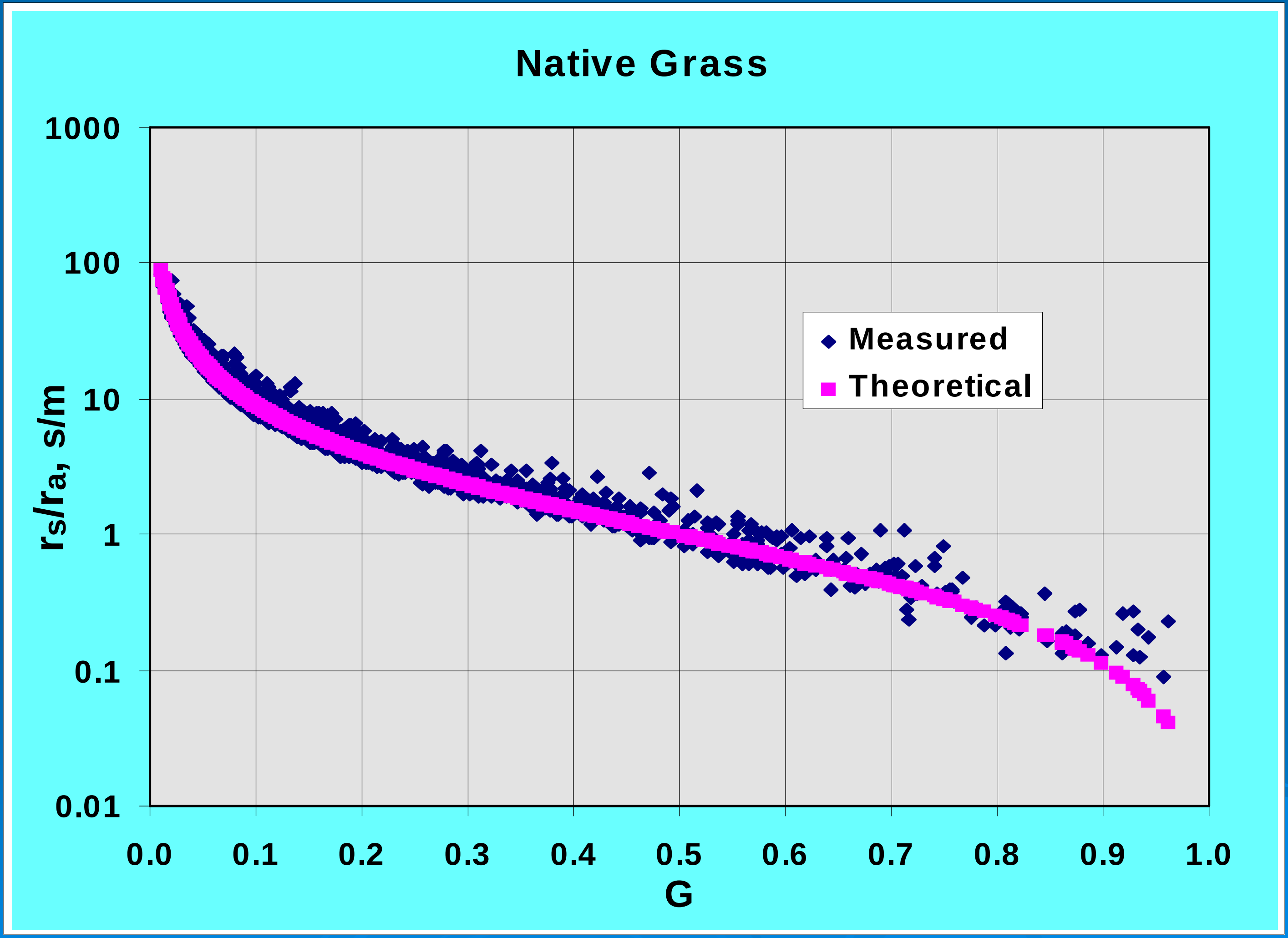
$$\boxed{G = \frac{r_a}{r_s + r_a}}$$

$$\boxed{\frac{r_s}{r_a} = \frac{[1 - G]}{G}}$$

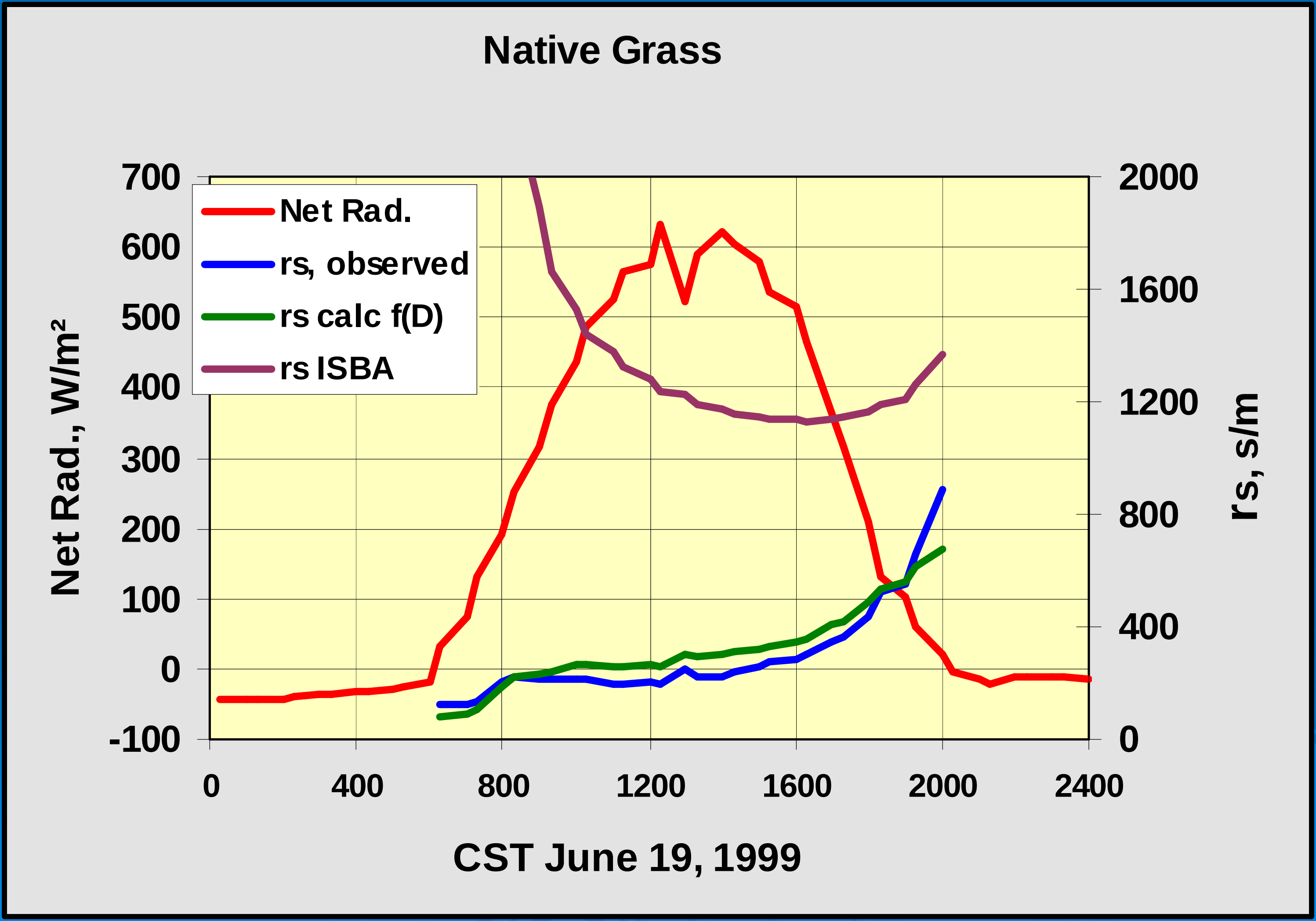
Relationship between G and r_s/r_a



Relationship between r_s/r_a and G



Estimating surface resistance, r_s, using The G-D relationship



Estimating Lake Evaporation

“It’s saturated, right?.. Gotta be easy!”

Estimating Lake Evaporation: Mass balance

$$E = P + I - dS - O - Og$$

where P = precipitation,
I = surface Inflow
dS = change in storage
O = surface outflow, and
Og = seepage to groundwater

Estimating Lake Evaporation: Empirical Methods

Meyer formula (used by Sask.)

$$E = K\,f(u)\,(e_o - e_a)$$

where K = calibration coefficient,
f(u) = function of wind, generally linear $(a + bU_2)$
e_a = vapour pressure in the air
e_o = vapour pressure at water temperature

Estimating Lake Evaporation:

Empirical Methods

Meyer formula (used by Sask.)

Advantage:
simple, requires only wind speed, humidity of the air, and water temperature.

