Evapotranspiration Measurement Methods

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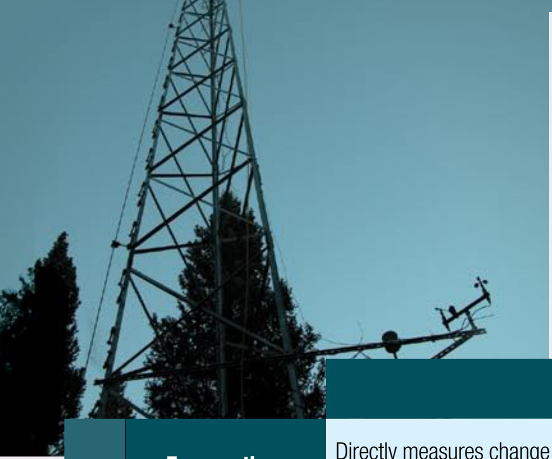

In the United States and several other countries, the term "evapotranspiration" (ET) is used when considering evaporation from vegetation-covered ground. It describes the total evaporation from the soil and wet plants plus transpiration from dry plants. The two most common types of direct-measurement methods, *water budget* and *water vapor transfer* measurements, are described first in the table below. Water budget measurements deduce ET as a loss of liquid water by measuring or estimating all the other components in a water budget. Such methods are long-established and have been refined over the years.

Water vapor transfer methods measure the

		Brief Description	Assumptions
Water budget measurements	Evaporation pan	Directly measures change in water level over time for a sample of open water in a "pan" with well-specified dimensions and siting.	Assumes relationship between measured evaporation from pans and actual evaporation from adjacent area can be calibrated, and calibration is transferable between locations and climates.
	Water balance of basin	The unmeasured difference between other measured components of the basin water balance, including incoming precipitation, surface and groundwater outflow, and soil water storage.	Assumes all other components of the basin water balance can be measured as spatial averages with sufficient accuracy for evaporation to be reliably calculated as the difference between them.
	Lysimetry	Measures change in weight of an isolated, preferably undisturbed, soil sample with overlying vegetation (if present) while measuring precipitation to and drainage from the sample.	Assumes the sample of soil and overlying vegetation on which measurements are made are representative in terms of soil water content and vegetation growth and vigor of the plot or field in question.
	Soil moisture depletion	Measures change in water content of a representative sample of undisturbed soil and vegetation while measuring precipitation and run-on/runoff and estimating deep drainage for the sample plot.	Assumes that soil water measuring devices (resistance blocks, tensiometers, neutron probes, time-domain reflectometers, capacitance sensors) adequately determine change in soil water, the effects of deep roots and sensor placement are small, and deep drainage can be estimated adequately.
Water vapor transfer methods	Bowen Ratio - Energy Budget	Calculates evaporation as latent heat from the surface energy budget using the ratio of sensible to latent heat (Bowen ratio) derived from the ratio between atmospheric temperature and humidity gradients measured a few meters above vegetation.	Assumes the turbulent diffusion coefficient for sensible heat and latent heat are the same in the lower atmosphere in all conditions of atmospheric stability, and that plot-scale measurements of energy budget components (net radiation, soil heat) are representative of upwind conditions.
