

TRANSPIRATIONAL WATER LOSS FROM STREAMSIDE
VEGETATION IN WYOMING: HIGH ELEVATION
SOURCE STREAMS AND ALLUVIAL/IRRIGATION
CHANNELS OF VALLEYS

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1986

WWRC-86-12

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Final Report

(Project #5-38679)

Submitted to

Wyoming Water Research Center
University of Wyoming

Contents of this publication have been reviewed only for editorial and grammatical correctness, not for technical accuracy. The material presented herein resulted from objective research sponsored by the Wyoming Water Research Center, however views presented reflect neither a consensus of opinion nor the views and policies of the Water Research Center or the University of Wyoming. Explicit findings and implicit interpretations of this document are the sole responsibility of the author(s).

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ABSTRACT

Transpirational water use (TWU) by riparian vegetation in the Little Laramie River drainage of southeast Wyoming was estimated from field measurements of leaf areas, stomatal conductances, and microclimate at five representative study sites. These sites were large and small natural streams and large and small irrigation ditches at low elevation (below 8,000 ft), and an alpine source basin at high elevation (10,600 ft). Woody phreatophytes - cottonwood and willow species - were the major consumers of water, per unit of leaf area and for entire riparian zones, at the low-elevation sites. In the alpine source basin, dwarf willows, broadleaved herbs, and sedges were the major consumers of water. Cottonwood used more water per unit leaf area (185 lbs ft^{-2}) than did the willows ($103 \text{ to } 119 \text{ lbs ft}^{-2}$) at low elevation, but annual willow TWU was larger than cottonwood because willow thickets occupied a greater area than did cottonwood groves. At high elevation, marsh marigold used more water per unit leaf area (40 lbs ft^{-2}) than did willows or sedges ($30 \text{ to } 33 \text{ lbs ft}^{-2}$), but its annual TWU was less than the other species because of its lesser total leaf area.

Riparian zone TWU for the growing season of 1986 was 5 inches in the alpine source basin and ranged from 19 to 47 inches in the low-elevation riparian zones. TWU/streamflow ratios increased as streamflows decreased because the ratio of transpiring leaf area to streamflow was higher along smaller streams. The combination of low streamflows, maximum riparian leaf areas, and maximum daily water use rates in late summer resulted in greater TWU/streamflow ratios in August.

Annual TWU/streamflow ratios in 1986 were less than one percent for the large and small natural streams and the large irrigation ditch, two percent for the small irrigation ditch, and four percent for the alpine source basin. Mid- to late summer TWU/streamflow ratios exceeded ten percent for both the small natural stream and the small irrigation ditch. When TWU was extrapolated to the entire Little Laramie drainage, the annual TWU/streamflow ratio was about three percent. The proportion of total drainage TWU contributed by each major class of riparian zone decreased from low-elevation natural streams (62 percent) to low-elevation irrigation ditches (34 percent) to alpine source basins (4 percent).

Riparian zone TWU is a relatively minor quantity compared to total streamflow along most stream channels in southeast Wyoming. Small streamflow increases might be achieved in mid- to late summer by substituting willows for cottonwoods along irrigation ditches. TWU of alpine riparian vegetation needs to be accounted for in models of water delivery from mountains to valleys. When growing season precipitation and water storage in reservoirs and water tables is taken into account, riparian TWU is a quantitatively unimportant component of river drainage water budgets in southeast Wyoming.

INTRODUCTION

Very little quantitative or even qualitative information is available regarding the potential avenues of water loss as stream water moves from source regions at high elevations to low-elevation valleys and plains in Wyoming. Because most of Wyoming is semiarid, water is in short supply relative to demand in some areas, especially in the overappropriated North Platte River drainage. Agriculture is dependent on irrigation, while municipal and industrial demands for water are growing.

Most streamflow in Wyoming originates as snowmelt in the mountains. This water follows natural stream channels and artificial irrigation channels downhill and out across the plains. At all points along these stream systems, streamflow is subject to conveyance losses. These losses may be permanent (evaporation, transpiration, loss to deep aquifers) or temporary (bank storage). Clearly, the identification and quantification of conveyance losses is necessary for developing models of water availability. Furthermore, these losses may be subject to direct human manipulation to reduce their magnitude or to make them occur at times of the year when water availability is high.

One potentially important conveyance loss which has received little attention is transpiration by vegetation of riparian zones. The diurnal and seasonal patterns of water lost via riparian plant transpiration are virtually unknown in Wyoming or for any high-elevation, semiarid ecosystem. We do not know whether these losses are quantitatively significant compared to streamflows or how they compare to other conveyance losses.

This study measured transpirational water consumption by riparian vegetation growing along natural streams and irrigation ditches in southeast Wyoming. Comparisons were made between species, between riparian plant communities, between stream types, and between different elevations. Relationships between transpiration, streamflows, and water table depths were examined.

Previous Research

Riparian vegetation in North America consists mostly of phreatophytes, perennial woody plants whose deep roots draw upon water tables throughout the growing season (Meinzer 1927). Most previous research on riparian water use has focused on phreatophytes, with the major interest being removal of water from streams due to phreatophyte evapotranspiration (ET), a phenomenon referred to as "streamflow depletion."

The potential for streamflow depletion has been a special concern in the arid southwest U.S. for many years (Robinson 1958). Direct measurement of phreatophyte ET in non-weighing lysimeters showed annual values ranging from 2 to 12 inches in Utah (White 1932), 13 to 47 inches in Nevada (Robinson 1970), and 36 to 96 inches in Arizona (Gatewood et al. 1950, McDonald and Hughes 1968, van Hylckama 1970). Annual ET from willow thickets in Nevada was 6 to 15 inches (Robinson 1970). Actual water loss from the plants themselves (transpiration) was less than these figures indicate, since soil evaporation ranged from 3 to 6

inches in Utah (White 1932) and 3 to 45 inches in Arizona (Gatewood et al. 1950, McDonald and Hughes 1968). Daily transpiration of saltcedar (Tamarix chinensis) grown in tanks was 0.9 to 6.2 inches per day (Davenport et al. 1982). A water budget method estimated annual phreatophyte ET along an Arizona river at 52 inches, with maximum daily ET of 0.4 inches (Qashu and Evans 1967). Removal of phreatophyte vegetation along a stretch of the Gila River in Arizona reduced riparian ET and increased streamflow (Culler 1970).

Annual ET estimates for temperate zone phreatophytes are few. Meyboom (1964) derived riparian ET use from daily streamflow fluctuations in Saskatchewan, Canada. Annual ET of willows (Salix discolor) and western cottonwood (Populus sargentii) was estimated to be 13 and 41 inches, respectively. Non-weighing lysimeters installed in a willow (Salix viminalis) thicket in Sweden indicated annual ET of 5 inches, of which ca. 20 percent was evaporation (Kowalik and Eckersten 1984).

In Wyoming, annual ET estimates of 18 to 27 inches have been made for irrigated pastures with non-weighing lysimeters (Borelli and Burman 1982, Pochop et al. 1986), but no direct measurements have been made for phreatophytes, which in our region are primarily cottonwoods (Populus species) and willows (Salix species). VanKlaven et al. (1975), using the Blaney-Criddle equation, combined long-term weather data and water use coefficients (determined from lysimeter studies) measured for willows and cottonwoods in Arizona with the total area of riparian vegetation to estimate a mean annual phreatophyte ET along the Big Laramie River of 34 inches.

Combined energy budget/aerodynamic methods have also been used to estimate phreatophyte ET. These methods give good agreement with lysimeter values, provided diurnal changes in plant stomatal conductance are accounted for (van Hylckama 1980, Kowalik and Eckersten 1984).

To summarize, previous research on phreatophyte ET has indicated that significant fluxes of water occur from riparian vegetation. In arid regions, annual phreatophyte ET exceeds annual rainfall, and the plants draw upon water tables and, presumably, streamflows to meet their water needs.

Hypotheses

- (1) Phreatophytes, woody plants whose deep roots tap perennial water tables, are the greatest consumers of water in low-elevation riparian zones. In high-elevation riparian zones, phreatophytes and shallow-rooted herbaceous species are the most important water consumers.
- (2) Tributary (small-order) stream systems have the greatest relative water depletion (annual transpiration as a proportion of annual streamflow) due to the greatest ratio of riparian plant leaf area to stream volume.
- (3) Total riparian transpiration is quantitatively most important during low streamflow periods in late summer.

Objectives

- (1) Identify the major species and plant communities occurring in low- and high-elevation riparian zones along large and small, natural and artificial, stream channels.
- (2) Determine total leaf area of each major species and cover of each major plant community.
- (3) Directly measure daily transpiration rates for each major species and estimate seasonal transpiration rates.
- (4) Calculate total riparian zone transpirational water consumption for various low- and high-elevation streams and compare it to streamflows.
- (5) Correlate transpiration rates and streamflows with water table fluctuations.
- (6) Extrapolate results to an entire watershed.

METHODS

Overall Framework

We chose to estimate riparian water use by multiplying water use rates per unit of leaf area, as measured directly using diffusion porometry, by total leaf areas for specific study areas. This method has several advantages over lysimeters: 1) it measures the transpiration component of ET, 2) it is comparatively inexpensive and highly portable, and 3) water use rates can be measured with temporal resolution as short as one hour, while lysimeters at best measure only weekly water use.

Transpiration per unit of leaf area (E) is calculated with the following equation, an analogy to Ohm's law for electricity:

$$(1) E = 1/(1/g_s + 1/g_b) \text{ LAVD}$$

where g_s = stomatal conductance to water vapor, g_b = boundary layer conductance to water vapor, and LAVD = leaf-to-air water vapor concentration difference. $\text{LAVD} = (p_1 - p_a)$, where p_1 = saturation water vapor concentration at leaf temperature (T_1), and p_a = atmospheric water vapor concentration at air temperature (T_a) and relative humidity (RH). g_s , T_1 , T_a , and RH can be measured directly. g_b can be calculated from leaf diameter and windspeed using convective heat transfer equations.

If E values are plotted over entire days, the areas under the curves may be integrated to calculate cumulative daily transpiration (E_d). Since E_d is expressed per unit of leaf area, and since individual species differ in E_d , each species' leaf area and the total leaf areas of each plant community and of entire riparian zones must be known to calculate total riparian water use (TWU):

$$(2) \text{ TWU} = \sum_{n=1}^i \sum_{n=1}^j E_{d(i,j,k)} \text{ LAI}_{i,j,k} C_k$$

where $E_{d(i,j,k)}$ = E_d of ith species at jth canopy level in kth plant community, $\text{LAI}_{i,j,k}$ = leaf area index (ft^2 projected leaf area per ft^2 ground area) of the corresponding species, height level, and plant community, and C_k = total cover of each plant community.

As this discussion shows, prediction of riparian TWU requires a knowledge of g_s , the microclimate surrounding leaves, and LAI. Each of these three components undergoes continuous change in the natural environment. For example, LAI increases early in the growing season and decreases late in the growing season. LAVD and g_b can change in seconds in response to fluctuations in T_1 , T_a , and RH. g_s may respond to a host of microclimatic (e.g., photosynthetic photon flux density (PPFD), T_1 , LAVD) and physiological (e.g., internal water status) factors. Our ability to measure these changes, both spatially (e.g., between canopy levels) and temporally (e.g., between days) is limited.

There are two methods to deal with these difficulties. The first is to interpolate spatially (e.g., between different study sites or canopy levels) or temporally (e.g., between hourly

measurements of E or biweekly measurements of E_d). A more accurate, but much more complex method, is to develop predictive relationships for unmeasured quantities, e.g., microclimate at various canopy levels or g_s at various times of the day. The necessary relationships are parameterized with field measurements. For example, g_s is monitored concurrently with those environmental variables presumed to influence g_s . Another example: vertical vertical profiles of microclimatic variables are made in selected plant canopies.

In this research, we collected field data to parameterize both simple (linear interpolation) and complex (predictive relationships) models to estimate seasonal riparian TWU at several representative riparian zone study sites. We measured streamflows and water table depths at each site for comparison with TWU. Finally, we compared TWU and streamflows for an entire river drainage, based on a knowledge of total riparian zone cover and drainage stream discharge. Our overall strategy for calculating riparian TWU is summarized in Figure 1.

Study Sites

A preliminary reconnaissance was carried out in the Little Laramie River drainage, a tributary of the North Platte River in southeast Wyoming, to qualitatively categorize stream channel systems within which representative stream reaches could be chosen for intensive study. The Little Laramie is fed by snowmelt and springs on the crest of the Medicine Bow Mountains (elevation 10,000 to 12,000 ft). Headwater streams flow across a rolling subalpine plateau, then descend more precipitously to Centennial Valley at the foot of the mountains (elev. 7,500 to 8,000 ft). Here the streams coalesce to form a single main channel crossing the flat Laramie Basin.

General features of riparian zones

We observed two major areas of occurrence of riparian zones, low- (below 8,000 ft) and high- (above 9,500 ft) elevation. Stream gradients at intermediate elevations were too steep for significant riparian zones to form.

At low elevation, riparian zones occur along natural streams and along irrigation ditches which divert water from natural streams to reservoirs or onto irrigated pastures. We divided these low-elevation stream channels into four categories: 1) large natural streams; 2) small natural streams, tributary to the large streams; 3) large irrigation ditches which provide water to a number of users; and 4) small irrigation ditches, usually providing water to individual pastures.

Near the mountains, the natural stream riparian zones are continuous, but as distance from the mountains increases, they become discontinuous and sometimes disappear completely. Along large natural streams, the riparian zone varies in width from ca. 30 to 500 ft, while along small natural streams the width ranges from ca. 5 to 50 ft. The dominant vegetation is woody phreatophytes: narrowleaf cottonwood (Populus angustifolia James) and various willow (Salix) species. Willows tend to form

thickets, whereas cottonwoods cluster together in groves, or, along small streams, occur singly.

Cottonwoods and willows have colonized the edges of large and small irrigation ditches well out onto the plains, forming narrow, discontinuous riparian zones. Generally, cottonwoods predominate along the larger ditches and willows along the smaller ditches.

Topographic depressions near the crest of the Medicine Bow Mountains are the primary sources of water for the Little Laramie. These "alpine source basins" vary in size from 0.2 to 2 acres and from 5 to 50 ft deep. All contain late-melting snowbanks and many contain springs and small lakes. Riparian vegetation in source basins consists of several visually distinct plant communities, with generally sharp boundaries delineating adjacent communities. The willow community consists of 1 to 3 ft tall willows with sedge (*Carex* species) forming an understory. The sedge-willow community is a mixture of dwarf willow species and sedge growing either on moist peat or in shallow standing water; herbs usually grow beneath the canopy. The sedge community consists of a tall form of sedge growing in standing water; if the water is shallow enough, broadleaved herbs form a sparse understory. The moist meadow community consists primarily of a short form of sedge, with varying cover of broadleaved herbs, growing on moist peat elevated above the water table. The snowbank community covers areas where snowmelt occurs so late in the growing season that continuous vegetative cover does not develop; most of the ground is bare mud, with scattered sedges and herbs.

Low-elevation study sites

A study site representative of a large natural stream was laid out along the Little Laramie River at the mouth of Centennial Valley (elev. 7,560 ft). Cottonwoods formed groves of 10 to 80 ft tall trees set within a nearly continuous thicket of 8 to 15 ft tall willow shrubs. The soil, derived from Quaternary alluvium, was highly organic near the surface and underlain by silt at 1.5 to 3 ft depth.

A small natural stream site was chosen along Hecht Creek above its juncture with the South Fork of the Little Laramie in Centennial Valley (elev. 7,580 ft). The riparian zone was discontinuous, 10 to 50 ft in width, consisting primarily of small willow thickets or isolated willow shrubs with 6 to 15 ft tall canopies. The soil was highly organic near the surface and underlain by clay.

A large irrigation ditch site was located along the Bellamy Canal, a short distance downstream of the canal's beginning on the Little Laramie at the mouth of Centennial Valley (elev. 7,560 ft). The stream channel lay 1 to 3 ft below the level of the surrounding prairie and was lined with dirt ridges, 1 to 6 ft tall, cast up by the excavation of the ditch in 1890. Cottonwoods lined these ridges, forming a riparian zone 30 to 75 ft wide. Soil was rocky Quaternary alluvium.

A final site was laid out along a small irrigation ditch (Hecht Ditch) which diverted water from Hecht Creek just below

the Hecht Creek site onto a nearby pasture. Dirt ridges 0.5 to 2 ft high, cast up during ditch excavation, lined either side and possessed a discontinuous cover of 3 to 10 ft tall willow shrubs, creating a riparian zone 5 to 25 ft wide. Soil was clay with some organic matter near the surface.