Disadvantage:
water temperature not often measured;
assumes that humidity over land is representative of humidity over the lake.

Estimating Lake Evaporation: Models

Priestley-Taylor method

$$E = a \, \frac{\Delta R_n}{\Delta + g}$$

this is the Penman Eq. with the assumption that over water, the vapour pressure deficit will tend to zero. α is the Priesltey Taylor coefficient.

Estimating Lake Evaporation:

Models

Priestley-Taylor method

Advantage:
Simple. Requires only net radiation.

Disadvantage:
Does not work because Penman’s original assumptions on the energy balance do not apply to open water.

Estimating Lake Evaporation: Models

Complementary Relationship Lake Evap. (CRLE) (used by Alta.)

Based on the CRAE with the assumption that lake evaporation is wet environment evaporation, with some modifications to the energy balance for water.

Estimating Lake Evaporation: Models

CRLE

Advantage:

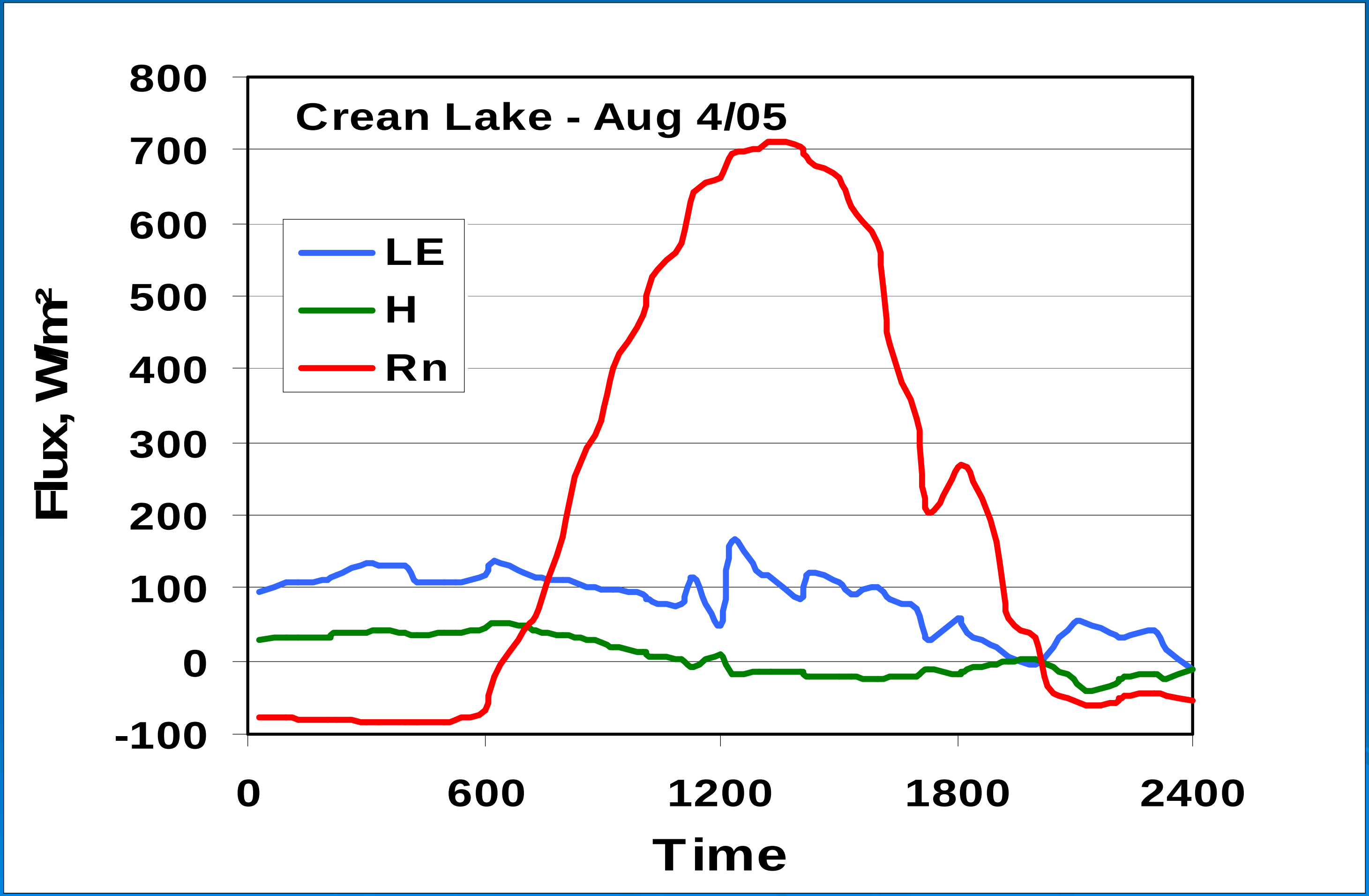
Works reasonably well for monthly time steps.

