USE OF A HEMISPHERICAL CHAMBER

FOR MEASUREMENT OF EVAPOTRANSPIRATION

By David I. Stannard

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CONVERSION FACTORS

International System of Units (SI) in this report may be converted to inch-pound units by using the following conversion factors:

Multiply SI units	*By*	*To obtain inch-pound units*
calorie (cal)	0.003968	British thermal unit
cubic meter (m^3)	35.31	cubic foot
gram (g)	0.03527	ounce
hectare (ha)	2.471	acre
kilogram (kg)	2.205	pound
meter (m)	3.281	foot
micrometer (μm)	0.00003937	inch
millimeter (mm)	0.03937	inch
square meter (m^2)	10.76	square foot

The following terms and abbreviations also are used in this report:

calorie per gram (cal/g)
gram per cubic meter (g/m^3)
gram per cubic meter per second [$(g/m^3)/s$]
gram per minute (g/min)
gram per square meter per second [$(g/m^2)/s$]
millimeter per day (mm/d)
minute (min)
ohm (Ω)
second (s)
square volt per ohm (V^2/Ω)
volt (V)

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ABSTRACT

A small acrylic hemispherical chamber can be deployed over vegetation by one person to estimate ET (evapotranspiration). Equipment cost is less than one-fourth that of micrometeorological (Bowen-ratio or eddy-correlation) equipment. The chamber is more portable than conventional chambers used in agriculture and it is deployed for less than two minutes per measurement, which makes it ideal for measuring ET of wild-land vegetation or for measuring ET where limited fetch (such as in cities and suburbs) invalidates micrometeorological methods. The hemispherical shape of the chamber is an innovation to obtain efficient mixing of water vapor inside the chamber. Essential details of construction and calibration help the reader prepare a chamber for onsite use.

The homogeneity of agricultural crops and the large size of the chambers typically used on crops enable researchers to assume that ET measured inside large chambers approximately is equal to the average ET rate of the crop. If vegetation is scattered or diverse, the procedures are more complicated. A chamber needs to be deployed over each species present, and the measured ET rates need to be combined in a weighted average to estimate ET of the plant community. Criteria for selecting plants over which to deploy the chamber and a procedure for characterizing species distribution yield parameters that are used in a suggested algorithm to calculate ET of each species and the average ET of the plant community.

INTRODUCTION

Several methods of measuring ET (evapotranspiration) of wild-land vegetation currently are available to researchers (Sharma, 1985). Profile methods are costly (about $3,000) and are subject to large errors (Tanner, 1960). Bowen-ratio and eddy-covariance methods are more accurate, but they also are more costly (about $3,500 for a Bowen-ratio system and $6,000 to $7,000 for an eddy-covariance system). All three micrometeorological methods require a fetch, or homogeneous upwind land cover, and in mixed plant communities they cannot be used to isolate transpiration rates from different species or to isolate evaporation from bare soil.

Chambers primarily have been used to measure ET in cultivated fields. Continuous chambers are lowered onto a section of crop and usually they remain in place from sunrise to sunset (Koch and others, 1971; Saugier, 1976; Puckridge, 1978; Greenwood and Beresford, 1979). Continuous chambers are not moved easily, and they significantly alter net radiation and the wind, temperature, and vapor profiles which affects ET by as much as 100 percent (Sharma, 1985). Reicosky and Peters (1977) developed a chamber to make rapid measurements of ET. Rapid chambers typically are deployed for less than 2 min while the increase of vapor density inside the chamber is measured. The rate of vapor-density increase is proportional to ET. The effects of altered climatic variables on ET apparently are minimized by making measurements rapidly, as indicated by the ±5-percent agreement between ET measured inside rapid chambers and ET measured using adjacent weighing lysimeters or solution absorption systems (Reicosky and Peters, 1977; Reicosky, 1981; Reicosky and others, 1983). Reicosky was able to assume that there was equality between measured ET rates and average crop ET rates because the crops were dense and uniform and the chambers were large--typically 3.7 m^2. These rapid chambers were portable, but usually a farm tractor was needed to move them. A recent trend toward increased portability has led to the use of smaller rapid chambers that enclose an entire plant or plants and that can be maneuvered by two people (Morgan and Willis, 1983; Charles and others, 1987).

Purpose and Scope

The purpose of this report is to describe a rapid chamber that can be maneuvered by one person. The chamber was developed for three applications: 1) To estimate areal average ET of small wild-land vegetation, such as desert shrubs and grasses; 2) to separate ET of small wild-land vegetation into components from each species present and from bare ground; and 3) to measure ET where limited fetch invalidates micrometeorological techniques, such as in cities and suburbs. A small acrylic chamber was built for about $800, and it was calibrated in the laboratory; then it was used by Goetz and Shelton (U.S. Geological Survey, oral commun., 1987) to measure ET of urban land surfaces. Details of construction and calibration are presented, and methods of estimating average ET and ET components of diverse plant communities are suggested.

