AN EXAMINATION OF THE CONCEPT OF POTENTIAL EVAPORATION

R.J. GRANGER
Division of Hydrology, College of Engineering, University of Saskatchewan, Saskatoon, Sask. (Canada)
(Received November 14, 1988; accepted after revision February 6, 1989)

ABSTRACT

A survey of the literature reveals that the concept of potential evaporation has been the source of some ambiguity; there exists a multiplicity of "definitions", which can in fact represent several distinct parameters.

A systematic approach is used to derive a series of distinct "potential evaporation parameters". The evaporating surface is considered as a system to and from which energy and vapor can be transferred; the potential evaporation parameters describe the evaporation rates which occur when prescribed changes, including saturating the surface, are imposed on this system. Of the defined potential evaporation parameters, the most useful are: (1) the "equilibrium" evaporation rate, governed solely by the available energy, which represents a lower limit to evaporation from moist surfaces; (2) the "wet-surface" evaporation, governed by the available energy and atmospheric considerations, and which is represented by the Penman equation; and (3) the "potential" evaporation, which is defined by the atmospheric conditions and the saturation vapor pressure at the actual surface temperature, and which represents an upper limit to evaporation from a moist surface.

INTRODUCTION
Potential evaporation (or potential evapotranspiration) has been freely used as a hydrological parameter for forty years. The term potential evapotranspiration was introduced by Thornthwaite (1948) in the context of the classification of climate: "There is a distinction, then, between the amount of water that actually transpires and evaporates and that which would transpire and evaporate if it were available. When water supply increases, as in a desert irrigation project, evapotranspiration rises to a maximum that depends only on the climate. This we may call "potential evapotranspiration", as distinct from actual evapotranspiration". He then classed a climate as moist or dry depending on whether precipitation was greater or less than potential evapotranspiration.

Although the concept of potential evaporation was first developed as a climatic index, it has been most extensively used by agriculturalists, interested in the efficient use of water by crops, as an indication of the potential for evaporation, and by hydrologists as a more predictable, or accessible, index
from which the actual evaporation could be estimated. Indeed, the latter is what motivated Penman (1948), who was "seeking an absolute relation between weather elements and open water evaporation, and comparative relations between losses from the soil and losses from open water exposed to the same weather". His intent was not to develop or conceptualize a "potential" evaporation. However, perhaps because what Penman calculated appeared to be similar to what Thornthwaite had defined, his expression came to be known as the "Penman potential evaporation", and has since been extensively used by both agriculturalists and hydrologists.

Potential evaporation has become a standard ingredient in the development of new schemes for estimating actual evaporation; the majority of evaporation models in use estimate evaporation as some fraction of this "maximum potential evaporation". However, for all its years of existence, for all the use that it has seen, the concept of potential evaporation has yet to be adequately and clearly defined in a generally accepted manner. A survey of the appropriate literature reveals that there are several different types of "definitions" available for potential evaporation. These vary from a simple statement equating potential evaporation to evaporation from a free water surface, to verbal descriptions of the Penman equation, and to somewhat elaborate descriptions of conditions under which potential evaporation might be measured. These definitions do not always concur.

The often used definition equating potential evaporation to evaporation from a saturated or free water surface (i.e., Konstantinov, 1963; LeDrew, 1979) is an example of an "open-ended" statement; an infinite number of values are possible if the atmospheric conditions or the conditions of the evaporating surface (i.e. temperature) are not specified. This type of definition would appear to be inadequate.

Bouchet (1963) recognized the need to specify the conditions for potential evaporation; he defined "l'evapotranspiration potentielle, l'eau susceptible d'être perdue dans les mêmes conditions quand elle n'est plus facteur limitant". However, Bouchet did not specify what was meant by the statement "under the same conditions".

