ET MEASUREMENTS OVER RIPARIAN SALTCEDAR ON THE COLORADO RIVER

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Abstract

Evapotranspiration (ET) from an extensive stand of saltcedar on the Colorado River floodplain was defined throughout the growing season by a series of Bowen ratio energy budget measurements in 1980 and 1981. The water table depth at the site near Blythe, California, was about 3 m during the two summers of measurement. Daily ET totals ranged from 2.9 mm/day in early April up to 11.0 mm/day in late June, and dropped down to 1.8 mm/day in late October. These values are means from two separate measurement systems, averaged over measurement periods of two to four days in length. The highest single day total measured by an individual system was 12.7 mm on June 28, 1981. The mid-summer ET rates from the saltcedar at this experimental site are substantial, and rank among the highest rates that have been reported elsewhere for irrigated cropland. The seasonal saltcedar water use of 1727 mm (including 90 mm of annual precipitation) is somewhat lower, however, than earlier, more speculative estimates for saltcedar that ranged up as high as 2100 mm per year.

Introduction

The lower Colorado River flows through one of the warmest, driest regions in the United States. For example, the average annual rainfall at Blythe, California airport is only 78.7 mm (3.1 inches), and the maximum temperature of record is 50°C (122°F). Maximum temperatures frequently exceed 46°C in each month from May through September. The Colorado River serves as a large source of irrigation water for this arid region, however, and this supports a prosperous, flourishing agricultural industry.

The Colorado River also supports extensive riparian plant communities on its floodplain. The composition of these communities has changed through the years, as native species such as mesquite (*Prosopis* sp.) have been generally replaced by saltcedar (*Tamarix chinensis*). Saltcedar is widely perceived as a heavy user of water that might otherwise be available for more beneficial use by man, and so it has been studied extensively for many years in the southwest.

The studies have evaluated both the consumptive use of saltcedar, and means for eradicating the plant in order to "salvage" water and thus augment existing water supplies. The earlier work on water use was summarized by Horton and Campbell (1974) who concluded (1) that a dense, mature stand of saltcedar would use 1.8 to 2.1 m (6 to 7 ft) annually on the Gila River near Phoenix, (2) the somewhat higher elevation sites at Safford, Arizona, and Carlsbad, New Mexico, would lose about 1.5 to 1.8 m (5 to 6 ft), and (3) use at the still higher elevation Bernardo site near Albuquerque would be about 1.2 to 1.4 m (4 to 4.5 ft) per year. The climatic conditions along the lower Colorado River are even more extreme than on the Gila River, and this should increase riparian water use, especially since the stable flows of the now-controlled Colorado provide for relatively high ground water tables beneath the extensive, heavily vegetated floodplains.

It is surprising to conclude that definitive estimates of water use by riparian species are lacking in the southwest, despite the wide interest in this topic. This is partly due to the complexities of the problem. Water use depends not only upon the climatic regime, but also upon type and density of vegetation and the supply and salinity of water. The lack of water use measurements is also partly due to limitations of the various experimental approaches. For example, Van Hylckama's (1974) lysimeter water budget studies are the basis for the Gila River water use figures cited above. Van Hylckama pointed out that lysimetric measurements are not only time consuming, but the results can be extrapolated only to areas of similar characteristics. The same restriction applies to water budget studies such as the comprehensive measurements described by Hansen, et al. (1972) along a 15-mile reach of the Gila River in eastern Arizona. The energy budget approach offers possibilities for generalization, but the energy budget studies in saltcedar have extended over periods of only a few days (Gay and Fritschen, 1979a).

It is apparent that improved estimates of water use by riparian communities would contribute to better management of our limited water resources. ET should be estimated from measurements that take into account environmental and vegetative differences between sites. The energy budget is such a method that has proven useful for field estimates of ET in agriculture and in natural communities as well. Consequently, we began several years ago to evaluate ET with the energy budget method in a large stand of saltcedar along the lower Colorado River.

Objectives

The objectives of this study were threefold: (1) to develop an estimate of seasonal ET; (2) to evaluate short term ET rates as an aid for process studies and for later modeling; and (3) to refine and develop measurement techniques for the energy budget method.