CONSTRUCTION

The size and shape of the chamber are best determined by the vegetation over which the chamber will be placed. A hemisphere minimizes the occurrence of dead air spaces and causes minimal disturbance to net radiation; also, many shrubs are approximately hemispherical. Tall, slender plants can be accommodated by adding a cylindrical skirt to the bottom of a hemisphere. Alternatively, the chamber can be cylindrical and have a flat circular top. However, a cylindrical chamber causes a greater disturbance to net radiation and it has a region near the upper perimeter where mixing of air is decreased. A cylindrical chamber probably is less expensive than a hemispherical one of equal volume.

The chamber described in this report, purchased for $250 from Plasticrafts, Inc.[1] in Denver, Colo., was made from a sheet of 4.76-mm-thick Plexiglas G, which has 92 percent transmittance of all wavelengths greater

[1]Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

than 0.374 µm. After 2 years of constant outdoor exposure in Pennsylvania, the plastic transmitted 92 percent of all wavelengths greater than 0.433 µm (Rohm and Haas, 1965). A thermoforming process used to create skylights was extended to produce a 1.06-m-diameter hemisphere rather than to produce the usual watch-glass shape. The finished hemisphere weighed 25.3 kg, and had an average thickness of 2.38 mm, and a 38-mm-wide flange around the bottom. Riecosky and others (1983) used a rectangular Plexiglas chamber to measure alfalfa ET. Although the Plexiglas reduced solar irradiance by 8 to 10 percent, the daytime total ET was 96.7 percent of that measured using an adjacent lysimeter.

Two 12-V fans, with 80-mm-diameter blades, were mounted on the inside wall of the chamber, about 0.27 m above the flange. Experiments were done to optimize air mixing that used threads of different lengths to indicate air flow. With two fans, optimal mixing was obtained by installing the fans opposite each other, and by aiming them 5 degrees above horizontal, and 27 degrees away from the center of the chamber (fig. 1).

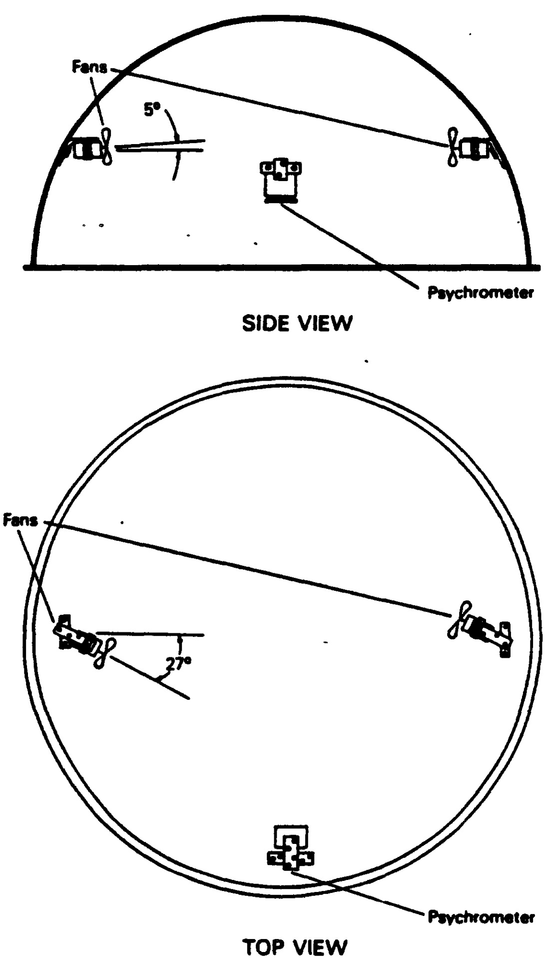


Figure 1.--Location of fans and psychrometer inside chamber.

The fans need to be selected to produce a windspeed that approximates the average expected onsite windspeed at one-half the height of the chamber. Alternatively, onsite windspeed can be measured and a rheostat can be used to vary internal average windspeed to match external.

A wet- and dry-bulb psychrometer, made by Delta-T Devices and marketed by Campbell Scientific, Inc., in Logan, Utah, was installed midway between the fans. Mounting details are shown in figure 2. The fans and psychrometer were easily removable to facilitate cleaning the inside chamber surface. Any sensor that measures two independent psychrometric parameters (saturation vapor pressure, vapor pressure, vapor pressure deficit, wet-bulb temperature, dew-point temperature, relative humidity, or air temperature) can be used instead of a psychrometer to determine vapor density (Fritschen and Gay, 1979).