Others as well have identified the need to specify conditions for potential evaporation; however, there appears to be no general consensus as to which conditions need be specified. Some (i.e. WMO, 1974; Fortin and Seguin, 1975) indicate that potential evaporation represents the "demand" exerted by the climate, and is thus governed by atmospheric conditions. For example, the WMO (1974), in its International Glossary of Hydrology, defines potential evaporation (evaporation capacity) as the "Quantity of water vapor which could be emitted by a surface of "pure" water, per unit surface area and unit time, under the existing atmospheric conditions".

Others (Van Bavel, 1966; Priestley and Taylor, 1972) place more importance on the surface parameters. Priestley and Taylor state that the apportionment of energy between sensible and latent heat fluxes will be governed by the dryness of the surface and the surface temperature. Van Bavel indicated that
"the fundamental condition that defines potential evaporation is that the surface vapor pressure can be found from the surface temperature". He thus provided the following definition: "A direct approach is to state that the potential evaporation rate \( E_0 \) shall be defined from a Dalton-type equation:

\[
E_0 = f(u) (e'_0 - e_s)
\]

in which \( f(u) \) is a function of windspeed at a stated height, \( e_s \) is the vapor pressure of the air at the same height, and \( e'_0 \) the saturation vapor pressure of the surface, determined by its temperature, \( T'_0 \).

Some definitions presented appear to be descriptions of the equations used to calculate the parameter; for example, the WMO (1974) definition and others like it would appear to be attempts to describe the Penman equation. On the other hand, some definitions presented appear to be more akin to a description of an "ideal" evaporation pan, or of how one might attempt to measure the potential, than to a definition per se; for example, Morton (1969) stated: "Potential evapotranspiration is defined as the evapotranspiration that would occur from a continuously moist surface with regional radiation absorption, vapor transfer, and heat transfer characteristics, which has an area so small that the transfers of heat and water vapor from the surface have no significant effect on the evaporability of the overpassing air. Thus it may be visualized as the evaporation from a hypothetical potential evaporimeter with reflectivity and roughness similar to those of the surrounding region". It is unlikely that such calculated and measured potential evaporation rates would concur; however, notwithstanding his verbal definition, Morton (1983) uses a variation of the Penman method to calculate potential evaporation in his Complementary Relationship Areal Evapotranspiration (CRAE) model.

This brief survey shows that not only are there several different definitions in use for identifying the parameter called potential evaporation, but also that these can represent different, distinct and definable terms. This in fact represents the major source of confusion surrounding the concept of potential evaporation. (In what follows, these different terms will be referred to generally as potential evaporation parameters.)

AN APPROACH TO THE DEVELOPMENT OF A DEFINITION OF POTENTIAL EVAPORATION

The type of parameter being sought will then depend on the end use, and this will also influence the approach used in its development. If the main purpose of the potential evaporation parameter is to serve as an index of, or as an aid for estimating the actual evaporation from a natural nonsaturated surface, the major criteria governing its usefulness are: (1) that it represent a unique value for each set of conditions; (2) that it be easily calculated from readily measured input data; or (3) that it be easily measured; (4) that the relationship between it and the actual evaporation can be established; or (5) that its introduction
into the analysis facilitate the establishment of a relationship between other parameters from which the actual evaporation can be calculated.

Brutsaert (1982) indicated that the fact that potential evaporation is often calculated by means of meteorological data observed under nonpotential conditions represents a source of ambiguity since this is not the same rate as that which would be observed if the surface had been saturated. When using Penman’s equation some hydrologists (Kohier and Parmele, 1967; Morton, 1983) provide a correction for the net radiation to account for the difference between actual and potential conditions. However, it is important to point out that if the Penman equation is to be used only as an index (potential evaporation parameter) of the actual evaporation from a nonsaturated surface, then this type of adjustment becomes unnecessary. It is not necessary that the index represent a real or attainable situation to be useful; it is more important that it be unique, definable, predictable and related to the actual conditions. If, on the other hand, the Penman equation is to be used to provide an estimate of the evaporation from an open body of water or from an irrigated field, then some adjustments become necessary for the radiant transfer and the turbulent transfer coefficients, since what is being sought in this case is a model describing evaporation from such surfaces.