Methods

The energy budget method was chosen for this study because its fundamental basis allows generalizations to areas other than where the experiments were conducted. The method requires a moderate level of technical sophistication in order to operate in the field and away from the laboratory. The theory is well-known and has been thoroughly described (see, for example, Monteith, 1973).

The Bowen Ratio Energy Budget Model

The energy balance equation is a statement of the conservation of energy, i.e., the sum of all energy fluxes for a given system must equal zero. The major thermal fluxes in the soil-plant-atmosphere system at the surface of the earth are expressed as:

$$Q^* + G + H + LE = 0. \qquad (1)$$

The symbols are: Q^*, net radiation; G, soil heat flux or change in thermal storage; H, convection or sensible heat; and LE, latent heat of vaporization. Photosynthetically fixed energy is small and is disregarded. The units are either energy flux densities (i.e., W/m^2) or energy totals for a specified time period (i.e., J/m^2). All fluxes directed to the earth's surface, whether from above or below, are positive and all fluxes away from the surface are negative.

Bowen (1926) introduced the ratio of convection to latent energy ($\beta = H/LE$) as a means of estimating some of the fluxes in Equation (1). The Bowen ratio reduces to:

$$\beta = H/LE = \lambda \ \partial\theta/\partial e \qquad (2)$$

where λ is a coefficient equal to 0.66 mb/^{o}C at sea level, and $\partial\theta/\partial e$ is the ratio of potential air temperature gradient ($\partial\theta/\partial z$, ^{o}C/m) to vapor pressure gradient ($\partial e/\partial z$, mb/m).

The model assumes that the eddy diffusivities for heat and for vapor are equal to unity over the distance across which the temperature and vapor gradients are measured. In practice, $\partial\theta/\partial z$ and $\partial e/\partial z$ are approximated by measurements of differences ΔT and Δe across a vertical distance Δz. The distance Δz is usually about 1 m, and the bottom level of measurement is a little above the top of the canopy. The Bowen ratio method has been widely used for measuring ET, and the basic accuracy of the model is well documented (see, for example, Fritschen, 1965). The measurements do require careful work and high precision, however, in order to achieve the desired accuracy.

The Measurement System

The system used for the Bowen ratio measurements is similar to that described earlier by Gay (1979). The key features are: a data acquisition system of excellent precision; a microprocessor computer; precisely calibrated, ceramic wick psychrometers (Gay, 1973; Hartman and Gay, 1981); and an exchange mechanism to interchange the psychrometers between observations. Net radiation and soil heat flux are also measured, and supplementary measurements are made of solar radiation, wind speed and direction. The data acquisition and processing equipment is housed in a small van; power is provided by a portable generator. Two sets of sensors are mounted on separate masts so that two independent ET estimates are obtained.

The psychrometer mechanisms were placed so that the lower psychrometer was just above the tips of the canopy, and the two sampling levels were separated by a vertical distance of 92 cm. The pair of psychrometers was interchanged every 6 minutes so that mean temperature and humidity gradients could be obtained each 12 minutes, free of instrument bias (Sargeant and Tanner, 1967). The exchange mechanism is described in detail by Gay and Fritschen (1979b). The mean 12-minute gradients were based on 40 samples at the two levels, after the psychrometers had comne into equilibrium following the interchange.

Data Acquisition and Processing

The data logger houses a 40 channel scanner, an integrating digital voltmeter, a real-time clock, and a strip printer, all in a compact case. The maximum resolution of the voltmeter is better than 0.001% (1 μV in 120 mV full scale), at a scan rate of 2.4 readings per second. The data logger has an averaging option that compresses many sequential samples into a single average for transmission to the microprocessor computer for analysis.

The Tektronix 4051 computer is a microprocessor-based system with graphics capability on a CRT screen. Computing and graphics functions are specified in BASIC language. The unit has 32K bytes of internal memory, and has an internal magnetic tape cassette with capacity of 450K bytes. Raw and processed data are stored on the magnetic tape for subsequent retrieval and further analysis when desired.

