Bowen ratio estimates of evapotranspiration for *Tamarix ramosissima* stands on the Virgin River in southern Nevada

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Abstract. A Bowen ratio energy balance was conducted over a *Tamarix ramosissima* (saltcedar) stand growing in a riparian corridor along the Virgin River in southern Nevada. Measurements in two separate years were compared and contrasted on the basis of changes in growing conditions. In 1994, a drought year, record high temperatures, dry winds, and a falling water table caused partial wilt of outer smaller twigs in the canopy of many trees in the stand around the Bowen tower. Subsequently, evapotranspiration (ET) estimates declined dramatically over a 60-day period (11 mm d^{-1} to <1 mm d^{-1}). In 1995, the Virgin River at the Bowen tower area changed its course, hydrologically isolating the *Tamarix* stand in the vicinity of the tower. In 1996, a 25% canopy loss was visually estimated for the *Tamarix* growing in the area of the tower. Higher soil temperatures relative to air temperatures were recorded in 1996 in response to this loss in canopy. With a more open canopy, thermally induced turbulence was observed in 1996. On day 160 of 1996, a 28°C rise over a 9-hour period was correlated with increased wind speeds of greater than 4 m s^{-1}. Subsequently, higher ET estimates were made in 1996 compared to 1994 (145 cm versus 75 cm). However, the energy balance was dominated by advection in 1996, with latent energy flux exceeding net radiation 65% of the measurement days compared to only 11% in 1994. We believe this advection was on a scale of the floodplain (hundreds of meters) as opposed to regional advection, since the majority of wind (90%) was in a N–S direction along the course of the river, and that a more open canopy allowed the horizontal transfer of energy into the *Tamarix* stand at the Bowen tower. Our results suggest that *Tamarix* has the potential to be both a low water user and a high water user, depending on moisture availability, canopy development, and atmospheric demand, and that advection can dominate energy balances and ET in aridland riparian zones such as the Virgin River.

1. Introduction

Tamarix ramosissima (saltcedar) has invaded much of the riparian habitat in the southwestern United States. Monospecific stands of *Tamarix*, ~30 years in age, now dominate a 1.2-km-wide floodplain surrounding the lower stretches of the Virgin River in southern Nevada. Only remnant pockets of willow (*Salix exigua* and *Salix gooddingii*) and mesquite (*Prosopis pubescens*) now exist on the southernmost reach of the river. *Tamarix* invasion not only represents a deterioration of this riparian habitat, but it also represents a potential source for higher water loss from this riverine system via transpiration. Transpiration estimates for *Tamarix* growing on the Virgin

River using the stem heat balance method have been reported to exceed potential evapotranspiration by a factor of 1.6–2.0 during hot summer months when water availability was high [*Sala et al.*, 1996]. Irrigation studies with *Tamarix* on the Virgin River revealed that 87% of the variability in transpiration could be accounted for when irrigation volume, leaf area density and average ratio of height to distance of nearest neighboring trees were included in a regression equation [*Devitt et al.*, 1997a]. It was concluded from these studies that any attempt to characterize evapotranspiration of full stands of *Tamarix* would require a detailed spatial assessment of stand density and an evaluation of water availability relative to atmospheric water demand as a function of time. Further studies by *Devitt et al.* [1997b] suggested that even after *Tamarix* was subjected to water deficit conditions (90% soil water depletion) in which sapflow approached zero, sapflow increased to near prestress values within 24 hours of a water application. All of these results suggest a complex approach would be required to scale transpiration estimates from the leaf/tree level to the

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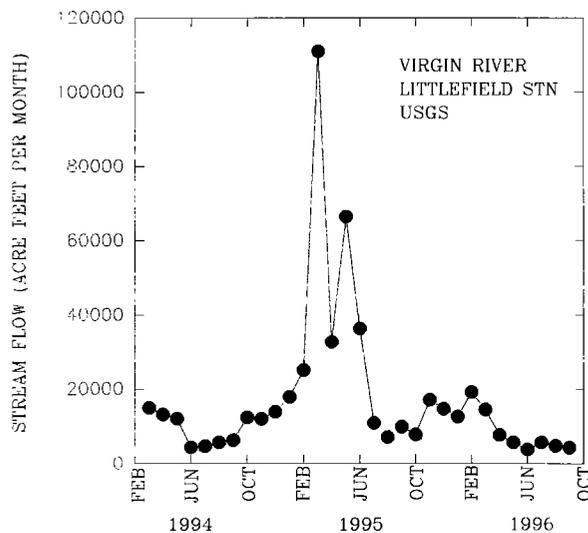[1]Now at Department of Biological Sciences, University of Nevada, Las Vegas.