	Eddy correlation (also called eddy covariance)	Calculates evaporation as 20- to 60-minute time averages from the correlation coefficient between fluctuations in vertical windspeed and atmospheric humidity measured at high frequency (~10 Hz) at the same location, a few meters above vegetation.	Assumes only turbulent transfer of water vapor at sample point, and that corrections for water vapor transfer in turbulence at time scales less than ~0.1 seconds or greater than the selected averaging time are acceptable.
Components of evaporation	Transpiration measurement by porometry or monitoring sap flow	Porometry: measured from humidity increase in a chamber temporarily enclosing transpiring leaves/shoots. Sap Flow: measured from rate of sap flow in trunk, branches, or roots using heat as a tracer, with an estimate of the area of wood through which flow occurs.	Porometry assumes the enclosure of leaves and shoots in the chamber does not significantly alter transpiration rate. Sap Flow assumes installation of sensors does not alter sap flow rate, and cross-sectional area over which flow occurs can be determined accurately.
	Rainfall interception loss from tall vegetation	Measured as difference between cumulative rainfall above/below tall (usually forest) canopy. Requires careful below-canopy sampling with gauges/troughs that sample at spatial scale of canopy features, preferably randomly relocated after each measurement interval.	Assumes below-canopy sampling is adequate, a requirement rarely met for a typical 1-2 week measurement interval. It becomes feasible over several measurement intervals if gauges are regularly and randomly relocated.
	Soil evaporation	A small-scale, shallow implementation of lysimetry or soil moisture depletion methods for a near-surface soil sample below vegetation using several "microlysimeters" or sequential gravimetric multisampling.	Assumes the average of all small soil samples, regardless of their below-canopy location, are representative of the entire soil surface.
Large-scale evaporation	Scintillometer measurements	Uses theoretical relationship between sensible and latent heat fluxes and atmospheric scintillation introduced into a beam of electromagnetic radiation between source and detector by temperature and humidity fluctuations.	Applies strictly in an ideal turbulent field close, but not too close, to a surface with uniform aerodynamic roughness. However, field experiments suggest a worthwhile measurement is possible over a mixture of vegetation covers.
	Remote sensing estimates	Evaporation is deduced indirectly from the surface energy balance, with sensible heat calculated from the difference between air temperature and the temperature of the evaporating surface, along with an estimate of the aerodynamic exchange resistance between these two.	Assumes the "aerodynamic" surface temperature (that which controls sensible heat transfer from the surface), is the same as (or can be estimated from) the "radiometric" surface temperature (that which can be measured using an airborne or satellite radiometer).
	LIDAR (LIght Detection And Ranging) method	The local time-average vertical gradient of water vapor is sampled remotely using LIDAR. Local evaporation flux is calculated from this using similarity theory and supplementary measurements of friction velocity and atmospheric stability.	Assumes Monin-Obukov similarity theory applies and the supplementary measurements of friction velocity and atmospheric stability are locally applicable within the measurement field of the LIDAR.

