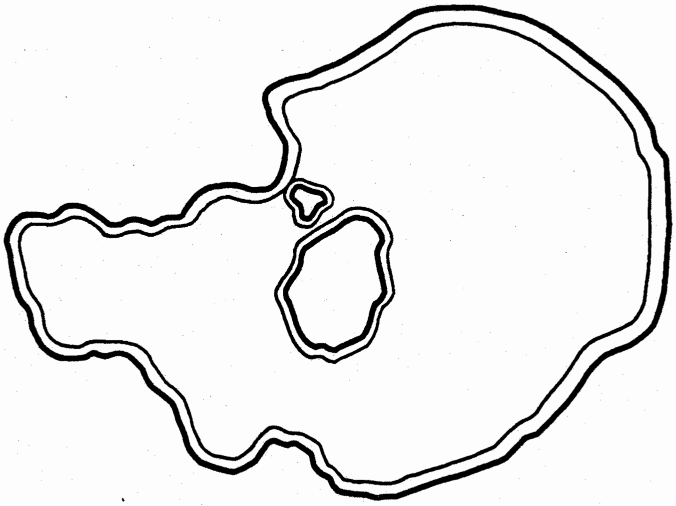
An Auxiliary Report
Prepared for the

MONO BASIN WATER RIGHTS EIR

Instream Flow Relations of Riparian Cottonwood Trees in the Mono Basin



Prepared under the Direction of:

California State Water
Resources Control Board
Division of Water Rights
P.O. Box 2000
Sacramento, CA 95810

Prepared With Funding from:

Los Angeles Department of
Water and Power
Aqueduct Division
P.O. Box 111
Los Angeles, CA 90051

Mono Basin EIR Auxiliary Report No. 7

An Auxiliary Report
Prepared for the
Mono Basin Water Rights EIR Project

This auxiliary report was prepared to support the environmental impact report (EIR) on the amendment of appropriative water rights for water diversions by the City of Los Angeles Department of Water and Power (LADWP) in the Mono Lake Basin. Jones & Stokes Associates is preparing the EIR under the technical direction of the California State Water Resources Control Board (SWRCB). EIR preparation is funded by LADWP.

SWRCB is considering revisions to LADWP's appropriative water rights on four streams tributary to Mono Lake, Lee Vining Creek, Rush Creek, Parker Creek, and Walker Creek. LADWP has diverted water from these creeks since 1941 for power generation and municipal water supply. Since the diversions began, the water level in Mono Lake has fallen by 40 feet.

The Mono Basin water rights EIR examines the environmental effects of maintaining Mono Lake at various elevations and the effects of possible reduced diversions of water from Mono Basin to Owens Valley and the City of Los Angeles. Flows in the four tributary creeks to Mono Lake and water levels in Mono Lake are interrelated. SWRCB's decision on amendments to LADWP's water rights will consider both minimum streamflows to maintain fish populations in good condition and minimum lake levels to protect public trust values.

This report is one of a series of auxiliary reports for the EIR prepared by subcontractors to Jones & Stokes Associates, the EIR consultant, and contractors to LADWP. Information and data presented in these auxiliary reports are used by Jones & Stokes Associates and SWRCB, the EIR lead agency, in describing environmental conditions and conducting the impact analyses for the EIR. Information from these reports used in the EIR is subject to interpretation and integration with other information by Jones & Stokes Associates and SWRCB in preparing the EIR.

The information and conclusions presented in this auxiliary report are solely the responsibility of the author.

Copies of this auxiliary report may be obtained at the cost of reproduction by writing to Jim Canaday, Environmental Specialist, State Water Resources Control Board, Division of Water Rights, P.O. Box 2000, Sacramento, CA 95810.

Instream Flow Relations of Riparian Cottonwood Trees in the Mono Basin

Final Report

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March 1992

ABSTRACT

This study estimates instream flow needs for maintenance of mature black cottonwood (Populus trichocarpa) along two streams in the Mono Basin (Lee Vining and Rush Creek). These estimates are based on relationships described between incremental stem growth (i.e., radial growth) and stream flow volume, in conjunction with relationships described between radial growth rate and two indices of population maintenance (canopy vigor and survivorship).

Stream flow volume (a correlate of riparian water availability) is the primary factor regulating growth of riparian cottonwoods along Rush Creek and along those portions of Lee Vining Creek with unconstrained floodplains. Annual flow volume generally explained more variance in annual growth than did summer (April-September) flow, and the combination of present year and prior year flows generally produced more significant models than did present year flow alone. This indicates that flows throughout the year contribute to recharge of the riparian water table and/or riparian soils. Nonlinear models explained more variance than did linear models, because growth response leveled off at very high flow volumes. Stream flow volume explained similar amounts of growth variance for floodplain and channel-side trees, although a given volume of flow produced about half as much growth for floodplain trees than for channel-side trees. Air temperature increased the variance explained by stream flow by a small amount for some populations.

Floodplain trees had lower canopy vigor than did channel-side

trees. Canopy vigor varied curvilinearly with radial growth rate, with about 2 mm/yr acting as a threshold below which trees had low values for canopy vigor. Analyses of dead trees at Rush Creek, most of which died during drought years, confirmed that very low growth values (e.g., <1 mm/yr) were associated with the ultimate extension of low canopy vigor, i.e., tree death.

Based on the above data, three estimates of instream flow needs were produced for Rush Creek cottonwoods and for Lee Vining Creek cottonwoods in unconstrained floodplains. These included maintenance flow needs (i.e., flow volumes associated with growth rates of 2.00 mm/yr and thus with relatively vigorous canopies), subsistence flows (those producing growth rates of 1.75 mm/yr and thus some decline in canopy vigor), and attainment flows (those producing growth rates of 2.5 mm/yr and vigorous canopies, and thus allowing attainment of biotic potential). Maintenance flows for channel-side trees at Rush Creek are in the range of flow volumes that occurred during LADWP diversion times, whereas maintenance flows for floodplain trees (i.e., those 70-90 m from the stream channel) are greater than flows occurring during the prediversion period. These data suggest that instream flow needs of floodplain trees are higher under existing conditions then they were under historical conditions, probably because channel incision has reduced the water available to floodplain trees from a given flow volume. Maintenance flows for Lee Vining Creek floodplain trees (about 20 hm^3/yr) are intermediate between diversion period flows are natural flow rates.

Because the flow-growth models provide an index of the amount of flow needed to maintain populations growing at various distances from the stream, they also can be used to estimate relationships between instream flow and riparian strip width. Data indicate that the width of the riparian cottonwood strip is strongly related to instream flow, with wide riparian strips (>150 m) at Rush Creek being associated with high flow volumes (>80hm^3).

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INTRODUCTION

Riparian vegetation plays a crucial role in the functioning of riparian ecosystems. For example, riparian vegetation regulates many aspects of fish habitat and contributes to the stability of channel and floodplain landforms (Groeneveld and Griepentrog 1984; Platts and Rinne 1985). Knowledge of instream flow requirements for riparian trees is thus essential for maintaining quality riparian ecosystems. Within the Mono Basin of the eastern Sierra Nevada, instream flows for the primary streams are currently being adjudicated. This report addresses some aspects of riparian vegetation flow needs for two Mono Basin streams.

Riparian tree species require specific amounts and seasonal patterns of flow for seedling establishment and for maintenance of mature trees. Many cottonwood (*Populus*) tree species, for example, require overbank flows during the spring germination period for successful establishment (Fenner et al. 1985; Stromberg et al. 1991) and then require a certain average (as well as minimum) volume of annual or seasonal flow for maintenance of healthy tree canopies (Stromberg and Patten 1990, 1992). With respect to maintenance needs, instream flow models that relate annual flow volume to radial growth rate of riparian black cottonwoods (*Populus trichocarpa*) have been previously developed for diverted Rush Creek within the Mono Basin (Stromberg and Patten 1990). These models were developed for a sample of cottonwood trees distributed throughout the Rush Creek floodplain, rather than for populations growing in specific areas within the floodplain. Cottonwoods often have wide lateral distribution within riparian floodplains because of differences in initial establishment areas (i.e., edges of main channels vs. abandoned channels) and because of post-establishment channel realignment, and these spatial differences may influence water availability. Also, while the models assessed relationships between flow and growth rate, they did not relate flow rate to more direct indicators of population maintenance, and also did not take into account local irrigation losses in calculation of flow rates.

One objective of this study was to develop flow-growth models for cottonwood populations growing at various locations within the riparian floodplain (i.e., near-channel sites vs. sites farther from the channel) and to relate growth rate to indices of population maintenance. A second objective was to use these models to estimate maintenance flow needs for cottonwoods on Rush Creek and Lee Vining Creek.

STUDY SITES AND METHODS

Overview of Study Areas

Rush Creek is the largest tributary to Mono Lake. It flows from the eastern slope of the Sierra Nevada through a narrow mountain valley until it is impounded in Grant Lake Reservoir, from which water is diverted to the City of Los Angeles (Fig. 1). Diversion by LADWP (Los Angeles Department of Water and Power) was limited during the first few years after construction of the reservoir (1940), but from 1948 on downstream releases were minimal except in wet years. Streamflows during the 1980s were higher than during most diversion years, because of a combination of a series of above average snowpack years and of court orders requiring flows to maintain fish populations. In addition to the large-scale diversion by LADWP, Rush Creek was diverted locally for many years. Irrigation diversions were most abundant in the early part of this century and tapered off during the early years of the LADWP diversions. A large percentage of the irrigation water is believed to have returned to the Rush Creek aquifer, either as groundwater seepage or irrigation "tail water" (Kondolf 1988a). Although originally an influent (gaining) stream, Rush Creek presently is considered to be an effluent (losing) stream, with water being "lost" to underlying geologic structures particularly at two contact points (Kondolf 1988b). Arboreal riparian vegetation along lower Rush Creek is dominated by black cottonwood, several species of willow (<u>Salix</u> spp.), and Jeffrey pine (<u>Pinus jeffreyi</u>). The vegetation underwent extensive mortality during the LADWP diversion period (Stine et al. 1984). The wetter flow conditions of the 1980s stimulated some riparian recovery (Stromberg and Patten 1989).

Lee Vining Creek is the second largest tributary to Mono Lake. It is impounded at an intake located about 3.5 km (2.2 mi) upstream from the town of Lee Vining. Water is delivered from the impoundment by conduit and siphon to Grant Lake and then to Mono Craters Tunnel for delivery to Los Angeles. Lee Vining

Creek also has been used locally as a source of irrigation water. Most irrigation diversions occurred in the early part of this century, although limited diversion still continues today. Dominant riparian plant species along Lee Vining Creek are generally the same as along Rush Creek with some exceptions (e.g., aspen [Populus tremuloides] and dogwood (Cornus spp). are more abundant along Lee Vining Creek). Riparian vegetation underwent mortality during the LADWP diversion period, although vegetation within canyon areas was less affected by diversion. Some drought-stressed riparian vegetation was destroyed by fire in the early 1950s, while other riparian vegetation was directly killed by drought in the 1960s (Taylor 1982; Stine 1991). Cottonwood, willows and other riparian species have undergone substantial recruitment in these areas in recent years (pers. obs.).

Methods

Research approach. The general research approach involved: (1) developing relational models between stream flow volume and radial growth rate of black cottonwood; and (2) using two indices to assess relationships between cottonwood growth rate and population maintenance. These indices were: (1) growth rates associated with high canopy vigor; and (2) growth rates associated with high survivorship. General methodology entailed: (1) field sampling to collect increment cores from live and dead trees and to assess tree vigor; (2) laboratory work to prepare the increment cores and measure tree ring widths; and (3) data analysis.