Figure 1. Monthly stream flow in m^3 at the Littlefield gauging station on the Virgin River during 1994–1996.

stand/watershed level over time. Use of an energy transfer approach such as the Bowen ratio technique has proved to be accurate at this larger stand level, both in floodplains dominated by *Tamarix* [*Gay and Fritschen*, 1979; *Weeks et al.*, 1987; *Leppanen*, 1981] and in other forest settings [*Gash and Steward*, 1975; *Dawson*, 1996]. The objective of this reseɛrch was to make longterm (2+ years) Bowen ratio ET estimates of a monospecific *Tamarix* stand growing on the Virgin River and then to evaluate ET and energy balance changes over time with changes in growing conditions.

2. Material and Methods

A field study to quantify Bowen ratio ET estimates of *Tamarix ramosissima* (Ledeb) was conducted during 1994–1996 along the lower Virgin River (southern Nevada). The site was located in the floodplain near the northern boundary of Lake Mead National Recreational Area (36° 35′ N, 114° 20′ E, elevation 380 m). The site consisted of a monospecific stand of mature *Tamarix* thickets growing on raised river sediment deposits within the 1200-m-wide floodplain. At the experimental area, the height of the *Tamarix* was ~4 m. Annual rainfall in this region is usually <10 cm y^{-1}, with maximum air temperatures recorded in July of 50°C and annual potential evapotranspiration of 220 cm [*Devitt et al.*, 1989]. Depth to the water table at the site varied throughout the year and from year to year with values ranging from 2 to >3 m.

A Bowen ratio energy balance (BREB) approach was used to estimate canopy level ET by *Tamarix* [*Bowen*, 1926]. An 8-m Bowen tower was erected over a dense full canopy stand of *Tamarix*, ~312 m from the desert edge. Local fetch requirements were typically met, as prevailing wind direction was N–S, along the riparian corridor, where *Tamarix* canopy formed a fairly continuous cover over the width of the floodplain.

The instrumentation used was based upon the design commercially available from Campbell Scientific (Logan, Utah). A net radiometer (REBS, Seattle, Washington) was mounted at 4 m above the canopy. Vapor pressure, air temperature, wind speed, and wind direction were measured at 1.5 and 4 m above the canopy. Vapor pressure above the canopy was measured in

air samples taken alternately at each sensor height, from the end of an arm extending 1.3 m from the main tower structure. The air samples were aspirated to a single relative humidity/air temperature sensor (Humicap, Vaisala, Sweden) after passing through a mixing chamber. Air temperatures were measured with fine wire chromel-constantan thermocouples (0.025 mm), mounted at the end of the arms. Wind speed and direction were measured with a RM Young wind sentry wind set (Traverse City, Michigan). Soil heat flux was estimated from measurements ɩaken with a soil heat flux plate mounted at 8 cm below the soil surface (REBS, Seattle, Washington) and changes in soil heat storage estimated from changes in soil temperature above the plate. Soil heat transfer calculations were based on measured soil bulk densities and soil relative water contents. All sensors were operated by a CR10 data logger (Campbell Scientific, Logan, Utah), and data were recorded as 20-min averages.

Surface flow in the Virgin River (U.S. Geological Survey (USGS), Littlefield, Arizona, gauging station, 57.9 km upstream from Lake Mead) was obtained as 1-day total stream discharges (USGS, Surface water data retrieval, http://h20. usgs.gov/swrl 1997). The electrical conductivity of the river water averaged 2.84 dS m^{-1}. Complete chemical analysis of the water is reported elsewhere [*Devitt et al.*, 1997a].

Data were analyzed with descriptive statistics and regression analysis. Significant results were reported only when the regression coefficient had a $p \leq 0.05$.

3. Results

During the 3-year monitoring period of this study, surface flow in the Virgin River (Figure 1) remained below 24.7 × 10^6 m^3 (20,000 acre feet) per month except during a five month period in 1995 when a flood event occurred in March (123.3 × 10^6 m^3; >100,000 acre feet). In 1995 the accumulated yearly flow was 440.3 × 10^6 m^3 (357,000 acre feet), which was typical of high flow years on the Virgin River which occur on the average every 5 years. Thirteen yearly flow totals >317.0 × 10^6 m^3 (257,000 acre feet) have occurred since 1930. The 1995 flow was at least 2.7 times greater than that measured in 1994 or 1996. Of greater significance was the fact that the flood event in 1995 caused the river to change its course, thereby subjecting the *Tamarix* near the Bowen tower to decreased moisture availability in 1996. The *Tamarix* in the area around the Bowen tower (>500 m) had full canopy development prior to 1996. A shift in the river did not cause increased growth in the area around the new channel, but it did cause increased plant stress in the area around the old channel. This would suggest that subsurface flow of water had been significantly altered. Because the flood event that occurred in 1995 damaged the Bowen tower, enabling only limited data to be acquired during a significant portion of the year, we have focused our data analysis and interpretation on the 1994 and 1996 growing seasons.

