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Author(s): Vanessa B. Beauchamp and Juliet C. Stromberg
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# FLOW REGULATION OF THE VERDE RIVER, ARIZONA ENCOURAGES *TAMARIX* RECRUITMENT BUT HAS MINIMAL EFFECT ON *POPULUS* AND *SALIX* STAND DENSITY

Vanessa B. Beauchamp[1] and Juliet C. Stromberg
*School of Life Sciences, Arizona State University*
*Tempe, Arizona, USA 85287*

[1]*Present address:*
*U.S. Geological Survey, Fort Collins Science Center*
*2150 Centre Avenue, Building C*
*Fort Collins, Colorado, USA 80526*
*E-mail: vanessa_beauchamp@usgs.gov*

*Abstract:* *Populus* spp. (cottonwood) and *Salix* spp. (willow), the dominant overstory trees in many western riparian forests, are disturbance-adapted species with short seed dispersal periods. Changes to flood cycles often lead to a decrease in recruitment success and survival of these species, and may increase the recruitment success of *Tamarix* spp. (saltcedar), an introduced riparian tree species that has a longer seed dispersal period. This investigation compared *Populus*, *Salix,* and *Tamarix* stem density in 63 stands on unregulated and regulated reaches of the Verde River. *Populus* and *Salix* stem density were not different between the unregulated and regulated reaches in sapling (1–10 year) stands. However, *Populus* stems showed a trend towards higher density in mature stands (11–40 year) in the unregulated reach, and *Populus* density was significantly higher in old-growth (41+ year) stands in the unregulated reach. *Tamarix* stem density was higher in the regulated reach for the sapling class ($4.75 \pm 1.83$ stems/m$^2$ versus $0.03 \pm 0.03$ stems/m$^2$). Analysis of flow conditions during a recent recruitment year (1995) suggests that water release patterns in the regulated reach created favorable conditions for *Tamarix.* Results from this study suggest that where major flooding still occurs in regulated reaches, or where managed flooding is an option, recruitment of *Populus* and *Salix* is possible at similar levels to unregulated reaches. However, careful attention to later season water releases may be important in managing *Tamarix* recruitment opportunities.

*Key Words:* flood, *Populus fremontii*, restoration, riparian, *Tamarix ramosissima*

## INTRODUCTION

*Populus* spp. (cottonwood) and *Salix* spp. (willow), the dominant trees of many riparian forests in western North America, are disturbance adapted species with short seed dispersal periods. These trees have copious, wind-dispersed seed crops and short seed viability (Ware and Penfound 1949, Horton et al. 1960), fast growth rates (Glenn et al. 1998), high inundation or sedimentation tolerance (Gladwin and Roelle 1998, Levine and Stromberg 2001, Kozlowski 2002, Tallent-Halsell and Walker 2002), and low shade tolerance (Johnson et al. 1976, Friedman et al. 1995, Scott et al. 1996). Seed dispersal temporally coincides with recession of the winter, spring, or early summer floods that clear stream banks of vegetation and deposit alluvium, creating moist, open germination beds (Fenner et al. 1984, Johnson 1994, Braatne et al. 1996, Karrenberg et al. 2002).

Regeneration is episodic and dependent on specific patterns of flood magnitude, timing, and recession rates (Fenner et al. 1985, Bradley and Smith 1986, Cordes et al. 1997, Scott et al. 1997, Mahoney and Rood 1998, Shafroth et al. 1998). Flood events must have sufficient volume and stream power to erode and deposit bed and bank material (Johnson et al. 1976, Rood and Mahoney 1990, Rood and Mahoney 1995, Scott et al. 1997, Stromberg 1997), occur shortly before or during seed release (Stromberg et al. 1991, Scott et al. 1997), and recede slowly enough to allow seedling roots to maintain contact with moist soil throughout the summer (Mahoney and Rood 1992, Segelquist et al. 1993, Johnson 1994, Kranjcec et al. 1998, Mahoney and Rood 1998). When stream discharge patterns are altered by activities such as irrigation diversions, dam operation, or ground-water pumping, the flow regime (magnitude, timing, and recession rate) often

no longer satisfies these germination requirements, and the frequency of *Populus* regeneration declines (Fenner et al. 1985, Rood and Mahoney 1990, Howe and Knopf 1991, Rood and Mahoney 1995).

*Tamarix* spp., a riparian forest dominant in western North America that was first introduced to the region in the 1800s, colonizes the same open sites used by *Populus* and *Salix* (Brock 1994, Di Tomaso 1998, Shafroth et al. 1998) but has a longer seed dispersal period than most *Populus* and *Salix* species (Warren and Turner 1975, Shafroth et al. 1998) and greater drought tolerance (Busch and Smith 1995, Cleverly et al. 1997, Stromberg 1998a, Shafroth et al. 2000). Changes to flood timing may not be as detrimental to *Tamarix* recruitment because this species can recruit after later summer flood flows, allowing it to become more competitive in areas where floods are no longer timed correctly for *Populus* and *Salix* (Everitt 1998, Stromberg and Chew 2002, Cooper et al. 2003). *Tamarix* density is often higher in below-dam reaches when compared to areas above dams with unregulated flow (Shafroth et al. 2002); however, few studies have documented the specific hydrograph conditions that enable it to recruit in such reaches.