Study populations. The study focused on black cottonwood rather than on other riparian species because of cottonwood's role as a riparian dominant prior to diversion and at present. Nevertheless, the limited distribution of surviving black cottonwoods limited the number of subpopulations that could be studied. Study areas were selected based on the presence of large populations of mature cottonwoods (i.e., >15 trees greater than 20 cm [8 in] in stem diameter) and thus may not be representative of Rush Creek as a whole. Two areas were selected along Rush Creek and four areas were selected along Lee Vining Creek (Fig. 1). RC1 was located about 2 km (1.2 mi) upstream from Highway 395, at 2125 m (6,970 ft) elevation. The stream at this point had emerged from a narrow canyon, and the floodplain was unconfined and wide (up to 150 m [500 ft] in some areas). Cottonwoods, however, were generally restricted to near-stream areas (i.e., within 20 m [65 ft] of the stream edge). RC2 was about 1.3 km (0.8 mi) downstream from the geologic fault area variously referred to as the "narrows" or the "gorge", at 1985 m (6,515 ft) elevation. The floodplain here was unconfined, spanning widths of up to 200 m (650 ft). This site was divided into a "channel-side" site (RC2c) in which study trees were <20 m (65 ft) from the edge of the primary channel, and a "floodplain" site (RC2f) in which study trees were between 70 and 90 m (230 and 295 ft) from the channel (Table 1). The floodplain trees were located along the edge of a dry, abandoned channel. This latter group is the only surviving cottonwood stand of any significance at Rush Creek that grows at this distance from the stream.

LV0 and LV1 were within the upper end of the Lee Vining "delta canyon" and were respectively located above and below Highway 395 (elevations of 2070 m [6,790 ft] and 2065 m [6,775 ft]). The delta canyon is so named because it consists of late Pleistocene Lee Vining delta sediments (Stine 1991). LV2 and LV3 were within the downstream edge of this delta canyon, in an area where the floodplain is less confined (i.e., with floodplain widths of up to 80 m). LV2 (at 2015 m, or 6610 ft elevation) was just upstream from the Lee Vining sewage treatment plant (which is perched on a bench about 40 m [130 ft] above the floodplain), and LV3 (at 1970 m, or 6465 ft) was about 0.5 km (0.3 mi) upstream from the County Road. Three of these four Lee Vining areas were divided into channel-side and floodplain sites. The channel-side trees were within 5 m (16 ft) of the primary channel, while the floodplain trees were those growing at the greatest distance from the primary channel. This distance varied from 40 ± 10 to 54 ± 4 m (130-175 ft) among the three sites. The "floodplain" trees at LV2 and LV3 were growing along the edges of dry, abandoned channels. Those at LV0 were growing near the abandoned "Lee Vining" ditch diversion channel.

<u>Increment core and vigor analysis</u>. From 10 to 15 live black cottonwood trees were randomly selected per site. Two replicate

increment cores were taken per tree in 1991. All cored trees were measured for stem diameter and assessed for canopy vigor. Vigor was assessed subjectively by assigning each tree a canopy vigor class, based on fullness of the canopy. The classes were as follows: class 5 trees had 81-100% of potential canopy; class 4, 61-80%; class 3, 41-60%; class 2, 21-40%; and class 1, <21%. Although subjective and thus subject to sampling error, the large range of the classes minimizes the error rate. Increment cores (two per tree) were also collected from 15 mature, dead black cottonwoods at Rush Creek. Seven of the 15 cores were collected at RC1, and eight from RC2.

Increment cores were prepared following standard methods (Fritts and Swetnam 1989). After drying, the cores were mounted and sanded with a graded series of sandpaper, ranging from 60 to 12 micron. Cores with cellular decomposition (i.e., "heart-rot") were discarded from the sample. The remaining chronologies were cross-dated and measured to the nearest 0.01 mm using an automated measurement system (Fred Henson Co.). Ring width chronologies were generated for each tree by taking the mean value for the two replicates. Site chronologies were generated by averaging the standardized chronologies for the largest group of same-aged cohorts. At most sites, all cored trees were within the same age cohort (i.e., within 10 years apart) and thus all contributed to the site chronology. Because of this approach of using same-aged cohorts, the chronologies were not standardized to remove age-related growth trends. Rather, raw growth values were used for subsequent analysis after discarding juvenile rings (i.e., those produced during the first 10 years of the trees life, when age-related effects are most pronounced). Record lengths for growth analyses differ between areas, depending on population age. Channel and floodplain sites within areas supported trees of similar age and had similar record lengths for growth analysis.

Precipitation, temperature and stream flow data. Monthly precipitation and air temperature data (1951-1987) for a Mono Lake station were obtained from the Western Regional Climate Center, University of Nevada System Desert Research Institute. Flow data for Rush and Lee Vining Creeks were obtained from LADWP. Flow data are presented either as annual flow in the water year (October-September), "winter" flow (half-year period from October-March), or "summer" flow (half-year period from April-September). The summer flow period encompasses the active growing season as well as a prior several week period. Prediversion flow data for Rush Creek were obtained as inflow to Grant Lake for the period 1935-1941. These data were extended back to 1920 by using a regression equation to predict Grant Lake flow data from flow measured 5 km (3 mi) upstream at Rush Creek power plant: $y = 1.27x + 8.94$; $r^2 = 0.89$; df = 40; values in hm^3 $[(100m)^3]$. Diversion-period flow data are Grant Lake release flows from Mono Gate 1. Rush Creek flow data were adjusted for "natural" losses and irrigation losses to produce site-specific flows for the RC1 and RC2 study areas. Natural losses were determined from Kondolf's (1988b) synoptic flow study of Rush Creek, and irrigation losses were obtained from LADWP records. With respect to natural flow losses, RC1 is in a reach (Kondolf's reach A-C) in which very little to no natural loss occurs from the stream to the groundwater. RC1 flows were thus considered to be equivalent to Grant Lake release flows. RC2 lies within Kondolf's reach D-H, an area downstream from two major points of flow loss to underlying geological units. The following equations were used to estimate summer (April-September) and winter (October-March) flows for RC2: summer flows, $y = 0.941x - 4.97$; winter flows, $y = 0.90x - 1.1$ (x = Grant Lake release flows in f^3/s). RC1 flows were adjusted for irrigation losses to "A" and "C" ditches, two of the three main irrigation diversions that operated on Rush Creek ("A" ditch operated from 1920-1970, "B" ditch from 1925-1967, and "C" ditch from 1920-1934) (Stine 1991). All three are upstream from Highway 395, with RC1 lying downstream from "A" and "C" ditch and upstream from "B" ditch. RC2 flows were calculated with and without losses to the irrigation ditches because of the probability that some irrigation "tail water" returned to the riparian system prior to reaching the site.

Prediversion flows (1935-1941) for Lee Vining Creek were based on County Road flow measurements. Diversion-period flows were based on intake release flows. County Road data overlap with release data for the period 1942 to 1968, although County Road records are poor through 1946. County Road data are somewhat lower than intake release data. A regression equation was thus developed to predict County Road flows (y) from intake flows (x): $y = 0.89x - 0.21$; df = 21; values in hm^3). Lee Vining Creek flow data were not adjusted for irrigation losses because all irrigations in the study area ceased prior to or during the 1950s (Stine 1991) or for natural losses or gains because of the absence of synoptic flow data.

Riparian water table data. Groundwater monitoring wells (i.e., peizometers) were installed at three areas along Rush Creek in 1991 by Balance Hydrologics under subcontract to Jones and Stokes Associates, Inc. A series of wells (3 to 6) were installed along a floodplain transect at each area. One of the well areas ("Mojo") was about 0.5 km (0.3 mi) downstream of RC1 and another ("Big Scallop") was directly at RC2. The third well area ("Meadow") was about 0.8 km (0.5 mi) downstream from RC2. Data on depth to subsurface water below the stream level and below the ground surface were collected by Balance Hydrologics beginning in May 1991.

Data analysis. Pearson correlation analysis was used to determine the degree of similarity in annual growth pattern between trees within sites and between site chronologies. Linear and nonlinear univariate regression analyses were used to identify the single abiotic variable that was most significantly related to annual radial growth (ring width) of black cottonwood. Abiotic variables for this procedure included: (1) present-year annual stream flow volume; (2) prior-year annual stream flow; (3)

present-year summer flow; (4) prior-year summer flow; (5) present-year winter flow; (6) prior-year winter flow; (7) annual precipitation; (8) mean annual temperature; (9) mean summer temperature (April-September); and (10) mean winter temperature (October-March). Mean monthly flows were not included as variables because prior work has shown seasonal or annual flows to be of greater significance (Stromberg and Patten 1990). Data were also analyzed with multivariate stepwise regression (employing both forward and backward stepping techniques) to develop best-fit models that predicted annual growth of the cottonwood trees from these same variables. Analyses were conducted separately for channel and floodplain sites. Analyses were not conducted for LV3 because of the young age of the cottonwood population, or for LV0c because of small sample size of trees with usable increment cores.

Radial growth rates were compared between channel-side and floodplain sites using Student's t-tests. Student's t-test was also used to compare growth rates between Rush Creek channel-side groups. Radial growth rates of cottonwood trees were related to two variables associated with population maintenance: canopy vigor (both streams) and tree survivorship (Rush Creek only). For the former, response curves were developed between radial growth rate (for the 10-year period from 1981-1990) and canopy vigor, assuming that present vigor reflects a composite and time-lagged response to past growth rate of trees (Stromberg and Patten 1991a). These curves were assessed to determine growth rates associated with maintenance of "vigorous" canopies. Although the growth-canopy data are presented in such a way as to suggest that canopy vigor is a unidirectional function of growth rate, it is also true that canopy fullness (e.g., total photosynthetic area) can influence growth rate. The unidirectional growth-vigor models are most valid for situations where confounding effects on canopy fullness are minimal. One primary confounding effect is tree density, because competition for space often results in reduced canopy area per-tree (Kramer and Kozlowski 1979). At the Rush Creek reaches, however, stream dewatering has reduced tree density and thus reduced its influence on canopy fullness.

The second method entailed determining growth rates associated with tree mortality. Although mortality in some cases can be independent of growth rate (e.g., if death results from episodic events such as physical removal of trees during floods), mortality and growth rate are directly linked in cases where death results from chronic stress (Kauffman 1990). Year of death was calculated for the cored trees at RC1 and RC2 to identify flow conditions (e.g., droughts or floods) associated with mortality periods. To accomplish this, the dead tree chronologies were cross-dated against reach chronologies developed for live trees at each site. Mean growth rates during the two years prior to death were then calculated.

RESULTS

Hydrology

Stream flows. Flows in Rush Creek prior to the LADWP diversion period were relatively constant from year to year (Fig. 2). Flows in the last 45 years, however, were characterized by extended periods of low or no flow during drought and "normal" snowpack years, to >220 hm^3 (>180,000 acre-feet) per year during wet years. Annual flows averaged about 50% lower than natural flows during the LADWP diversion period (Table 2). Flows were relatively high in the last decade because of several high snowpack and runoff years (e.g., 1980, 1983, 1986) and because of court orders requiring sufficient flows to maintain the stream's fisheries. Irrigation diversions substantially reduced stream flow volume during the prediversion period (e.g., from 78 hm^3/yr below Grant Lake to 43 hm^3/yr at Highway 395), but irrigation losses tapered off substantially during the diversion period. Natural losses between Grant Lake and Mono Lake are estimated to have reduced stream flows by a few hm^3/yr. Approximately 2/3 of the annual flow occurred in the 6 month period from April-September.

Flow patterns in Lee Vining Creek were similar to those in Rush Creek (Fig. 3). High flows occurred in similar years (e.g., 1952, 1958, 1967, 1969, 1978, 1980, 1983, 1986), as did droughts (e.g., early and mid 1960s and 1970s). Diversion period flows were characterized by high annual fluctuation but low annual mean. During both prediversion and diversion periods, Lee Vining carried about half as much stream flow as Rush Creek (Table 3). Local irrigation losses were fairly small.

Riparian water table. At the time of report submission, water table data from Balance Hydrologics were available for the "Meadow" area but not for the "Mojo" area. Data for the "Big Scallop" area (i.e., RC2 site) were available for only a portion of the floodplain.

