Challenges and Cautions in Measuring Evapotranspiration

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In recent decades, our ability to measure evapotranspiration (ET) has improved dramatically with the availability of new instrumentation and field-portable computing power. The resulting methodologies include micrometeorological techniques, remote sensing approaches, and lysimetry. Potential users should be aware of the pitfalls, limitations, and costs of these methods when evaluating their applicability to a site.

The requirements and assumptions associated with these methods impose limits on the practical application and absolute accuracy of the data in ways that potential users should understand.

ET Measuring Techniques

Remote sensing is appealing because it can be done without on-site instrumentation and provides estimates for broad geographical areas. However, it is still primarily a research application, with no commercially available equipment or software for routine applications.

Weighing lysimetry involves placement of a load cell beneath soil that is then planted with the same vegetation as its surroundings. When properly installed, these probably yield the most accurate ET data, but installation is challenging and expensive.

Non-weighing lysimetry, also known as a water-balance approach, consists of installing soil moisture sensors at various depths beneath the surface to measure changes in soil moisture due to ET. This is probably the least expensive and most commonly used method for estimating ET, but it has numerous limitations. Chief among them is temporal resolution: ET usually cannot be measured at less than weekly resolution.

Micrometeorological methods include Bowen ratio/energy balance (BREB) and eddy covariance. Both have commercially available systems and can provide hourly data. They are now considered mature technologies, creating the impression that continuous, accurate measurement of ET is routine. However, the requirements and assumptions associated with these methods impose limits on the practical application and absolute accuracy of the data in ways that potential users should understand.

Bowen Ratio/Energy Balance

The BREB method is an indirect method based on conservation of energy. Net radiation (Rn) is measured above the surface, and soil heat flux (G) is measured below it. The difference between these two must be consumed by either evaporating water (latent heat) or heating the air (sensible heat). The ratio of sensible to latent heat, known as the Bowen ratio (ß), can be estimated from temperature and humidity measurements, each made concurrently at two heights above the surface. Measurements of Rn, G, and ß can thus be used to solve directly for the ET rate. However, all three measurements are subject to error.

New and properly calibrated net radiometers are probably accurate to within 5 percent, but age and dust deposition make them subject to drift, and they are not easily recalibrated. Long-term accuracy is typically to within 10 percent. Soil heat flux is generally measured with calibrated plates installed at a defined depth below the surface, supplemented by thermocouples in the surface layer. The accuracy of this measurement is probably not better than 10 to15 percent. The gradient measurement of air temperature is usually made with thermocouples through which air is pulled by a fan. The temperature difference between the two heights is often quite small, but data loggers can measure it with relatively high accuracy. The humidity gradient is more difficult. In most systems it is measured with either an infrared gas analyzer (IRGA) or a dew point hygrometer. Either instrument must be periodically recalibrated, and the tubing through which the air is drawn must be kept clean. Collectively, these multiple measurements with their associated errors means the overall accuracy of BREB-based ET measurements will probably not be better than 20 percent unless extreme care is taken.

Eddy Covariance

The primary attraction of eddy covariance is its conceptual simplicity. Consider a point in the atmosphere not too far above a vegetated surface. Parcels of air (eddies) will move past that point constantly. While the principal direction of movement will be horizontal, each eddy may have a vertical component as well; that is the nature of turbulence. When water is evaporating from the surface below, the upward-moving eddies will have, on average, a slightly higher mixing ratio than the downward-moving eddies. If the vertical velocity, w, and mixing ratio, h, of each eddy passing this point can be measured, then the vertical transport of water vapor through the plane containing the point can be calculated from the mean covariance of w and h.