All of the low-elevation sites were underlain by perennial water tables. In addition, since all sites were located on private ranches, cattle grazing and human activity had disturbed each site to varying degrees. This is true of virtually all low elevation riparian zones in the Laramie Basin.

Nine years of records (1977-1985) from a U.S. Forest Service weather station at Centennial, WY, about 6 miles away from and 870 ft higher than the study sites, gave mean annual rainfall of 26.0 inches; mean annual T_a of 36.9°F ; and June-September mean daily maximum T_a of 65.7°F and mean daily minimum T_a of 40.5°F .

High-elevation study site

The high-elevation site was a small topographic basin (450 ft long, 100 to 200 ft wide, 30 to 50 ft deep) located on Libby Flats, a large alpine meadow within the timberline ecotone (elev. 10,600 ft). The flat basin floor was underlain by a water table fed by springs, a shallow pond, and a late-melting snowbank. A small stream drained the basin. A mosaic of riparian plant communities covered the basin floor, growing on peat of varying thickness up to 3 ft. The peat was underlain by an unknown depth of silt. Dolomite bedrock was exposed on the sideslopes of the basin.

Seven years of records (1977-1983) from a Wyoming Water Research Center weather station at nearby Telephone Lakes, 1.3 miles north of and 118 ft higher than Libby Flats, gave mean annual rainfall of 53.9 inches; mean annual T_a of 29.3°F ; and June-September mean daily maximum T_a of 65.1°F and mean daily minimum T_a of 27.7°F .

Species composition

Plant specimens were collected from each site and identified using taxonomic keys. Identifications were confirmed by personnel at the Aven Nelson Herbarium, University of Wyoming. Nomenclature follows Nelson (1984).

The major species, in terms of stem density and leaf area, were cottonwood, mountain willow (*S. monticola* Bebb), and sandbar willow (*S. exigua* Nutt.) at Little Laramie, mountain willow and Geyer willow (*S. geyeriana* Anderss.) at Hecht Creek, cottonwood at Bellamy Canal, sandbar willow at Hecht Ditch, and planeleaf willow (*S. planifolia* Pursh) at Libby Flats. Also occurring occasionally were Bebb willow (*S. bebbiana* Sarg.) and whiplash willow (*S. lasiandra* Benth.) at Little Laramie, mountain alder (*Alnus incana* (L.) Moench) and Bebb willow at Hecht Creek, mountain willow at Hecht Ditch, and shortfruited willow (*S. brachycarpa* Nutt.) and mountain willow at Libby Flats.

Other woody plant species were absent at Hecht Creek, Hecht Ditch, and Libby Flats and occurred only as scattered low shrubs at Little Laramie and Bellamy Canal. A sparse understory of grasses grew beneath the cottonwood grove and willow thicket

canopies at Little Laramie and Hecht Creek.

A single sedge species (Carex scopulorum Holm) was widespread at Libby Flats, a tall form (3 to 10 inches high) growing in the sedge community and a much shorter form (0.5 to 3 inches high) in the moist meadow community. The predominant herb in all communities was marsh marigold (Caltha leptosepala DC.). Other herbs occurred as minor components of the sedge-willow, moist meadow, and snowbank communities.

Leaf Areas

Total leaf area at each study site was the product of LAI and total cover (areal extent) of the riparian zone. Cover was constant, but LAI varied seasonally because all of the plant species were deciduous. Since we expected TWU to differ between species and between plant communities, we separately measured cover of each plant community and LAI of each species within each community.

Plant community cover

The boundaries of each plant community on the basin floor at Libby Flats were visually mapped onto a 16.4 x 16.4 ft grid delineated with stakes and string. At the low-elevation sites, the edges of willow thickets and cottonwood groves were mapped separately using compass and tape along a sufficient length of each stream channel to give a representative picture of each riparian zone. These lengths were 449 ft at Hecht Creek, 656 ft at Hecht Ditch and Bellamy Canal, and 1,200 ft at Little Laramie.

Leaf area indices

LAI's were measured at their seasonal maxima (August, 1986, following cessation of growth) for each major species in each plant community. Twenty cottonwoods of varying size from saplings to large trees were felled in the riparian zone of Rock Creek, 30 miles north of and at a similar elevation to the Little Laramie site. Diameter at breast height (DBH; 4.5 ft) of each trunk was measured. Leaves were counted on random subsamples of the branches within each 6.56 ft height level along each trunk. Projected (one-sided) areas of 200 randomly-chosen leaves were measured with a video area meter (Decagon Devices). These data were used to estimate total projected (one-sided) leaf area of each tree. Then a linear regression was developed between \log_{10} DBH and \log_{10} leaf area.

All cottonwood stems at Little Laramie and Bellamy Canal were counted and their DBH's measured. These DBH's were then used in the DBH/leaf area equation to estimate leaf area per tree. Leaf areas were summed across all trees at each site, then divided by the total cover of cottonwoods at each site to calculate LAI.

Current-year shoots of varying length were removed in August from clumps of mountain willow, sandbar willow, Geyer willow, and beaked willow at Little Laramie (n = 70 to 100). Subsamples of leaves (100 or more) from these shoots were measured for length, width, and projected area. From these data, regressions between leaf area and leaf length and width, and between total shoot leaf

area and shoot length, were developed for each species.

Ten randomly-located, 30.28 x 30.28 ft quadrats were laid out within the willow thickets at Little Laramie. The total number of live stems in each clump was counted. Every tenth live stem of each species was sawn off at the base and its basal diameter and height measured ($n = 50$ to 144). These stems were divided into 3.28 ft height levels and the lengths of subsamples of current-yr shoots within each level were measured. At Hecht Creek, the basal diameter of every live stem in every fifth clump of each willow species was measured. At Hecht Ditch, all live stems in ten randomly-chosen, 30.28 x 13.12 ft quadrats were counted and the basal diameter of every twentieth stem in each quadrat was measured.

Regressions between stem basal diameter and stem total leaf area were developed for each species using the data from Little Laramie. These relationships were then applied to the stem diameter data for each quadrat at Little Laramie and Hecht Ditch and to each willow clump at Hecht Creek to calculate total leaf area of each species. Cumulative leaf areas of each species in each quadrat or clump were divided by quadrat or clump area to yield estimates of species' LAI, broken down by 3.28 ft height levels within the canopy.

The harvest method was used to estimate LAI at Libby Flats. During maximum seasonal LAI in mid-August, 1985, randomly-located 0.82 x 1.64 ft quadrats were laid out, ten within each plant community. All vegetation in each quadrat was clipped to ground level and placed in plastic bags. Clippings were oven-dried for 48 hr at 122° F and separated into two or three height levels for each community. Each height level was further sorted into individual willow species, marsh marigold, and tall and short forms of sedge, and these subsamples were weighed to ± 0.004 oz. Other herbaceous species in the sedge-willow and moist meadow communities were included with marsh marigold.

Projected areas of random subsamples of leaves of each species were measured with the area meter. These leaves were then oven-dried and weighed. Specific leaf areas (ft^2 leaf area per ounce dry weight) were computed for each species. Dry weights of the clipping samples were multiplied by the specific leaf areas and divided by quadrat area to calculate each species' LAI.

Seasonal changes in leaf area

We measured changes in LAI over the course of the "transpiration growing season," i.e., the period between leaf budbreak and the cessation of transpiration due to hard autumn frosts (T_a less than 25°F) in 1985 and 1986. At two-week intervals, one current-year shoot was removed from each of twenty cottonwoods at Little Laramie, ranging in size from saplings to large trees, and from twenty separate clumps of mountain willow at Little Laramie, Geyer willow at Hecht Creek, sandbar willow at Hecht Ditch, and planeleaf willow at Libby Flats. Shoot lengths were measured and leaf areas per shoot calculated from the shoot length/leaf area regressions. Sampling continued until mid-August when shoot growth had ceased.

Starting the first week of September, observations of leaf

senescence and abscission were made at weekly intervals until transpiration ceased. Every leaf on each of twenty shoots from each species was placed in one of the following categories: 95 to 100 percent green (the rest of the leaf yellow), 50 to 95 percent green, 5 to 50 percent green, 0 percent green, or fallen off.

Leaf area changes were also observed on sedge and marsh marigold. At two-week intervals following plant emergence, one plant of each species was collected from random locations across the basin floor at Libby Flats. Projected area of each leaf on each plant was measured with the area meter and mean leaf area per plant calculated.

Because the basin at Libby Flats filled with snow during the winter, the total cover of each riparian plant community was initially zero at the beginning of the growing season, then gradually increased through the summer as the melting snowbank exposed additional area. Once weekly in 1985 and 1986, from the first appearance of bare ground until all snow had melted, the boundaries of the snowpack were sketched onto a map of the riparian plant communities. From these maps, the total snow-free area of each community was measured at weekly intervals.

Microclimate

Above-canopy microclimate

Meteorological variables were measured continuously in the field over the course of the growing seasons of 1985 and 1986. Two automated weather stations were established each year, one each at low and high elevation. In 1985, the low-elevation station was located in short-grass prairie ~300 ft west (upwind) from Bellamy Canal, whereas in 1986 it was located ~100 ft inside a willow thicket at Little Laramie. In both years, the high-elevation station was located in the middle of the basin floor at Libby Flats.

Instrumentation was identical at both stations. Photosynthetic photon flux density (PPFD) was measured with a quantum sensor (Li-Cor model LI-190SB). Air temperature (T_a) and relative humidity (RH) were measured with a combination thermistor and thin-film capacitance sensor (Weathermeasure model 5123-B) inside a radiation shield. Windspeed was monitored with a cup anemometer (Weathermeasure model 2032). Rainfall was measured with a tipping-bucket rain gauge (Rainwise model 111) surrounded by a wind baffle. Except for the rain gauges, which were installed near ground level, all instruments were mounted on sectional steel towers at sufficient heights (approximately 18 ft at Bellamy Canal, 29 ft at Little Laramie, 9 ft at Libby Flats) to measure meteorological variables beyond the influence of the vegetation canopy.

The sensors at each site were scanned every five minutes by battery-operated data loggers (Campbell Scientific model CR-21X). Once hourly, these observations were summed (rainfall) or averaged (all other parameters) and stored in solid-state memory modules (Campbell Sci. model SM16). Every ten days the contents of the modules were transferred to a microcomputer (IBM PC) via an RS-232 interface.

Within-canopy microclimate

We measured vertical profiles of windspeed, T_a , and RH in the willow thicket at Little Laramie and in the sedge-willow, sedge, and moist meadow communities at Libby Flats. These data were used to develop relationships between each variable and either LAI or height above ground. PPFD is very difficult to measure in plant canopies, so we used relationships from previously published studies on broadleaved canopies. Profiles were not measured in cottonwood groves or the riparian zones at Hecht Creek and Hecht Ditch because the canopies were so narrow that they probably did not substantially alter the properties of the airflow passing through them.

At Little Laramie, T_a sensors (0.13 inch diameter copper-constantan thermocouples) and windspeed sensors (miniature cup anemometers; Rimco model R/AMI) were mounted at three heights (top, middle, and base of canopy) on the weather station tower. A single RH sensor (Vaisala model HMI-14) was mounted at mid-canopy height. The sensors were left in place, connected to the data logger, for three days in late August, 1986.

At Libby Flats, thermocouples and miniature anemometers were mounted at three heights on a movable aluminum rod and left in place for two to three days in each plant community during late August, 1985. A portable data logger (Campbell Scientific model CR-7) scanned the sensors every five minutes and averaged the values once hourly. Short-term profiles of RH at Libby Flats were measured with a thermocouple psychrometer (Cole-Parmer model 8520-50) hand-held at different heights during a single day in late August, 1985.

Soil microclimate

Spot measurements of soil temperature (T_s) and soil water potential (ψ_s) were performed in 1985 at each of the study sites. These measurements showed that the soil in all plant communities at Libby Flats and on low-lying river terraces at Little Laramie was at or near saturation throughout the growing season. This was attributable to late spring flooding at Little Laramie and to a combination of snowmelt, frequent rainfall, and poor drainage at Libby Flats.

An intensive sampling program was carried out during the growing season of 1986. At Little Laramie, T_s was measured at 9.8 and 23.6 inch depths (three replicates each depth) on two flat, alluvial terraces. One ("lower") terrace, was ~2 ft above the stream channel and was subject to late spring flooding. The other ("upper") terrace lay ~6 ft above the stream channel and was not subject to flooding. On the lower terrace, copper-constantan thermocouples (0.13 inch diameter) were scanned hourly by the weather station data logger. On the upper terrace, T_s and ψ_s were measured once weekly with thermocouple psychrometers and a dewpoint microvoltmeter (Wescor model HR-33T).

At both Hecht Creek and Hecht Ditch, T_s and ψ_s were measured at 2.0 and 9.8 inch depths (three replicates each depth) using psychrometers. At Libby Flats, T_s was measured with thermocouples at 2.0 and 7.9 inch depths in the sedge-willow community, at 1.2 inch depth in the sedge community, and at 1.2

and 7.9 inch depths in the moist meadow community (three replicates each depth). Values were recorded hourly by the data logger for the shallow depths in the sedge-willow and moist meadow communities and weekly with a digital thermometer (Omega model 2176A) for the other depths and communities.

Stomatal Conductances

Daily patterns of g_s

We measured dawn-to-dusk changes in g_s of the major (greatest leaf area) riparian species at hourly intervals on representative clear or mostly-clear days. Preliminary measurements in 1985 were conducted during two days in August on a variety of species at Little Laramie, Hecht Creek, and Libby Flats. These measurements indicated that absolute g_s values and the daily pattern of g_s were similar between mountain and Geyer willow at Hecht Creek, and between the three willow species at Libby Flats. Sandbar willow showed different patterns from mountain and Geyer willow. There were also differences between the two forms of sedge. Therefore, more intensive g_s measurements were carried out in 1986, focusing on fewer species.

Measurements of g_s in 1986 occurred at approximately three-week intervals between June 3 and August 30 for cottonwood, mountain willow, and sandbar willow on the upper river terrace at Little Laramie and at two-week intervals for planeleaf willow, marsh marigold, and the tall and short forms of sedge at Libby Flats. Sandbar willow leaves were not large enough to sample until June 29.

Five fully sunlit and five fully shaded leaves of cottonwood and of each willow species at Little Laramie were sampled during each set of hourly measurements. At Libby Flats, five sunlit and five shaded leaves were measured hourly for planeleaf willow, whereas five leaves total, without regard to degree of shading (most leaves were fully sunlit) were measured for marsh marigold and sedge. Each leaf came from a different shoot (cottonwood, willows) or plant (marsh marigold, sedge). Plants in the same vicinity were measured on successive dates. Plants at Libby Flats were chosen in areas that had been snow-free for at least one week.

Conductances were measured separately on top and bottom leaf surfaces with a transient diffusion porometer (Li-Cor model LI-700) and summed in series to give total g_s (Eq. 1). The porometer cuvette was shaded from direct sunlight during measurements to maintain temperature differentials between the leaf and the air inside the cuvette at 4°F or less. Calibrations were performed immediately following each set of measurements using a plastic plate backed by wet filter paper and perforated with different sizes and densities of holes to simulate various g_s . This plate was calibrated under isothermal conditions in the laboratory against a perforated metal plate, for which g_s values were calculated from diffusion theory (Monteith 1973). Plate g_s values were corrected for changes in the diffusion coefficient of water vapor in air (D_w) attributable to temperature and to elevational differences in ambient pressure (Smith and Geller

1979).

Natural leaf temperatures of cottonwood, willows, and marsh marigold were measured to within 0.9°F immediately before individual g_s measurements using an infrared thermometer (Barnes Engineering Model 111) calibrated after every fifth measurement. Sedge T_l was measured ($\pm 0.4^{\circ}\text{F}$) by pressing a 0.003 inch diameter thermocouple against the shaded side of each leaf. Before each set of g_s measurements on a given species, T_a and RH were measured at sample height with a shielded copper-constantan thermocouple (0.01 inch diameter) and a thin-film capacitance sensor (Weathermeasure model 5121).

Seasonal patterns of g_s

The maximum g_s value occurring on clear days for each species (g_{\max}) was assumed to represent that species' maximum possible g_s for that time of year. Additional g_s measurements at the beginning and end of the low- and high-elevation growing seasons were performed on clear days for each of the above species to ascertain seasonal patterns of g_{\max} . The same plants were used as for diurnal measurements. Beaked willow g_{\max} was measured on four days at Little Laramie for comparison with other low-elevation willows.

In mid-September, g_{\max} was compared between green leaves and yellow (senescing) leaves of cottonwood and mountain, sandbar, and beaked willows at Little Laramie, and of planeleaf willow at Libby Flats.