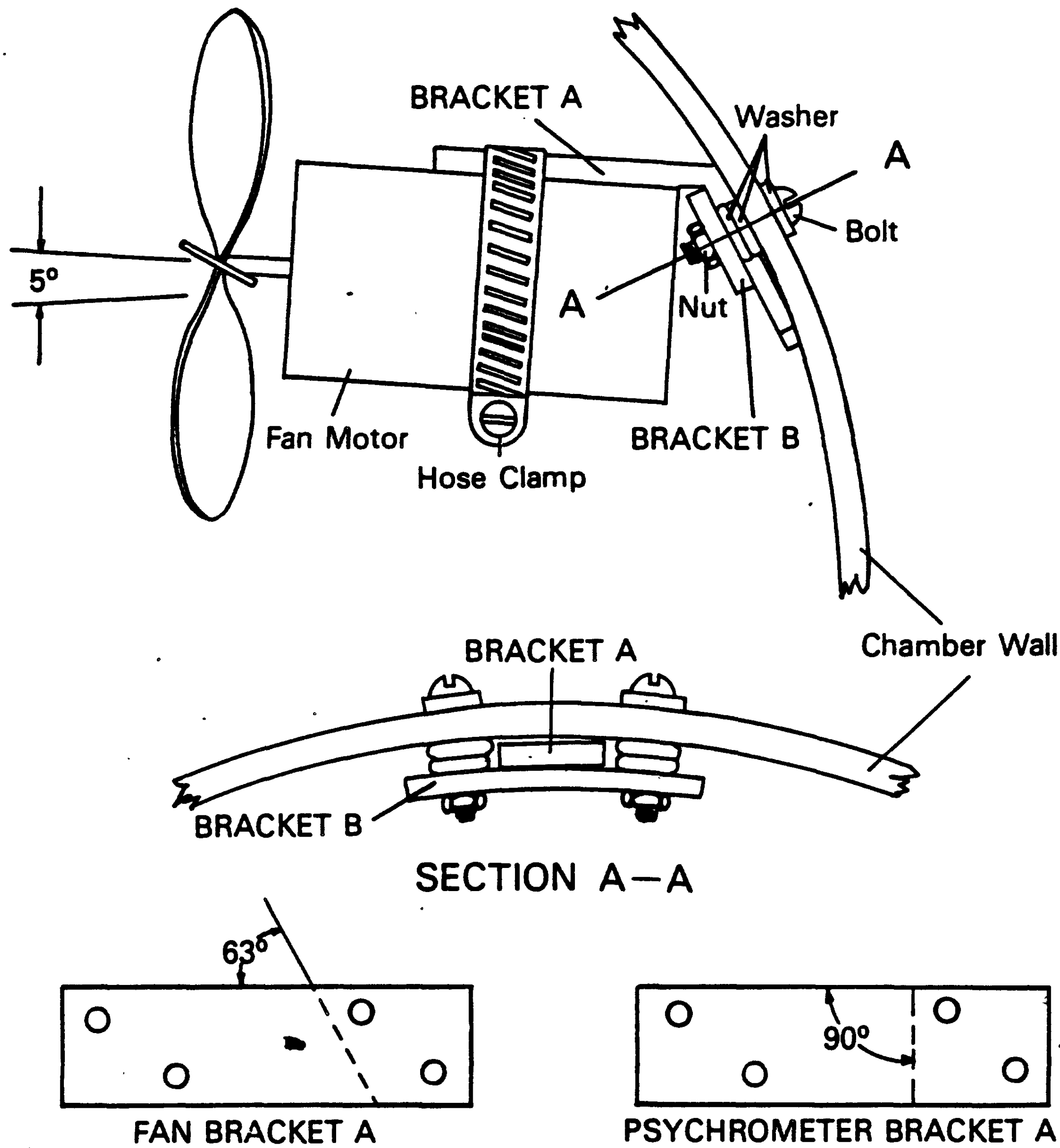
Three drawer-pulls were attached to the flange for manipulation of the chamber. If the operator cannot maneuver the chamber by gripping it at the perimeter, a cantilever rod or a two-wheeled dolly can be made to suspend the chamber using strings. Alternatively, an assistant can help maneuver the chamber.

CALIBRATION

The acrylic (Plexiglas G) used in the chamber is slightly hydrophylic. Therefore, some of the water vapor entering the chamber adsorbs to the inside surface and is not measured by the psychrometer. Any chamber that adsorbs water needs to be calibrated to determine the ratio of water-vapor flux measured to that entering the chamber. The procedure described in this report is a modification of a procedure used by Morgan and Willis (1983). Water is boiled at a known rate, the chamber is placed over the boiling water, and the known boiling rate is compared to the rate measured by the chamber.

Materials

1. Chamber, complete with fans, psychrometer or equivalent, battery, and data logger.
2. Digital top-loading balance, readability to 0.01 g, range of at least 0 to 600 g, preferably with capability to weigh automatically and to send data electronically to a computer or data-storage module.
3. Small 110-V heating coil, as is used to heat a cup of water.
4. Variable voltage source, or rheostat (light dimmer).
5. If data is to be sent electronically, need a destination (computer or data-storage module) for data.
6. Ringstand or equivalent, and test-tube clamp.
7. Beaker.
8. Weather strip.



Notes:

1. Brackets A and B are 19mm by 76mm shelf brackets.
2. Fan bracket A bent along broken line to aim fans 27° off center.
3. Psychrometer bracket A bent along 90° broken line.
4. Bracket B curved slightly to conform to curvature of hemisphere.
5. Thickness of two washers slightly greater than bracket thickness to allow bracket A to slip between bracket B and chamber wall.
6. Psychrometer or equivalent sensor suspended from Psychrometer Bracket A. Details vary with sensor.