It is unlikely that a parameter can be found such that criteria (2) and (3) are both satisfied. For example, although evaporation pan measurements (which are easily and readily obtained) have proven useful as an evaporation index in many situations, the calculation of pan evaporation is not a simple task given the complex advection and heat transfer regimes involved. It follows as well that pan measurements do not accurately reflect those calculated terms such as the Penman evaporation parameter.

Given that more than one potential evaporation parameter can be described, it should be possible to classify these if a systematic approach is taken for the development of a definition of potential evaporation. A first distinction could be made between measured and calculated parameters. Perrier (1977) provides a classification of the "measured" parameters, and suggests appropriate nomenclature for each. The following analysis deals only with "calculated" potential evaporation parameters.

A natural evaporating surface may be considered as a system to or from which both energy and mass (water vapor) can be transferred. Assume, for the sake of convenience, that the simplest of situations exists: the net supply of radiant energy is the dominant source of energy; the transfer of heat by conduction in the soil is negligible even when relatively large changes in surface temperature are encountered (although at times not very realistic, this has been a common assumption; for those cases where soil heat flux is significant, the net supply of energy is taken as the sum of the radiative and conductive heat fluxes); the surface is of a sufficient size such that there are no significant inputs of energy by local advection. The system then is one where the net energy supplied to the surface, $Q_n$, will be dissipated by the turbulent transfer of sensible, $Q_s$, and latent heat, $Q_e$, into the overlying air layer. These
energy fluxes are governed by a turbulent transfer coefficient and by the 
gradients defined by the difference between the surface parameters (tem-
perature, \( T_0 \); vapor pressure, \( e_0 \)) and those measured in the overlying air layer 
(\( T_a \), \( e_a \)). Assume also that all the state variables and energy fluxes describing 
the actual conditions are measured or known.

Faced with the problem of defining a "potential evaporation" for this system 
one would have to specify those changes to the system, or to the state variables 
or parameters of the system, that would result in evaporation taking place at a 
maximum, or "potential", rate. Those parameters which can be controlled in 
this exercise are the net available energy, \( Q_a \), and the atmospheric and the 
surface parameters. It is convenient to group the atmospheric variables (wind, 
temperature and humidity) into a single parameter since it is difficult to predict 
how a change in one will affect the others. The drying power of the air, which 
takes into account the wind speed and the vapor pressure deficit of the air, 
\( e^* \) (the superscript * is used to denote saturation), is then the appropriate 
parameter. The minimum condition for the definition of potential evaporation 
would be the specification that the surface be brought to saturation; the 
surface temperature is then the parameter controlling the vapor pressure at the 
surface. By specifying different conditions or different combinations of 
conditions for these parameters (i.e., by providing different definitions) 
different values would be obtained for the "potential" evaporation rate.

(1) Consider first the minimum condition alone. Suppose that our natural 
surface, for which the initial conditions are known, was to be supplied with 
water so as to become saturated. All the other parameters (\( Q_n \), \( Q_e \), \( Q_a \), 
\( T_0 \), \( e_0 \)) could change and a new equilibrium state could be reached. Let the 
evaporation rate reached in this case be known as \( E_{P1} \). (\( E_{P1} \) represents 
the situation where potential evaporation is simply defined as evaporation from a 
saturated, or free water surface.) The solution of this new equilibrium state is 
indeterminate since there are too many unknowns for the number of available 
equations. Thus the specification of a saturated surface alone is not sufficient 
to define a useful parameter which might be called potential evaporation.

(2) If the net energy supply, \( Q_n \), is held constant while the surface becomes 
saturated, the surface temperature and the air temperature and vapor pressure 
will change (\( T_{s2} \), \( e_{s2}^* \), \( T_{a2} \), \( e_{a2} \)) and a new equilibrium state will be established. 
Let the evaporation rate, governed by the gradient \( e_{s2}^* - e_{a2} \), in this case be 
denoted by \( E_{P2} \). This equilibrium condition cannot be solved since there too 
many unknowns for the available equations. However, the evaporation rate 
resulting from the specification of the available energy with a saturated 
surface has been used as a hydrological parameter. It has been referred to as 
the "wet-environment", "equilibrium" or the "advection-free potential 
evaporation". Because it cannot be calculated directly, \( E_{P2} \) has been empirically 
related to the radiant energy supply. (Priestley and Taylor, 1972; Davies 
and Allen, 1973; Brutsaert and Stricker, 1979).