The riparian water table at the "Meadow" area (located 0.8 km [0.5 mi] from site RC2) averaged about 0.06 m (0.2 ft) below the stream level for channel-side areas (based on wells located 3-20 m [10-65 ft] from the stream) during June through August 1991. The water table declined gradually with distance from the channel and averaged about 0.25 to 0.30 m (0.8 to 1.0 ft) below the stream level for floodplain areas (i.e., areas about 90 m [300 ft] from the channel). The floodplain ground surface gradually rose with distance from the stream and was about 1.3 m (4.3 ft) above the stream level for channel-side areas and about 1.75 m (5.7 ft) for floodplain areas. Total depth to the water table from the ground surface thus averaged about 1.4 m (4.6 ft) for channel-side areas and about 2.0 m (6.6 ft) for floodplain areas.

The ground surface at site RC2 was about 1.2 m (3.9 ft) above the stream level for channel-side trees and about 2.4 m (7.9 ft) above the stream level for floodplain trees as of May 1991. The water table at this area was nearly level with the stream water at least within the first 55 m (180 ft) from the stream, but data were not available for sites farther from the stream including that of the RC2 floodplain trees. Assuming that the water table remained level at this distance, total depth to water for the floodplain trees was at least 2.4 m (7.9 ft).

Instream Flow - Growth Relationships

Rush Creek. Ring width chronologies for Rush Creek cottonwoods were significantly correlated between trees and between sites, indicating that growth of the trees was regulated by common environmental variables (Table 4). Univariate regression analysis indicated that: (1) growth of all three groups of Rush Creek trees varied more significantly with stream flow volume than with precipitation or air temperature; (2) nonlinear growth-flow models generally explained a slightly greater amount of variance than did linear models; (3) annual flows generally explained more variance than did summer flows; and (4) summer flows explained more variance than winter flows. Results of multiple regression analyses indicated that: (1) prior year flows increased the variance explained by present year stream flow volume for two of the three study populations; (2) air temperature did so by a small amount for one population; and (3) precipitation did not increase the variance explained for any population. "Forward stepping" and "backward stepping" in all cases provided similar results. Relationships of growth with the various flow volume and air temperature parameters differed between channel-side and floodplain groups, as discussed below.

The two channel-side groups of cottonwoods at Rush Creek had fairly similar growth rate (2.41 mm/yr and 2.05 mm/yr; $P > 0.05$; Table 1) and similar growth responses to stream flow (Fig. 4). For both groups, annual flow explained more growth variation than did summer flow (48% vs. 35% for RC1c and 45% vs 33% for RC2c) (Table 5) and summer flow explained more variance than did winter flow (35% vs 31% for RC1c and 33% vs 15% for RC2c). Prior-year flows significantly increased the variance explained by present-year flows for both groups. The combination of present-year and prior-year annual flows explained equal or greater variance than the combination of present and prior summer flows (62% vs. 60% for RC1c and 48% vs. 48% for RC2c). Growth of trees at RC2c in all cases was more significantly related to non-irrigation adjusted flows than to irrigation-adjusted flows (e.g., $r^2 = 0.45$ vs. 0.40 for univariate annual flow models and $r^2 = 0.33$ vs. 0.27 for univariate summer flow models) and thus relationships with the former are presented. Mean annual air temperature (negative effect) increased the growth variance explained by flow volumes from 62% to 66% for RC1c but was not a significant component of multiple variable models for RC2c.

Average annual growth rate differed significantly ($P < 0.05$) between channel-side and floodplain trees at RC2, with floodplain trees having about half the growth of channel-side trees (Table 1; Figs. 5 and 6). Floodplain trees also had lower values for canopy vigor (3.2 ± 0.4 for RC2f vs. 4.3 ± 0.8 for RC2c). Growth of both groups closely tracked flow volume (Fig. 7) but in contrast to channel-side trees, growth of floodplain trees was more significantly related to summer flow ($r^2 = 0.72$) than to annual flow ($r^2 = 0.64$) (Table 5). The slopes of the flow-growth regression equations were lower for floodplain trees than for channel-side trees, as were the y-coordinate intercepts (i.e., growth rate when annual flow was at 0 hm^3/yr was 0.99 mm/yr for floodplain trees and 1.51 mm/yr for channel-side trees) (Fig. 5). Neither prior-year flows (annual or summer) or air temperature significantly increased the growth variance explained by present-year flows for floodplain trees.

<u>Lee Vining Creek</u>. Ring width chronologies for Lee Vining Creek cottonwoods were highly correlated within sites but not between sites, indicating that common environmental variables regulated growth within sites but that nonidentical variables influenced growth between sites (Table 4; Fig. 8). Growth rate varied substantially between areas at Lee Vining, in large part because of large differences in tree age (e.g., trees were about 80 years old at LV0 compared to about 20 years at LV3). Within areas, growth of the channel-side trees at Lee Vining Creek generally was about twice as high as for floodplain trees, as was true at Rush Creek (Table 1).

Univariate growth-flow relationships were weaker for Lee Vining trees than for Rush Creek trees (e.g., annual flow explained from 19% to 41% of the variance in growth among Lee Vining sites compared to 45% to 64% among Rush Creek sites) (Table 5). Similar to Rush Creek sites, however, annual flows explained more growth variance than did summer flows (i.e., mean

r^2 among sites of 0.30 vs. 0.25), summer flows explained more than winter flows (mean of 0.25 vs. 0.15), and nonlinear equations had higher significance than did linear equations (e.g., mean of 0.30 vs. 0.26 for annual flow). Inclusion of prior-year flow as a variable nearly doubled the variance explained for trees on unconstrained floodplains (LV2 sites) but did not significantly increase the variance explained for those in canyons (LV0 and LV1). For trees at LV2c, in fact, prior-year flow was more significantly related to tree growth than was present-year flow. At both LV2 sites, the combination of present and prior annual flows explained an equal or greater amount of variance as did the combination of present and prior summer flows (i.e., 68% vs. 65% for LV2c, and 49% vs. 49% for LV2f). Air temperature did not improve on flow regressions for the LV2 sites. Mean winter air temperature (negative effect) was significantly related to tree growth at LV0f and increased the variance explained by flow alone from 19% to 26%. Backward stepping provided similar results as forward stepping for all sites.

Growth - Maintenance Relationships

<u>Canopy vigor</u>. Canopy vigor varied as a curvilinear function of radial growth rate at Rush Creek and Lee Vining Creek (Fig. 9). All trees with a growth rate >2 mm/yr had canopies ranked in either the highest vigor class (i.e, class 5, >80% potential canopy) or second highest class (class 4), while most with a

growth rate <1.5 mm/yr had low vigor (i.e., most with class 3 or lower, <60% potential canopy). Trees with growth rates between 1.5 and 2 mm/yr had intermediate canopy vigor values.

Tree death. Number of growth rings for the dead trees at Rush Creek averaged 47 ± 9, with most having died 13-23 years before sampling (i.e., 1968-1978). They were thus in the same age cohort as live, mature trees at the sites. Seven of the dead trees died during years (1972-1977) with very low flow (i.e, 0 to 5 hm^3/yr) and thus presumably died from drought stress (Fig. 10). Two died during or immediately after flood years (1967, 1983), probably because of erosion of rooting substrates. Year of death could not be determined for one tree.

Growth rates of the dead trees were very low in the two years prior to death (Table 8). Pre-death growth rates at RC1 averaged 0.77 mm/yr and ranged from 0.19 to 1.57 mm/yr among trees (compared to recent growth rates of 2.4 mm/yr for live trees). Values at RC2 averaged 0.70 mm/yr and ranged from 0.39 to 1.23 mm/yr (compared to growth rates of 1.6 mm/yr for live trees). Lifetime growth rates were also lower for the dead trees than for live trees at both sites.

Summary of Results

The data in this study support the following conclusions about relationships between growth and instream flows for Rush Creek and Lee Vining black cottonwood populations:

(1) growth of black cottonwoods was significantly related to

stream flow volume, with annual flow volume variously explaining from 14-63% of the annual variance in growth among sites;

(2) annual flow generally explained more growth variance than did summer flow, and present-year flow in combination with prior-year flow generally explained more variance than did present-year flow alone;

(3) stream flow volume explained similar amounts of growth variance for floodplain and channel-side trees, although floodplain trees grew at about half the growth rate of channel-side trees;

(4) within Lee Vining Creek, relationships between tree growth and stream flow volume were stronger for trees in unconstrained floodplain areas than in canyon areas.

The data also indicate the following about population maintenance and about its relationship to growth rate:

(1) canopy vigor varied curvilinearly with radial growth rate, with 2 mm/yr acting as a threshold below which trees had very low values for canopy vigor;

(2) floodplain trees had lower canopy vigor than did channel-side trees;

(3) dead trees had low growth rates in the years prior to death, with values ranging among trees from 0.2 to 1.6 mm/yr, and averaging 0.7 mm/yr;

(4) most of the dead black cottonwood trees died during

chronic drought periods.

DISCUSSION

Instream Flow Needs: Management Implications

The analyses presented in this study indicate that stream flow volume (an indicator of riparian water availability), rather than precipitation and air temperature, is the primary factor regulating growth of riparian cottonwoods along Rush Creek and Lee Vining Creek. The data also show strong relationships between tree growth rate and canopy vigor and between growth rate and survivorship. These relationships between stream flow volume and radial growth rate, and between radial growth rate and canopy vigor and mortality, allow for estimation of flow needs for maintenance of cottonwood stands and ultimately for maintenance of a high degree of ecosystem "integrity" (sensu Karr 1991).

Growth-vigor relationships. According to the growth rate-canopy vigor relationships, radial growth rates of >2 mm/yr were associated with maintenance of vigorous black cottonwood canopies, and those between 1.5 and 2 mm/yr were associated with somewhat less vigorous canopies. Similar types of relationships have been described for cottonwoods on another diverted stream in the eastern Sierra Nevada, Bishop Creek (Stromberg and Patten 1991a). These relationships strongly suggest that canopy vigor varies directly as a function of growth rate, and thus in large part as a function of riparian water availability. The fact that some variability in canopy vigor existed between trees within sites subject to the same flow regime is no doubt a function of the fact that genetically distinct individuals within populations often have varied response, in terms of physiology, morphology, or allocation of resources, to environmental stress. For example, certain individuals are physiologically better able to withstand drought stress and thus can maintain higher growth rates and larger canopies than other trees under similar environmental conditions. Also, trees of one gender may allocate more resources to reproduction and less to vegetative structures than those of the other gender, further contributing to within-site variability in canopy vigor (Farmer 1964; Sakai and Burris 1985).

<u>Growth-mortality relationships</u>. The growth-mortality data confirm that very low growth values (i.e., <1 mm/yr) are associated with the ultimate extension of low canopy vigor, i.e., tree death. Most of the dead trees assessed at Rush Creek died from chronic stress imposed by drought, with the remainder dying during or after flood years. A mortality study at diverted Bishop Creek also implicated chronic drought and episodic floods as primary causes of cottonwood death, and showed low growth rates (i.e., about 0.5 mm/yr) for trees in reaches where drought was the primary mortality cause (Stromberg and Patten 1991a). The data presented in this Rush Creek study and in the Bishop Creek study do not allow the relationship between growth rate and population mortality rate to be quantified, but do strongly implicate values in the range of <1 mm/yr as growth rates associated with heightened population mortality.

<u>Flow-growth relationships</u>. Using the criteria delineated

above as indices of growth values associated with maintenance of riparian cottonwood populations, the flow-growth models can be used as tools to estimate riparian instream flow needs (Table 9). The best-fit flow-growth models (Tables 6 and 7) indicate that various volumes of flow will produce differing rates of growth and thus differing levels of canopy vigor. For example, "maintenance" flows (i.e., those producing growth of 2 mm/yr and thus relatively vigorous canopies) for floodplain trees at Lee Vining are 18 hm^2 (a value intermediate between natural flow volumes and flows during the LADWP diversion period), while "attainment flows" (i.e., those producing growth of 2.5 mm/yr and thus very vigorous canopies) are 36 hm^2, a value closer to the mean volume of prediversion flows.