Stomatal responses to environmental factors

Previous work on cottonwood, willows, marsh marigold, and alpine herbaceous species has indicated that potentially important factors influencing g_s include PPFD, T_a , T_l , LAVD, internal water status, T_s , and ψ_s (Kuramoto and Bliss 1970, Ehleringer and Miller 1975, Regehr et al. 1975, Stoner and Miller 1975, Drew and Bazzaz 1979, Oberbauer and Billings 1981, Pallardy and Kozlowski 1981, Pezeshki and Hinckley 1982, Korner 1982, Kowalik and Eckersten 1984, Magnussen 1985, Young et al. 1985). Predictive relationships between these factors and g_s or g_{\max} were sought to improve our ability to estimate E , E_d , and WU .

In addition to the environmental measurements already made in conjunction with the sampling for daily and seasonal changes in g_s and g_{\max} , data on PPFD and shoot xylem pressure potential (ψ_p , a measure of internal water status) were gathered during the daily g_s measurements. Following each set of g_s measurements on each species, the shoots to which the sample leaves were attached (cottonwood, willows) or the individual sample leaves (marsh marigold) were excised and placed in plastic bags over ice in the dark. Xylem pressure potentials were measured with a pressure bomb (PMS Instruments model 1000) no later than one hour after excision. It was not possible to measure sedge ψ_p with the pressure bomb. PPFD incident on the top and bottom surfaces of sample leaves was measured on three days at Little Laramie and on one day at Libby Flats using a quantum sensor (Li-Cor model 190S).

Water Tables and Streamflows

Water table depths were measured weekly in 1985 and 1986 using PVC piezometers at eight locations on the periphery of the willow thickets at Little Laramie, ten locations within the riparian zone at Hecht Creek, four locations adjacent to Hecht Ditch, and twenty locations on the basin floor at Libby Flats. At Bellamy Canal, the soil was too rocky to drill holes to the water table, even with power equipment.

Daily streamflows in 1985 and 1986 were calculated from water-stage recorder data collected by the Albany County Water Commissioner (James Pugh, Laramie, WY, personal communication). The gauging stations from which these data were derived were located in the middle of the Little Laramie site and at the upstream end of the Bellamy Canal site.

Midday streamflow was measured weekly at Hecht Creek, Hecht Ditch, and Libby Flats in 1985 and 1986. Cross-sectional velocity profiles were measured at Hecht Creek and Hecht Ditch using a measuring tape and a pygmy current velocity meter (Scientific Instruments Co. model SIW-003). Stream velocity was observed directly at Libby Flats with a Parshall flume installed at the outlet of the basin.

Transpirational Water Use

Two computer simulation models were envisioned, a "simple" model based on interpolation between measured E_d values and a "complex" model which would predict g_s from various environmental factors and calculate transpiration rates separately for each canopy layer in each community.

TWU at the study sites: simple model

Transpiration rates were calculated from Equation 1, using g_s and LAVD values observed in the field. Boundary layer conductances were estimated for "typical" leaves of each species as follows: Windspeed at mid-canopy height in each plant community was estimated from above-canopy windspeed values measured by the weather stations, using relationships between windspeed and LAI or windspeed and height above ground developed from the microclimate profile measurements and data on seasonal changes in LAI. We used mid-canopy height values of 32.8 ft for cottonwood groves, 9.8 ft for willow thickets, 9.8 inches for the sedge-willow community, 5.9 inches for the sedge community, and 2.0 inches for the moist meadow community. Mean leaf diameters of each species were determined from the biweekly shoot leaf area measurements. A relationship from Campbell (1977) was used to calculate g_b :

$$(3) \ g_b = 1/(283(\text{diameter/windspeed})^{.5}))$$

Integration under the diurnal E curves for sunlit and shaded leaves of each species yielded estimates of cumulative daily water use (E_d). We interpolated between measured E_d values to estimate E_d of sunlit and shaded leaves of each species for each

day in the growing season of 1986. Equation 2 was used to calculate daily TWU of the riparian zone at each site on each day. TWU values were then summed across all days to estimate seasonal TWU.

Sunlit LAI of each species in each community ($LAI_{i,k}(\text{sun})$) was calculated as (Monteith 1973):

$$(4) \quad LAI_{i,k}(\text{sun}) = \exp(-K LAI_k) LAI_{i,k}$$

where LAI_k = LAI of community k , $LAI_{i,k}$ = LAI of species i in community k , and K = an "extinction" coefficient. This equation assumes a random distribution of foliage with respect to leaf inclination and azimuth. $LAI_{i,k}(\text{shade})$ was simply $LAI_{i,k}$ minus $LAI_{i,k}(\text{sun})$. We used values of K from the literature: 0.27 for cottonwood canopies (value for aspen canopies, Rauner 1976), 0.50 for willow canopies (value for Salix viminalis thickets, Cannell et al. 1986), and 0.35 for the sedge and moist meadow communities (value for alpine sedge meadows, Korner 1982). The sedge-willow community was assumed to have a K value intermediate to willow thickets and the sedge community.

The field data on maximum seasonal LAI's and seasonal changes in LAI were used to construct seasonal curves of LAI for each species in each community:

$$(5) \quad LAI_{i,d} = LAI_{k,\text{max}} (SLA_{i,d}/SLA_{i,\text{max}})$$

where $LAI_{i,d}$ and $SLA_{i,d}$ = LAI and mean shoot leaf area of species i on a given day, $LAI_{k,\text{max}}$ = maximum seasonal leaf area of community k , and $SLA_{i,\text{max}}$ = maximum seasonal shoot leaf area of species i .

Once leaf senescence started in autumn, sunlit and shaded LAI's of cottonwood and all the willow species were broken down into separate fractions representing leaf area which was still green and leaf area which was yellow (senescing), based on the field sampling for leaf senescence. The green fraction of LAI for each species was assumed to transpire at the "normal" observed rates, while the yellow fraction of LAI was assumed to transpire at a lower rate equal to the ratio of yellow to green g_{max} measured in September.

A correction factor was applied to all cover values (C_k) at Libby Flats to account for the gradual increase in cover of each plant community as the snowbank filling the basin melted back. This was simply a scalar ranging from zero (entire community snow-covered) to one (entire community snow-free).

We assumed, on the basis of the comparative g_s measurements in 1985 and 1986, that Geyer willow, beaked willow, whiplash willow, and mountain alder had identical E_d to mountain willow at Little Laramie, and that shortfruited willow and mountain willow had identical E_d to planeleaf willow and other broadleaved herbs had identical E_d to marsh marigold at Libby Flats. We further assumed that mountain willow and sandbar willow at Hecht Creek and Hecht Ditch had identical E_d to their values at Little Laramie. Because these sites were at similar elevations (+30 ft) and within 5 miles of each other, and thus experienced similar

weather conditions, this seemed a reasonable assumption.

The seasonal E_d values used in this model were measured on clear or mostly-clear days, with mean daytime values of PPFD and T_a above the seasonal average and mean daytime values of RH below the seasonal average. Many days were characterized by considerable cloudiness (low PPFD) and/or unseasonably low T_a and high RH. Since PPFD, T_a , and RH all influence LAVD (Eq. 1), the E_d values on the sampling days were not representative of all days during the growing season. Most days probably had lesser E_d and some days probably had greater E_d .

When rain occurred, leaves were wet and E was probably near zero. This assumption is supported by the results of Larsson (1981), who found that E of willow was reduced 95% after leaves were sprayed with water. Since dew occurred on all sampling days at Libby Flats, the influence of dew was assumed to have been accounted for in the measured E_d values there. At Little Laramie, however, dews did not occur on the sampling days, although they did occur earlier and later in the growing season.

Stomatal conductances of woody plants are known to be reduced on days following nights with low air temperatures. For example, nighttime T_a of 39°F decreased g_s of plains cottonwood (Populus deltoides) by two-thirds in mid-Summer (Drew and Bazzaz 1979). Nighttime T_a less than 43°F reduced g_s of conifers growing in the Medicine Bow Mountains, with complete inhibition ($g_s = 0$) occurring following nighttime T_a of 27°F in early Summer or 15°F in early fall (Smith 1985, Delucia 1987).

This discussion indicates that the influence of several factors - cloudy or cool weather, rain, dew, and freezing or near-freezing T_a - needed to be accounted for by the model. There was no reasonable way to handle the LAVD problem, but the other factors were dealt with in simple fashion. Using the hourly meteorological data collected by the weather stations, we calculated, for both Centennial Valley and Libby Flats, mean T_a during the daylight hours on each day of the growing season of 1986. If mean T_a was less than 43°F on any given day, all E_d values were multiplied by a constant which ranged from zero at 15°F to one at 43°F or above. We also calculated the number of daylight hours with measurable precipitation during each day. For Centennial Valley, all hours with RH = 100%, i.e., dew forming, were included as if rain were occurring. All E_d values were multiplied by a constant which varied from zero (rain all day) to one (no rain all day), based on the fraction of daylight hours with rain.

We feel that the TWU values calculated by this model were moderately overestimated because the model did not account for days when low T_a , low PPFD, and/or high RH reduced E_d .

TWU at the study sites: complex model

As discussed above, the influence of day-to-day variation in weather was not well-accounted for by the simple model. Furthermore, T_a and RH were measured and g_b values calculated only for mid-canopy leaves during the field sampling and the resultant E_d values were used by the simple model. Leaves at the top of the canopy were exposed to greater windspeeds and lesser

RH, and thus probably transpired at greater rates. Leaves near the base of the canopy were exposed to lesser windspeeds and higher RH, and thus probably transpired at lesser rates. Integrated whole-canopy E_d rates may therefore have been somewhat different from those calculated for mid-canopy leaves.

To provide more realistic estimates of TWU, a more complex canopy layer model was envisioned which would estimate hourly changes in E throughout the growing season from hourly meteorological data, as measured by the weather stations, and calculate the concomitant responses of g_s , g_b , LAVD, and E at each height level in the canopies of the various riparian plant communities. However, for reasons discussed under Results, construction of a model of this type was judged not to be feasible.

TWU in the Little Laramie drainage

Aerial infrared photographs (1:24000) taken by the Soil Conservation Service in 1982 were analyzed to estimate the total cover of various riparian plant communities in the entire Little Laramie River drainage. Cottonwood groves were distinguished from willow thickets by differences in canopy height when viewed under a stereoscope. The different alpine plant communities were not distinguishable in the photographs, so only total cover of alpine source basins was measured. The narrow, poorly-developed riparian zones at intermediate elevations were not measured.

The outline of each cottonwood grove, willow thicket, or alpine source basin was traced and the areas of each tracing measured with a digitizing tablet (Numonics Corp. model 2400). Areas were summarized separately for cottonwoods and willows, for low-elevation natural streams and irrigation ditches, and for alpine source basins.

Water use values were estimated for the entire drainage by multiplying each plant community's total growing season TWU by its total area within the drainage. TWU values for the cottonwood groves at Little Laramie and the cottonwoods lining Bellamy Canal were applied, respectively, to cottonwood groves along natural streams and cottonwoods growing along irrigation ditches. TWU values for the cottonwoods lining Bellamy Canal were applied to all cottonwoods along irrigation ditches. TWU values for the willow thickets at Little Laramie and the willows lining Hecht Ditch were applied, respectively, to willows growing along natural streams and along irrigation ditches.

Because individual plant communities could not be discerned on aerial photos, the relative proportion of total riparian zone cover at Libby Flats occupied by each plant community and, hence, the TWU for the entire Libby Flats riparian zone, was assumed to hold true for all alpine source basins in the Medicine Bow Mountains.

To assess the relative importance of TWU to the water budget of the entire drainage, we estimated drainage-wide streamflow and rainfall. There were too few stream gauging stations in the Little Laramie drainage to calculate total drainage streamflow. However, the flow of the Little Laramie at the gauging station at the Little Laramie site was probably a reasonable approximation

because all of the river's tributaries but one coalesced above this site. The flow added by that downstream tributary (Mill Creek) may have been roughly balanced by the flow removed by several upstream irrigation ditches.

Drainage-wide rainfall was estimated by assuming that 1) all of the drainage area from the foot of the Medicine Bow Mountains to the junction of the Little Laramie with the Big Laramie received the same rainfall as that observed during the 1986 growing season at Little Laramie and 2) all of the drainage area in the mountains received the same rainfall as that observed during the 1986 growing season at Libby Flats. An area-weighted mean rainfall was calculated for the entire drainage.

RESULTS

Leaf Areas

Leaf area indices

Cottonwood groves at Little Laramie had greater LAI than the willow thickets (Table 1), due to both to greater canopy height (15 to 80 ft vs. 6 to 18 ft) and larger leaves (15 to 25 in² vs. 6 to 13 in² at full expansion) compared to willows. Cottonwoods did not form a continuous canopy at Bellamy Canal, as was the case for the groves at Little Laramie, and hence had lower LAI at the Canal. Mountain willow and sandbar willow were codominant in terms of LAI at Little Laramie.

At Hecht Creek, similar numbers of clumps consisted of Geyer and mountain willow, but the lesser height and substantially smaller leaves of Geyer willow resulted in its having much lower LAI than mountain willow (Table 1). The much higher total LAI at Hecht Creek compared to Little Laramie was largely a sampling artifact. At Little Laramie, we mapped the outer boundaries of the willow thickets. Within the thickets, there were many small openings and areas with low stem density. At Hecht Creek, we mapped the outlines of individual willow clumps, within which stem density was very high.

Except for a few mountain willow shrubs, the Hecht Ditch riparian zone consisted exclusively of sandbar willow (Table 1). Although most of the willow clumps were of shorter stature than those at Little Laramie, a much greater stem density resulted in a higher LAI than at Little Laramie.

Planeleaf willow was the dominant willow in the widespread sedge-willow community at Libby Flats, but mountain willow had higher LAI in the small areas occupied by the willow community (Table 1). Tall sedge had similar LAI to planeleaf willow in the sedge-willow community, but completely dominated the sedge community. LAI of the moist meadow community consisted primarily of short sedge, but with a substantial component of marsh marigold and other broadleaved herbs.

Seasonal changes in leaf area

Figure 2 shows seasonal changes in relative shoot leaf area (SLA) for each major riparian species in 1986. Qualitative patterns of SLA were similar in 1985, with the exception that the growing season was compressed at Libby Flats because of later snowmelt than in 1986 (Table 2).

Budbreak of cottonwood and mountain willow at Little Laramie commenced in early May in both 1985 and 1986, followed two weeks later by budbreak of sandbar willow (Fig. 2). Shoot growth of these species continued until late July, leaf senescence began in early September, and leaf abscission began in mid-September. Hard frost (T_a less than 23°F) coincided with an abrupt decrease in g_s to zero or near-zero, indicating seasonal stomatal closure, at both high and low elevation in 1985 and 1986. Hard frost arrived sooner in 1985 than in 1986 (September 23 vs. October 11); thus, the low-elevation growing season, despite similar budbreak dates, was shorter in 1985 than in 1986 (Table 2).

Budbreak of the alpine species occurred shortly after snowmelt exposed the plants. Shoot growth was rapid until early August and leaf senescence and abscission commenced only a few weeks later, at the end of August (Fig. 2). Snowmelt occurred so late in the snowbank community that the growing season was less than 60 days. Hard frost, causing stomatal closure, occurred in late September in both 1985 and 1986 at Libby Flats. However, the growing season was shorter in 1986 than in 1985 (Table 2) because more snow accumulated in the basin in 1986, delaying the appearance of the first bare ground until late June.

Microclimate

Above-canopy and soil microclimate

A summary of climatic differences between Centennial Valley (Bellamy Canal in 1985, Little Laramie in 1986) and Libby Flats is shown in Table 2. It is readily apparent that the alpine site had a shorter growing season with lower T_a , a shorter frost-free period, and higher RH than did Centennial Valley. Rainfall averaged 0.06 inches d^{-1} in both 1985 and 1986 in Centennial Valley, compared to 0.07 and 0.08 inches d^{-1} , respectively, in 1985 and 1986 at Libby Flats. These results suggested that, all other factors being equal, seasonal TWU of the alpine riparian vegetation would be lower than that of low-elevation riparian vegetation.

Detailed seasonal patterns of meteorological variables in 1986 are shown in Figure 3. Soil T_s and ψ_s patterns at Hecht Creek and Hecht Ditch are not shown because they were similar to the patterns at Little Laramie. Patterns of T_a , T_s , and ψ_s in 1985 (not shown) were similar to 1986 patterns.