Figure 2.--Details of fan and psychrometer installation.

Procedure

1. Attach weather strip to bottom edge of chamber, in order to provide seal around electrical cords.

2. Place balance on flat surface. Fill beaker with water until total weight is slightly less than balance range; place on balance pan.

3. Use ringstand and test-tube clamp to suspend heating coil into water. DO NOT LET ANY PART OF COIL TOUCH BEAKER. Connect coil to variable voltage source or connect coil in series with rheostat to 110-V.

4. Establish steady evaporation rate at a given voltage setting, as determined by timing weight loss on balance display. The following equation can be used to determine the voltage drop across the coil needed to produce a desired evaporation rate. The equation is approximate, and it is based on a latent heat of vaporization of water equal to 585 cal g^{-1}.

$$M = \frac{0.0245\ V^2}{R} \qquad (1)$$

   where M is the evaporation rate, in grams of water per minute;
   V is the voltage drop across the coil, in volts;
   R is the resistance of the coil, in ohms; and 0.0245 is the factor that converts volts squared per ohm (power) to grams of water per minute.
   Calibration evaporation rates need to be of the same order of magnitude as rates that will be measured onsite.

5. Turn on fans in chamber. Activate data logger to begin recording time and wet- and dry-bulb temperatures (or any two independent psychrometric parameters). Typical logging interval is 2 s. If data is to be sent electronically, activate balance to begin sending time and weight of beaker and water to computer or data-storage module.

6. Emplace chamber over apparatus, noting time chamber touches flat surface; this is the start time. If data is not to be sent electronically, begin reading balance display at equal time intervals (5 s is briefest interval practical). Leave chamber in place for approximately 2 min.

7. Stop data collection and prop chamber up to obtain ambient humidity inside. Wait a few minutes to repeat at same rate or change rate and wait for steady state; repeat.

Analysis

Use of simple computer programs, plotting routines, and linear regressions greatly expedites the analysis.

1. For each measurement, plot weight loss of water in beaker and vapor accumulated by chamber as functions of time. Accumulated vapor is calculated as:

$$V_a = qV \qquad (2)$$

where V_a = accumulated vapor, in grams;
q = vapor density as measured by chamber, in grams per cubic meter; and
V = volume inside chamber, minus volume of apparatus inside chamber, in m^3.

Determination of vapor density from any two independent psychrometric parameters is a standard procedure (Fritschen and Gay, 1979) and is not described in this report.

2. Determine time period when weight loss and vapor gain are both at steady state, or constant slope. The record of the start time is used to help identify the steady-state periods. Typically, both functions accelerate for a few seconds after start time, then they increase steadily for 10 seconds to 1 min, then they decelerate, similarly to their behavior during onsite use (fig. 3). Determine the slopes in grams per minute of both functions for the same steady-state period. These slopes are the production and accumulation rates.

3. Plot production rate as a function of accumulation rate for all measurements. Determine the best-fit line that passes through origin, using the method of least squares. Slope of line is the calibration factor of the chamber. The calibration factor accounts for water adsorption, sensor error, and incomplete mixing and is usually slightly greater than 1.0.