Canopy loss in 1996 was visually estimated to be 25%, covering an area that was several hectares in area. To determine if this estimated canopy loss associated with the change in the course of the river had any significant impact on heat transfer within the canopy, the relationship between air temperatures (1.5 m above the canopy) and soil temperatures (6 cm depth) were compared in both years (Figure 2). Air temperatures were higher than soil temperatures during the active growing period (days 120–300) in 1994 (air 36.7°C, soil 29.8°C, df 167, 2 tailed t test 0.001). However, in 1996, no clear separation in
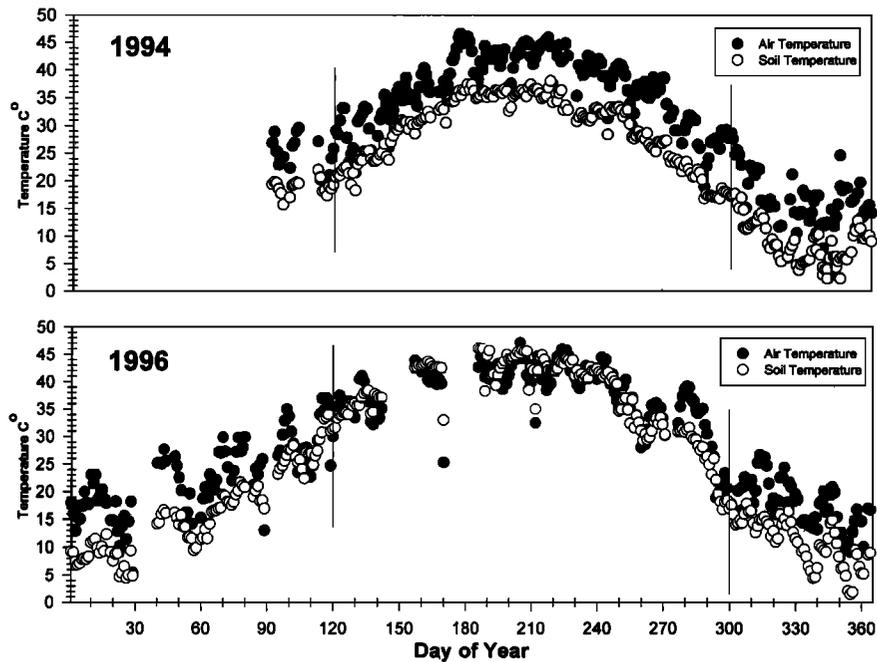
Figure 2. Maximum air temperatures (°C) at 1.5 m above the Tamarix and maximum soil temperatures (°C) at 6 cm below the soil surface at the Bowen tower site during 1994 and 1996.

air and soil temperatures could be observed (air 37.1°C, soil 36.3°C, df 154, 2 tailed t test 0.346). Although we recognize that maximum air and soil temperatures would not occur at the same time, the shift observed clearly substantiates that significant loss in canopy did occur. Near surface soil moisture content measured with TDR in a companion study [*Devitt et al.*, 1997a] indicated that soil moisture in the region of 6 cm remained extremely low ($\theta < 0.05$) throughout the summer months, suggesting that changes in soil temperatures were not driven by changing soil moisture contents. With a more open canopy, thermally induced turbulence was observed to occur in

1996. On day 160 of 1996, a 28°C rise over a 9-hour period was correlated with increased wind speeds of >4 ms^{-1} (wind (m s^{-1}) $= -1.8959 + 0.1124$ temperature (°C), $n = 72$, $r = 0.87$, $p = 0.001$), with the most dramatic rise occurring between the hours of 1000 and 1400 (Figure 3).

Evapotranspiration (ET) estimates (Figure 4) generated from energy balance calculations were averaged for each month and plotted with average net radiation (R_n) values to determine if significant change in ET occurred that could not be explained by energy input (Figure 5). R_n curves developed for both years were not significantly different ($p = 0.001$). In
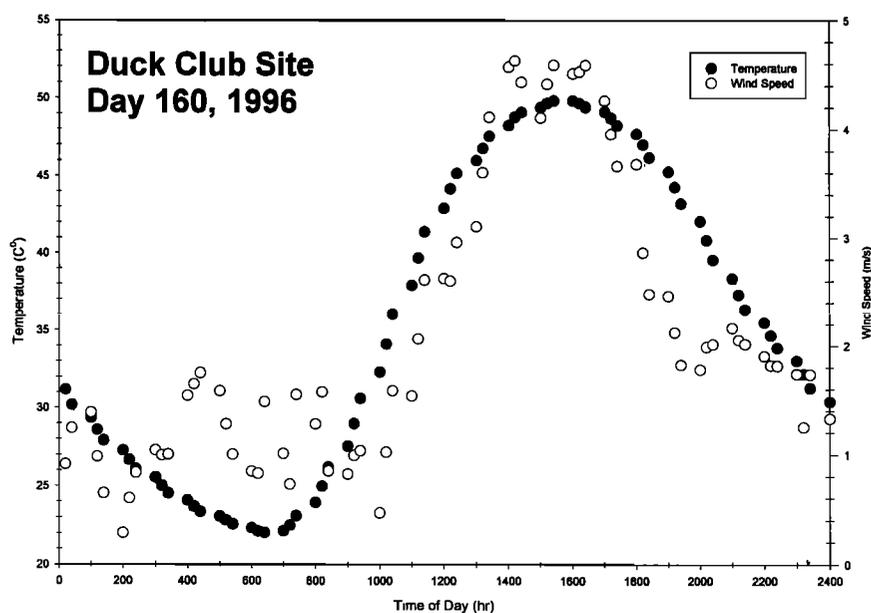