Maximum and minimum daily T_a and day-to-day variation in these variables were less at Libby Flats than at Little Laramie. Soil temperature at all depths at Little Laramie increased from early May into August, then declined. At Libby Flats, changes in T_s at 20 cm (7.9 in) depth lagged behind changes in T_s at 3 cm (2.0 in) depth, and T_s values were 2 to 5°C (4 to 10°F) less than at Little Laramie. Soil water potential remained above -0.5 MPa (-5 bars) on the upper terrace at Little Laramie until mid-June, decreased to minimum values in mid-August, then increased again. Precipitation occurred frequently at both sites, with large between-event variation in amounts.

Within-canopy microclimate

Windspeed at the top (7.3 ft) of the willow thicket canopy at Little Laramie was linearly related to above-canopy (weather station, 29 ft) windspeed, always being 60 to 65 percent less. Within the willow thicket canopy, windspeed was related to LAI as follows:

$$(6) U_h = \exp(-K LAI_k) U_r$$

where U_h = windspeed at height h , U_r = windspeed at the top of the canopy, K = an extinction coefficient, and LAI_k = LAI of the willow thicket. The value of K was -2.0, as determined by

logarithmic regression ($r^2 = 0.96$).

In contrast to windspeed, T_a showed little variation with height. Relative humidity measured at mid-canopy was linearly related to above-canopy RH, being greater than above-canopy RH when humidity was low (daytime) and less than above-canopy RH when humidity was high (nighttime).

At Libby Flats, windspeeds in the sedge and moist meadow communities were better predicted from height above the ground than from LAI:

$$(7) U_h = \exp(-K h) U_r$$

($K = -2.2$, $r^2 = 0.87$). Problems with the miniature cup anemometers prevented collection of windspeed profile data in the sedge-willow community.

RH and T_a decreased with height above ground in each plant community. T_a RH in the middle of the day was as much as 30 percent higher near the ground (0.1 ft) than at the top of the weather station tower (9 ft). T_a increased 3 to 10°F near the ground in the moist meadow community, but only 1 to 4°F near the ground in the sedge-willow and sedge communities. The windspeed, T_a , and RH profiles followed Equation 7 with varying degrees of predictability ($r^2 = 0.27$ to 0.85).

Stomatal Conductances

Diurnal patterns of g_s

Figures 4 and 5 show diurnal patterns of sunlit leaf g_s , T_1 , T_a , LAVD, E, and ψ_p for one representative, midsummer clear day in 1986 at Little Laramie and Libby Flats. Transpiration was calculated following the procedures described for the simple model of TWU, with g_b calculated from Equation 3. Patterns for short sedge are not shown because they were similar to those of tall sedge. For simplicity, we have not shown patterns for other days, but the following discussion compares different days as well as different species and elevations.

On all sampled days at Little Laramie, T_a , T_1 , and LAVD of cottonwood, mountain willow, and sandbar willow reached maximum values between 1200 and 1600 hr (Fig. 4). Qualitative patterns of diurnal g_s at Little Laramie did not differ much among species or with time in the growing season. The most commonly observed pattern was for g_s to increase steadily throughout the day to a maximum value between 1600 and 1800 hr, but on a few occasions stomata partially closed in the afternoon, then reopened (e.g., mountain willow on August 6; Fig. 6). Transpiration, for most species on most days, was usually maximal in late afternoon, when g_s was also maximal, but sometimes LAVD's at midday were large enough that E was maximal at midday, prior to maximum g_s . Following rapid morning declines, minimum ψ_p values were attained at 1200 hr. Subsequent increases in ψ_p occurred either immediately or after a 2 to 4 hr delay.

At Libby Flats, T_a , T_1 , and LAVD of planeleaf willow, marsh marigold, and tall sedge showed broad maxima between 1000 and 1600 hr (Fig. 5). Early morning dewfall or moisture left on

leaves from rain the previous evening prevented measurement of g_s until between 0730 and 0945 hr on all sampling days. On August 23 and September 2, evening thunderstorms terminated g_s measurements at 1845 and 1545 hr, respectively. Conductance of planeleaf willow rose steadily throughout each day, reaching peak values at 1600 to 1800 hr. This same pattern occurred on three out of five days for marsh marigold and on all days for both forms of sedge. On two days, g_s of marsh marigold declined in late afternoon following maxima^s at 1400 hr. Transpiration increased in parallel with g_s for all alpine species until 1400 or 1600 hr, then declined as LAVD dropped, even when g_s remained constant or continued to increase. Daily ψ_p patterns were similar to the low-elevation species. However, on both August 5 and 23, the morning ψ_p decline was delayed until evaporation of dew from leaf surfaces was completed.

Shaded leaves always had lower g_s (Fig. 6) and lower T_l , LAVD, and E than sunlit leaves of the same species on the same date. Between-leaf variation in these parameters was usually less for shaded than for sunlit leaves.

Seasonal changes in g_s

Values of g_{max} for cottonwood increased rapidly from about 5 $mm\ s^{-1}$ (0.2 in s^{-1}) shortly after budbreak to near 17 $mm\ s^{-1}$ (0.7 in s^{-1}) by the beginning of June, then more gradually to a broad maximum of 28 to 30 $mm\ s^{-1}$ (1.1 to 1.2 in s^{-1}) from late June to early August (Fig. 7). A steady decline in g_{max} occurred for the remainder of the growing season. Values of g_{max} for mountain willow and sandbar willow followed similar patterns to cottonwood.

Maximum values of E_d for mountain willow coincided in time with maximum g_{max} , but maximum E_d of cottonwood and sandbar willow occurred later than maximum g_{max} (Fig. 7). E_d early and late in the growing season was similar among the low-elevation species, but in the middle of the growing season cottonwood had considerably greater E_d than the willow species. Sandbar willow used only slightly more water than mountain willow, despite its substantially greater g_{max} . The reason for this was that, on all days, T_l values and, hence, LAVD's, were lower for sandbar willow than for mountain willow (Fig. 5).

Maximum (0600 hr) ψ_p was similar among cottonwood, mountain willow, and sandbar willow early and late in the growing season, but from mid-August until early October, maximum ψ_p was lower in cottonwood than in the two willow species (Fig. 8). Minimum (early to mid-afternoon) ψ_p of the willows was 0.4 to 0.9 MPa (4 to 9 bars) less than maximum ψ_p throughout the growing season. For cottonwood, however, the difference between maximum and minimum ψ_p became increasingly larger after late May and in August both values were substantially less than those measured for the willow species.

Following budbreak, g_{max} of planeleaf willow and tall sedge at Libby Flats increased to maxima value in August, followed by gradual declines (Fig. 7). Marsh marigold g_{max} peaked in early August, then declined rapidly. E_d of all three species reached maxima slightly earlier in the growing season than maximum g_{max} .

Maximum ψ_p of planeleaf willow fluctuated between -0.3 and -1.2 MPa (-3 and -12 bars), but maximum ψ_p of marsh marigold remained above -0.3 MPa (-3 bars), throughout the growing season. Minimum ψ_p of both species was similar, declining steadily over the growing season.

Except for g_{max} of marsh marigold in early summer, the high-elevation species had much lower g_{max} and E_d values throughout the growing season than any of the low-elevation species (Fig. 7). These differences in E_d were larger than could be accounted for by differences in g_{max} , for two reasons. First, T_a was lower and RH higher during clear summer days at Libby Flats compared to Little Laramie (Table 2, Fig. 2), leading to lower LAVD's and, thus, lesser evaporative demand at a given g_s (Figs. 4 and 5). Second, on all days heavy dewfall at Libby Flats delayed the onset of E until between 0730 and 0930 hr.

The values of g_{max} for the low-elevation cottonwood and willows we studied (greater than 25 mm s^{-1} (1.0 in s^{-1})) were substantially higher than those previously observed for low-elevation cottonwoods and willows outside of Wyoming (less than 10 mm s^{-1} (0.4 in s^{-1}); Small 1972, Stoner and Miller 1975, Anderson 1982, Pezeshki and Hinckley 1982). This result may be attributed in part to the increase in the diffusion coefficient for water vapor in air (D_w) with increasing elevation (Smith and Geller 1979). Oberbauer and Billings (1981) found 25 percent lower g_{max} in alpine willow species growing in the Medicine Bow Mountains compared to the g_{max} we observed for planeleaf willow. Young et al. (1985), working in the Medicine Bow Mountains, found that mean, midsummer g_{max} for two low-elevation (7,400 ft) willow species was 49 percent less than for three high-elevation (9,400 ft) willow species, the opposite situation to what we observed. Because of lesser g_{max} , maximum seasonal E_d of Young et al.'s (1985) low-elevation willows was only one-third as large as that of our low-elevation willows.

The g_{max} values observed for all species in our study were at the upper end of the range for woody plants (Korner et al. 1979). In fact, g_{max} values at low elevation approached theoretical limits for wide-open stomata. At such large values, g_s and g_b were similar in magnitude and the influence of g_b on E_s was substantial (Eq. 1). During mornings, when g_s and windspeeds were low, g_b probably was the limiting conductance determining E.

Stomatal responses to environmental factors

It was evident from the daily patterns of g_s that the stomata of each species were responding to some set of environmental factors. In an attempt to elucidate these patterns, we plotted the mean g_s values of each species for all five days of diurnal measurements and over specified intervals of concurrently measured PPFD, ψ_p , T_1 , and LAVD (Figs. 8 to 10). Plots for the four woody phreatophytes (cottonwood plus mountain, sandbar, and planeleaf willow) and for the herbaceous alpine species (marsh marigold, tall sedge) were grouped together to facilitate comparisons between similar growth forms. Patterns for short sedge (not shown) were similar to those of tall sedge.

Between-shoot and between-plant variation on any given day and

hour was substantial, as indicated by the large standard deviations in Figures 4 to 6, explaining why the confidence intervals in Figures 8 to 10 were generally large. This natural variation may have obscured relationships between g_s and various environmental factors.

Stomata of each of the low-elevation species were fully open at PPFD of $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ ($28 \mu\text{mol ft}^{-2} \text{s}^{-1}$) (Fig. 8). The data for the three alpine species suggest that stomata were fully open at PPFD greater than $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ ($11 \mu\text{mol ft}^{-2} \text{s}^{-1}$). PPFD values less than 100 were not observed in the field at Libby Flats because they occurred only when leaves were wet in the early morning and g_s could not be measured.

Changes in g_s were not correlated with ψ_p for any species (Figs. 8 to 10). There was no relationship between T_1 and g_s or LAVD and g_s for any of the low-elevation species (Fig. 9). However, T_1 values less than 14°C (45°F) were always associated with PPFD values less than $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ ($28 \mu\text{mol ft}^{-2} \text{s}^{-1}$), i.e., g_s light-limited, so these T_1 values and the associated LAVD values were excluded from Figure 9. For planeleaf willow and marsh marigold, significant positive correlations existed between T_1 and g_s and LAVD and g_s (Fig. 10). Because T_1 and LAVD were also positively correlated, we do not know if this response was to T_1 , to LAVD, or to both.

Seasonal g_{max} of each of the low-elevation species was significantly and positively correlated with T_s at 25 cm (9.8 in) depth and ψ_s at 60 cm (23.6 in) depth, and g_{max} of planeleaf willow was significantly correlated with T_s at 10 cm (7.9 in) depth. However, there was no correlation between T_s and g_{max} of marsh marigold and sedge, or between g_{max} of any species and daily maximum T_a , daily minimum T_a , and daily rainfall. We do not know if the significant correlations reflected direct cause and effect relationships. Most likely, g_{max} was determined by the interaction of several environmental factors, with the relative importance of each factor changing over the course of the growing season (cf. Smith 1985).

Streamflows and Water Table Depths

Streamflows

Qualitative streamflow patterns at each site were similar between 1985 and 1986, but streamflow volumes of the natural streams were higher throughout the growing season in 1986 than in 1985 (Fig. 11) because of a deeper spring snowpack and greater precipitation in the mountains in 1986 (Table 2). In the case of the irrigation ditches, streamflows did not increase in 1986 compared to 1985 because they were artificially regulated. However, irrigators extended the season of flow in both ditches in 1986.

Water table depths

Water table depths proved difficult to quantify. At Little Laramie, Hecht Creek, Hecht Ditch, and Libby Flats, the water table dropped over the course of the growing season, falling successively below the bottoms of more and more piezometers.

Thus, the sample size declined over time and the mean depths in late summer were underestimated. In addition, there was great variability among individual piezometers. These differences were related both to microtopography, e.g., varying river terrace heights at Little Laramie, and to distance from the stream channel, i.e., depths were greater at further distances. Because of these problems, we were unable to correlate TWU's or streamflows with water table depths.

General patterns of water table depths at Little Laramie and Libby Flats are shown in Figure 13. Flooding at Little Laramie covered most of the river terraces starting the third week of May; this explains why the mean depths were negative. Flooding continued for one month, then the water table dropped slowly. Late September rains decreased depth somewhat. Mean water table depth at Libby Flats when the first bare ground appeared in late June was 3 cm (1.2 in) and some areas were still under standing water produced by snowmelt. The water table then dropped gradually throughout the summer.

Transpirational Water Use

Simple vs. complex models

We decided that it was not feasible to construct the complex model to predict TWU. Our reasons for this were twofold. First, the observed relationships between g_s and environmental factors in the field were weak or absent. For example, there was no apparent relationship between g_s and either T_1 , LAVD, or ψ_p for any species at Little Laramie (Figs. 8 and 10) and the relationships between g_s and PPFD indicated, at best, that stomata were fully open at very low light levels (Fig. 8). Reasons for this lack of relationships may have included the fact that a limited number of g_s measurements were made on each species (maximum sample number less than 200) and that there was a lot of between-leaf variation (i.e., the large standard deviations in Figs. 5 to 7). Since several environmental factors might have been influencing g_s simultaneously, larger sample sizes, spatially and temporally, may have been needed to reduce g_s variation enough to pick out the relationships with individual factors.

Second, the significant role of g_b in determining E, as discussed above, rendered calculations of E critically dependent on a precise knowledge of windspeed and mean leaf diameter at each height level in the plant canopies. We had only a moderately good ability to predict windspeed at a given height, particularly in the alpine plant communities. Nor did we measure leaf diameters separately for different plant canopy levels.

The following results and discussion are based on TWU estimates derived from the simple model which interpolated between measured E_d values. The qualitative results are unlikely to have been altered if we had generated more accurate TWU estimates from a canopy layer model. However, as previously discussed, the simple model probably overestimated TWU somewhat. Thus, the TWU/streamflow ratios presented below are probably also slightly overestimated.

TWU at the study sites

Figure 14 compares the major low- and high-elevation species in terms of cumulative clear-day transpiration (E_d) over the growing season. Per unit leaf area, cottonwood was the greatest consumer of water, mountain willow used less, and sandbar willow used the least. The alpine species used substantially less water than the low-elevation species, with marsh marigold having the greatest E_d . E_d was very similar among planeleaf willow, tall sedge, and short sedge.

Table 3 shows the values of TWU calculated by the simple model for the different species, plant communities, and riparian zones, and compares these values to streamflows. All values were standardized to total riparian zone area (all plant communities plus stream channel) at each site. Woody phreatophytes (cottonwood, willows) were the major water consumers in the low-elevation riparian zones, whereas both woody phreatophytes (dwarf willows) and non-woody vegetation (broadleaved herbs, sedges) were major water consumers in the alpine riparian zone. This result is in agreement with the prediction of Hypothesis (1) (see Objectives section).

For the entire growing season, it is apparent that riparian TWU was negligible in comparison to streamflows at Little Laramie, Bellamy Canal, and Hecht Creek (Table 3). At Hecht Ditch and Libby Flats, TWU/streamflow ratios were larger, two and four percent, respectively. The smaller the streamflow, the larger the TWU/streamflow ratio. The reason for this was that smaller streams had a higher ratio of total leaf area to streamflow than did larger streams (Table 4). The order of cumulative streamflow volumes among sites was exactly the reverse of the order of TWU/streamflow ratios. Thus, Hypothesis (2) was correct: smaller streams had larger TWU/streamflow ratios than larger streams.

Examining monthly TWU/flow ratios (Table 3), these were always less than one percent for the larger streams, Little Laramie River and Bellamy Canal, but could reach substantial values for the smaller streams. Maximum ratios occurred at all sites in August, excluding Hecht Ditch, which was shut off by the rancher in mid-July and therefore had no late-summer flow. The reasons for this were 1) LAI's were at their seasonal maxima in the riparian plant communities (Fig. 2), 2) g_{max} values were at or near their seasonal maxima for all species (Fig. 7), and 3) streamflows were much lower than in late spring and early summer (Fig. 11). Thus, Hypothesis (3) was shown to be correct: riparian TWU was largest compared to streamflows in late summer.