Site Description

The saltcedar study area was a vast saltcedar thicket of some 10 km^2 in area, located on the floodplain of the Colorado River some 50 km south of Blythe, California. The elevation was about 90 km. The fetch at the measurement site was about 1 km to the west, and from 2 to 3 km in the other cardinal directions. The height of the vegetation was about 7 m. The sandy soils were spotted with coarse pockets laid down by the meandering river channel in the past. The water table remained constant at about 3.3 m throughout the two summers of measurement.

Sampling

The effects of spatial variability were minimized by selection of a site in a dense, relatively homogenous portion of the stand. The two masts were separated by about 10 m, and they are considered to sample the same area. Temporal variability was minimized by frequent sampling within a given day and by sampling for several consecutive days within each month. The energy budget (and latent energy) each day was summed from the 12-minute means, each of which was based on 40 measurements.

Results and Discussion

The data collected in this study represent an unusually precise evaluation of ET rates from saltcedar throughout the growing season. We shall first examine some of the daily measurements, and then look at the implications for seasonal water use.

Daily Measurements

The energy transfer rates throughout the day are illustrated in Figure 1 for July 28, 1980, for the daylight period when $Q^*>0$. This day was the warmest of all those sampled. The midafternoon air temperature reached 45.1°C, with a relative humidity of 15.6%. The Figure shows the single value of G, mean values (averaged

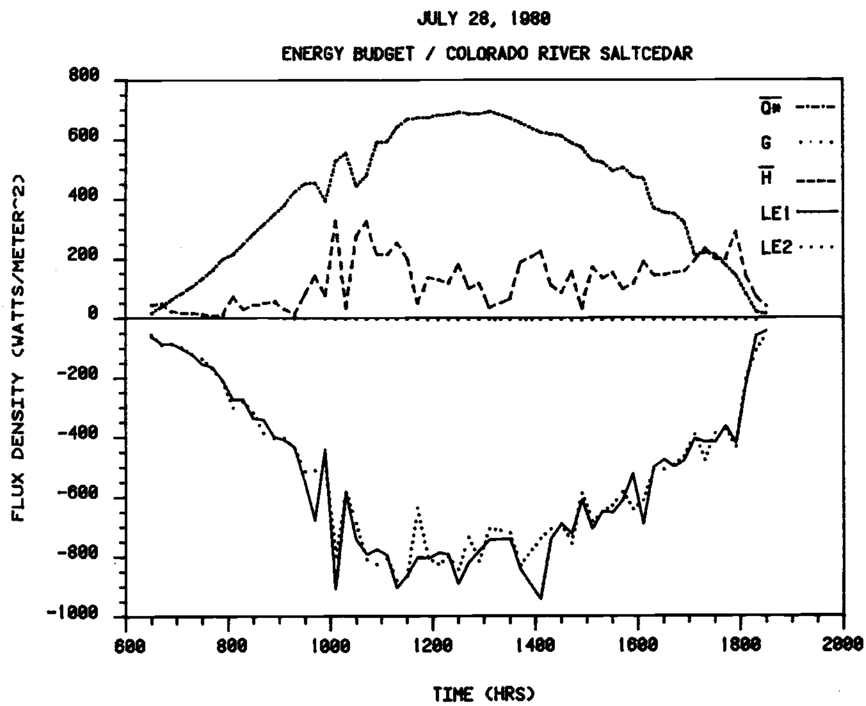

Figure 1.--Daytime energy budget over saltcedar on the Colorado River floodplain. Net radiation ($\overline{Q^*}$) and convection ($\overline{H}$) are means from two sets of sensors; latent energy (LE_1 and LE_2) is shown separately for each set of sensors. Soil heat flux (G) was measured with a single disc.

Table 1.--Energy budget totals (in MJ/m^2 and equivalent mm depth of evaporated water) for 0624-1836 July 28, 1980.

Flux	MJ/m^2	mm
$\overline{Q^*}$	18.3	7.32
G	- 0.2	-0.08
$\overline{H}$	5.4	2.16
$\overline{LE}$	-23.5	-9.40
(LE_1/LE_2)	(-23.8/-23.2)	(9.52/9.28)

between masts) of $\overline{Q^*}$ and $\overline{H}$, and the separate mast estimates of LE_1 and LE_2.