The models also indicate that substantially different flow levels are necessary to maintain floodplain vs. channel-side trees (Table 9). For example, maintenance flows for channel-side trees at Rush Creek are 10-30 hm^3/yr, while maintenance flows for floodplain trees at Rush Creek are >100 hm^3/yr. Whereas maintenance flows for Rush Creek channel-side trees are lower than natural flow volumes, attainment flows for this same group are in the range of natural flow volumes.

"Subsistence" flows (i.e., those that will produce a level of growth [1.75 mm] associated with some decline in canopy vigor) for floodplain trees at Rush Creek are about 85 hm^3/yr. This value is in the range of prediversion flows for that section of Rush Creek, assuming either that most irrigation water had returned to the stream prior to reaching the site and/or that flows were supplemented by groundwater. Maintenance flows (>100 hm^3/yr) for RC2f, however, are greater than average prediversion flows. These data suggest that flow needs of floodplain trees are higher under existing conditions than they were under historical conditions. Higher present day flow needs may be a function of the channel incision which occurred on lower Rush Creek during the LADWP diversion period, a result of the combined effects of Mono Lake drawdown and major flooding (mainly in 1967 and 1969) on a nearly devegetated floodplain. This incision may have decreased the amount of water available to the riparian trees from a given volume of surface flow. It is also possible that chronic drought stress has reduced the growth potential of these floodplain trees and thus reduced the ratio of growth increment to flow volume increment, producing artificially high instream flow needs. From another perspective, however, the instream flow estimates for the RC2 floodplain trees may err on the low side when considered as an indicator for floodplain tree flow needs in general. This is because the sample of floodplain trees is biased in that is excludes trees that did not survive under low flow conditions, either because they had higher intrinsic water requirements or because site conditions did not provide sufficient water. Without replication, however, it is unknown to what extent instream flows for maintenance of floodplain trees at RC2 differ from those for trees that might be planted or established naturally on other floodplain sites along

Rush Creek.

It is possible that channel restoration work to rewater specific subsidiary channels would reduce the instream flow needs of remaining floodplain trees, and increase their vigor and survivorship. However, such manipulation would provide only a temporary "fix" and should not be considered as a mutually exclusive alternative to providing adequate flow needs of floodplain trees in general. Isolation of cottonwood populations at large distances from main channel establishment sites via channel meandering and realignment is a natural process within "healthy" riparian systems. Among other things, these flood driven channel dynamics create open establishment sites and allow for the development of a greater abundance and a greater age class diversity of cottonwood stands (Stromberg and Patten 1991b).

The flow volume values indicated in Table 9 are mean average flow volumes. Acceptable levels of annual or summer flow fluctuation were not addressed in this study. However, it is reasonable to conclude that riparian vegetation is adversely affected by the extreme fluctuation characteristic of diverted Rush Creek, which was caused by the diversion of proportionally more water in "dry" years than in "wet" years. Flow extremes, be they high peak flows and low annual flows, both can cause riparian mortality. Although floods are natural processes essential for such riparian dynamics as seedling establishment, they can exacerbate tree mortality in systems denuded by prior dewatering. Low flows, in contrast, are associated with heightened periods of mortality from drought stress. Thus, instream flows for riparian vegetation in Rush Creek and other regulated streams should have annual fluctuations similar to that characteristic of free-flowing streams. In terms of low flows, for example, data from other diverted streams in the eastern Sierra Nevada suggest that mortality would be reduced if low annual flows were no lower than about 0.4 times the mean (a range typical for some undiverted eastern Sierra Nevada streams). Thus, at Rush Creek, for example, if mean annual flows were set at 50 hm^3, low flows perhaps should not drop below 20 hm^3/yr. Future real-time monitoring of plant response to various flow volumes (and to riparian water availability as indicated by monitoring of piezometer data and soil moisture data) would allow refinement and testing of these and other flow volume relationships.

<u>Relationships between flow and floodplain width</u>. The flow-growth models developed for channel-side and floodplain trees provide an index of the amount of flow needed to maintain populations growing at various distances from the stream. They thus are useful in depicting the width of the riparian zone that will be maintained by various stream flow volumes, assuming that black cottonwood flow needs are representative of general riparian vegetation flow needs. A plot of the relationship between mean annual stream flow and cottonwood strip width for Rush Creek (based on best available data) is presented in Fig.

11. X-coordinate values were generated by using a growth value of 1.75 mm/yr for determining instream flows, and y-coordinate values were generated by calculating the average distance of the cottonwood trees from the stream (multiplied by two). These data show a strong relationship between stream flow volume and width of the riparian cottonwood zone at Rush Creek, with wide riparian strips (>150 m) being associated with high flow volumes (>80hm^3). This is not surprising, in light of studies indicating strong correlations between flow volume and riparian zone width for eastern Sierra Nevada alluvial streams (Taylor 1982). Nevertheless, the exact shape of the curve between flow and riparian width is unknown for Rush Creek because past stream dewatering has reduced the availability of study populations and thus reduced the number of data points (i.e., cottonwood populations) on which the curve is based.

Instream-flow summary. The instream flow findings of this study can be summarized as follows:

(1) stream flow volume is the primary factor regulating cottonwood tree growth at Rush Creek and in those portions of Lee Vining Creek with unconstrained floodplains;

(2) flow volumes associated with maintenance of Lee Vining Creek black cottonwoods and of channel-side black cottonwood trees at Rush Creek are on the order of flows that have occurred during the LADWP diversion period;

(3) flow volumes associated with maintenance of floodplain trees several 10s of meters (i.e., 70-90 m) from the Rush

Creek stream channel are equal to or greater than flow volumes characteristic of prediversion times;

(4) width of the riparian cottonwood strip is a function of instream flow volume, with wide riparian strips (>150 m) at Rush Creek being associated with high flow volumes (>80hm^3).

Riparian Water Sources

Two phenomena discussed in this paper need further discussion: the differences in growth-flow responses between channel-side and floodplain trees, and the differences in response between reaches within Lee Vining Creek.

Channel-side vs. floodplain trees. The question of why growth responses and growth rates differed between channel-side and floodplain trees is, rephrased, an issue of defining the sources and availability of water for riparian trees. Floodplain and channel-side trees both had strong relationships between growth rate and flow volume, indicating that tree growth for both groups was influenced directly by stream flow or by a correlate of stream flow. Streamflow can directly influence tree growth rate by means of localized lateral movement of stream flow into the riparian zone soils, followed by uptake of the water into the trees root system. However, isotopic studies of water in plants and their environment suggest that some riparian species rely on "deeper" water sources (such as groundwater) rather than on water absorbed directly from the stream channel (Dawson and Ehlringer 1991). The riparian water table may be one correlate of stream flow that functions as a water source for many cottonwoods. Indeed, data from Balance Hydrologics (preliminary interpretation) indicates that surface flows and subsurface water tables are not independent commodities for Rush Creek. The riparian water table fluctuates strongly in response to stream flows, and has a rapid response time to surface flow release and stage.

The question thus becomes, is the reduced growth of floodplain trees primarily a function of lower riparian water tables, reduced localized lateral seepage, both factors, or yet other factors? Lateral seepage would be expected to decline sharply with distance from the stream, thus contributing to lower growth rates for floodplain trees. However, the distance between the ground surface and the riparian water table also would be expected to increase with distance from the stream. Depth to the water table was at least 1.2 m (3.9 ft) greater for floodplain trees than for channel-side trees at RC2, assuming a linear water table. The discrepancy between depth to the water table for floodplain and channel trees may be even greater during years with very low flow, although this remains to be documented.

Timing of water release also may play a role in explaining growth differences between channel-side and floodplain trees. Natural flows in Rush Creek historically were lowest in winter and highest in spring, because flows are fed by snowpack runoff. Peak flows in the LADWP diversion period have shifted later in the season (i.e., to July) (Stromberg and Patten 1990).

Particularly in drier years, the low flows that precede the seasonal peak may not be sufficient to adequately recharge the water table or riparian soils for trees at great distances from the channel. Thus, leaf flush and other growth processes may be retarded by water stress, resulting in a relatively short growing season and thus low growth increments. Channel-side trees, in contrast, may be able to initiate early growth during very low flow periods because they are closer to the "source". For this group, even limited water table recharge by winter and early spring flows would allow for initiation of growth early in the season. This pattern may explain why growth of channel-side trees was related more strongly to annual flows than summer flows, whereas the reverse was true for floodplain trees.

With respect to the issue of riparian water sources, questions also remain as to: why tree growth generally was more strongly related to the combination of prior and present-year flows than to present year flows alone; why annual flows were more strongly related to growth than to summer flows; and why the y-intercepts (i.e., growth rate values) in the flow-growth models had non-zero values in years with no surface flow. The first effect may be due, in part, to autocorrelative effects of high growth in one year on high growth in the next (Kramer and Kozlowski 1979). However, the three findings in concert suggest that riparian water may have fairly long retention time. For example, flows throughout the entire year (including winter flows) may contribute to recharge of the riparian water table and of riparian soils, and thus to tree growth. Many isotopic hydrological studies support the idea that water can have fairly long retention time in the watershed, as indicated by the frequent large contribution of "old water" (i.e., water stored in watersheds as groundwater or soil water) to flow arising from new storm events (e.g., Burns 1991).

Lee Vining Creek reaches. Trees within the Lee Vining Creek delta canyon had less growth variance explained by flow volume than did trees in unconstrained canyon areas, suggesting that stream flow (and its correlates) are not strongly limiting the growth of the delta canyon trees. Trees in the delta canyon also have undergone less mortality than have trees elsewhere, and the riparian communities have been less affected by dewatering. Groundwater seepage, perhaps combined with a long period of water retention within the riparian systems, may play roles in maintaining riparian trees in the delta canyon. Seepage through the delta canyon sediments has been postulated as an explanation for the continued presence of aspen trees on the canyon wall throughout the LADWP diversion period (Stine 1991), and the same may be true for the black cottonwoods. The source of the groundwater, however, is unknown. Irrigation tailwater or seepage from unlined irrigation canals may have been primary sources in early years; present sources may include watershed snowpack runoff or subsurface leakage from impoundments. Slow movement of subsurface flow or runoff through the delta sediment system may explain why prior-year flow was more strongly related to growth of some Lee Vining Creek trees than was present-year flow, and may have buffered lethal effects of periodic no-flow years. The resulting high tree density within the delta canyon further contributes to weak flow-growth relationships, because high (and spatially varying) between-tree competition effects can override water limitation effects (Chen and Gomez 1990; Doyle 1990).

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Table 1. Location, size, age, and radial growth rate of _Populus trichocarpa_ along diverted Lee Vining and Rush Creeks. Record length for growth analyses also is indicated. Sample size indicates number of usable increment cores analyzed per site.

Site	Samp. size (no.)	Distance to 1° channel (m)	Stem diameter (cm)	Annual growth rings (no.)	Radial growth rate (mm/yr)	Record length (years)
RC1c	9	10 ± 8	46 ± 5	72 ± 11	2.41 ± 0.77	45
RC2c	9	13 ± 7	41 ± 8	67 ± 10	2.05 ± 0.42	45
RC2f	9	80 ± 8	33 ± 6	60 ± 03	1.29 ± 0.49	45
LV0c	3	1 ± 1	40 ± 2	81 ± 08	1.65 ± 0.14	45
LV0f	5	54 ± 4	25 ± 1	82 ± 06	0.90 ± 0.15	45
LV1c	9	9 ± 4	24 ± 3	30 ± 2	2.24 ± 0.34	20
LV2c	5	1 ± 1	31 ± 1	30 ± 4	4.38 ± 0.53	20
LV2f	9	40 ± 10	22 ± 2	33 ± 1	1.71 ± 0.99	20
LV3c	7	1 ± 2	23 ± 03	11 ± 1	10.36 ± 1.72	10
LV3f	5	44 ± 1	19 ± 02	16 ± 1	6.73 ± 1.08	10

Table 2. Annual stream flow (hm^3) in Rush Creek prior to and during the LADWP diversion period. Diversion-period values are presented with and without inclusion of the 1980s decade. Values are means followed by standard deviations, with minima and maxima in parentheses.