Figure 3. Air temperature (°C) and wind speed (m s^{-1}) at 1.5 m above the Tamarix (Bowen tower) recorded every 20 min on day 160 of 1996.
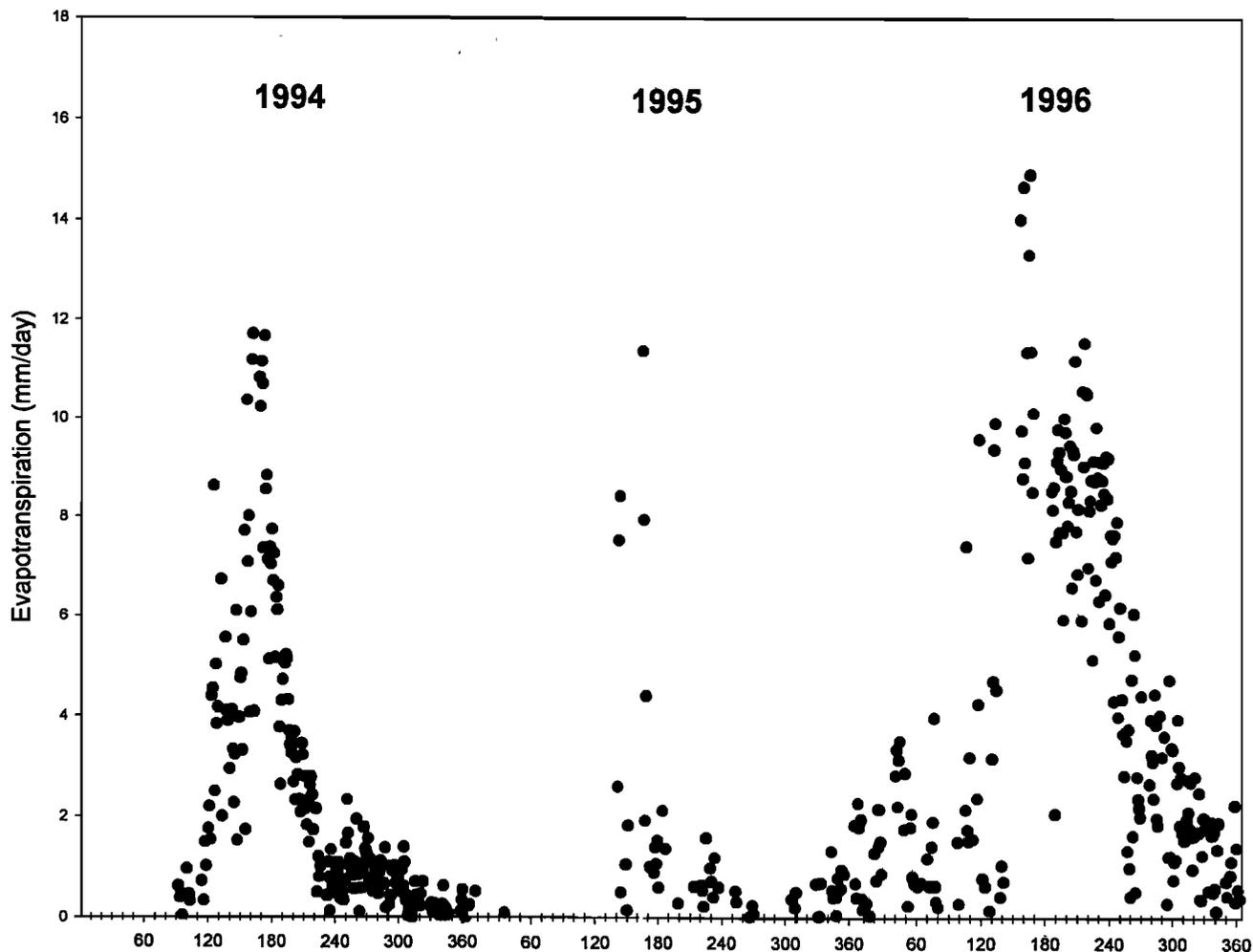
Figure 4. Bowen ratio evapotranspiration estimates (mm d^{-1}) during 1994–1996.