The significance of the TWU/streamflow ratios at local sites is best considered in the context of total water availability. Rainfall provided an additional input of water to all sites during the 1986 growing season: 10.5 inches at the low-elevation sites and 7.6 inches at the alpine site (Table 2). Rainfall alone could have accounted for 56, 29, 22, 30, and 141 percent of TWU at Little Laramie, Hecht Creek, Bellamy Canal, Hecht Ditch, and Libby Flats, respectively.

The natural stream sites had local water tables supplying

water to the roots of the phreatophytic cottonwoods and willows. For Little Laramie, assuming the water table was 3.28 ft deep, bedrock occurred at 9.84 ft, and soil pores occupied 10 percent of the soil volume (a reasonable value for alluvial soils in the Little Laramie drainage; Borelli and Burman 1982), 65.6 inches of water were stored in the water table. The same calculation for Hecht Creek, assuming bedrock at 6.56 ft depth, meant 33.9 inches of water table storage, while at Libby Flats, assuming water table depth at 1.64 ft and bedrock depth at 6.56 ft, the water table may have stored 30.6 inches. Water table storage alone could have accounted for 250, 94, and 575 percent of TWU at Little Laramie, Hecht Creek, and Libby Flats, respectively.

The TWU values we measured in the low-elevation riparian zones, 18.6 to 46.7 inches, lay within the range of TWU values measured for desert phreatophytes growing in lysimeters, 2 to 96 inches. This may seem surprising in light of the fact that the growing season is shorter and the climate cooler and less dry in southeast Wyoming than in deserts. The major reason for the similar TWU's is the much larger g_s values (greater than 25 mm s^{-1}) for Wyoming phreatophytes compared to desert phreatophytes (less than 10 mm s^{-1} ; Anderson 1982, Nilsen et al. 1984). The increased D_w value at the high elevations of the Wyoming sites was also a contributing factor.

TWU in the Little Laramie drainage

For the entire Little Laramie River drainage, riparian zone TWU during the growing season of 1986 was estimated to total only 0.1321 inches, when TWU was expressed for the surface area of the entire basin (229,116 acres). Ninety-six percent of this TWU was contributed by low-elevation riparian zones because they had higher water use rates per unit ground area (Table 3) and covered a much larger area (16,199 vs. 5,775 acres) than did high-elevation riparian zones (Table 5). Despite lower water use rates per unit ground area (Table 3), low-elevation, natural stream riparian zones contributed 62 percent of total drainage TWU compared to 34 percent for irrigation ditch riparian zones because they covered a much larger area (13,389 vs. 2,810 acres; Table 5).

Cumulative streamflow of the Little Laramie River during the growing season of 1986 was 4.17 inches for the entire drainage (Table 5). Riparian TWU was 3.2 percent of this value. Inclusion of growing season rainfall (10.54 inches in 1986) yielded a TWU/(streamflow + rainfall) ratio of 0.9 percent. When wintertime (October to May) streamflow and the water stored in natural lakes, reservoirs, and water tables are considered, it is obvious that TWU was an insignificant fraction of the total water budget for the Little Laramie River drainage in 1986. The large difference between rainfall inputs and streamflow outputs in this drainage suggested that water losses to evaporation, bank storage, and subalpine forest transpiration are much larger in magnitude than were losses to riparian zone transpiration.

It is of interest to compare riparian TWU in this study to riparian TWU calculated by VanKlavaren et al. (1975). They estimated a value of 9,734 acre-ft of riparian ET for the Big

Laramie River, exclusive of any tributaries (Larry Pochop, University of Wyoming, personal communication), being lost from a total cottonwood/willow riparian area of 3,432 acres. For comparison, we estimated riparian transpiration for natural streams in the Little Laramie drainage (1,339 acres) of 1,558 acre-ft (Table 5). If we assume that evaporation was 20 percent of ET (a generous estimate) and apply VanKlavaren et al.'s per acre transpiration values to the acreage of natural stream phreatophytes in the Little Laramie drainage, we arrive at a value of 3,038 acre-ft. It appears that VanKlavaren et al.'s value is a substantial overestimate. Given the fact that they used Blaney-Criddle coefficients derived from phreatophytic vegetation growing in the much drier and hotter climate of Arizona (Rantz 1968), this disparity is not surprising.

Additional considerations

Although rainfall differed little between 1985 and 1986 (Table 2), natural stream flows were considerably less in 1985 because of a much shallower snowpack in the mountains. Mean T was very similar between years, but mean VPD's were higher in 1985 than in 1986, at both low and high elevation (Table 2). Growing season length was a little longer in 1986 than in 1985 at low elevation, but was less in 1986 at high elevation. Thus, seasonal TWU was probably similar between years at low elevation (greater VPD offset by shorter growing season in 1985), but greater at high elevation in 1985 (both greater VPD and longer growing season). In summary, the seasonal TWU/streamflow ratios were probably somewhat higher at low elevation, whereas they were probably substantially higher at high elevation, in 1985 compared to 1986. This conclusion assumes that seasonal patterns and absolute values of E_d for each species were similar in both years.

We did not measure between-site variability in species composition and LAI's for the various study sites, preferring to measure these parameters at sites which we felt were representative. Thus, TWU/streamflow ratios along different stream stretches might have been lower or higher than those listed in Table 3, depending on variations in total leaf area, riparian zone cover, and streamflows within each stretch.

The ultimate termini of the Little Laramie drainage are represented by overland flow from melting snowbanks at high elevation and overland flow during flood irrigation of pastures at low elevation. Streamflows are very difficult to measure in these situations, so we chose to focus on definable stream channels. Field observations suggest that TWU/streamflow ratios in overland flow situations are probably low. For example, at high elevation overland flow occurs only for a short distance downhill from melting snowbanks. Since the ground there has only been free of snow for a few days, there is very little leaf area. Similarly, flood irrigation occurs primarily in May and June, before leaf areas of irrigated pastures are well developed.

CONCLUSIONS

Summary of research findings

Total riparian zone transpirational water use (TWU) during the growing season of 1986 was estimated for five representative stream stretches in the Little Laramie River drainage in southeast Wyoming. These sites represented large and small natural streams and large and small irrigation ditches at low elevation, and alpine source basins at high elevation.

Woody phreatophytes (cottonwoods and willows) were the major water consumers in low-elevation riparian zones. Dwarf willows and alpine herbaceous vegetation were the major water consumers in high-elevation riparian zones. Among low-elevation species, narrowleaf cottonwood consumed the most water per unit of leaf area (185 lbs ft^{-2}) and sandbar willow consumed the least (103 lbs ft^{-2}). Among high-elevation species, marsh marigold consumed the most water per unit of leaf area (40 lbs ft^{-2}), while willows and sedges consumed similar amounts (30 to 33 lbs ft^{-2}).

When water use per unit leaf area of each species was multiplied by each species' leaf area index and by the total cover of the riparian plant community within which each species occurred, it was found that willows were the major water consumers at the large and small natural stream sites (14 and 36 inches, respectively) and the small irrigation ditch site (35 inches), while cottonwood was the major water consumer at the large irrigation ditch site (45 inches). In the alpine source basin, dwarf willows and sedges used similar amounts of water (2 inches), while marsh marigold and other broadleaved herbs used about one-fourth as much water.

The ratio of seasonal TWU to seasonal streamflow increased from 0.04 to 3.96 percent as streamflow decreased from 84,320 to 20 acre-ft because the ratio of transpiring leaf area to streamflow increased. TWU/streamflow ratios increased from less than 0.1 percent in late spring to maximum values in midsummer when low streamflows, seasonal maximum leaf areas, and seasonal maximum daily water use coincided. Midsummer ratios were less than one percent along the large and small natural streams and the large irrigation ditch, but greater than ten percent along the small irrigation ditch and in the alpine source basin. After midsummer, ratios decreased as leaf areas and daily water use diminished.

For the entire Little Laramie River drainage, TWU by riparian zones was 3.2 percent of streamflow during the growing season of 1986. Since large amounts of water were added to the drainage as rain or were stored in reservoirs and water tables, the ratio of TWU to total water flux through the drainage was probably less than one percent.

Recommendations

Along low-elevation natural streams, riparian vegetation stabilizes streambanks and, by trapping sediments with its roots, builds permeable soil masses within which local water tables

develop. Simple calculations suggest that these water tables contain sufficient water to supply one or more years of riparian zone transpiration. Thus, the amount of water consumed by riparian vegetation along natural streams may be more than balanced by the extra water stored in local water tables. If this hypothesis is correct, then the current trend in Wyoming towards riparian zone rehabilitation seems highly desirable, since this vegetation may incur no net water loss while reducing erosion, providing wildlife habitat, and improving scenery. Comparisons between riparian TWU and water table water storage along different stream types in Wyoming would be a fruitful arena for future research.

Along large irrigation ditches, riparian water use is negligible compared to streamflows, so the colonization of man-made canals by cottonwoods seems desirable because of aesthetic and wildlife considerations. Along small irrigation ditches, TWU/streamflow ratios can be large in mid-summer, i.e., near the end of the irrigation season, but remain low during the major portion of the irrigation season in May and June. The water available for irrigation might be increased somewhat by substituting sandbar willow for mountain willow, since sandbar willow uses 13 percent less water per unit of leaf area (Fig. 13).

In alpine source basins, TWU/streamflow ratios are the highest of any stream type. However, the total amount of water used by alpine riparian vegetation is much less than that consumed by low-elevation riparian vegetation because cooler air temperatures, higher relative humidities, and shorter growing seasons greatly reduce daily water use, and because there is less riparian zone cover at high compared to low elevation. Nevertheless, alpine riparian water use is quantitatively important enough that it needs to be considered in models which predict water delivery to the lowlands based on rainfall and snowmelt in the alpine zone.

Estimation of riparian TWU for other local riparian zones in southeast Wyoming will require measurement of: 1) leaf area index of cottonwood groves and willow thickets, 2) the relative proportion of willow thicket leaf area index consisting of mountain/Geyer willow vs. sandbar willow, and 3) the total area of cottonwood groves and willow thickets. TWU can then be computed from the TWU per unit leaf area values in Figure 13, using Equation 2. Individual canopy layers need not be considered separately unless direct field measurement of transpiration rates is planned.

For calculation of basin-wide water budgets in southeast Wyoming, the amount of water consumed by riparian vegetation can be calculated from the data in Table 5 by multiplying the seasonal water use for each major riparian vegetation type per unit ground area by the total area of each vegetation type, estimated on the ground or from aerial photographs. Since the area of cottonwoods along both natural streams and irrigation ditches is generally much less than the cover of willows, the mean TWU values and areas for these two vegetation types could be combined without much loss in accuracy. However, riparian

vegetation along irrigation ditches uses more water per unit ground area than does riparian vegetation along natural streams. Therefore, these two types of stream channels need to be considered separately. For most river systems, the area of alpine riparian zones is much less than that of low-elevation riparian zones and consumes much less water per unit ground area. Thus, alpine riparian TWU can probably be neglected in most water budget calculations.

A considerable portion of Wyoming's riparian habitat lies below 6,000 ft elevation, where a different cottonwood species, plains cottonwood (Populus deltoides), replaces narrowleaf cottonwood, and where some of the willow species are different from those in the Little Laramie drainage. Our TWU data should not be applied directly to these species because their environment differs in at least three ways: 1) The growing season is longer, implying greater TWU. 2) The climate is hotter and drier. This suggests greater transpiration rates and, hence, greater TWU. However, sufficient internal water stress may develop in late summer to induce stomatal closure and thus reduce TWU. 3) Water diffuses slower through air as elevation decreases, reducing TWU at the same stomatal aperture compared to higher elevations. Field measurements of maximum daily stomatal conductance, particularly in late summer, will be necessary if riparian TWU is to be estimated for these lower elevation riparian zones.

ACKNOWLEDGEMENTS

We thank Mark Lindquist, Dan Richards, Ken Nanri, and Diana Haemmerle for assistance with field work and Jim Cole, Lucille Francis, Robert Twist, Keith Lowham, George Crouse, and Howard Brokaw for permission to sample on private ranches. The assistance given by Albany County Water Commissioner Jim Pugh, regional State Forester Ike Muniz, the staff of the Soil Conservation Service in Laramie, and the staff of the Wyoming Water Research Center is also gratefully acknowledged.

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Table 1. Riparian plant community cover and leaf area indices of the major species at each study site.

Site (area in acres) ¹	Plant Community (area in acres)	Species	Leaf Area Index
Little Laramie R. (19.78)	cottonwood groves (0.95)	cottonwood	4.32
	willow thickets (15.51)	mountain willow	0.70
		sandbar willow	0.50
		whiplash willow	0.04
		beaked willow	0.01
Bellamy Canal (1.76)	cottonwood groves (1.58)	cottonwood	2.24
		mountain willow	0.10
Hecht Creek (0.62)	willow clumps (0.34)	mountain willow	4.81
		Geyer willow	0.77
		mountain alder	0.08
		beaked willow	0.06
Hecht Ditch (0.40)	willow thickets (0.23)	sandbar willow	2.51
		mountain willow	0.94
		beaked willow	0.01
		planeleaf willow	0.57
Libby Flats (1.64)	willow (0.03)	shortfruited willow	0.02
		mountain willow	1.19
		planeleaf willow	0.93
	sedge-willow (0.33)	mountain willow	0.08
		tall sedge	0.98
		short sedge	0.07
	sedge (0.09)	marsh marigold	0.10
		other herbs	0.20
		tall sedge	2.86
	moist meadow (0.26)	marsh marigold	0.04
		short sedge	1.36
		marsh marigold	0.09
	snowbank (0.13)	other herbs	0.49
		marsh marigold	0.14
		short sedge	0.05

¹Includes area of stream channel.

Table 2. Comparison of growing season climates at the low-elevation sites in Centennial Valley and the alpine site on Libby Flats.

Climatic Variable	Year	Centennial Valley	Libby Flats
growing season length	1985	146 days	104 days
	1986	162	92
frost-free season	1985	100 days	45+24 days ¹
	1986	109	64
mean air temperature	1985	55.9°F	45.3°F
	1986	54.0	46.0
mean relative humidity	1985	52.6 %	68.7 %
	1986	58.0	72.3
mean windspeed	1985	10.1 mph	9.6 mph
	1986	7.6	9.2
cumulative rainfall ²	1985	9.2 inches	7.4 inches
	1986	10.5	7.6

¹Three consecutive days with frost occurred in mid-August.

²For the growing season.

Table 3. Transpirational water use by riparian vegetation, cumulative growing season streamflows, and transpiration/streamflow ratios at the study sites in 1986.

		Transpiration (inches)								Streamflow (inches x 1000)								Transpiration/Streamflow x 100 ^I							
Site	Species	May	June	July	Aug	Sept	Oct	Total	May	June	July	Aug	Sept	Oct	Total	May	June	July	Aug	Sept	Oct	May-Oct			
Little Laramie River (large natural stream)																									
mountain willow ²								8.6																	
sandbar willow								5.9																	
narrowleaf cottonwood								4.1																	
Total		0.6	3.0	6.2	7.0	2.0	<0.1	18.6	8.9	30.0	8.0	2.1	1.1	0.4	47.5	.01	.01	.08	.33	.17	.01	.04			
Hecht Creek (small natural stream)																									
mountain willow ²								30.0																	
Geyer willow								5.9																	
Total		1.6	7.1	10.7	12.5	3.9	<0.1	35.9	5.3	3.3	1.9	0.7	0.6	0.3	12.0	.03	.21	.56	1.87	.74	.02	.30			
Bellamy Canal (large irrigation ditch)																									
narrowleaf cottonwood								45.2																	
mountain willow								1.5																	
Total		1.9	8.5	15.6	16.2	4.4	<0.1	46.7	13.2	13.6	12.8	3.0	0.0	0.0	42.6	.01	.06	.12	.54	0	0	.11			
Hecht Ditch (small irrigation ditch)																									
sandbar willow								24.4																	
mountain willow								10.3																	
Total		0.5	3.9	12.1	13.9	4.4	<0.1	34.7	0.7	1.0	<0.1	0.0	0.0	0.0	3.6	.07	.38	33.6	0	0	0	1.97			
Libby Flats (alpine source basin)																									
planeleaf willow								2.1																	
tall sedge								1.2																	
marsh marigold ³								1.1																	
short sedge								0.9																	
Total		0.0	<0.1	2.0	3.0	0.3	0.0	5.3	0.0	<0.1	<0.1	0.02	<.01	<.01	0.2	0	.07	2.53	16.5	6.88	0	3.96			

¹Equals zero when streamflow zero.

²Includes a small component of beaked and whiplash willow.