Sensor Requirements: Eddy covariance requires instruments capable of measuring vertical wind speed and water vapor mixing ratio at the same point, at a sampling rate sufficient to capture all eddies contributing to the transport, typically 10 hertz. Suitable sonic anemometers are available, but the humidity measurement again presents a challenge. IRGAs are sufficiently fast and accurate if properly calibrated, but a choice must be made between open-path and closed-path systems. In closed-path systems, a pump draws air from the sampling point through a tube and routes it to the IRGA, in a shelter. In open-path systems, the source and detector of the IRGA are suspended in the air with open space between them. With no pump, an open-path system is easier to operate and requires less power, but is more susceptible to interference from rainfall, condensation, dust, and bird droppings. And since open-path systems measure vapor density rather than mixing ratio, the ET measurements must be corrected for density fluctuations due to sensible

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heat transfer, which can be substantial. Finally, recall that the goal is to measure fluctuations in humidity and wind speed at the same point; in a closed-path system it is possible to pull the sample air from the same volume being measured by the anemometer. In an open-path system there is a gap of at least 10 centimeters between sensors that causes an underestimation of the covariance. Corrections can be applied, but inevitably introduce additional uncertainty. Both types of IRGAs require periodic calibration, usually with a dew-point generator, adding several thousand dollars to the $25,000 to $30,000 cost of the basic eddy-covariance instrumentation.

Data analysis can be the most intimidating aspect of eddy covariance. Data collected at 10 Hertz accumulate quickly and require numerous steps to process. Software is available to perform these processes, but it requires a knowledgeable user. Detailed mathematical descriptions can be found in the listed references, but the first step, data screening, deserves a few words.

Not all data collected with an eddy-covariance system are usable. Instrument failures and environmental factors—particularly precipitation, winds from an unfavorable direction, or extremely calm conditions—can cause erratic, nonsensical results. Algorithms must be used to flag these gaps and suspicious values and replace them with informed estimates.

Site Requirements for BREB and EC

To accurately measure the ET of a given surface type, the entire "flux footprint," or area over which surface exchange is being measured, should be uniform. The surface should extend upwind for a distance approximately 100 times as great as the height of measurement. Thus, a two-meter tower requires placement at a site with 400-meter study area on each side, or around 40 acres, so that ET can be measured from any wind direction. Tower height can be lowered over shorter crops to reduce the flux footprint, but eddy size decreases and eddy frequency increases near the surface, factors which can cause systematic underestimation of the flux. Thus sensors should be at least one meter above a relatively smooth surface like grass or a row crop, and higher over rough surfaces. Additional complications arise if the measured surface is not level.

Eddy covariance and BREB are powerful methods for measuring ET, but neither is a routine, turnkey technique with universal application. Potential users should evaluate the characteristics of their site, their ability to periodically calibrate gas analyzers, and their willingness to learn and apply the necessary data processing procedures before investing the money and effort required to install either system.

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Resources

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The initial rate ranges were assessed and refined using ET rates measured for one near-average precipitation year at six eddy-covariance ET sites established specifically for this study (Moreo and others, 2007). Five of these sites were located in shrubland to evaluate the effect of vegetation density on ET rates, and to better understand the relation between ET and groundwater discharge in the dominant (greater than 80 percent) vegetation type of the study area. One site, established near a boundary between the grassland and meadowland ET units, was located in a mixed-grass riparian area to represent an environment indicative of greater ET (part C on figure). Annual ET rates based on a combination of reported and measured ET data vary slightly between basins, and range from 0.8 feet to 5.0 feet for the ET units in Spring Valley (part E on figure).

Estimating Groundwater Discharge

Average annual ET from a discharge area is estimated as the sum of the ET (the product of the ET rate and its acreage) of all the component ET units. In Spring Valley, total annual ET was estimated to be 200,000 acre-feet.Regional groundwater discharge is estimated from total ET by subtracting the volume of local precipitation falling directly on the discharge area (part F on figure). In Spring Valley, about 0.69 feet or 124,000 acre-feet of local precipitation annually falls on the 180,000-acre discharge area, thus annual regional groundwater discharge from the valley is estimated to be 76,000 acre-feet.

As the population of the Southwest increases, so will the competition and need for additional water supplies. Agencies responsible for water-resources management must be prepared to tap the limited water supply in the most efficient manner and will require more thorough quantification of the water budget beyond our current reconnaissance-level understanding. The accuracy of these estimates will rely, to a large degree, on a representative basin- or region-wide coverage of spatial and temporal ET measurements. And just as importantly, accurate estimates of ET and groundwater discharge will improve confidence in the results of modeling efforts, particularly those directed at predicting the effects of increased groundwater pumping.

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