(3) If the net energy supply, \( Q_n \), and the atmospheric parameters, \( T_a \) and \( e_a \), 
are held constant while the surface becomes saturated, the surface temperature
will change \((T_a)\) and a new equilibrium state will be established. This equilibrium condition can be solved by using the vapor transfer and energy balance equations, as was done by Penman (1948). This evaporation rate, \(EP_3\), defined by the gradient \(e^*_s - e_a\), has most often been referred to as the "Penman potential evaporation".

(4) If the energy supply, \(Q_a\), and the surface temperature, \(T_0\), are held constant while the surface becomes saturated, the air temperature and vapor pressure will change and a new equilibrium state will be established. In this case again there is insufficient information available to solve for the equilibrium condition. This evaporation rate, \(EP_4\), has not been used as a hydrological parameter, probably because in such a development it is not practical to hold constant a parameter which is not usually measured while allowing those readily measured parameters to vary.

(5) If the atmospheric parameters, \(T_a\) and \(e_a\), and the surface temperature are held constant while the surface becomes saturated, the evaporation rate established, \(EP_5\), defined by the gradient \(e^*_a - e_a\), can be calculated using the vapor transfer equation if the fixed surface temperature is known. This parameter has

**TABLE 1**

Summary of definitions of "potential evaporation parameters"

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Calculation</th>
<th>Common usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>(EP_1)</td>
<td>Evaporation rate which would occur if the surface was brought to saturation</td>
<td>Indeterminate</td>
<td>&quot;definition&quot; of potential evaporation</td>
</tr>
<tr>
<td>(EP_2)</td>
<td>Evaporation rate which would occur if the surface was brought to saturation and the energy supply to the surface was held constant</td>
<td>Indeterminate; regression with solar radiation (Priestley and Taylor, 1972)</td>
<td>Wet-environment or equilibrium evaporation; advection-free evaporation</td>
</tr>
<tr>
<td>(EP_3)</td>
<td>Evaporation rate which would occur if the surface was brought to saturation and the atmospheric parameters and the energy supply to the surface were held constant</td>
<td>Energy balance, vapor transfer equations</td>
<td>Penman potential; wet-surface evaporation</td>
</tr>
<tr>
<td>(EP_4)</td>
<td>Evaporation rate which would occur if the surface was brought to saturation and the energy supply and the surface temperature were held constant</td>
<td>Indeterminate</td>
<td>Not used</td>
</tr>
<tr>
<td>(EP_5)</td>
<td>Evaporation rate which would occur if the surface was brought to saturation and the atmospheric parameters and the surface temperature were held constant</td>
<td>Vapor transfer equation (if surface temp. is known)</td>
<td>Potential (Van Bavel, 1966)</td>
</tr>
</tbody>
</table>
also been used to define potential evaporation (i.e. Van Bavel, 1966). Although
EP5 is a very simple parameter, the general lack of availability of surface
temperature measurements has inhibited its use.

There are other possible combinations of conditions which could be imposed
on the system and which could result in the definition of other parameters, but
as with EP4 these are rather impractical in nature. Table 1 provides a summary
of the parameters presented above, along with the corresponding "definitions"
and how they may be estimated. The table also indicates which of these have
from time to time been referred to as "potential evaporation". Figure 1 is a
schematic representation of the vapor pressure gradient above a nonsaturated
surface and of the hypothetical gradients associated with the potential
evaporation parameters presented above.