June of 1994, record high temperatures and dry winds associated with falling water tables (zero surface flow) caused partial wilt of outer smaller twigs in the canopy of many trees in the stand around the Bowen tower [*Devitt et al.*, 1997a]. Following this stress period, ET estimates fell rapidly over the next 60 days. Maximal ET values in June were in excess of 11 mm d^{-1}, but by August, values had dropped to below 1 mm d^{-1}, even though net radiation values were still above 150 W m^{-2}. In 1996, even though canopy loss occurred (surface flow in channel), significantly higher ET rates were estimated for the summer months. The ET estimates in both years (days 120–300) were closely correlated with the change in net radiation (1994, ET = 8.84 − 0.16NR + 0.0007NR^2, r = 0.91, p = 0.01, 1996, ET = 11.02 − 0.17NR + 0.0008NR^2, r = 0.88, p = 0.01), however, yearly estimates of ET were 75 cm in 1994 and 145 cm in 1996. Average values for January–March 1994 were extrapolated from the data; minimal error was believed to occur with these estimates since the trees were without leaves during this time period.

Complete energy balances were plotted for four separate days in 1994 that represented the time period over which ET significantly declined in response to water stress. Days as close to those selected in 1994 were chosen in 1996 for comparison (Figures 6 and 7). On day 161 in 1994 latent energy (LE) exceeded net radiation (R_n) between the hours of 1200 and 1500 and ET was estimated at 11.2 mm d^{-1}. By day 184 (early July), ET estimates had dropped to 6.4 mm and LE was less than R_n between the hours of 0900 and 1600. A significant decline in ET (2.8 mm) occurred by day 212 (late July), with sensible heat exceeding LE between the hours of 0900 and 1600. Finally, by day 232 (mid-August), ET had declined to a value of 0.4 mm d^{-1} with sensible heat dominating the energy balance. In 1996, on day 160 ET was estimated at 14.7 mm and LE was significantly greater than R_n between the hours of 1000 and 1800. On day 187, ET was 8.2 mm and LE exceeded R_n between the hours of 1100 and 1700. By day 211, ET was still high at 8.2 mm and LE exceeded R_n between the hours of 1100 and 1800. Finally, by day 230 ET was estimated at 6.4 mm, with LE still exceeding R_n between the hours of 1300 and 1800.