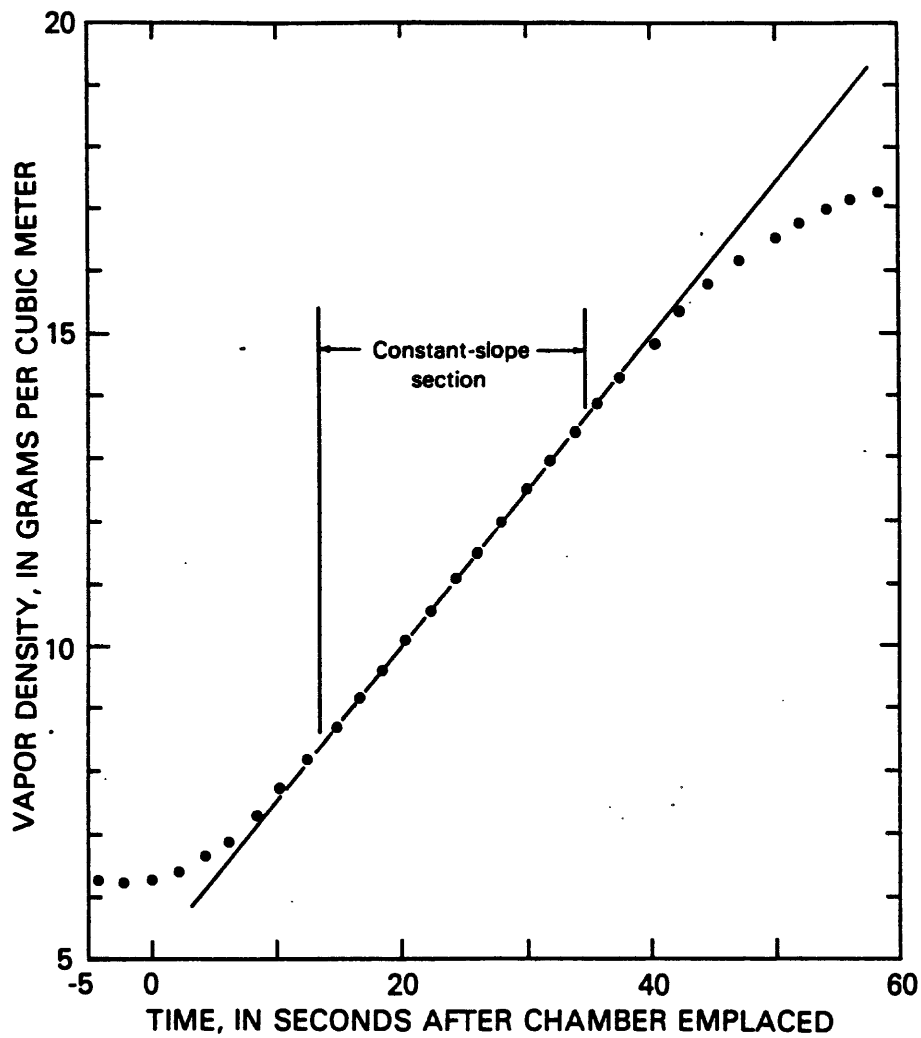


Figure 3.--Typical time series of vapor density inside chamber.

ONSITE USE

The chamber described in this report can be used to estimate ET of dense homogeneous stands of short vegetation (such as turf or meadow grasses), bare soil, or scattered diverse vegetation. The first two subsections summarize the procedures that are needed to estimate daily ET of dense homogeneous vegetation or of bare soil. The third subsection summarizes the procedures that are suggested to estimate daily ET of scattered diverse vegetation.

Basic Chamber Operation

A typical chamber measurement is analogous to a calibration measurement. The chamber is emplaced over a plant, or plants (only one species at a time), or bare soil, and the sensor records the increase of vapor density with time. The chamber remains in place long enough to establish the constant-slope section of the vapor-density time series.

1. Prepare land surface or chamber or both so that a seal is made around chamber perimeter. Usually a soil surface can be scraped and filled to match bottom edge of chamber. If surface is very rocky, either import finer grained material (sand) from nearby to smooth the perimeter of site, or attach weather strip to perimeter of chamber.

2. Activate fans and data logger and hold chamber about 1 m above land surface to obtain ambient humidity inside chamber. A typical logging interval is 2 s.

3. Quickly set chamber onto location, noting start time. The chamber needs to remain in place an extent of time determined by the ET rate. Lush vegetation can saturate the air in a 1-m-diameter hemisphere in 15 seconds, at which time the ET rate already will have begun decreasing. For most vegetation, an appropriate measurement interval is 2 min. Relatively dry soil can continue to evaporate water at a constant rate for many minutes. If unsure about the ET rate, operate the chamber for a few minutes. Condensation inside chamber always is a signal of a sufficiently long period of measurement; however, condensation does not always occur. If the data logger is programmed to compute the real-time ET rate (for example, a Campbell Scientific 21X program is presented in the Appendix), viewing the rate on the logger display will indicate when the rate begins to decrease and the measurement is completed.

4. Raise chamber, deactivate data logger and turn off fans. Wait a few minutes to dry the air in the chamber before repeating.

5. The chamber surfaces need to be kept relatively clean. Dust is removed by using a garden hose (after removing fans and sensor) or a wet cloth. A mild detergent is used to remove smudges. Ammonia should not be used on acrylic, because it will haze the surface. A plastic polishing compound is used to remove scratches.

Estimation of Daily Evapotranspiration at a Single Location

1. The ET rate at a single location for one measurement is computed from the constant-slope section of the vapor-density time series (fig. 3). A few factors contribute to the lack of immediate establishment of the constant slope after the start time. This transient period can last from approximately 5 to 15 s. The constant-slope section persists until increased vapor-density

concentration begins to decrease ET. The constant slope can be evaluated either visually with a straight edge or numerically with a simple program. Such a program begins by calculating the slope of a least-squares best-fit line through the first several points on the curve. The program then steps through the whole curve calculating slopes while maintaining the same number of points. If an appropriate number of points has been selected, the maximum slope calculated is very close to the average slope of the constant-slope section. The interval used (typically 4-5 points) is determined by visual inspection. An interval that is too short produces slopes that can be affected by small variations in the data, which yields erroneously large values of ET. An interval longer than the constant-slope section produces erroneously small values of ET. The ET rate is calculated as:

$$ET = 86.4 \frac{MVC}{A}, \tag{3}$$

where ET = evapotranspiration, in millimeters per day;
M = the slope of the constant-slope section, in grams per cubic meter per second;
V = the volume inside the chamber, in cubic meters;
C = the calibration factor of the chamber, unitless;
A = the area of land surface covered by the chamber, in square meters; and
86.4 = a conversion factor, that converts grams of water per square meter per second to millimeters of water per day.

Although ET is in millimeters per day, it is an instantaneous rate that occurs at the time of measurement.