Location	1921-1941	1942-1979	1942-1990
Grant Lake	78.4 ± 26.1	30.6 ± 38.9	39.1 ± 48.7
	(37.1; 131.0)	(0; 152.4)	(0; 221.8)
Site RC1[1]	51.9 ± 27.7	25.2 ± 34.4	35.0 ± 46.8
	(15.1; 113.9)	(0; 143.5)	(0; 221.8)
Highway 395[2]	42.5 ± 28.5	22.7 ± 33.4	33.0 ± 46.7
	(6.6; 110.2)	(0; 143.5)	(0; 221.8)
RC2[3]	70.5 ± 23.9[4]	19.7 ± 30.5	34.6 ± 44.5
	(32.8; 118.6)	(0; 132.8)	(0; 202.0)

[1] Grant Lake inflow or Mono Gate 1 release flow minus "A" and "C" ditch diversions.

[2] Grant Lake inflow or Mono Gate 1 release flow minus "A", "B", and "C" ditch diversions.

[3] Grant Lake inflow or Mon Gate 1 release flow minus "natural" losses.

[4] Data may be unreliable because extent of natural losses or gains during this time period are unknown.

Table 3. Annual stream flow (hm^3) in Lee Vining Creek during and prior to the LADWP diversion period. Diversion-period values are presented with and without inclusion of the 1980s decade. Values are means followed by standard deviations, with minima and maxima in parentheses.

Location	1935-1941[1]	1942-1979	1942-1990
Lee Vining intake	48.8 ± 16.8 (24.2; 84.6)	14.2 ± 22.2 (0; 72.7)	14.7 ± 22.1 (0; 80.1)
County Road	43.2 ± 15.5 (20.7; 76.2)	12.3 ± 19.6 (0; 63.8)	12.7 ± 19.5 (0; 70.3)

Table 4. Between-site and between-tree correlation coefficients for ring width chronologies collected from <u>Populus trichocarpa</u> along diverted Rush Creek and Lee Vining Creek.

	Between-site correlations		
Rush Creek	0.54 ± 0.15*	Lee Vining	0.23 ± 0.37
	Between-tree correlations		
RC1c	0.46 ± 0.25*	LV0c	0.61 ± 0.29*
RC2c	0.53 ± 0.24*	LV0f	0.71 ± 0.23*
RC2f	0.38 ± 0.16*	LV1c	0.71 ± 0.15*
		LV2c	0.77 ± 0.15*
		LV2f	0.60 ± 0.29*
		LV3c	0.85 ± 0.10*
		LV3f	0.85 ± 0.10*

* $P < 0.01$

Table 5. R^2 values for relationships between annual radial growth rate of <u>Populus trichocarpa</u> (dependent variable) and annual and summer stream flow volume (independent variables), as indicated by linear and nonlinear univariate analyses.

	Nonlinear univariate		Linear univariate		Bivariate[1]		
Site	Annual flow	Summer flow	Annual flow	Summer flow	Annual flow	Summer flow	df
RC1c	0.48**	0.35**	0.48**	0.35**	0.62**	0.60**	44
RC2c	0.45**	0.33**	0.42**	0.31*	0.48**	0.48**	44
RC2f	0.64**	0.72**	0.63**	0.72**	NS[2]	NS	44
LV1c	0.23*	0.20*	0.22*	0.18*	NS	NS	19
LV0f	0.19**	0.16**	0.16**	0.16**	NS	NS	44
LV2c	0.41**	0.28**	0.27**	0.22*	0.68**	0.65**	19
LV2f	0.38**	0.35**	0.37**	0.35**	0.49**	0.49**	19

[1] Includes present-year and prior-year flows

[2] NS = indicates that bivariate model was not more significant than univariate models

** P <0.01

* P <0.05

Table 6. Nonlinear univariate regression equations relating annual radial growth rate (mm/yr) of <u>Populus trichocarpa</u> to annual and summer stream flow volume (hm^3) in Rush Creek and Lee Vining Creek. Age of study trees for which equations were developed are listed in Table 1. The equations are applicable to the range of flow volumes from which they were developed (0 to 222 hm^3/yr and 0 to 140 hm^3/summer for Rush Creek; 0 to 80 hm^3/yr and 0 to 65 hm^3/summer for Lee Vining Creek). Significance level and degrees of freedom are shown in Table 5.

Site	Equation for annual flows	Equation for summer flows
RC1c	$y = 0.0146x - 1.16*10^{-5}x^2 + 1.87$	$y = 0.0291x - 8.41*10^{-5}x^2 + 1.94$
RC2c	$y = 0.0218x - 5.68*10^{-5}x^2 + 1.53$	$y = 0.0259x - 9.51*10^{-5}x^2 + 1.67$
RC2f	$y = 0.0101x - 1.40*10^{-5}x^2 + 0.97$	$y = 0.0119x - 3.49*10^{-6}x^2 + 1.02$
LV1c	$y = 8.35*10^{-3}x + 9.86*10^{-5}x^2 + 3.15$	$y = -0.0026x + 3.41*10^{-4}x^2 + 3.20$
LV0f	$y = -1.99*10^{-4}x + 1.03*10^{-4}x^2 + 0.74$	$y = 4.01*10^{-3} + 5.70*10^{-4}x^2 + 0.74$
LV2c	$y = 0.264x - 2.78*10^{-3}x^2 + 3.08$	$y = 0.227x - 2.59*10^{-3}x^2 + 3.44$
LV2f	$y = 0.0285x - 1.71*10^{-4}x^2 + 1.53$	$y = 0.0270x - 1.27*10^{-4}x^2 + 1.56$

Table 7. Bivariate regression equations relating annual radial growth rate (mm/yr) of Populus trichocarpa to annual and summer flow volume parameters (Q = present-year flow in hm^3, Q_{t-1} = prior-year flow in hm^3) for diverted Rush Creek and Lee Vining Creek. Age of study trees for which equations were developed ar listed in Table 1. The equations are applicable to the range of flow volumes from which they were developed (0 to 220 hm^3/yr and 0 to 140 hm^3/summer for Rush Creek; 0 to 80 hm^3/yr and 0 to 65 hm^3/season for Lee Vining Creek). Significance level and degrees of freedom are indicated in Table 5.

Site	Equation for annual flows	Equation for summer flows
RC1c	$y = 0.0138Q + 7.92*10^{-3}Q_{t-1} + 1.68$	$y = 0.0198Q + 0.0165Q_{t-1} + 1.68$
RC2c	$y = 0.0117Q + 5.33*10^{-3}Q_{t-1} + 1.51$	$y = 0.0172Q + 0.0116Q_{t-1} + 1.29$
RC2f	NS[1]	NS
LV1c	NS	NS
LV0f	NS	NS
LV2c	$y = 0.1013Q_{t-1} + 0.0697Q + 3.08$	$y = 0.1228_{Qt-1} + 0.0764Q + 3.15$
LV2f	$y = 0.01601_{t} + 0.01219_{t-1} + 1.49$	$y = 0.0188Q_{t} + 0.0153Q_{t-1} + 1.49$

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[1] NS = indicates that bivariate model was not more significant than univariate models

Table 8. Radial growth rate (mm/yr) for live and dead <u>Populus trichocarpa</u> at Rush Creek. Values are lifetime growth averages, and either growth during the two years prior to tree death or during the two most recent years of the trees life.

Site		Sample size	Lifetime growth (mm/yr)	Pre-death growth (mm/yr)	Recent growth (mm/yr)
RC1	Live trees	9	2.33 ± 0.48	----------	2.41 ± 0.88
	Dead trees	5	1.91 ± 0.85	0.77 ± 0.45	-----------
RC2	Live trees	18	1.87 ± 0.57	----------	1.65 ± 0.57
	Dead trees	5	1.38 ± 0.47	0.70 ± 0.28	-----------

Table 9. Annual and summer (April-September) instream flow needs for channel-side and floodplain *Populus trichocarpa* at Rush Creek and Lee Vining Creek. Three values are indicated: flows associated with attainment of high biotic potential (growth rates of 2.5 mm/yr); flows associated with population maintenance (growth of 2 mm/yr); and flows associated with population subsistence (growth of 1.75 mm/yr and some loss of canopy vigor). Flow volumes are in metric and english units.

	Annual flows (hm^3)			Annual flow needs (af)		
	Attn.	Maint.	Sub.	Attn.	Maint.	Sub.
Channel-side trees: RC1	40	15	5	32,500	12,200	4,000
Channel-side trees: RC2	60	30	15	48,700	24,300	12,200
Floodplain trees: RC2	>150	120	85	>120,000	97,400	69,000
Channel-side trees: LV2	<5	<5	<5	<4,000	<4,000	<4,000
Floodplain trees: LV2	36	18	2	29,200	14,600	1,600

	Summer needs (hm^3)			Summer needs (af)		
	Attn.	Maint.	Sub.	Attn.	Maint.	Sub.
Channel-side trees: RC1	25	10	1	20,300	8,100	2,400
Channel-side trees: RC2	40	25	15	32,500	20,300	12,200
Floodplain trees: RC2	>100	85	60	>80,000	69,000	48,700
Channel-side trees: LV2	<5	<5	<5	<4,000	<4,000	<4,000
Floodplain trees: LV2	30	15	2	24,300	12,200	1,600

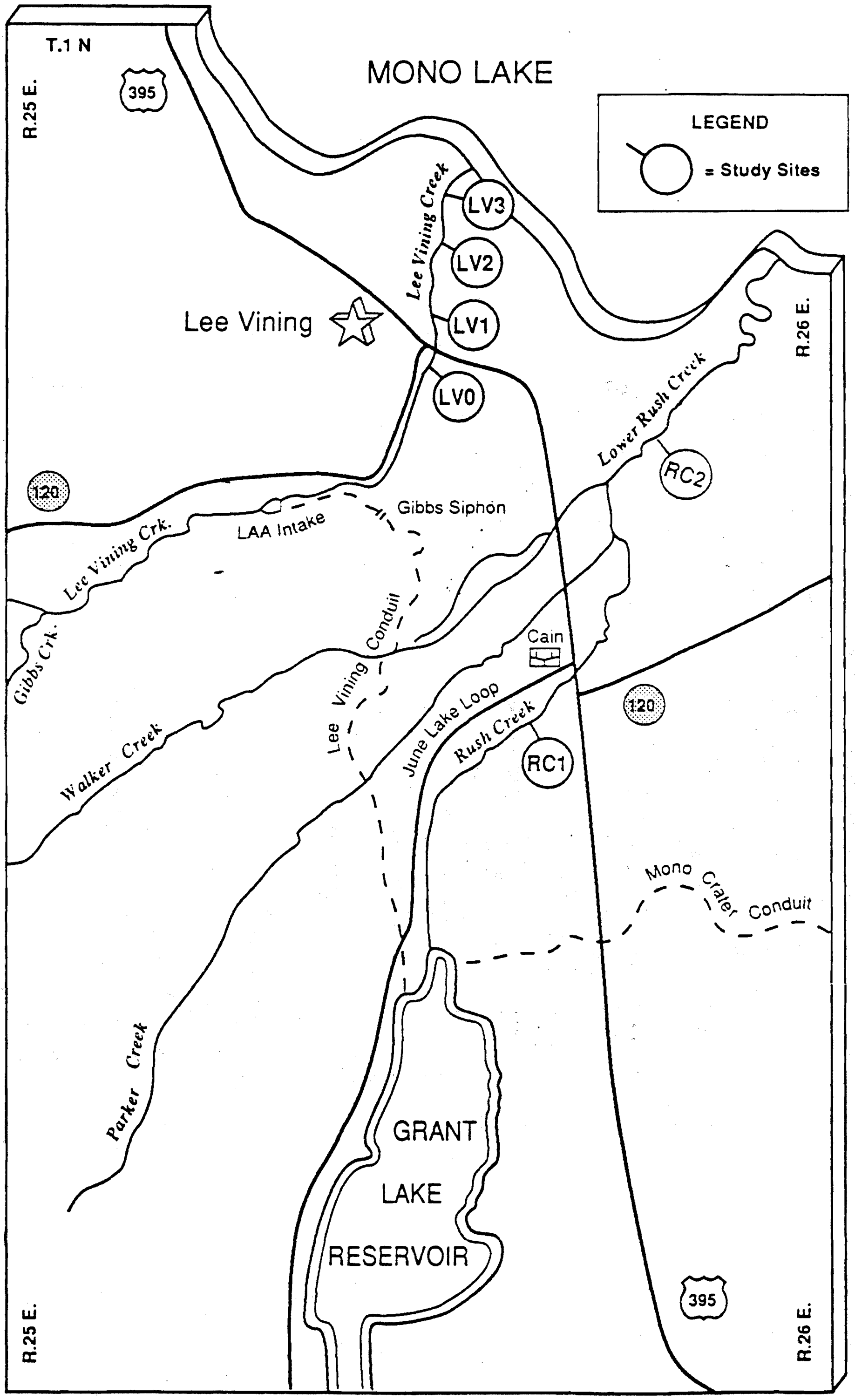

Fig. 1. Locations of black cottonwood (*Populus trichocarpa*) study sites along Rush Creek and Lee Vining Creek.