Advection was inferred whenever LE exceeded R_n. The percentage of days (between days 120 and 300) in which daily total estimates of LE exceeded R_n was 11% in 1994 and 65% in 1996. On those days in which LE exceeded R_n, LE surpassed R_n by an average of 35 ± 22% in 1994 and 36 ± 30% in 1996. Advection days were scattered throughout both years with no significant correlation (NS) with daily air temperatures. Although the riparian area was surrounded by dry desert areas with sparse vegetation, the prevailing wind pattern was in a north–south direction along the river course. Between the hours of 0600 and 2000, wind originating from either an east
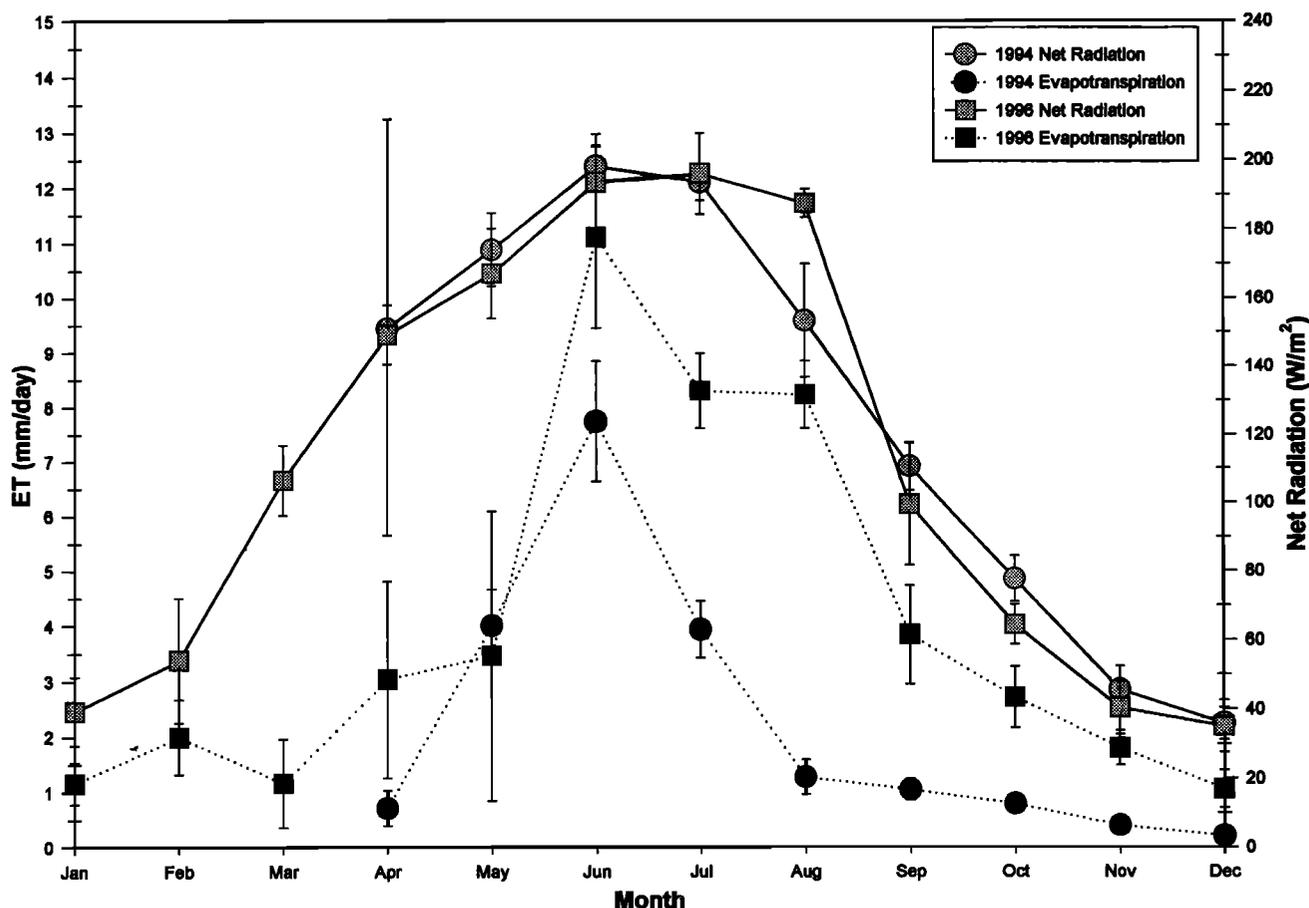
Figure 5. Average net radiation (MJ d^{-1}) and Bowen ratio evapotranspiration estimates (mm d^{-1}) with error bars on a monthly basis during 1994 and 1996.

(60°–120°) or west (240°–300°) direction was observed to occur only 10% of the time on a monthly basis in 1994 and 7% in 1996.

4. Discussion

Results from this study suggest that advective conditions are important in riparian corridors dominated by *Tamarix* in the arid regions of the Southwest. Because of advective conditions, ET estimates generated in this study should be used with extreme caution. Inability of the Bowen method to take into account incoming advective heat (horizontal energy flow), which would need to be added to the energy balance, leaves such ET estimates questionable. Results from this study, however, indicate that *Tamarix* can significantly reduce transpirational loss under limited water availability (1994 year), that *Tamarix* will reduce canopy volume (1996 year) in response to changes in river course (1995 year), and that ET estimates may be fueled by greater energy transfer within these open canopies. A significantly higher number of advective days occurring in 1996 may have been associated with advection originating from within the floodplain. *Tamarix* stands did not cover 100% of the land area; old river channels and random open areas occurred in the research area along with a more open canopy at the Bowen tower area in 1996. *Jarvis and McNaughton* [1986] stated that the saturation deficit at the surface of the leaves will usually vary systematically down through the canopy and that those leaves in the driest microenvironments will contribute

the most to canopy transpiration. Opening the *Tamarix* canopy up through a loss of 25% of the canopy volume resulted in an increase in soil temperature, suggesting that the evaporative demand inside the canopy may have increased. As a result, leaves deeper in the canopy may have contributed to transpiration loss at a higher rate than under full canopy conditions. Similarly, *Sala et al.* [1996] observed that transpiration on a leaf surface area basis increased as leaf area index (LAI) declined on the Virgin River.