³Includes a small component of other broadleaved herbs.

Table 4. Total riparian leaf area, cumulative growing season streamflow, and leaf area/flow ratios at each study site in 1986.

Site	Leaf Area (acres)	Streamflow (acre-ft)	Leaf Area/Flow ($\times 10^{-5}$)
Little Laramie River	23.50	84230	28
Bellamy Canal	3.76	6020	57
Hecht Creek	1.97	430	458
Hecht Ditch	0.81	60	1350
Libby Flats	1.63	20	8150

Table 5. Transpirational water use (TWU) by riparian vegetation in the Little Laramie River drainage during the growing season of 1986.

Riparian Zone	Area (acres)	TWU (inches x 10 ⁻³)	TWU (acre-ft)
valley natural streams	1339	81.6	1558
cottonwood groves	81	1.4	27
willow thickets	1258	80.2	1531
valley irrigation ditches	281	45.0	860
cottonwood groves	47	9.5	182
willow thickets	234	35.5	668
alpine source basins	577	5.5	105
total drainage	2197	132.1	3513

Figure. 1. Conceptual model for the calculation of transpirational water use by riparian vegetation.

Figure. 2. Relative shoot leaf areas at low (Centennial Valley) and high elevation (Libby Flats) during the growing season of 1986.

Figure. 3. Seasonal variation in microclimate at Little Laramie River and Libby Flats: maximum and minimum daily air temperature (T_a); mean daily soil temperature (T_s) on two (upper and lower) river terraces (Little Laramie) and in the sedge-willow (sw), moist meadow (mm), and sedge communities (Libby Flats); mean soil water potential (ψ_s) on the upper terrace (Little Laramie); and daily rainfall.

Figure. 4. Midsummer (July 27, 1986) values of air (T_a) and leaf (T_l) temperature; leaf-to-air vapor deficit (LAVD); leaf conductance to water vapor (g_s); transpiration (E); and shoot xylem pressure potential (ψ_p) for three riparian species at Little Laramie River. Mean values are shown for T_a , means \pm one standard deviation for T_l , LAVD, g_s , E , and ψ_p . T_l values are slightly offset for clarity.

Figure. 5. Midsummer (August 5, 1986) values of T_a , T_l , LAVD, g_s , E , and ψ_p for three riparian species at Libby Flats. Mean values are shown for T_a , means \pm one standard deviation for T_l , LAVD, g_s , E , and ψ_p . T_l values are offset slightly for clarity.

Figure. 6. Daily patterns of stomatal conductance to water vapor (g_s) for fully sunlit and fully shaded leaves of three riparian species (A - cottonwood, B - mountain willow, C - sandbar willow) at Little Laramie River on August 6, 1986. Values are means \pm one standard deviation. Shaded leaf values are offset slightly for clarity.

Figure. 7. Seasonal variation in 1986 of physiological parameters (means of five leaves) of riparian species at Little Laramie River and Libby Flats: maximum daily leaf conductance (g_{max}); total daily transpiration per unit projected leaf area (E_d); and maximum and minimum daily shoot xylem pressure potential (ψ_p).

Figure. 8. Stomatal conductance to water vapor (g_s) in relation to photosynthetic photon flux density (PPFD) and shoot xylem pressure potential (ψ) for the four phreatophytic species. Values are means $\pm 95\%$ confidence intervals for all g_s values lying within specified intervals of PPFD ($150 \mu\text{mol m}^{-2} \text{s}^{-1}$) or ψ (0.15 MPa). In the case of ψ , g_s values associated with PPFD less than $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ are excluded. Where the symbol (•) appears without confidence intervals, only one value of g_s was observed within the PPFD or ψ interval.

Figure. 9. Stomatal conductance to water vapor (g_s) in relation to leaf temperature (T_l) and leaf-to-air vapor deficit (LAVD) for the four phreatophytic species. Values are means $\pm 95\%$ confidence intervals for all g_s values lying within specified intervals of T_l (20°C) and LAVD (0.2 kPa). Values of g_s associated with PPFD less than $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ are excluded. Where the symbol (•) appears without confidence intervals, only one value of g_s was observed within the T_l or LAVD interval.

Figure. 10. Stomatal conductance to water vapor (g_s) in relation to PPFD, ψ , T_l , and LAVD for two alpine riparian species. Values are means $\pm 95\%$ confidence intervals for all g_s values lying within specified intervals of PPFD ($150 \mu\text{mol m}^{-2} \text{s}^{-1}$) or ψ (0.15 MPa). In the case of ψ , T_l , and LAVD, g_s values associated with PPFD less than $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ are excluded. Where the symbol (•) appears without confidence intervals, only one value of g_s was observed within the given interval. Patterns for short sedge (not shown) were similar to those for tall sedge.

Figure 11. Seasonal patterns of streamflow at each study site in 1985 and 1986.

Figure 12. Seasonal patterns of water table depths at Little Laramie River and Libby Flats. Solid lines connect the mean depths; bars show the range in depth.

Figure 13. Total water use per unit of leaf area (TWU) during the growing season of 1986 for sunlit leaves of each major riparian species.

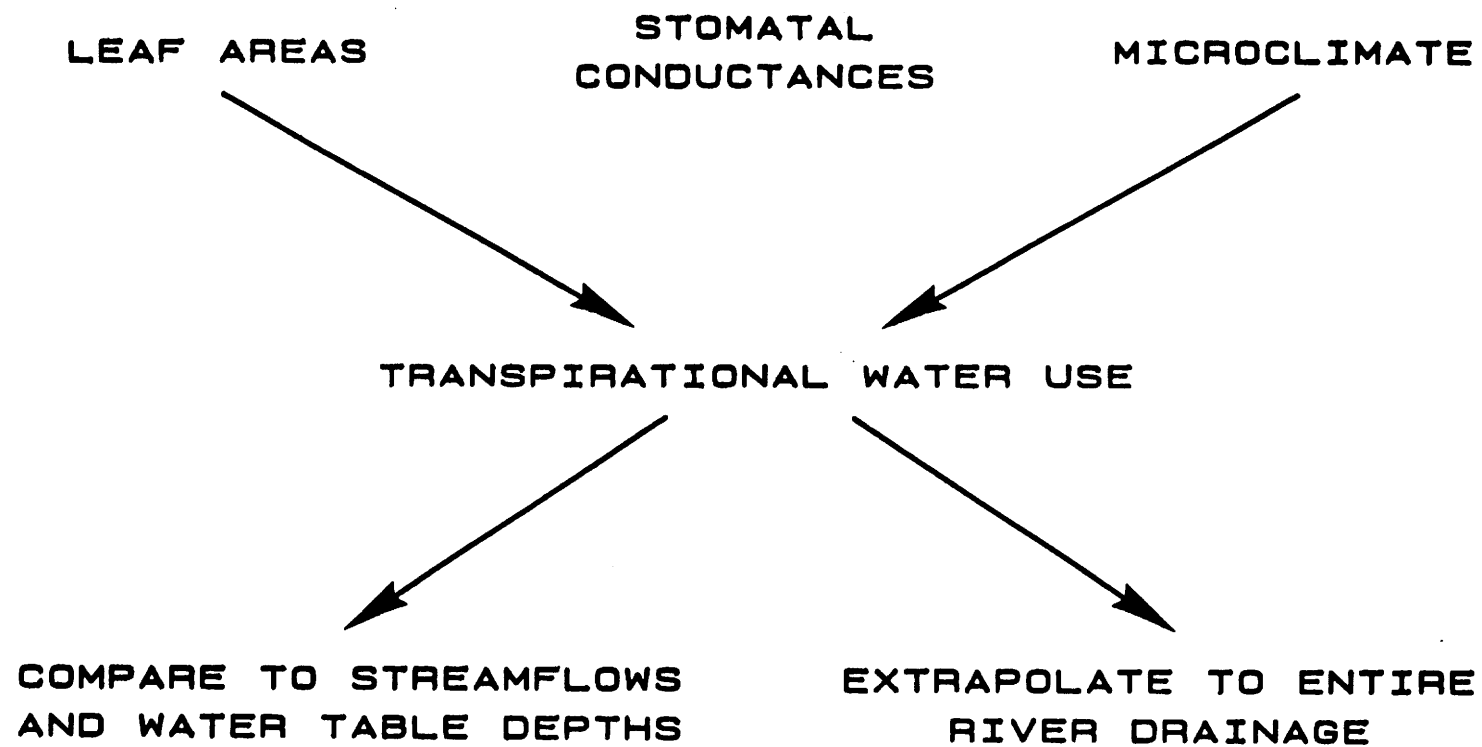
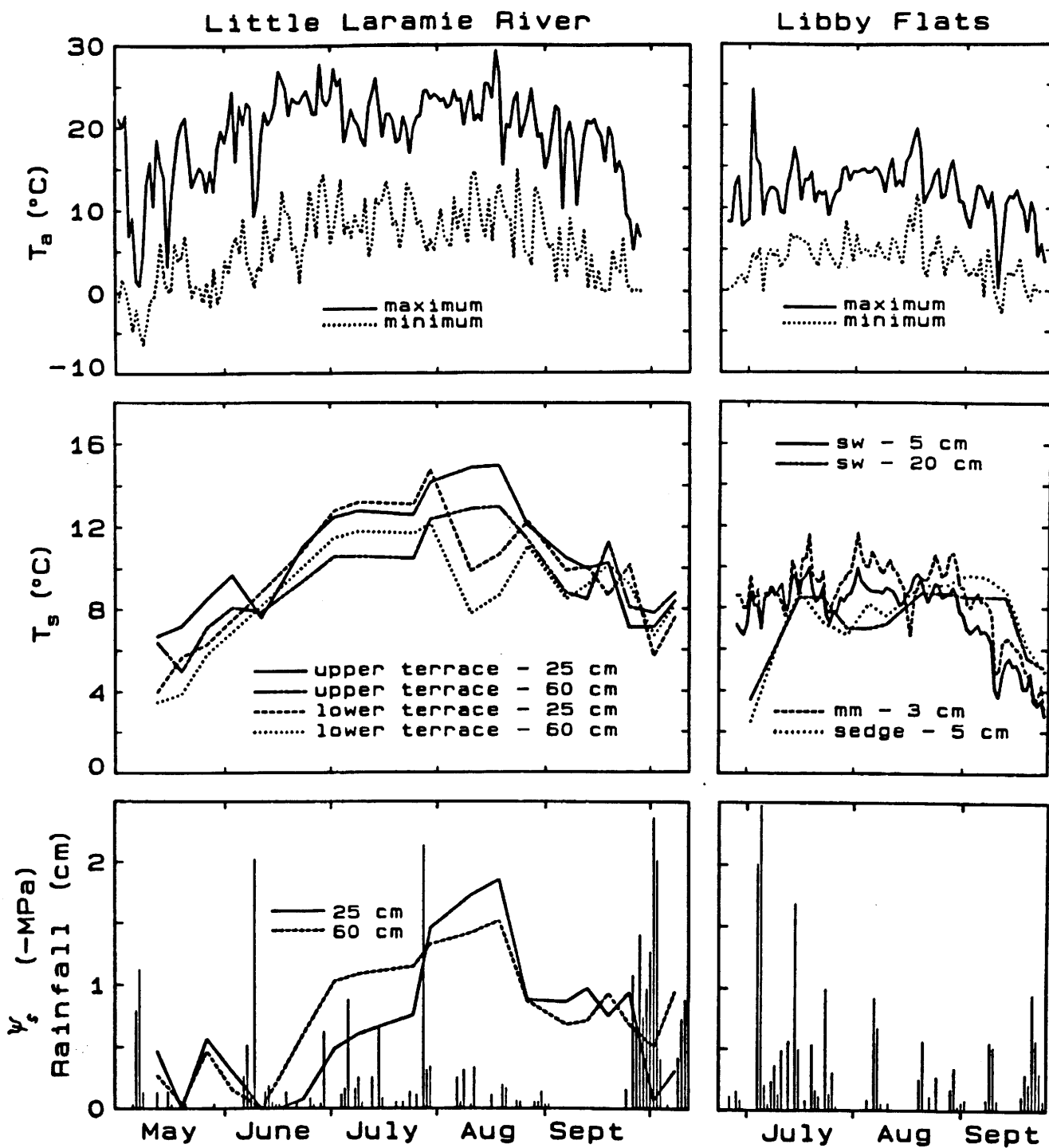