The smooth trace of Q* confirms the rather clear sky conditions that day, marred only briefly by clouds in midmorning. The value of G is quite small, confirming that very little soil heat flux takes place beneath the closed canopy in this stand. The amount of energy stored in the foliage was considered negligible, and no correction for this quantity was applied to G. The positive value of $\overline{H}$ confirms that advection took place all day long as warm air moved from the surrounding desert, across the relatively cool, evaporating canopy. $\overline{LE}$ is essentially the sum of $\overline{Q^*}$ and $\overline{H}$ since $G \to 0$.

The close correspondence of LE_1 and LE_2 is indicative of the precision with which the two sets of sensors are estimating $\overline{LE}$. It is apparent from the Figure that the two sets of sensors are in exceedingly close agreement, but serial correlation prevents us from establishing confidence limits on the precision. The closeness of the daily totals also serves as an index of precision. Flux totals are summarized for July 28, 1980, in Table 1 for the daylight period of positive net radiation. The range in estimates of $\overline{LE}$ by LE_1 and LE_2 is only ±1.3%. This is a very close comparison, especially since the commonly accepted accuracy estimates for Bowen ratio evaluations of LE are ±10% or 15%.

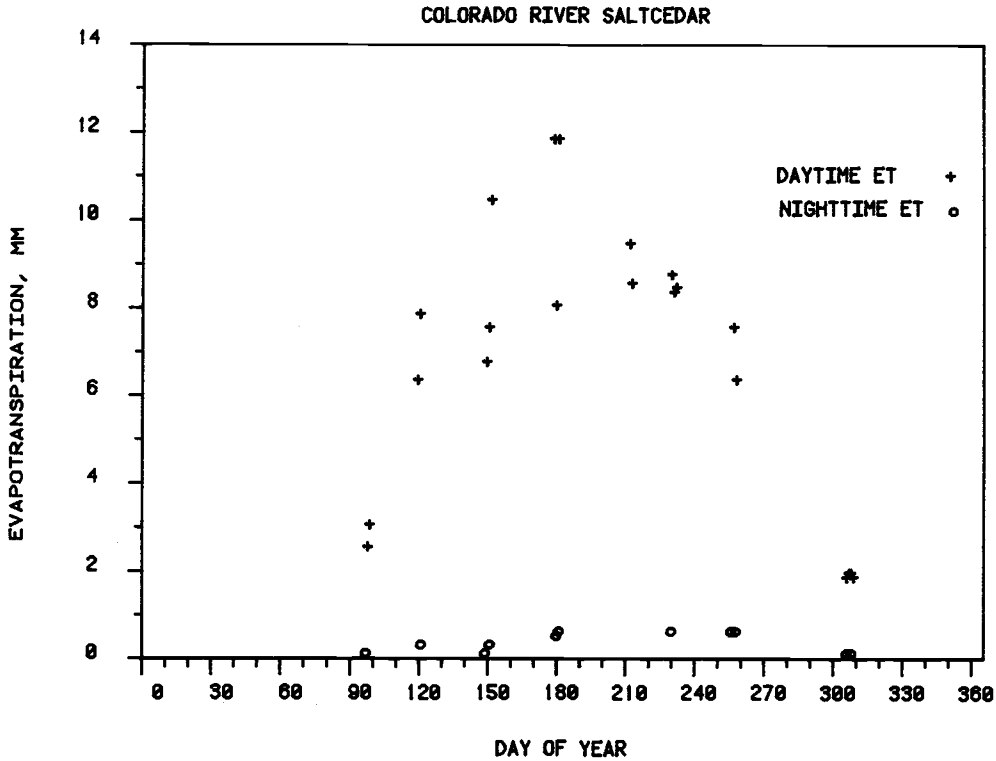

Figure 2.--Daytime and nighttime evapotranspiration totals from saltcedar on the Colorado River floodplain.