Water flow on the Virgin River is highly variable, and *Tamarix* growing on raised sediments must rely entirely on groundwater sources. Except for the plants growing adjacent to river channels, access to surface flow by other plants only occurs during major flood events. Any major alterations (that impact water availability) that occur just prior to or during the peak summer months of June, July, and August will have a significant effect on yearly total water use, as will high advective periods, as demonstrated by the 75-cm estimate in 1994 versus the 145-cm estimate in 1996. Although these estimates are open to challenge because of the importance of advection in this system, only a small percentage (4%) of ET estimates exceeded 10 mm d^{-1}. *Gay and Fritschen* [1979], estimated ET with the Bowen ratio method during a summer period in Arizona to be as high as 9.0 mm d^{-1} over saltcedar, whereas *Leppanen* [1981] estimated ET with the Bowen ratio over young saltcedar during August in Arizona at 7.0 mm d^{-1}. Total
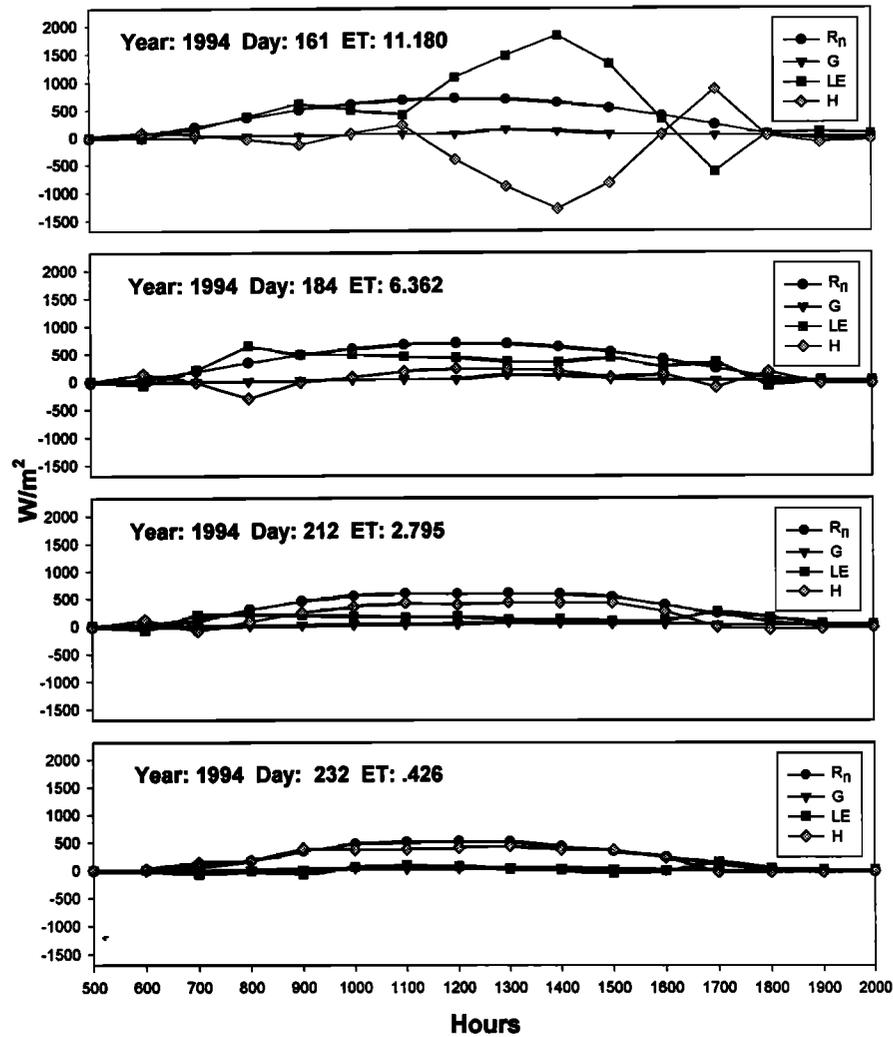
Figure 6. Total energy balance for days 161, 184, 212, and 232 in 1994 (where R_n is net radiation, LE is latent heat flux, G is soil heat flux, and H is sensible heat flux (all in KJ m^{-2})).

yearly ET estimates for *Tamarix* were far below reported potential ET estimates (220 cm) for this region [*Devitt et al.*, 1992]. This would suggest that even under advective conditions, *Tamarix* will not transpire at potential ET rates except during short periods under high water availability [*Sala et al.*, 1996]. The annual water use rates for *Tamarix* reported in this study (75–145 cm) are in the same range (77–107 cm) as those reported by *Weeks et al.* [1987]. To put the higher value of 145 cm into perspective, it is almost identical to that reported for high-fertility bermudagrass grown under golf course conditions in southern Nevada [*Devitt et al.*, 1992].

The hot, dry conditions that caused temporary wilt in 1994 were representative of the entire region. However, the change in the course of the river in 1995, which hydrologically isolated a portion of the stand of *Tamarix* around the Bowen tower from the river was site specific. Because the change in the river course was very rapid, causing a lower water table depth (>3 m), the root system may not have initially been able to adjust quickly enough to offset plant water stress. It was estimated that the distance to the point where the river changed its course was 463 m to the north, shifting the river from 212 m to the east of the tower to 206 m to the west of the tower. Trees to the north of the 463 m mark and to the west of the 206 m