DISCUSSION

With the exception of EP4, all of the above evaporation rates have from time
to time been referred to as the "potential evaporation" rate. Of these, EP3, the
Penman evaporation, has found the widest use, probably because of those
which can be calculated it is the only one which can be obtained from readily
available meteorological variables. Although the verbal definition associated
with EP1 is frequently encountered in the literature, the parameter itself is not
a practical one; it does serve to illustrate that whereas a wet surface will
everoporate at the potential rate, the specification of a saturated surface alone
is not sufficient to define the potential evaporation. The parameter EP5 is the
only one which accounts directly for the effect of the surface conditions;
however, since it requires knowledge of the surface temperature which is
rarely measured, it has found less use. Although the term wet-environment
evaporation is most often associated with the parameter EP2, some authors
(Fortin and Seguin, 1975; Granger, 1988) utilize the Penman equation, $EP_3$, to describe it. Seguin (1975) analyzed Morton’s verbal definition of potential evaporation, for which the effects of advection are significant; he showed that as the area of the hypothetical evaporimeter was reduced and approached zero, the calculated value for this potential evaporation rate increased and approached that of $EP_5$.

Of the parameters presented in Table 1, only $EP_2$, $EP_3$ and $EP_5$ appear to be useful, either because they are easily calculated ($EP_3$) or because they represent useful limits for evaporation from a saturated surface ($EP_2$, $EP_5$). As depicted in Fig. 1, these potential evaporation parameters are of course not equal; they are related in the following general manner:

$$EP_5 \geq EP_3 \geq EP_2 \geq E$$

(1)

where $E$ is the actual evaporation rate. Because they are different, it is important that they be recognized as such, and be given appropriate designations.

The net energy available, $Q_n$, is the only variable governing the parameter $EP_2$. The equilibrium condition described in this case cannot be solved; there are four unknowns ($EP_2$, $T_0$, $T_a$, $e_a$) and only the energy balance and vapor transfer equations available. Priestley (1959) provides the basis for an approximation; under these ideal conditions the overlying air will tend toward saturation ($e_a \approx e^*$) and the Bowen ratio can be approximated by $\beta \approx \gamma/\Delta$, where $\gamma$ is the psychrometric constant and $\Delta$ is the slope of the saturation vapor pressure curve. The resultant expression for $EP_2$ then is identical to the first term of the Penman equation, that is: $EP_2 \approx \Delta Q_n/(\Delta + \gamma)$. Slatyer and McIlroy (1961) and Brutsaert and Stricker (1979) discuss this term in the context of evaporation from large, homogeneous moist surfaces under advection-free conditions and suggest that it represents a lower limit to evaporation from wet surfaces; they refer to this term as "equilibrium evaporation".

$EP_3$, given by the Penman equation, is the most frequently used potential evaporation parameter. It is governed solely by energy supply and atmospheric considerations; it is independent of the surface conditions. $EP_3$ represents the evaporation rate from a moist surface exposed to the existing available energy and atmospheric conditions. For these reasons it would be more appropriate to refer to this parameter as the "Penman wet-surface evaporation", rather than as the potential evaporation rate as is frequently done.

The parameter $EP_5$ is the largest of the defined parameters; it is the only parameter which is governed by both atmospheric and surface conditions. These considerations are probably sufficient to justify calling this term the "potential evaporation". The fact that the surface temperature, which is rarely measured, is required for its calculation does appear to detract from its usefulness as an index from which relationships can be developed for estimating the actual evaporation. However, it is not necessary that the potential evaporation be the most practical parameter in this case, nor is it necessary that an evaporation index be called potential evaporation; the
Penman wet-surface evaporation, because it is easily calculated, has been most useful as an evaporation index.

Bouchet (1963) showed that as a surface dried from initially saturated conditions (where the actual and potential evaporation rates are equal), the actual evaporation decreases while the potential increases. He postulated that the decrease in the actual evaporation rate is equal to the increase in the potential evaporation rate. This relationship between actual and potential evaporation which Bouchet (1963) introduced is now recognized as the complementary relationship. The parameters $EP_2$, $EP_3$ and $EP_5$ also behave in a complementary-like manner in that the difference between the respective evaporation rates is greatest for the initially dry conditions and they are of course equal for initially wet conditions. However, a truly complementary relationship as described by Bouchet (1963), where the differences between respective evaporation rates are equal, does not necessarily follow. The form of the relationship will of course depend on the choice of potential evaporation parameters.