Disadvantage:

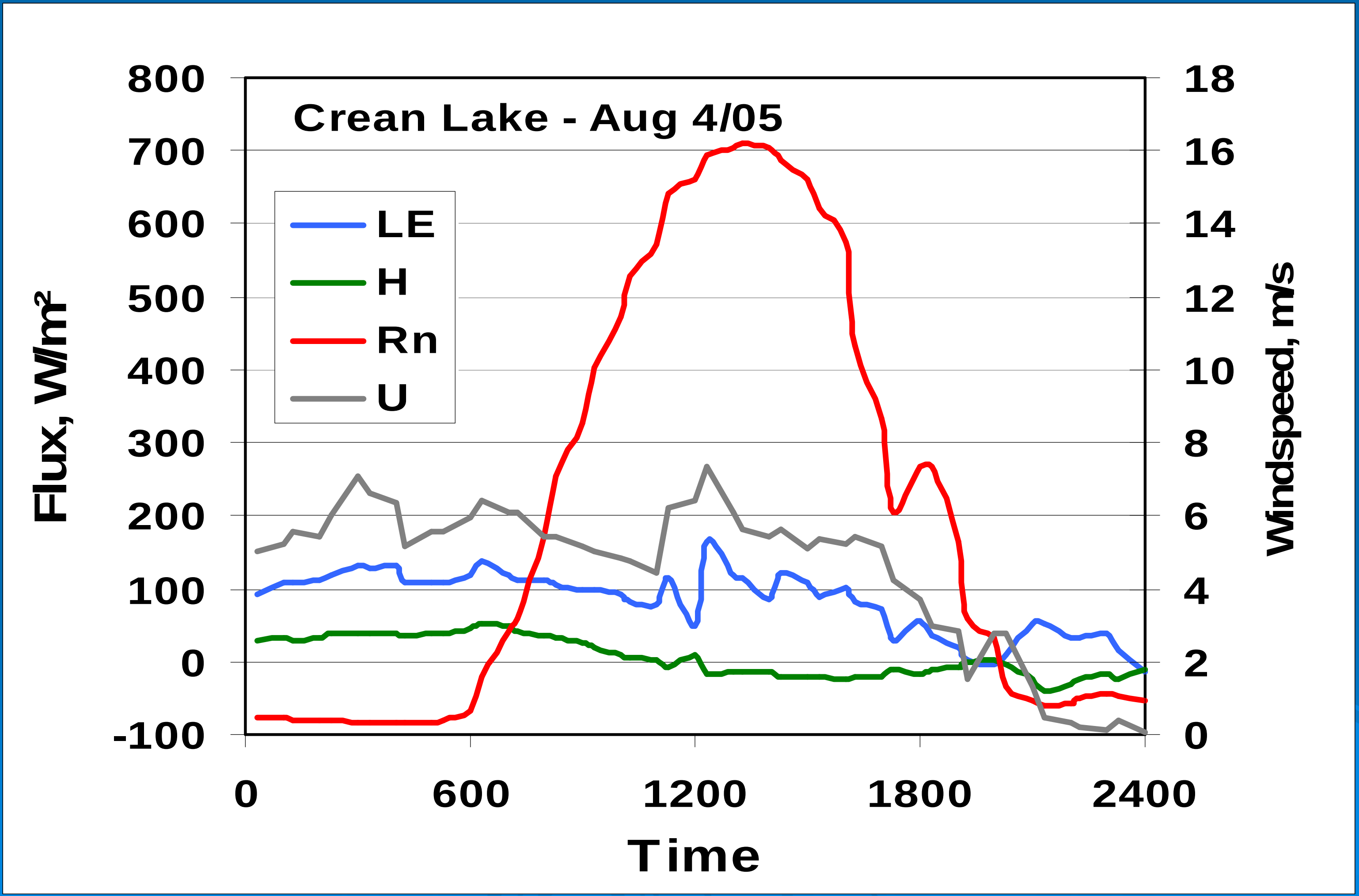
Relatively difficult to apply.

The energy balance modifications are still insufficient to correctly represent that for open water.