mark did not demonstrate any loss or gain in canopy in 1996 in response to the change in the course of the river. It can only be speculated as to what influence trees several hundred meters from the tower might have on Bowen estimates (fetch at least 75 to 1). However, it should be noted that most Western riparian zones, particularly in desert regions, do not meet fetch requirements and that our site had an unusually wide floodplain. Therefore we would anticipate that most desert riparian corridors are often exposed to intense advection, which would tend to increase ET in those stands if water availability is high. Leaf water potential and stomatal conductance from a companion study were higher in the more open areas, both near the Bowen tower and at a location adjacent to the river (L. K. Shaulis, personal communication, 1997). This would support our contention that a more open canopy allows greater energy transfer to occur from the soil surface to the boundary layer and to allow the flow of horizontal energy from open areas to move deeper into the plant stand, potentially fueling greater water loss via transpiration. Measurements taken in this experiment did not directly address the questions of turbulent transfer of energy. However, advection theory developed by *McNaughton* [1976] supports our contention, as the theory predicts that changes in boundary conditions such as alter-
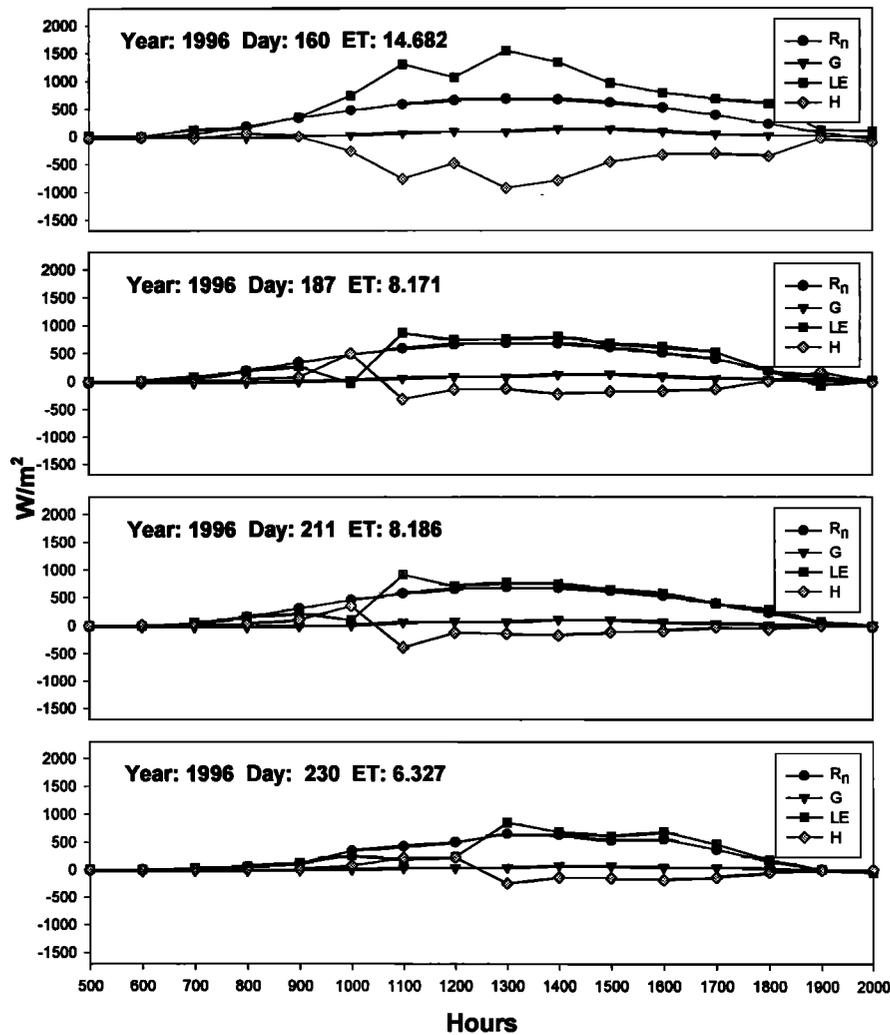
Figure 7. Energy balance for days 160, 187, 211, and 230 in 1996 (where R_n is net radiation, LE is latent heat flux, G is soil heat flux, and H is sensible heat flux (all in KJ m^{-2})).

ations in surface cover will produce changes in the ET rate. *Baldocchi* [1989] also concluded that local advection on a scale of tens and hundreds of meters can occur as a result of differences in roughness, water status, and evaporation potential and that variation in canopy evaporation to a controlling factor will indicate how well the leaf canopy is coupled to its environment. Our results would suggest that *Tamarix* is closely coupled to the surrounding air, with the opening and closing of stomata controlling transpiration. This would be supported by both the 1994 data in which ET estimates dropped when R_n remained high and the 1996 data in which high advective periods still did not cause *Tamarix* transpiration estimates to approach potential ET rates. Our results would suggest that *Tamarix ramosissima* can potentially be both a low water user and a high water user depending on moisture availability, canopy development, and atmospheric demand and that advection can dominate energy balance approaches to ET in the arid regions of southern Nevada.

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