2. Estimates of daily ET are made by integrating measurements made at a set frequency throughout the day (fig. 4). The confidence in an estimate at a single site increases with greater measurement frequency. However, the confidence in an estimate for a community increases as the number of sites characterized increases. A sampling schedule that balances frequency with number of sites needs to be determined. The frequency used also depends on the number of chambers and operators available and on the rate of change of insolation and temperature. If clouds are blocking the sun intermittently or temperature is changing rapidly, the frequency needs to be relatively large. If meteorologic conditions are changing slowly, measurements at a site need to be made no less often than once an hour during daylight hours.

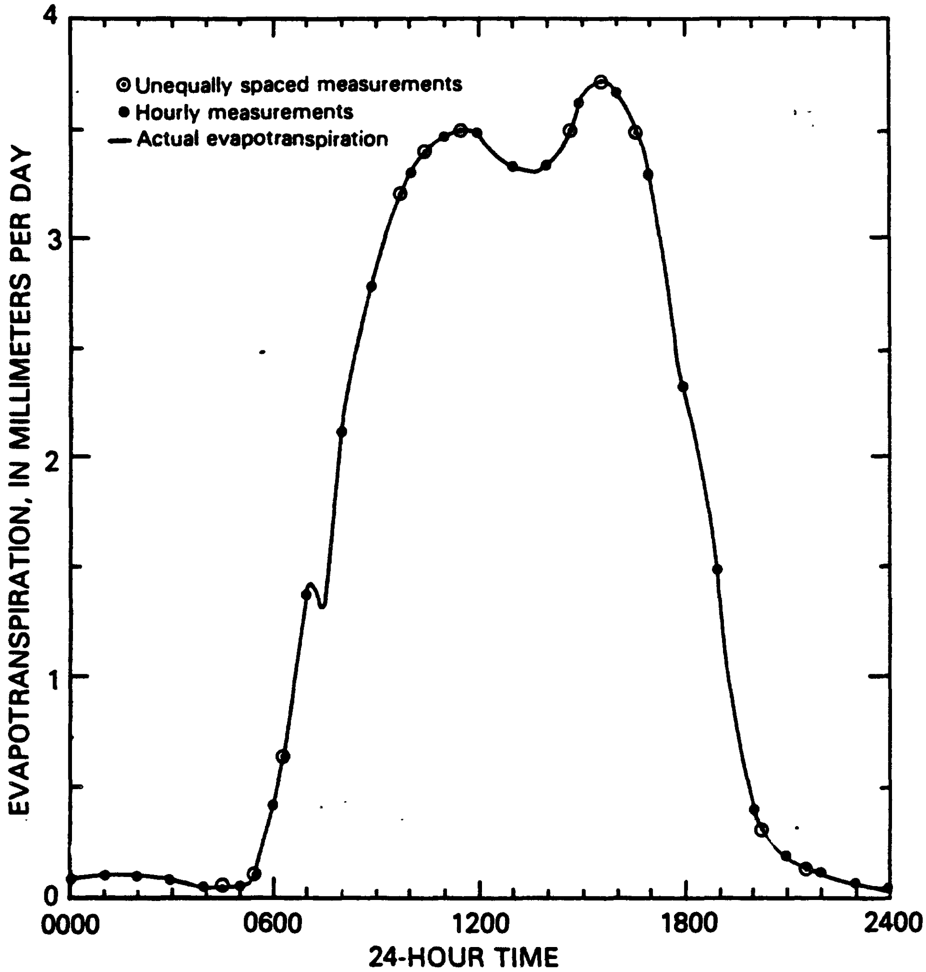


Figure 4.--Typical time series of evapotranspiration during 1 day.

Usually, in arid regions, ET is near zero shortly after sunset until sunrise, and setting ET equal to zero at these times incurs minimal error in computing daily totals. However, this labor-saving assumption needs to be verified by collecting data during a few typical summer nights. If significant ET occurs at night, the frequency of data collection can be decreased from that used during the daytime, because meteorologic conditions usually are changing slowly, and because ET is small. Dew formation cannot be measured with a chamber. This unmeasured dew would increase slightly the value of daily ET measured using a chamber, and would help to reduce the error incurred in ignoring nighttime ET.

It is not always possible to make measurements at regular time intervals. Unequally spaced measurements also are integrated to compute daily totals, using straight-line interpolation between measurements (fig. 4). Measurements made at strategic times, as in figure 4, produce a daily ET estimate with a substantial degree of confidence. Measurements need to be made more often when the magnitude of $\frac{d^2ET}{dt^2}$ is large[2] (where t is time) and less often when the magnitude is small. Without prior knowledge, one would not know when these times might occur at a site and measurements need to be made at least once each hour. However, if meteorologic conditions at a site are predictable, sampling frequency can be decreased to include more sites.

Estimation of Daily Evapotranspiration for a Plant Community

Extrapolation of point measurements to an area or region of wild-land vegetation is the least precise component in chamber measurements of ET. Typical plants of each species are selected for ET measurements, and the horizontal cross-sectional areas (shadow areas) of these plants are estimated. The measured rates are extended to the community by making a detailed account of each species along a set of transects. This relatively simple method of extrapolation is described in this report; other, more detailed methods (using leaf-area-index, for example) can be synthesized from this outline and plant-community literature.