Figure 1

Figure 2



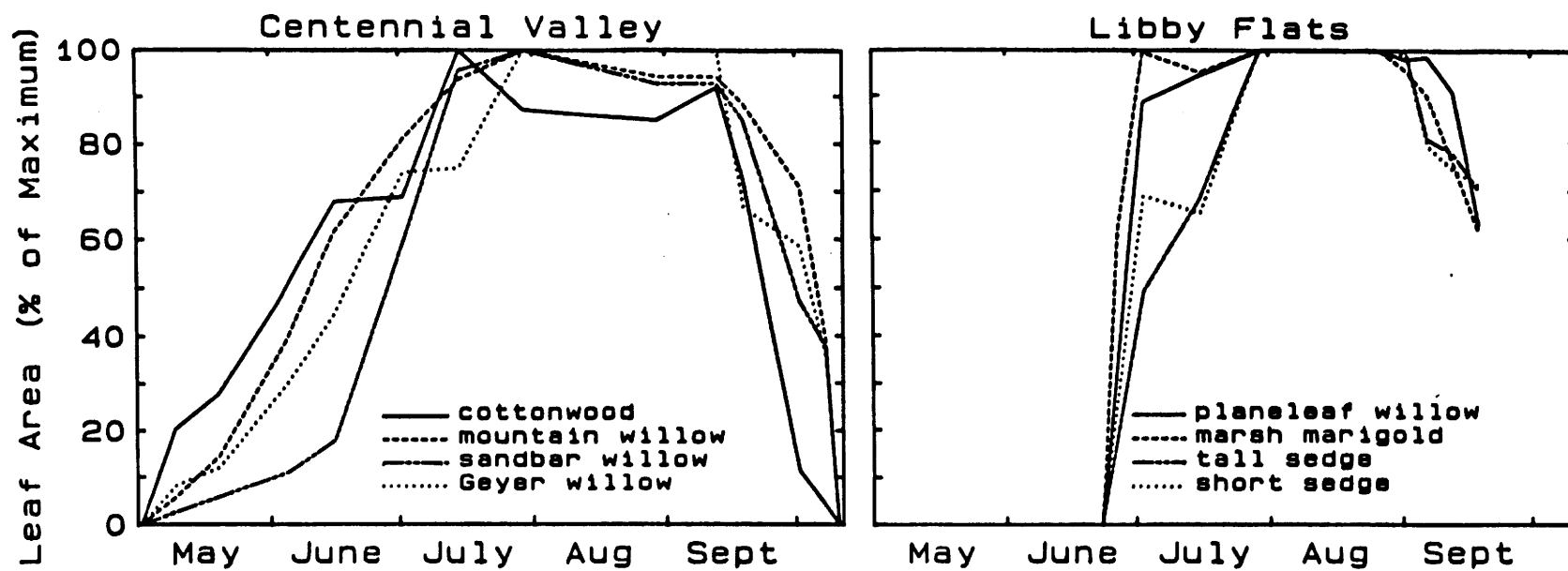


Figure 3

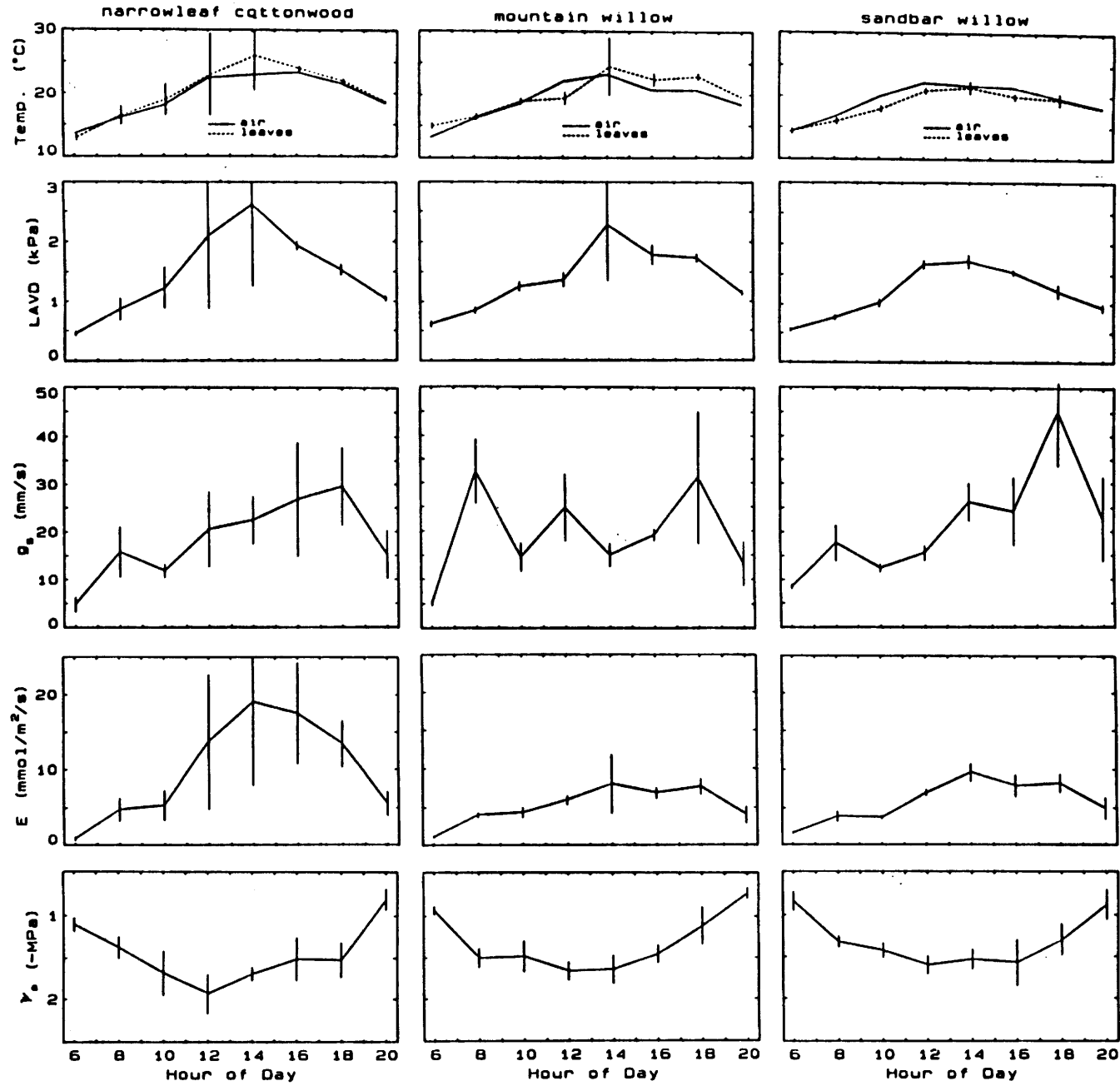


Figure 4

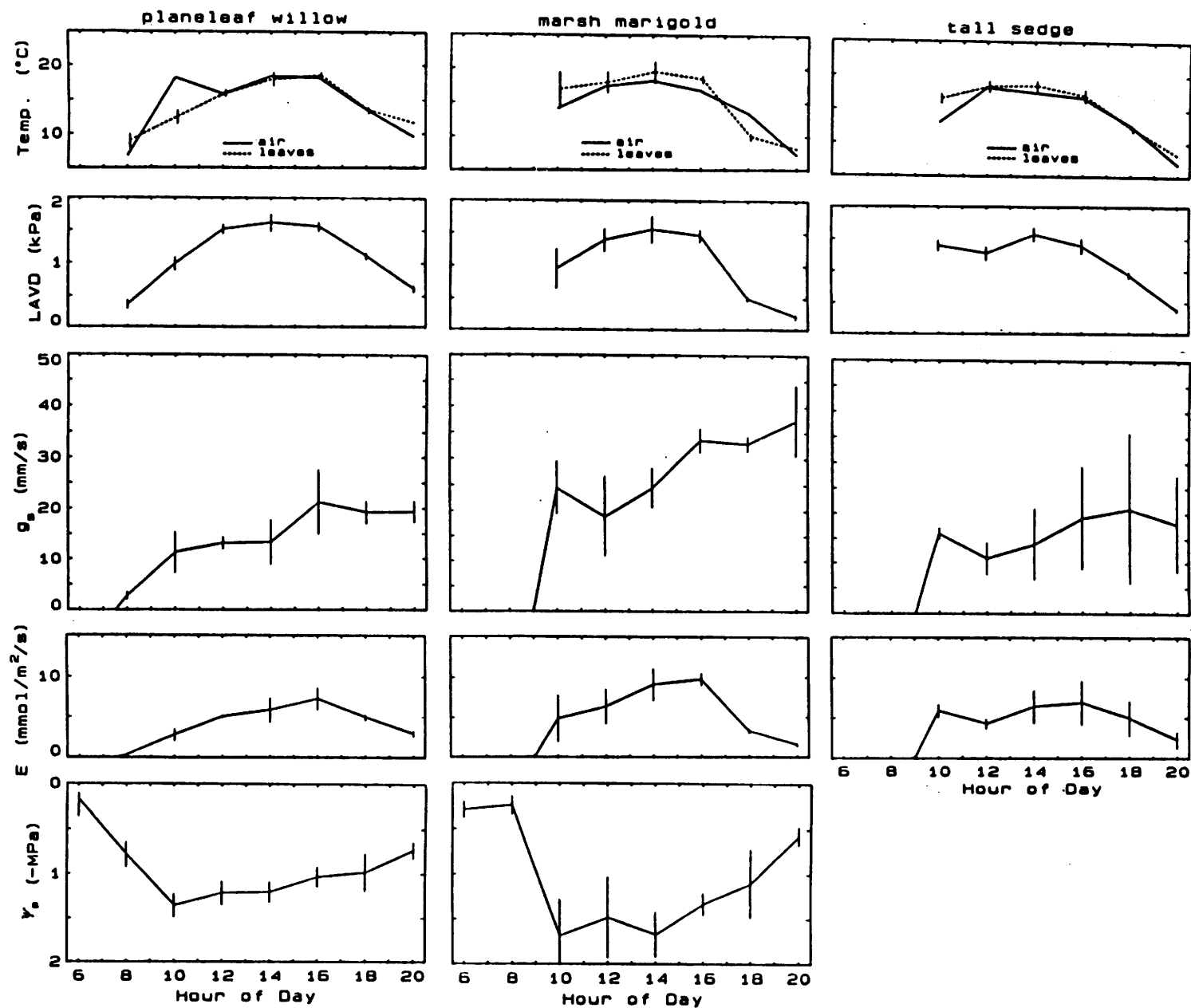
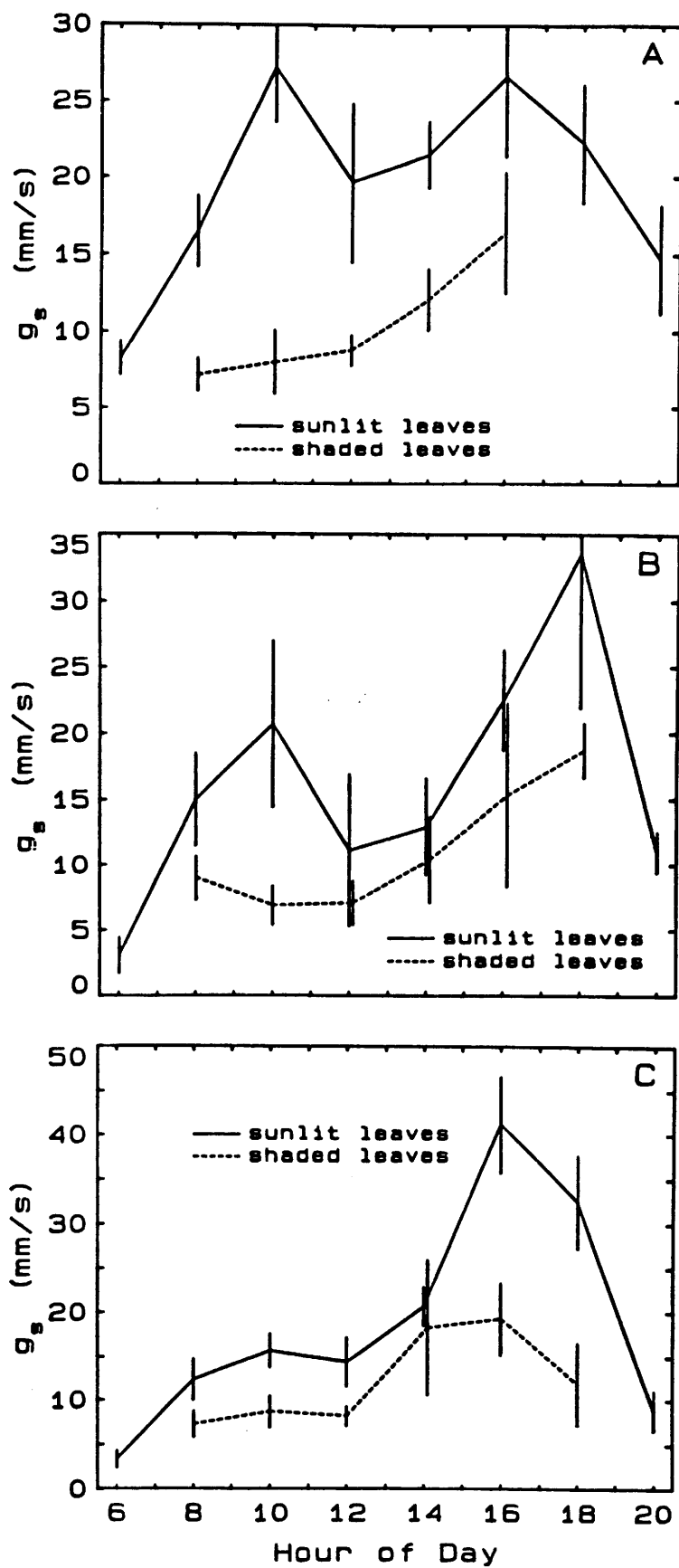