The inequality presented in eqn. (1) can form the basis for an evaporation model if the relationship between the actual evaporation, $E$, and one or more of the other evaporation parameters can be established. Those complementary relationship models developed to date (Brutsaert and Stricker, 1979; Morton, 1983) have focused on the parameters $EP_2$ and $EP_3$. However, because $EP_2$ has not been calculated directly from measured variables (it is generally estimated through regression), the exact form of the relationship between $E$, $EP_2$ and $EP_3$ has not been established; the above authors have assumed the relationship to be truly complementary. On the other hand, $EP_3$ and $EP_5$ can both be calculated from existing parameters; the form of the relationship between these and the actual evaporation should then be well-defined, and these as well may be suited to form the basis of a complementary-type evaporation model. Granger (this volume) used an analysis similar to that of Bouchet (1963) to establish the relationship between $EP_3$ and $EP_5$, and used these to form the bases of such an evaporation model.

It may also be possible to define a parameter other than those found in Table 1 in such a way that it is related to one of the previously defined potential evaporation parameters in a fixed or predetermined manner. This is in effect what Morton has done in the development of his CRAE model. Notwithstanding the definition that he provides for the wet-environment evaporation, he establishes its value by regression in such a way as to make it equal to one half of the "potential" which he adopts for a dry environment. This is in fact the same as defining a new parameter. By doing so, he thus ensures that the relationship between those parameters which he has chosen is truly a complementary one.

It has been the normal practice, when a potential evaporation parameter was adopted or defined, to establish an empirical relationship between it and the actual evaporation rate for the given conditions. Such regressions are generally not single-valued, and require calibration for each different
suggestion. Use of two potential evaporation parameters, as in the complementory relationship, appears to eliminate, or at least alleviate this problem; however the exact form of the relationship must first be established. Other approaches as well may be possible for using the potential evaporation parameters to obtain estimates of the actual evaporation rate. For example Granger and Gray (this volume) introduce the potential evaporation parameter into the analysis of the evaporation problem (vapor transfer and energy equations) in such a way that a nondimensional equation is developed. This approach brings with it two major advantages: firstly, the relationships established by a dimensionless analysis are generally single-valued and universally applicable; and secondly, as they showed, a dimensionless variable can be defined in such a way that, although the potential evaporation parameter is implicit in its definition, it is not necessary to measure or calculate it in order to solve the problem.

SUMMARY

The major source of confusion regarding the concept of potential evaporation originates from the fact that more than one such parameter can be found, and that several have been given the name "potential evaporation". A systematic approach is used to define and categorize a series of distinct "potential evaporation parameters"; these are related to the actual or initial conditions, but are governed by different sets of imposed boundary conditions. Of these parameters, the most useful are: (1) $EP_2$, the "equilibrium" evaporation rate, which is governed solely by the available energy, and which represents a lower limit to evaporation from moist surfaces; (2) $EP_3$, the "wet-surface", or "wet-environment" evaporation, which is governed by the available energy and atmospheric considerations; this term is represented by the Penman equation, and so can be referred to as the "Penman wet-surface evaporation"; and (3) $EP_5$, the "potential" evaporation, which is defined by the atmospheric conditions and the saturation vapor pressure at the actual surface temperature, and which represents an upper limit to evaporation from a moist surface (for the given conditions).

Complementary relationship models for estimating actual evaporation require the use of two potential evaporation parameters. These have generally focused on the parameters $EP_2$ and $EP_3$; however, because $EP_2$ must be found through regression, the form of the relationship between the actual evaporation and these two parameters has not been established, but has been assumed to be complementary. Since $EP_3$ and $EP_5$ can both be calculated, the relationship between these can be established, and they may thus be better suited to form the basis for an evaporation model.

REFERENCES