Estimates were obtained for the daylight period of positive net radiation on 21 days throughout the growing season. The number of successive days in each run ranged from 2 to 4. Night time data were obtained from 11 nights during this period. The totals obtained from each date (averaged between masts) are plotted in Figure 2, for day and for night. The daylight water consumption ranged from around 2 mm/day in spring and fall up to 12 mm in midsummer. The nighttime water use was small, and ranged from 0.08 mm in spring and fall up to 0.6 mm in midsummer.

Since there are "missing" nights, we shall examine measured daylight totals as an indication of accuracy, and then extrapolate nightime observations as needed to obtain 24-hour totals for estimating seasonal water use.

The daytime water use measured at site 1 (ET_1) is regressed against that measured at site 2 (ET_2) in Figure 3. The linear equation $ET_1 = -0.03 + 0.945\ E_2$ has $r^2 = 0.991$. The scatter is very small; 95% confidence limits at $ET_2 = 6.45$mm are only ±0.03%. The offset (-0.03 mm) and the failure of the slope coefficient to equal unity (0.945) suggest a difference in evaporation rates at the two sites. This was confirmed by exchanging sensors between masts during several successive runs. The small difference remained, thus eliminating instrumentation as the cause of the observed difference. The precision of these measurements derives from improvements described by Hartman and Gay (1981). These include the care used in sensor calibration, the experimental design (exchanging psychrometers, frequent samples, timing of analysis), and the high quality of the data acquisition and processing system.

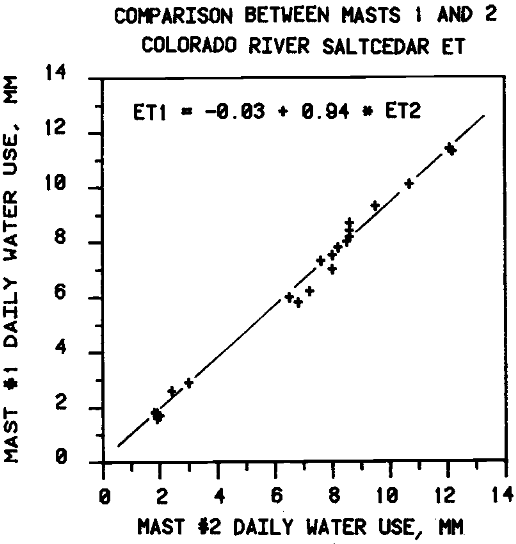

Figure 3.--Comparison of daytime ET from mast 1 versus mast 2.

Seasonal Water Use

The seasonal water use estimate is derived from averages for each of the two to four day runs. The values in Figure 2 are averaged and tabulated in Table 2, thus providing data for evaluating evapotranspiration losses throughout the growing season.

For this purpose, it is assumed that evapotranspiration is negligible throughout the dormant season. This is likely, since the saltcedar loses its leaves. Further, winter rainfall is low, and a layer of dry sand at least a meter thick overlies the water table which is 3.3 m deep. The spring greenup and fall dormancy date is arbitrarily set at March 23 and November 11, based upon inspection of the data in Table 2.

A simple trapazoidal integration of the evapotranspiration for the 233 day growing season yields the following totals: day, -1548 mm; night, -89 mm; total, -1637 mm.

The 1637 mm of evapotranspiration were developed from measurements of water transpired by the saltcedar. This total should be increased by some percentage of the annual rainfall to yield a better estimate of annual evapotranspiration. The annual precipitation at Ehrenberg, Arizona, 4 miles east of Blythe and about 25 miles north of the saltcedar site, averaged 89.7 mm (3.53 in) for the 1931-72 period (Sellers and Hill, 1974). Of this meager amount, 47% or 42.3 mm fell during the April through October growing season, and the remainder during the dormant season. The storms are generally light and infrequent, and it is probable that essentially all of the precipitation falling on the floodplain in this region evaporates, i.e., there is no effective runoff. Our measurements did not coincide with rain, and there was little evidence of any antecedent soil moisture in the dry blanket of sand at this site. In our judgment, the evapotranspiration estimate should then be increased 42 mm during the growing season and 48 mm during the dormant season to account for direct evaporation of rainfall, and thus yield a "best" estimate of 1727 mm of evapotranspiration over the year.