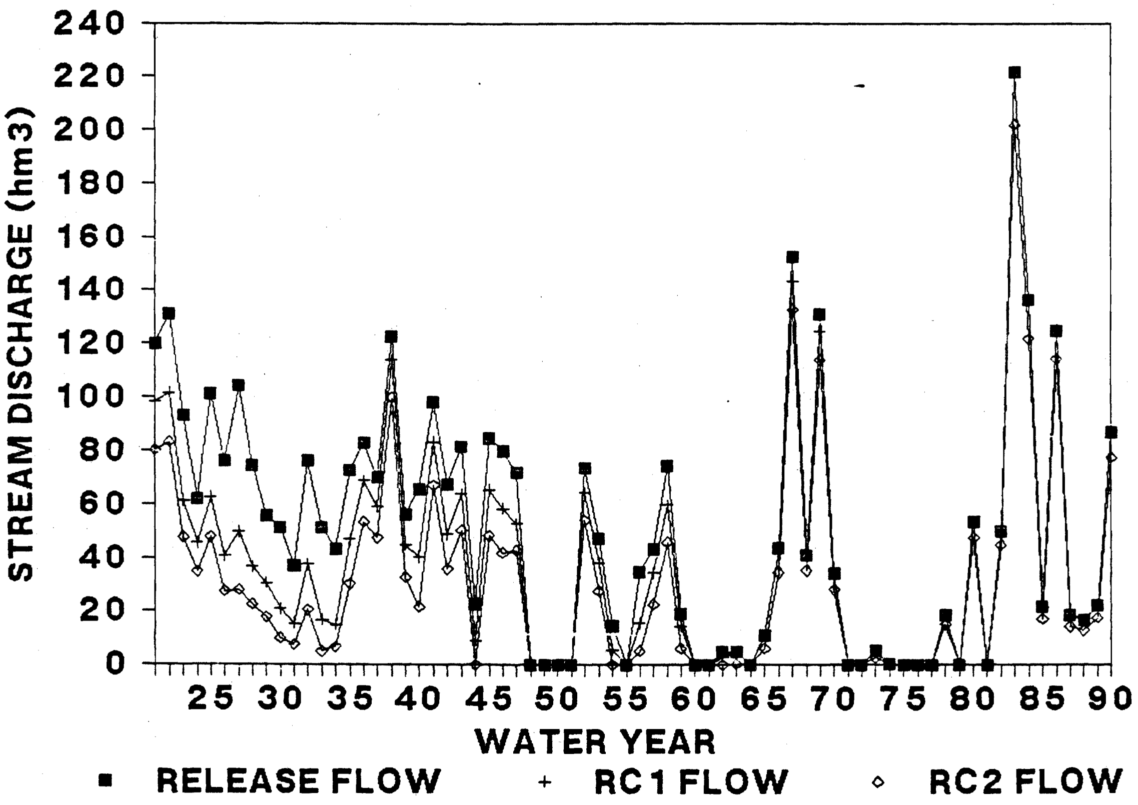

Fig. 2. Annual flow data for Rush Creek. Site specific flow data for RC1 and RC2 have been adjusted for irrigation losses and "natural" losses.

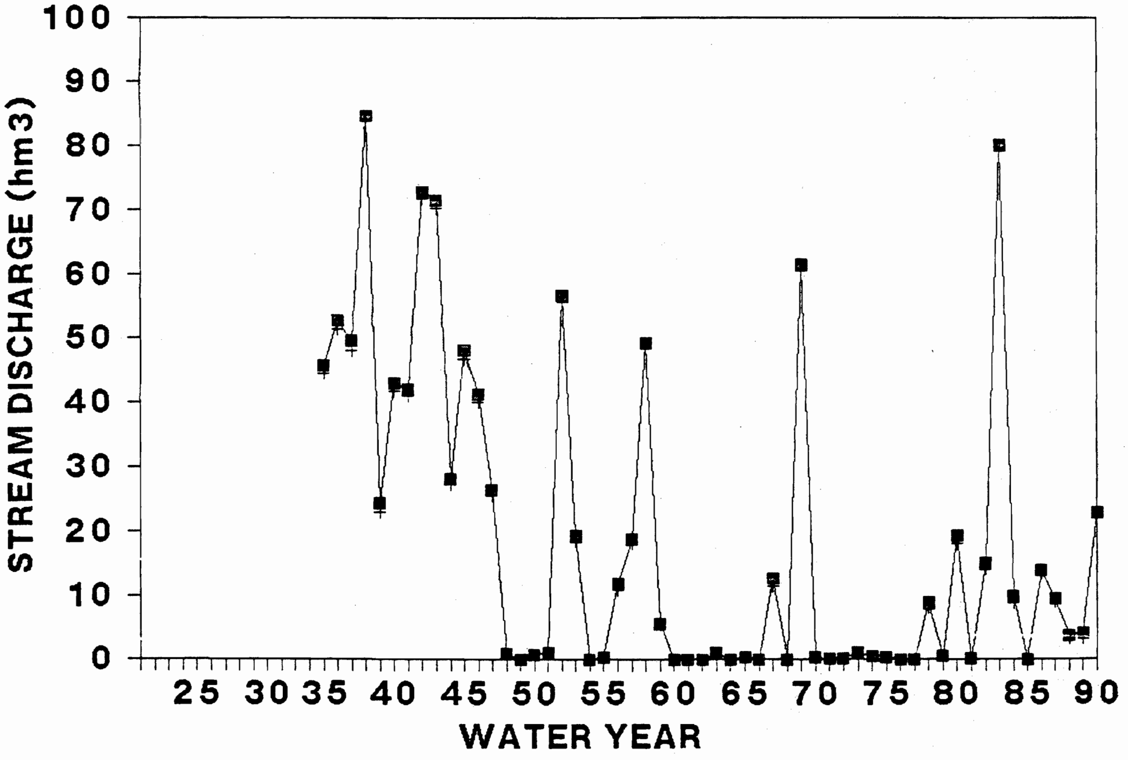

Fig. 3. Annual flow data for Lee Vining Creek.

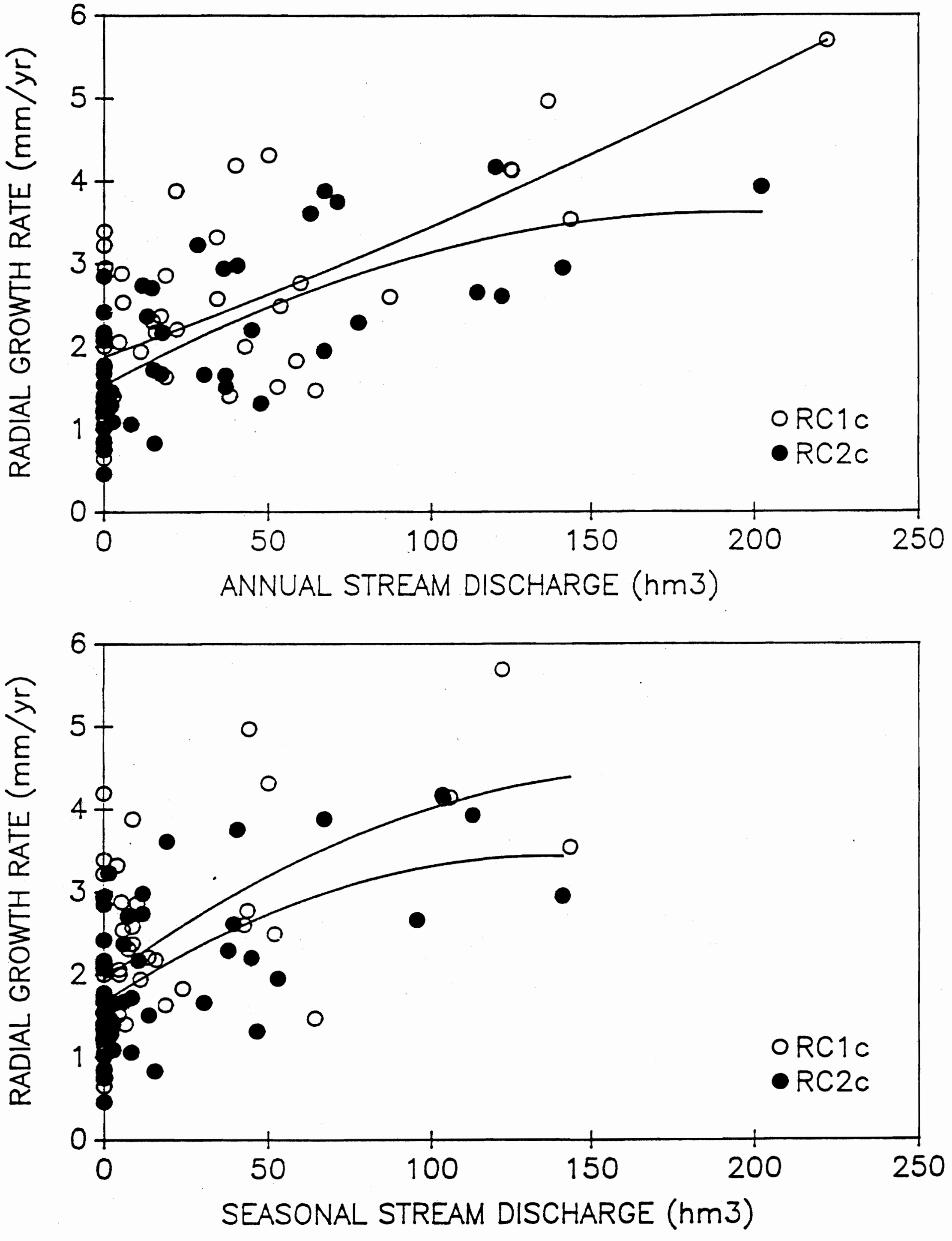

Fig. 4. Scatter plots with nonlinear regression curves relating radial growth rate of mature Populus trichocarpa to annual (above) and seasonal (below) volume of flow in Rush Creek, over the period 1946-1990. Data are presented for two groups of channel-side trees.