1. A set of line transects are established. A line transect can be thought of as a line segment drawn on an aerial photograph. The segment intersects plants of each species and bare ground. An ideal transect intersects species in the same ratio as they appear in the whole photograph. The shadow area of a plant is the area of the vertical projection of the foliage to the land surface; the relative shadow area is the sum of the shadow areas of a species per unit area of land surface. The transect length of a plant is the length along a transect of the vertical projection of the foliage to the land surface; the relative transect length is the sum of the transect lengths of a species per unit length of transect. The relative transect length of a species along an ideal transect is equal to the relative shadow area of that species in the community. The following line-transect procedure (Smith, 1972) provides a rapid, accurate estimate of the relative shadow area covered by each species in the study area:
   a) Stretch a steel tape between two stakes 33.5 m apart;
   b) The transect is 10 mm wide, along one side of the tape;
   c) Measure the distance along the transect covered by each plant, grouping totals by species; the length of grasses, rosettes, and short dicot herbs is measured at ground level; the shadow length is used for tall dicot herbs and shrubs;

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[2] At any point along the actual ET curve in figure 4, the slope of the curve is the rate at which ET is changing with respect to time. The rate at which the slope of the curve is changing with respect to time is $\frac{d^2ET}{dt^2}$.

Large magnitudes of $\frac{d^2ET}{dt^2}$ correspond to abrupt changes in slope.

d) The relative transect length of each species is the total intercepted length of that species divided by the transect length;

e) Twenty to 30 such lines are needed to characterize a community; the lines can systematically cover the study area, or be randomly spaced; the average of the relative transect lengths of each species is set equal to the relative shadow area.

In practice, this procedure can be modified. Often, the length and number of transects is changed according to the size of the study area, or one long transect through the study area is used (H.L. Weaver, U.S. Geological Survey, oral commun., 1987). The investigator needs to decide what length and number of transects adequately describes the community.

2. ET measurements are made for a group of plants that represent the plant community. Each plant chosen to represent a species needs to fit inside the chamber and also needs to be as large or larger than the average size of that species in the study area. Each plant chosen needs to have a height-to-width ratio equal to the average for that species and be of average vigorousness. The height-to-width ratio is estimated from a systematic or random sampling of the community, (the heights of all transect plants are recorded, for example) or simply estimated by visual inspection. The vigorousness is estimated by visual inspection. Both parameters are critical to accurate ET results and need to be estimated carefully. Color photographs are taken of each plant chosen and of the community to document the choices. A group consists of one plant from each species present and a typical bare-ground site. Selection of two or three full groups for ET measurement increases confidence substantially; increased confidence tapers off rapidly with more than three groups.

3. The chamber-relative-shadow area is estimated for each plant in the measurement group(s). The shadow area can be estimated onsite by projecting the foliage to the land surface using a plumb line and by measuring the dimensions of the resulting plane figure. The chamber-relative-shadow area is equal to the shadow area divided by the total area inside the chamber. This procedure is tedious for grasses and dicot herbs.

An alternate procedure is to take a photograph of each plant from directly above the plant, including an indicator of the chamber perimeter (the whole shape or the diameter) on the land surface. If the plant is seen easily through the top of the chamber, the chamber can be used in the photograph directly. The camera height and the height of the largest horizontal cross section of the plant are recorded. The chamber-relative-shadow area then is determined using a digitizer or planimeter on the enlarged photograph. If RC' is the ratio of plant area to chamber area in the photograph, then:

$$RC = \left(\frac{H - h}{H}\right)^2 RC' \qquad (4)$$

where RC = the chamber-relative-shadow area, unitless;
H = the camera height, in meters; and
h = the height of the widest plant cross section, in meters.
If the plants are very short compared to the camera height, RC ≈ RC'.

4. Daily ET totals calculated for each plant in the group are synthesized into an areal average ET as follows:

$$\overline{ET} = RT_1 \frac{ET_1 + ET_g(RC_1 - 1)}{RC_1} + RT_2 \frac{ET_2 + ET_g(RC_2 - 1)}{RC_2} + \ldots + RT_n \frac{ET_n + ET_g(RC_n - 1)}{RC_n} + RT_g ET_g \qquad (5)$$

where $\overline{ET}$ = the average ET for the plant community, in millimeters per day;
RT = the relative transect length of a species, or bare ground, unitless;
ET = the daily ET for a species or bare ground, measured in the chamber, in millimeters per day;
RC = the chamber-relative-shadow area for a species or bare ground, unitless.
The numbered subscripts refer to the species, the subscript n is the number of species, and the subscript g refers to bare ground.

In this simple model (eq. 5), the vegetated land surface is represented as a plane surface, divided into contiguous regions. Each region belongs to a species category, or to the bare-soil category. The ET per unit area is assumed to be constant (from plant to plant) for each species and for bare soil. Equation 5 computes a weighted average of the individual measured values of ET that accounts for the density of each species in the community and for the size of each plant sampled with the chamber. If two or three groups of plants are used, equation 5 is applied to each group, and the results are averaged. By treating each group separately, large systematic differences among groups can indicate inconsistencies in plant selection.