Figure 5

Figure 6



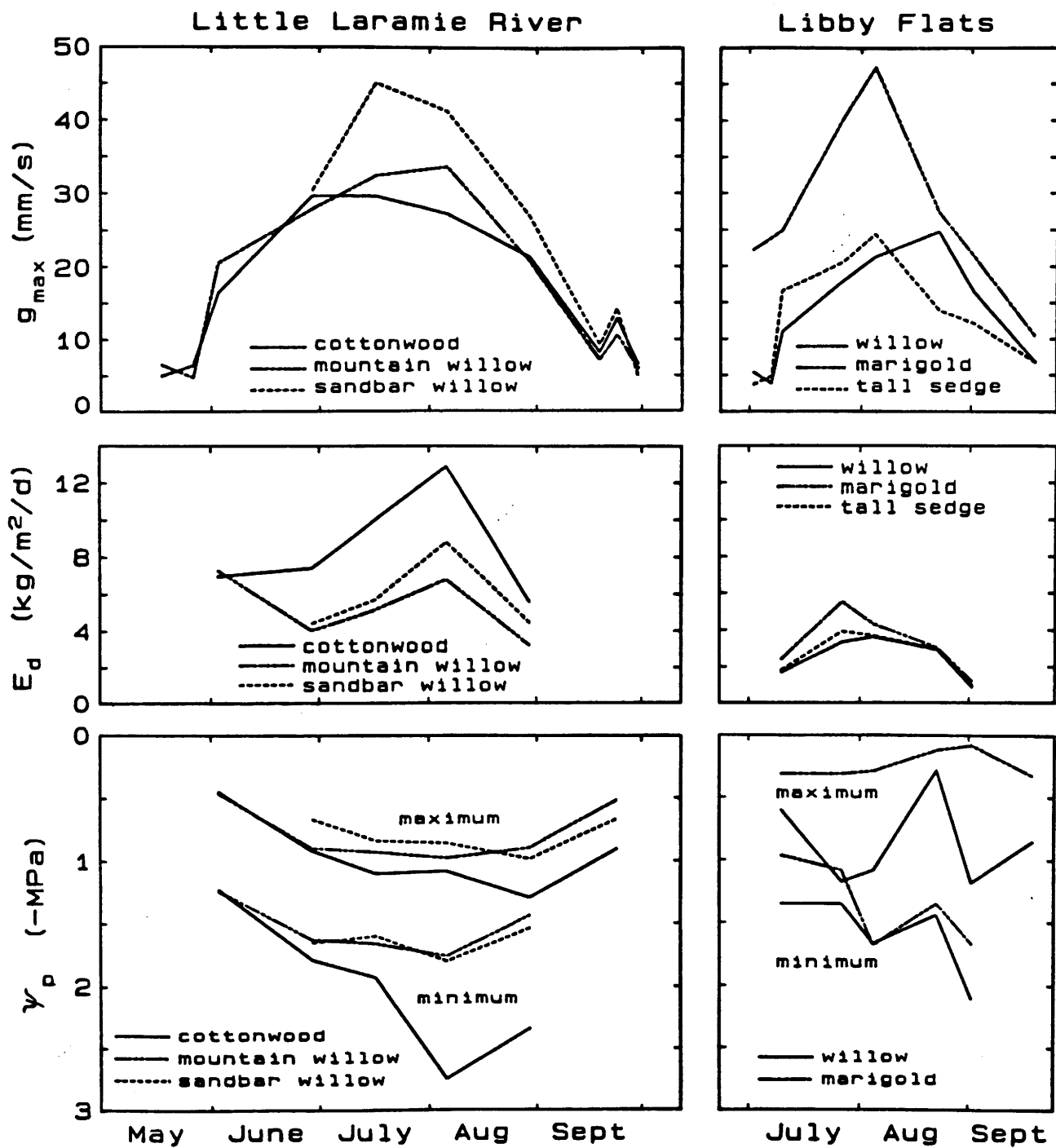


Figure 8

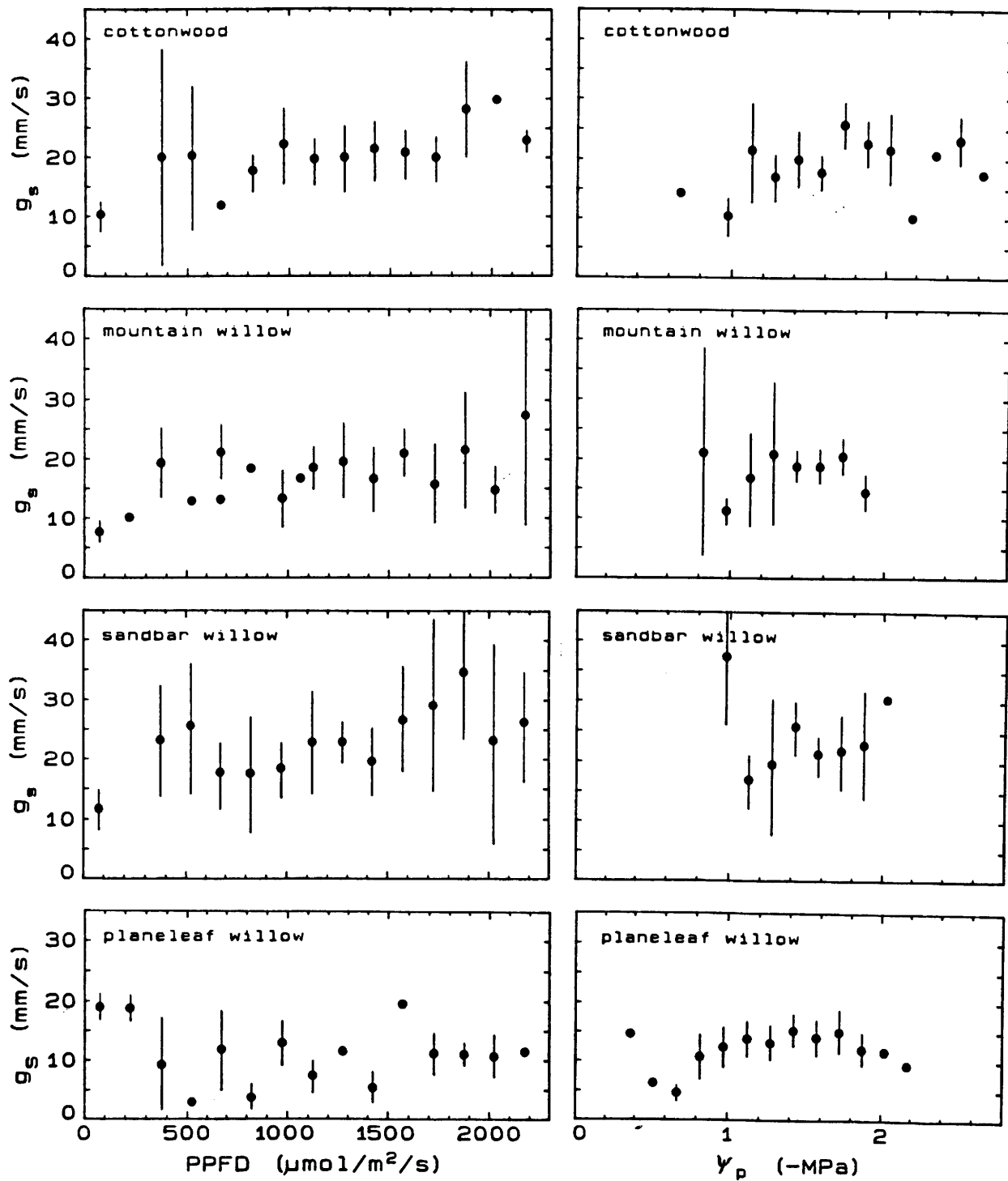


Figure 9

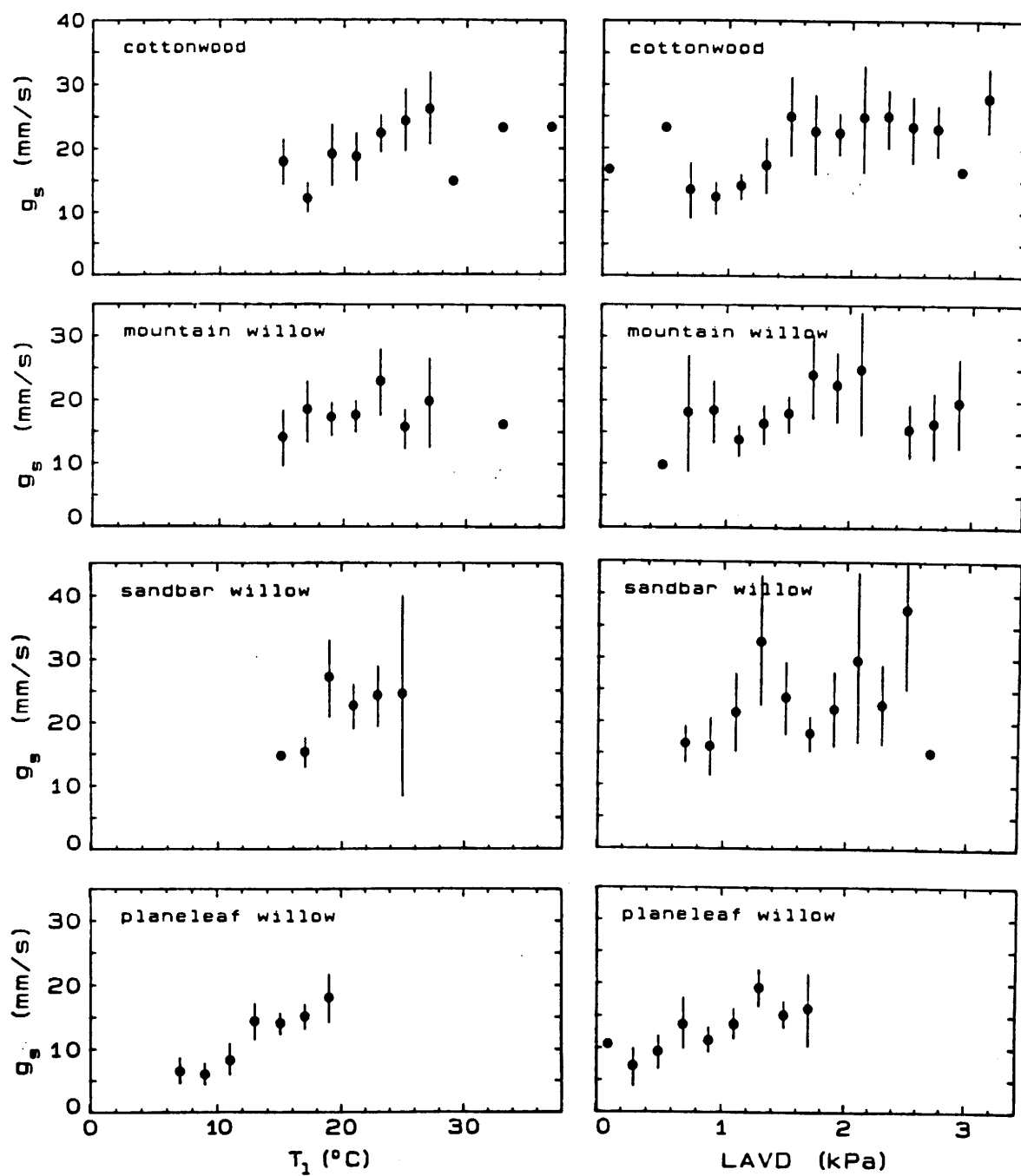


Figure 10

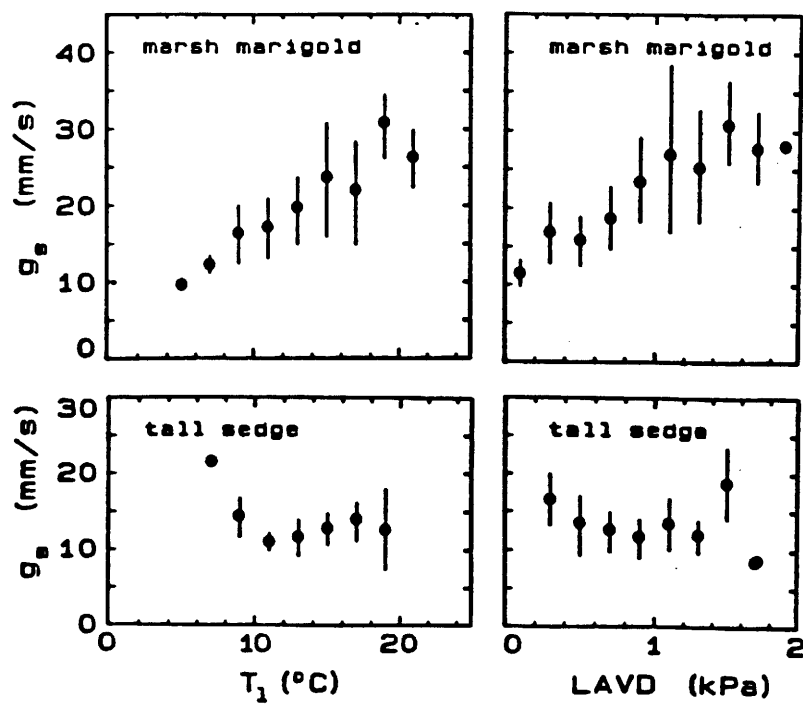
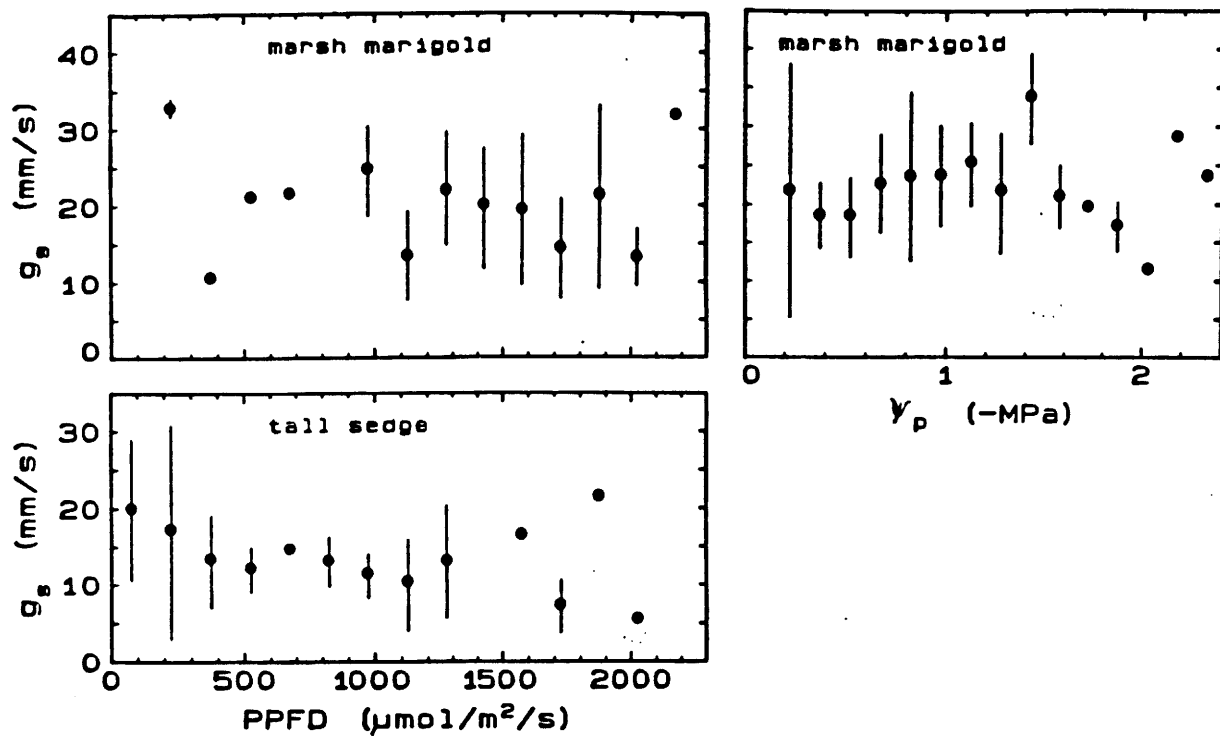
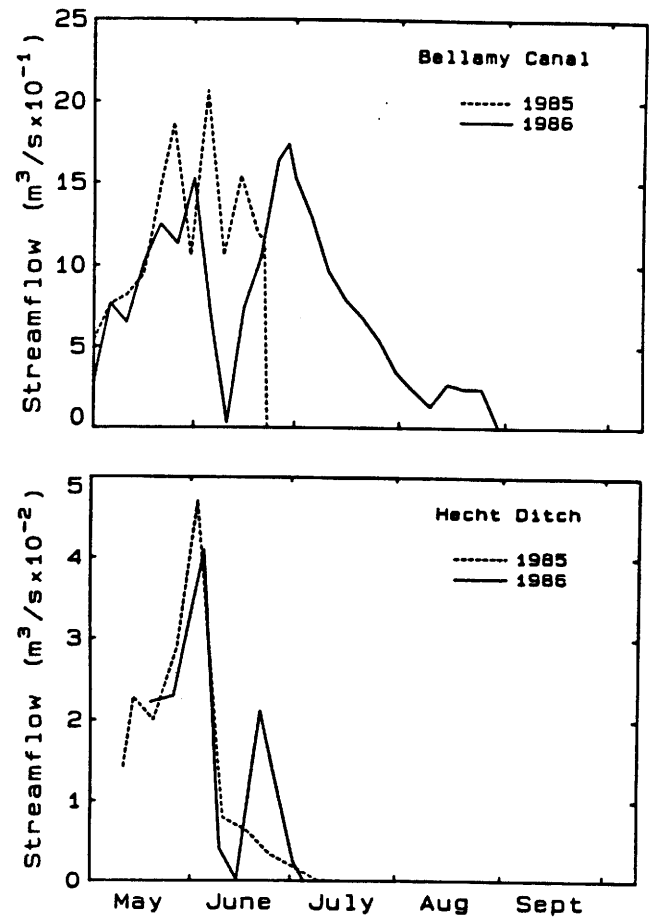
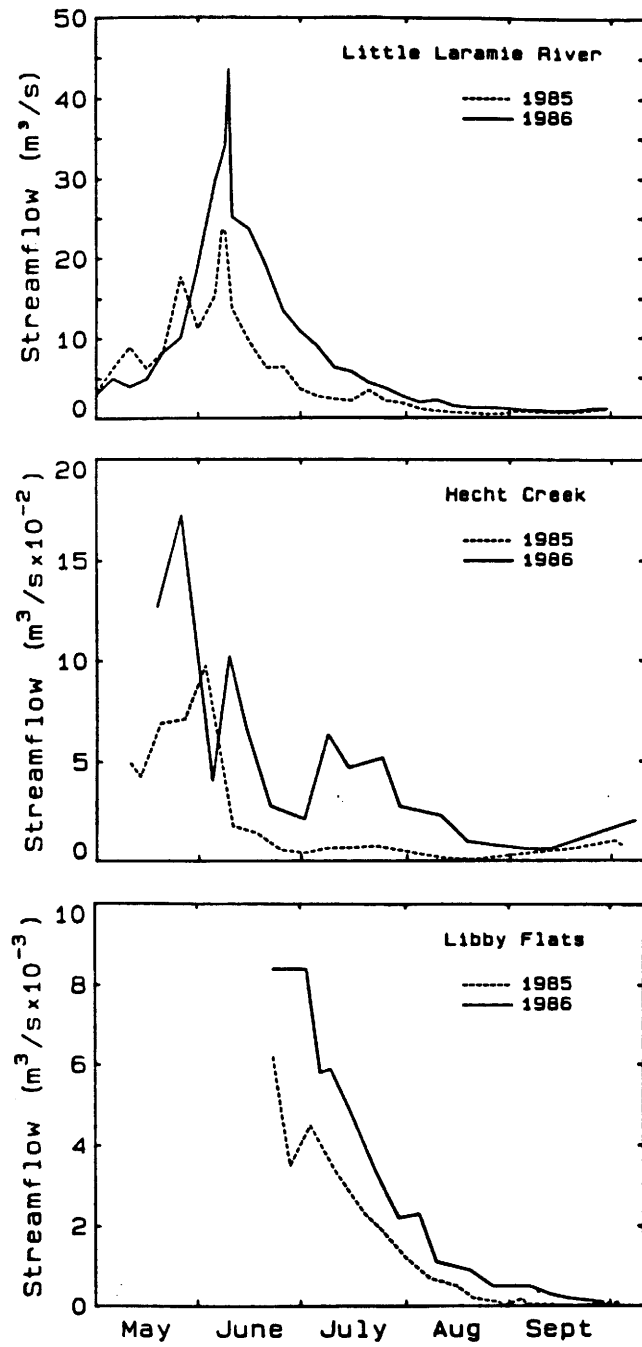


Figure 11



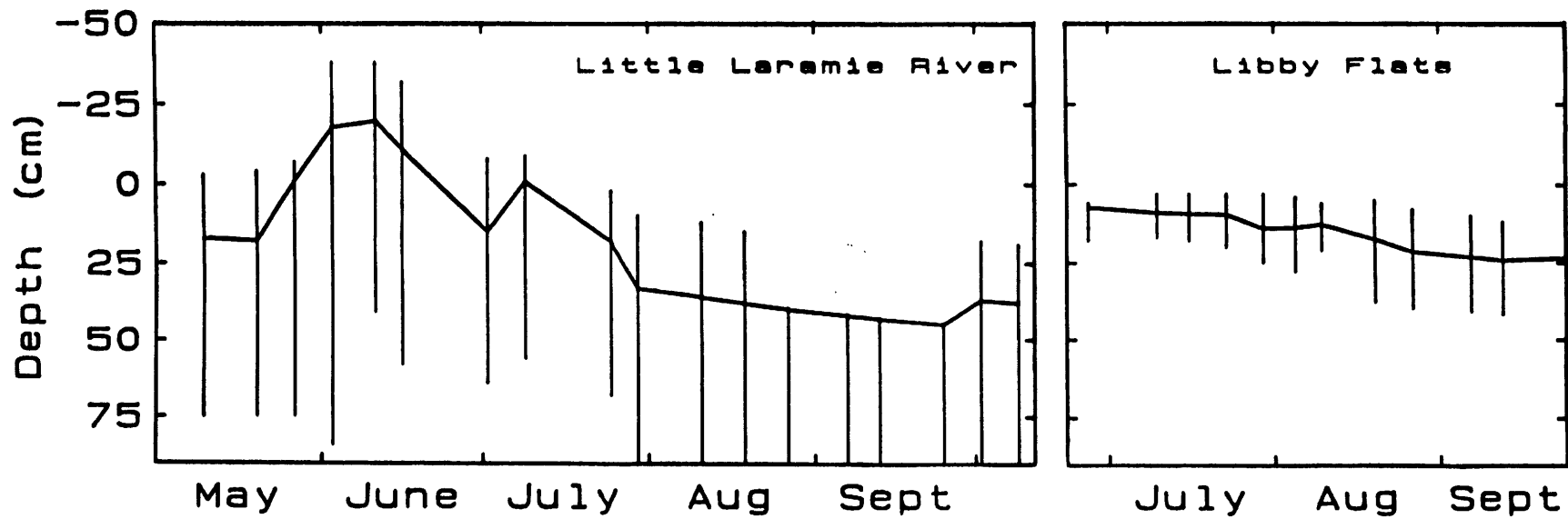


Figure 12