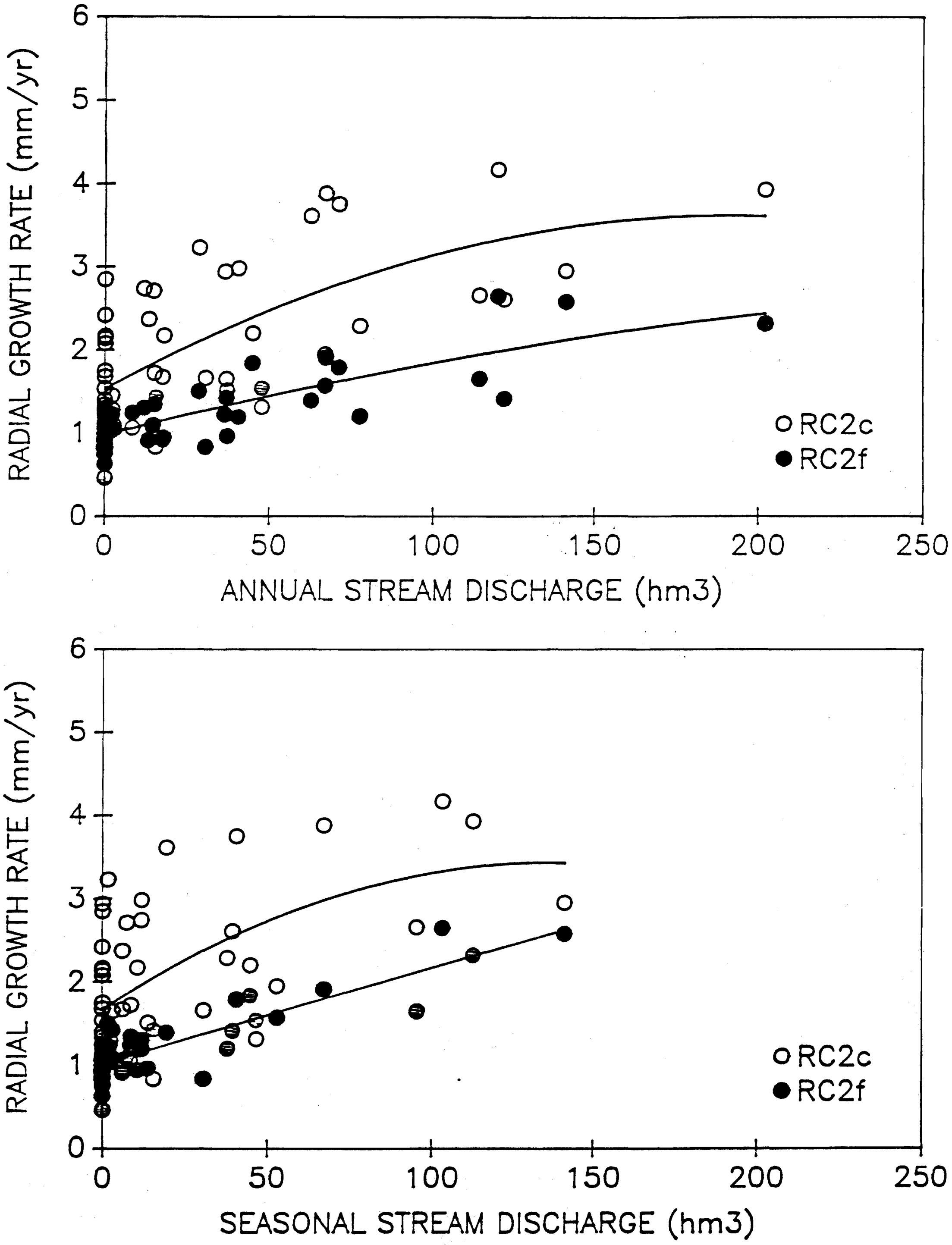

Fig. 5. Scatter plots with nonlinear regression curves relating radial growth rate of mature Populus trichocarpa to annual (above) and seasonal (below) volume of flow in Rush Creek, over the period 1946-1990. Data are presented for channel-side and floodplain trees at site RC2.

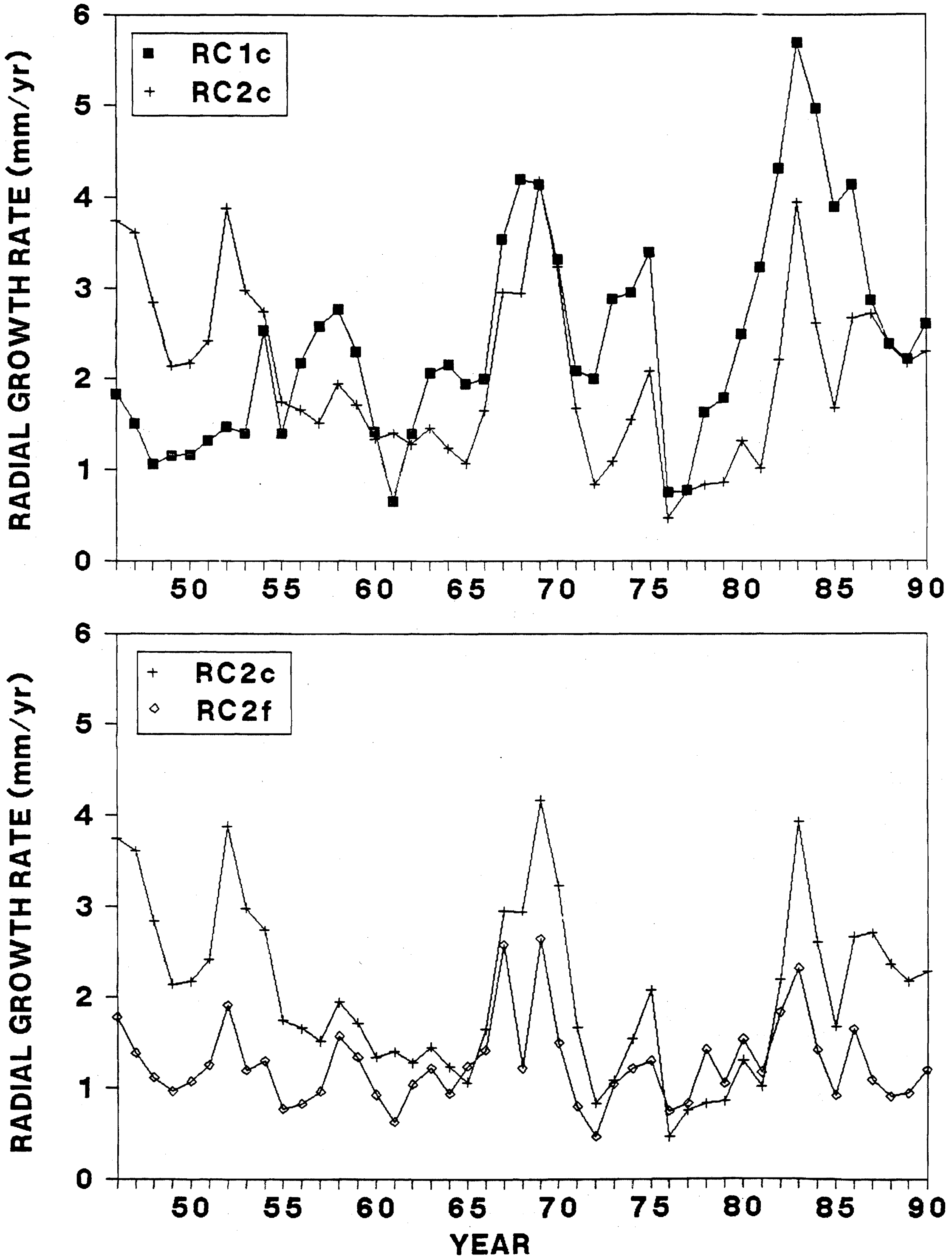

Fig. 6. Ring width chronologies for mature Populus trichocarpa at Rush Creek, over the period 1946-1990. Data are presented for two groups of channel-side trees (above) and for channel vs. floodplain trees (below).

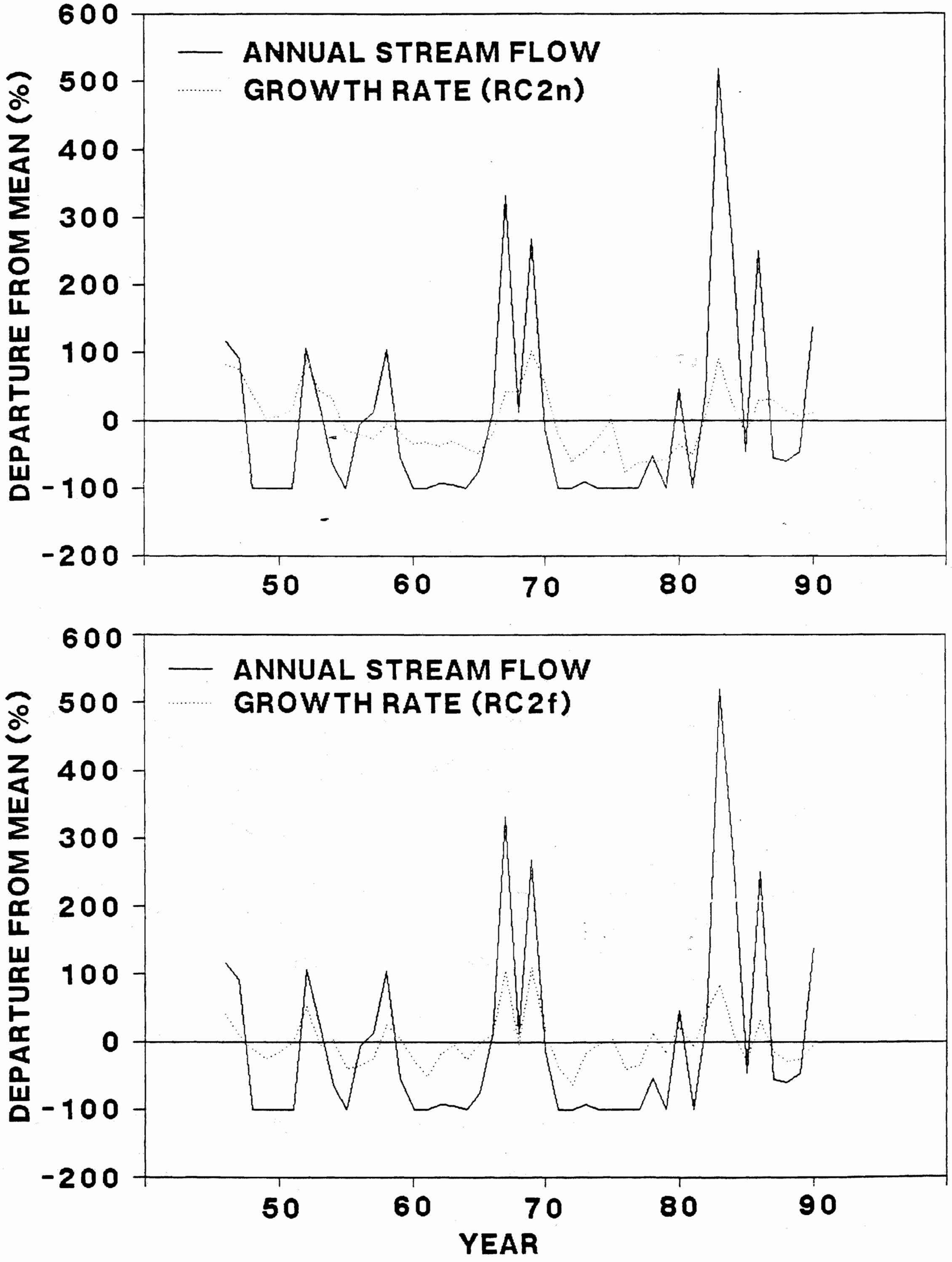

Fig. 7. Overlay of annual radial growth rate and annual stream flow volume (both expressed as percent departure from the mean) for channel-side and floodplain trees at Rush Creek site RC2.