Lake Evaporation: Observations



Lake Evaporation: Observations



Estimating Lake Evaporation

Will require a knowledge of the water surface temperature, combined with a boundary layer model capable of representing the advection of energy.

Estimating Evaporation

pitfalls, traps and misconceptions

“There’s a real world out there!”

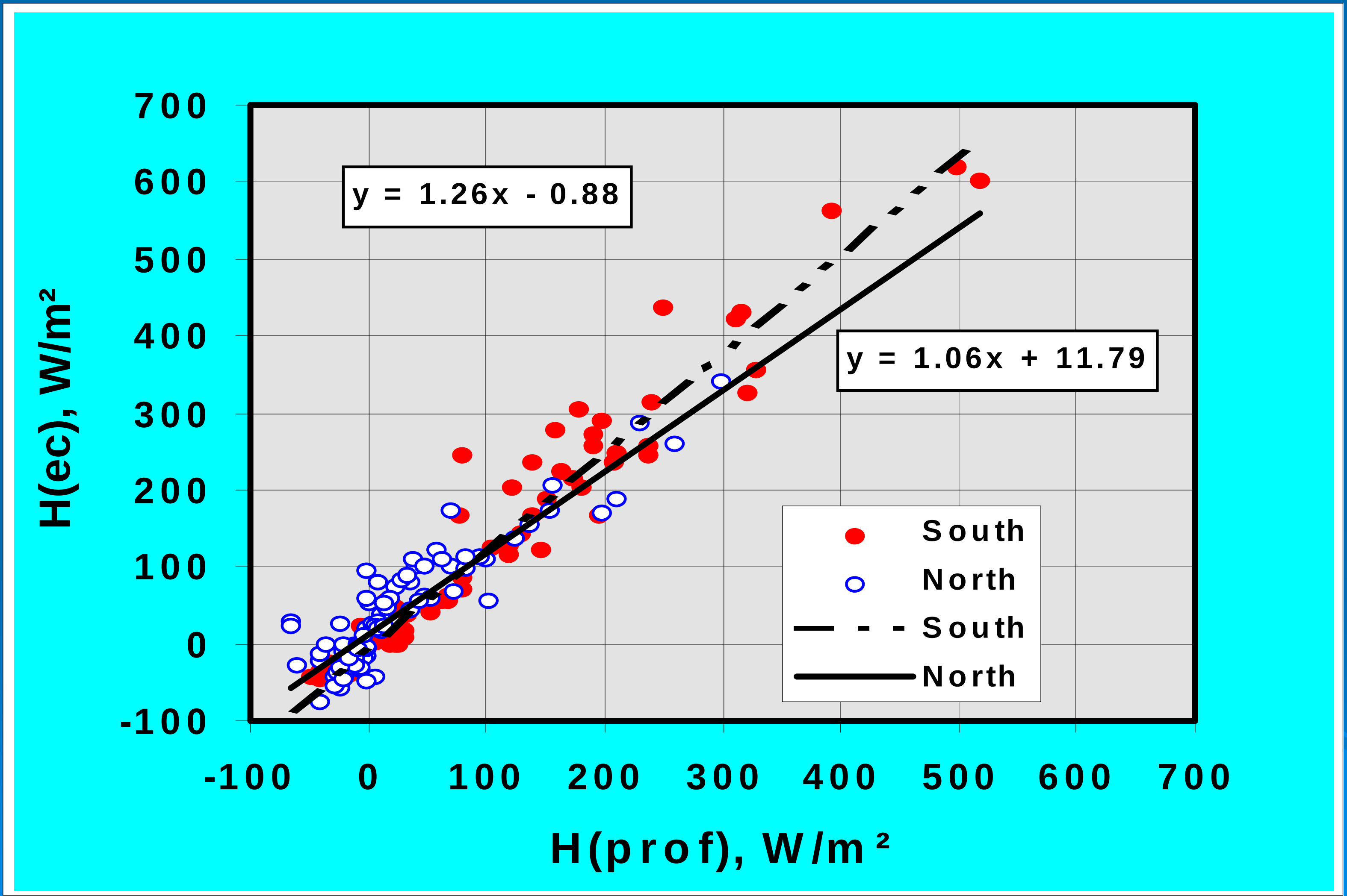
Estimating Evaporation

pitfalls, traps and misconceptions

Virtually all the evaporation estimation techniques are based on theory for steady-state conditions on a semi-infinite, uniform, flat plane.

These rarely exist!

Evaporation on slopes



Estimating Evaporation

pitfalls, traps and misconceptions

Night time and winter conditions.