flow of water vapor into the atmosphere using meteorological sensors mounted above the surface. Sometimes these sensors measure evaporation not in mass terms, but in the context of the surface-energy balance as *latent heat flux*. This is the flow of energy that is transferred with the water vapor and that leaves the surface in the form of latent heat.

It can be useful to measure the separate contributions to ET: transpiration from plants, rain or snowwater evaporated from the plant canopy, and evaporation from the soil surface. Some of these methods are described next in the table.

Other recent ET measurement efforts attempt to measure area-average ET. Examples of these also are included.

An alternative to the direct measurement methods described below is to model ET rates using local climate data in empirical and analytical equations. This approach is not covered here.

ET measurement methods tend to have their champions, individuals who are convinced their method is best. When appraising the strengths, weaknesses and likely errors of the different methods, I have sought to be impartial and conservative, but the appraisal is to some extent subjective and it *is* personal!

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Strengths and weaknesses	Scale of Measurement*	Error
A long-established and well-recognized method, simple to understand and implement, and reasonably inexpensive; but because it relies on the validity of an extrapolated calibration factor previously defined elsewhere, is primarily used for crop ET estimates rather than heterogeneous natural vegetation covers.	Plot	Varies with reliability and relevance of calibration factor, but 10 to 20% errors are possible for crops, with greater errors likely for natural vegetation because calibration may be unknown.
Gives an area-average measurement for vegetation covers for a hydrologically significant region, however, area-average measurement of the other water balance terms can be expensive and difficult, especially groundwater flow and soil moisture. Consequently only longer time-average estimates are possible.	Basin	Varies with quality of implementation and size and nature of basin, but errors as low as 10 to 20% may be achievable in research basins with persistent care.
If the soil and vegetation sample is truly representative, the lysimeter is widely accepted as being an unparalleled standard against which to compare and validate other evaporation measurements and models of crop evaporation. Modern high-precision lysimeters are expensive (~$50,000) and require expert supervision.	Sample	State-of-the-art lysimeters can provide daily measurements with high accuracy (few %), but errors can become substantial (few x 10%) if the sample is unrepresentative.
Most often used in crop-covered plots. Measurement is reasonably inexpensive and, in principle, representative of the plot in which it is implemented, but disturbance during installation of soil water sensors and deep roots extending below the measurement depth can negatively influence the measurement. Deep drainage is hard to estimate.	Plot	Varies with quality of implementation but neutron probe errors of less than 10% are achievable; TDR and soil capacitance sensors are highly variable but can attain as low as 10 to 20% error.
Well-established method. Relatively inexpensive proprietary systems can be purchased that work for both short crops and natural vegetation. Problematic over tall vegetation when atmospheric gradients are low. Often cannot be used near dawn and dusk when the Bowen ratio is minus one.	Field	Errors associated with assumptions and representativeness plus errors in required supplementary sensors result in overall errors of around 5 to 15%.
Currently preferred method for field-scale measurements in research applications. Implemented using relatively expensive proprietary logger and colocated sensors, but prone to systematic underestimation of fluxes. Perhaps best used to measure Bowen ratio, with evaporation deduced from surface energy budget.	Field	Systematic underestimation up to 25% can occur in the basic evaporation measurement. If sensible heat is also measured to determine Bowen ratio and energy balance is used to calculate evaporation, error can be reduced to 5 to 15%.
<u>Porometry</u>: a manual measurement that allows determination of environmental influences on stomatal control at leaf level. <u>Sap Flow</u>: allows routine unsupervised measurement of transpiration from whole plants or plant components over extended periods.	Leaf-to-plant; plot scale with multiple sampling	<u>Porometry</u>: small for leaves (~few %). <u>Sap Flow:</u> errors assumed to be 5 to 15% for individual plants. <u>Both</u>: at plot scale, errors are strongly determined by the number of samples taken and the variability in these samples.
Allows separate identification of wet canopy contribution to ET for tall vegetation. Rarely if ever attempted for short vegetation and crops, but possible in principle.	Plot	Strongly depends on below-canopy sampling. One-gauge arrangement provides only order of magnitude estimate, but time average with many gauge relocations can reduce error to around 5 to10%.
A comparatively simple and inexpensive manual measurement. Gravimetric approach is time-intensive and the sample is destroyed, preventing repeated measurement at same place.	Plot, with multiple sampling	Strongly depends on below-canopy sampling, but errors as low as 10 to 20% are possible with many samples and care.
The only micrometerological method that can be used to provide an (albeit indirect) measurement of the line-average sensible and latent heat over several kilometers.	Field to landscape	Field comparisons between the line-average flux over several types of vegetation and eddy-correlation measurements for each vegetation type agree at the 10 to 20% level or better.
Provides opportunity for instantaneous snapshots of evaporation over large areas in clear sky conditions, but uncertainties in the effective surface emissivity and effective aerodynamic exchange resistance can give systematic errors—both being worst for sparse canopies. Therefore, ground-truth evaporation measurements are usually required.	Field to regional	With ground-truth measurements, snapshot maps of evaporation in clear sky conditions may be accurate to 10 to 20%, but time-average estimation from these snapshots introduces additional uncertainty.
Gives detailed and frequent 3-D mapping of the water-vapor gradient, valuable in assessing variations over areas with heterogeneous evaporation. However, equipment costs are extremely high and independent ET measurement is required to assess accuracy.	Field to landscape	Provides a useful measure of spatial ET variations but requires independent validation/calibration.

***Scales:** Leaf-to-plant*: the size of the basic canopy, typically square centimeters to a few square meters;* Sample*: area of the soil and vegetation sample, typically a few square meters;* Plot*: typically a few to tens of square meters;* Field*: typically a few hundreds of square meters;* Landscape*: typically a few thousands of square meters;* Regional*: typically a few square miles;* Basin*: varies from landscape to regional scale and beyond.*