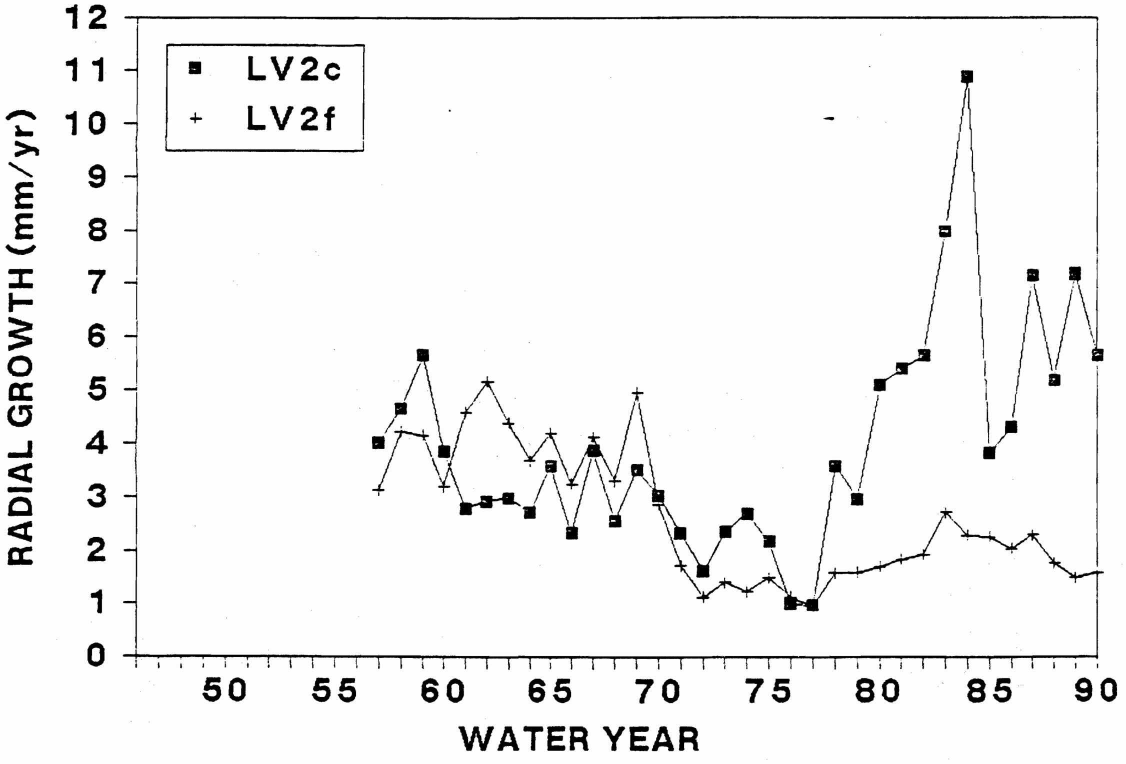

Fig. 8. Ring width chronologies for <u>Populus trichocarpa</u> at Lee Vining Creek, over the period 1946-1990. Data are presented for channel-side and floodplain trees.

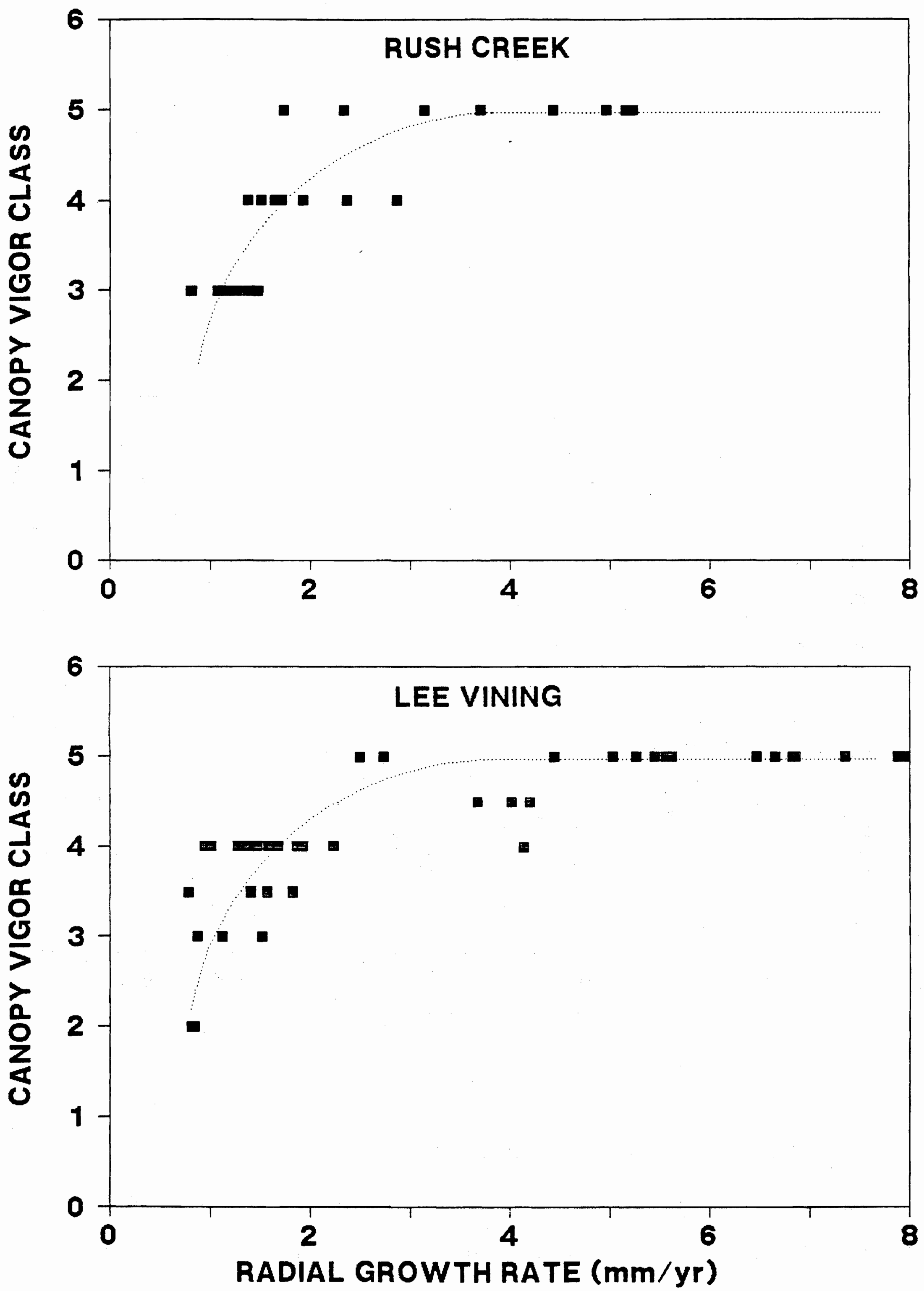

Fig. 9. Canopy vigor rank (scale of 1 to 5; see "Methods") as a function of average radial growth rate for Populus trichocarpa at Rush Creek and Lee Vining Creek.

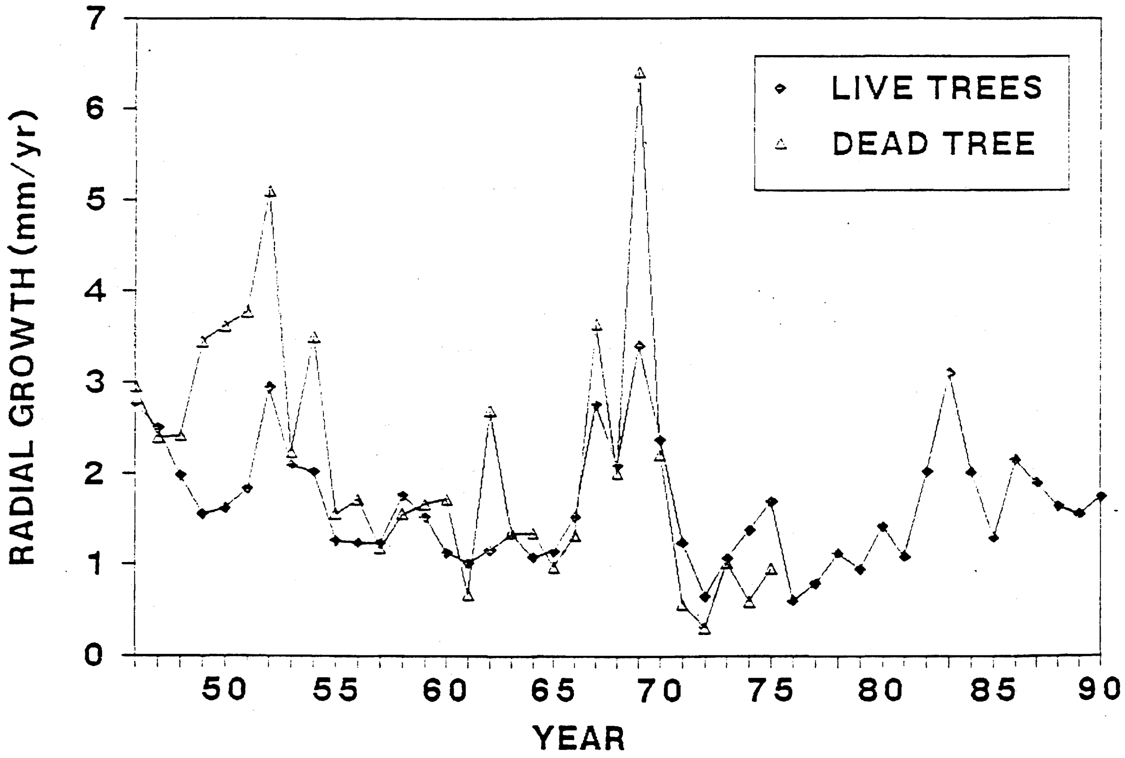

Fig. 10. Ring width chronology of a representative dead black cottonwood (Populus trichocarpa), overlain on the site chronology for live trees at Rush Creek site RC2.

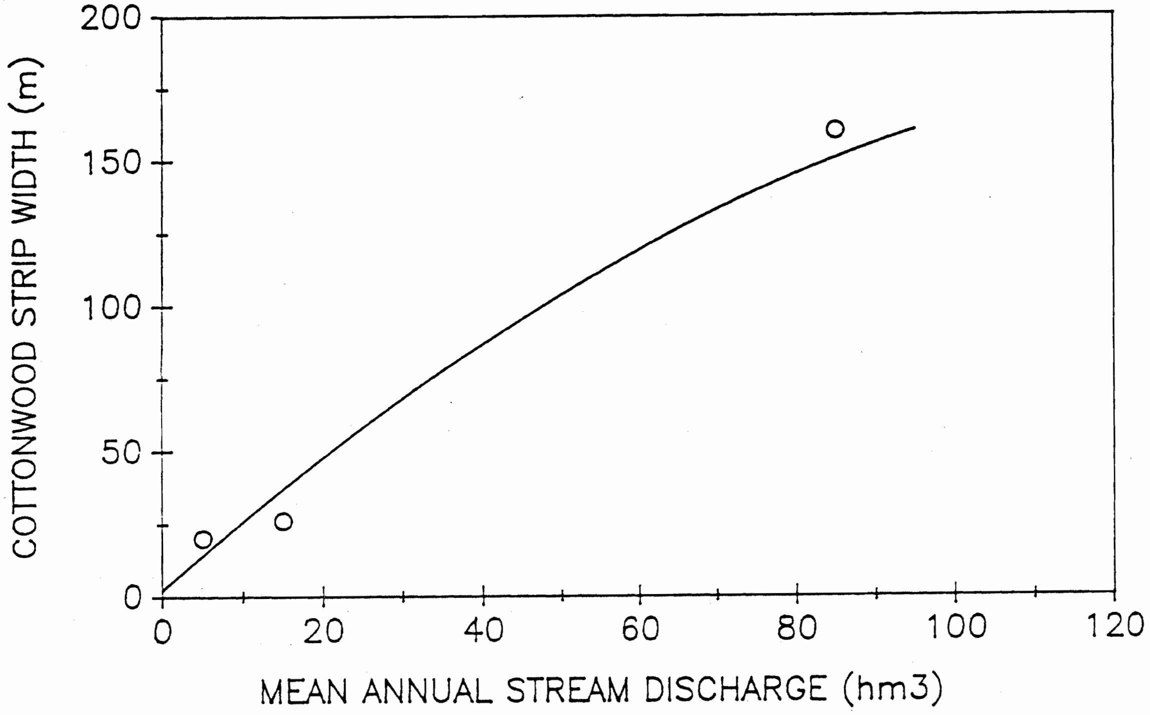

Fig. 11. Estimated relationship between mean annual stream flow volume and width of the riparian black cottonwood (Populus trichocarpa) strip at Rush Creek. Data points represent minimum acceptable flow needs for populations at three sites as determined from instream flow-growth models. Actual shape of the curve is unknown because of the small number of data points.