All Penman-type equations are limited to conditions with evaporation resulting from a positive net radiation supply.

They strictly do not apply for condensation, at night, when the net radiation is negative!

Estimating Evaporation

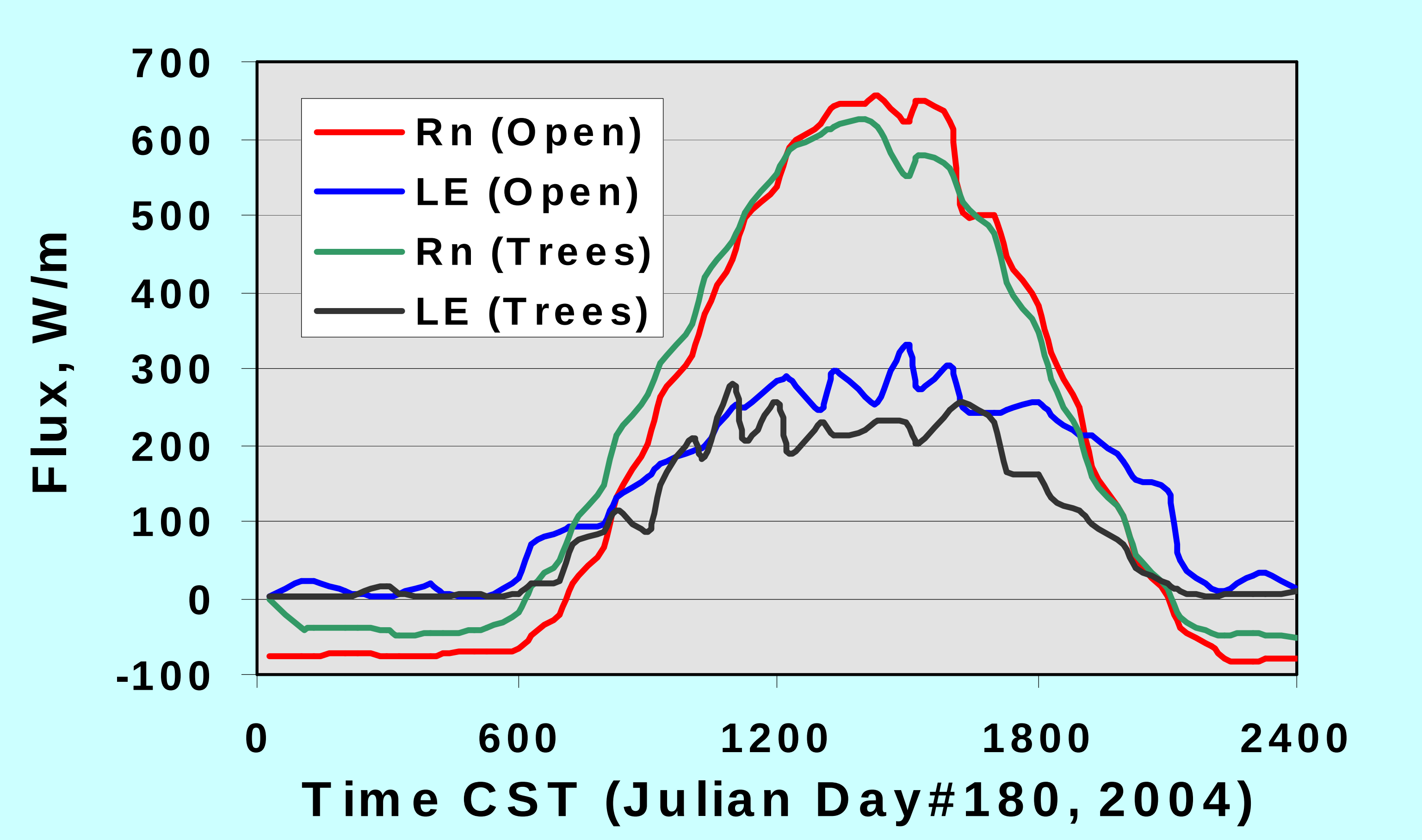
pitfalls, traps and misconceptions

Energy balance assumptions.

The energy balance assumptions used in Penman-type equations apply strictly only to surfaces for which all the net radiation is partitioned at the surface… with no heat storage effects.

They do not apply to wetlands and water surfaces.

Partitioning of Energy



- Evaporation from the open fen shows a “thermal inertia” effect resulting from the release of absorbed energy. (Dryland ET models will not work well here.)