Table 2.--Mean daily totals (in mm) based upon two separate masts and dates as shown.

	day	night*	24-hour
Apr 6,7	- 2.8	-0.1	- 2.9
Apr 28,29	- 6.8	-0.3	- 7.1
May 28,29,30	- 8.2	-0.4	- 8.6
Jun 26,27,28	-10.5	-0.5	-11.0
Jul 28,29	- 9.0	-0.6	- 9.6
Aug 15,16,17	- 8.4	-0.6	- 9.0
Sep 12,13	- 6.9	-0.5	- 7.4
Oct 30-Nov 2	- 1.8	-0.1	- 1.9

*includes interpolated values.

Other estimates from this region are quite generalized. For example, the U.S. Bureau of Reclamation (1964) estimated that there were 4,593 ha of saltcedar on reach number 4, which extends south from Blythe-Ehrenberg some 30 miles to a point just below the measurement site. The annual water use was given as 62,401,704 m^3, or a depth equivalent of 1359 mm excluding precipitation. The Bureau estimates were based on the Blaney-Criddle method, adjusted for density of vegetation throughout the reach. The agreement is quite good, considering that the saltcedar at our measurement site was quite dense, and should be using water at a near maximum rate.

More speculative estimates from other regions range up to 2100 mm for the Gila River near Phoenix (Horton and Campbell, 1974). The climatic conditions are warmer and drier on the lower Colorado River than on the Gila, and it seems unlikely that even more favorable vegetation density and water availability combinations could exist to generate the high water use estimates of Horton and Campbell.

References Cited

Bowen, I. S. 1926. The ratio of heat losses by conduction and evaporation from any water surface. Phys. Rev. 27:779-787.

Fritschen, L. J. 1965. Accuracy of evapotranspiration determinations by the Bowen ratio method. Int'l Assoc. Hydrol. Bull. 10:38-48.

Gay, L. W. 1973. On the construction and use of ceramic wick psychrometers. In: Brown, R. W., and B. P. Van Haveren (Eds.). **Psychrometry in Water Relations Research**. Pp. 251-258. Utah Agric. Experiment. Sta., Logan.

Gay, L. W. 1979. A simple system for real-time processing of energy budget data. Proc., Symposium on Forest Meteorology, Ottawa. WMO No. 527, pp. 224-226. WMO, Geneva.

Gay, L. W. and L. J. Fritschen. 1979b. An exchange system for precise measurements of temperature and humidity gradients in the air near the ground. Proc., Hydrol. Water Resour. Ariz. and SW 9:37-42.

Hansen, R. L., F. P. Klipple and R. C. Culler. 1972. Changing the consumptive use on the Gila River floodplain, southeastern Arizona. In: **Age of Changing Priorities for Land and Water.** Proc., ASCE Irr. Drain. Div. Spec. Conf. Spokane. Amer. Soc. Civil Engrs.

Hartman, R. K. and L. W. Gay. 1981. Improvements in the design and calibration of temperature measurement systems. Proc., 15th Conf. Agric. Forest Meteor., pp. 150-151. Amer. Meteor. Soc., Boston.

Horton, J. S. and C. J. Campbell. 1974. Management of phreatophyte and riparian vegetation for maximum multiple use values. Res. Pap. RM-117. USDA Forest Service, Rocky Mtn. Forest and Range Exp. Sta., Fort Collins.

Monteith, J. M. 1973. **Principles of Environmental Physics.** Arnold, London. 241 pp.

Sargeant, D. H. and C. B. Tanner. 1967. A simple psychrometric apparatus for Bowen ratio determinations. J. Appl. Meteor. 6:414-418.

Sellers, W. D. and R. H. Hill. 1974. **Arizona Climate 1931-1972.** Univ. Arizona Press, Tucson. 616 pp.

U. S. Bureau of Reclamation. 1964. Pacific Southwest Water Plan. Supplemental Information Report on Water Salvage Projects - Lower Colorado River. USBR, Boulder City, Nevada.

Van Hylckama, T. E. A. 1974. Water use by saltcedar as measured by the water budget method. U. S. Geol. Survey Prof. Pap. 491-E. GPO, Washington.

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