Each term on the right-hand side of equation 5 represents the transpiration of a specific species; the last term represents the evaporation of bare ground. These individual contributions to total ET are important data to land management officials who might need to assess the impact of a species or of a plant community on a ground-water reservoir.

To enable equation 5 to be independent of the size of plants used for ET measurements, the total leaf (and therefore stomatal) area of a plant is assumed to be proportional to the shadow area of the plant. If the leaves are located mostly at the outer surface or extremities of a plant, this assumption is valid. However, if the leaves are distributed homogenously throughout the plant volume, or throughout some outer fraction of the plant volume (such as the outer one-half or outer two-thirds), then a larger plant would transpire at a greater rate per unit shadow area than would a smaller plant. In this case the plant used for ET measurements needs to have a characteristic dimension (diameter, height, or height of the leafy portion if the leaves do not extend to the ground) determined by:

$$L = \frac{\Sigma L_m^3}{\Sigma L_m^2} \qquad (6)$$

where L = the characteristic dimension of the plant used for ET measurements, in meters;

L_m = the characteristic dimension of each plant in the transects that is of the same species as the plant used for ET measurements, in meters; and

m = an index that increases from 1 to the number of plants in the transects that are of the same species as the plant used for ET measurements.

The procedures outlined in this report use the term "plant community," which indicates that there are no large-scale inhomogeneities, or significant transitions in plant density, size, or vigorousness, or in relative frequency of species, across the community. Some inhomogeneity always exists, and the investigator needs to decide if the inhomogeneities are large enough to bias the results. The transects probably are the best source of information to identify trends and inhomogeneities. If the study area is not sufficiently homogeneous, it needs to be divided into homogeneous subareas, and the procedures in this report need to be applied to each subarea.

Yearly ET totals are estimated similarly to daily ET totals. For convenience, ET measurements are made for 2 or 3 consecutive days each month, and the results are integrated for the year. If measurement resources are limited, emphasis needs to be placed on times when ET is greatest (spring and summer), relying on empirical or semi-empirical estimates when ET is small.

CONCLUSIONS

Several methods, each with advantages and disadvantages, are available for measuring wild-land evapotranspiration. Hemispherical-chamber use is well suited for a project with a small equipment budget and access to inexpensive labor. Hemispherical-chamber use also is ideal for measurement of ET from small areas (less than about 1 ha), and for isolating species transpiration and evaporation.

Onsite objectivity, patience for tedious work, and chamber calibration are central to reliable estimates of ET. Because of the subjective nature of some of the procedures used, it is impossible to assign confidence limits to the ET estimates obtained. Instead, the investigator needs to document his work fully and present color photographs of the study area and the plants selected for measurement to substantiate his results. Future comparisons of chamber measurements of ET with measurements by other methods probably will help establish confidence limits.

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Appendix

Program for use with Campbell Scientific 21X data logger and WVU-7 ventilated psychrometer.

Description	Instruction #	Parameters 1	2	3	4	5	6	Locations 1	2	3	4	5	6	7	8	9
Activate psychrometer fan	20	1	1								$\overline{ET}$	VD*				
Record wet- and dry-bulb temperatures	11	2	1	1	1	1	0	T_W	T_D							
Barometric pressure in 9	30	P	9													P
Vapor pressure in 3	57	9	2	1	3					VP						
Kelvin dry-bulb temp. in 8	34	2	273.2	8											TD_K	
Gas constant for water in 7	30	2164	7											2164		
$\frac{2164}{TD_K}$ in 6	38	7	8	6									$\frac{2164}{TD_K}$			
Vapor density in 6	36	6	3	6									VD			
Change in vapor density in 3	35	6	5	3						ΔVD						
ET rate in 3	37	3	X	3						ET						
ET plus $\overline{ET}$ in 4	33	3	4	4							ET+$\overline{ET}$					
ET in 4	37	4	.5	4							$\overline{ET}$					
Update VD*	31	6	5									VD*	VD			
Set output flag	86	10														
Day, hr.-min., sec. into final storage	77	111														
T_W and T_D into final storage	70	2	1													

Notes

1. Instructions entered in Program Table 1 or 2 (*1 or *2), with a 2-second execution interval.
2. VD* is vapor density from previous execution.
3. P is local average barometric pressure, in kilopascals.
4. X = 43.2 VC/A,
   where V = volume of chamber, in cubic meters;
   C = calibration factor of chamber; unitless; and
   A = area of land surface covered by chamber, in square meters.
5. $\overline{ET}$ is a geometrically weighted mean of the 2-sec ET rates. Approximate onsite ET rate in millimeters per day can be obtained by using *6 to monitor location 4. Value in location 4 will increase to a maximum, then decrease. Maximum value is approximate ET rate.
6. This program stores Julian day, hour, minute, second, wet-bulb temperature and dry-bulb temperature in final storage. Additional parameters can be stored by repeating instruction 70.