The first objective of this investigation was to compare stand densities of *Populus fremontii* S. Watts, *Salix gooddingii* Ball, *Salix exigua* Nutt., and *Tamarix ramosissima* Ledeb. between unregulated and regulated reaches of the Verde River to determine if recruitment success and tree survival differ between the two reaches. We hypothesized that *Populus* and *Salix* density would be lower and *Tamarix* density would be higher in the regulated reach as a result of decreased spring flow magnitude and altered flow timing, because these common changes on regulated rivers are expected to limit recruitment opportunities for *Populus* and *Salix*, but not *Tamarix.* This assumes that seed availability and factors associated with creating germination space (flood magnitude, timing, and draw-down) largely control density of young stands (Scott et al. 1997, Shafroth et al. 1998, Johnson 2000, Dixon et al. 2002), and other factors such as climate, grazing, and ground-water fluctuations become important determinants of stand density as stand age increases. This study addressed density at the level of individual stands and did not quantify cohort area in the floodplain; thus, results should not be interpreted to apply at the landscape level.

The second objective was to develop stage-discharge relationships for the Verde River to identify flow conditions (flood timing, magnitude, and recession rates) that would have provided suitable recruitment conditions for *Tamarix* in the regulated reach in the most recent high-flow year (1995) on the Verde River. This objective was based on preliminary observations of high density of *Tamarix* in several sapling stands in the regulated reach. We hypothesized that in 1995 summer flow releases in the regulated reach provided a recruitment opportunity for *Tamarix* that did not occur in the unregulated reach.

## STUDY AREA

The Verde River originates in north central Arizona and flows freely for 200 km before being impounded by Horseshoe Dam (completed in 1945) and Bartlett Dam (completed in 1939) (Owen-Joyce and Bell 1983). Three study sites were established in the Upper Verde Basin (1,170 to 1,100 m) where flow is unregulated (hereafter, the unregulated reach), and four study sites were located below Horseshoe and Bartlett dams in the Lower Verde Basin (440 to 580 m) where flow is regulated by reservoir operations (hereafter, the regulated reach) (Figure 1).

Typically, spring runoff is stored in Horseshoe and Bartlett reservoirs and released in summer to satisfy agricultural and municipal water demands in Phoenix, Arizona. Water from the reservoirs is delivered via the Verde River channel into the Salt River and then into the Central Arizona Project canal system for delivery. No water is diverted from the Verde River below the dams, although ground water in the stream aquifer near the farthest downstream study site has been extracted for municipal use. Bartlett and Horseshoe reservoirs have a combined storage capacity of $3.9 \times 10^8$ $m^3$ (310,000 acre-feet) of water. The average annual flow of the Verde entering the reservoirs (USGS 09508500) is $5.2 \times 10^8$ $m^3$ (418,800 acre-feet), giving the Verde River a capacity/yield ratio of 0.74.

Flood events greater than or equal to the10-year recurrence interval are typically sufficient to promote regeneration of woody pioneer species on rivers such as the Verde (Stromberg et al. 1991, Stromberg et al. 1993, Scott et al. 1996, Scott et al. 1997). The most recent 10-year recurrence interval flood occurred in 1995, at both the Clarkdale (unregulated) and Bartlett (regulated) gages (USGS 9504000 and USGS 9510000; Pope et al. 1998).

As with any above-below dam comparison, the unregulated and regulated reach of the Verde River differ in several ways. The unregulated reach is 600 m higher in elevation and thus slightly cooler and less arid than the regulated reach. The reaches also have different grazing histories; however, all of the study sites have been grazed by livestock in recent decades, and one site in both the unregulated

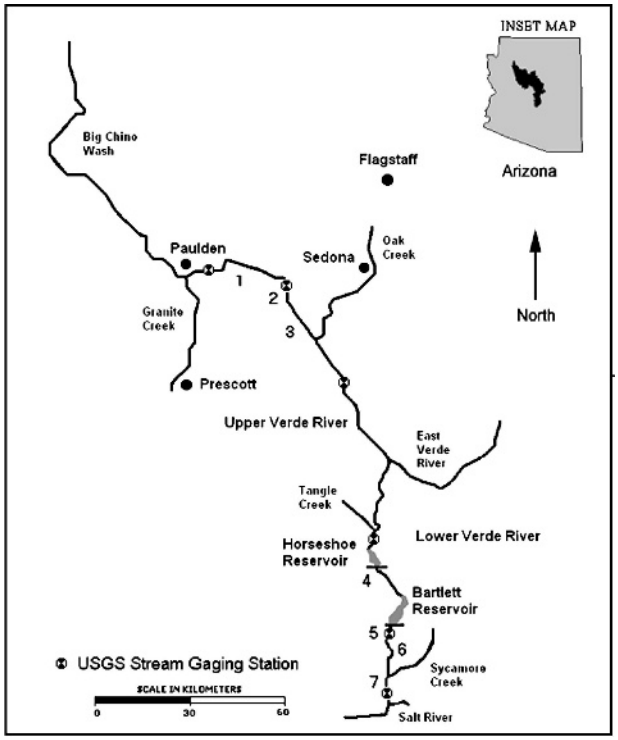


Figure 1. Map of the Verde River, Arizona showing study sites, and stream gage and dam locations. Study sites: 1 = Perkinsville (34.8949° N, 112.2084° W), 2 = Tapco (34.7931° N, 112.0463° W), 3 = Dead Horse Ranch (34.7507° N, 112.0179° W), 4 = Horseshoe Dam (33.9503° N, 111.6839° W), 5 = Bartlett Dam (33.8092° N, 111.6481° W), 6 = Rio Verde (33.7461° N, 111.6618° W), 7 = Fort McDowell (33.5772° N, 111.6715° W). The Clarkdale gage is adjacent to site 2 and the Bartlett gage is directly below Bartlett dam, adjacent to site 5.

and regulated reach are currently grazed. Adult *Tamarix* are present on both reaches, but *Tamarix* stands are more extensive on the regulated reach (Beauchamp, pers. obs). Finally, water quality data collected by USGS show slightly lower specific conductance of surface water in the unregulated reach (values from 200 to 522 μS/cm at Verde-Clarkdale gage in 1995–96) than in the regulated reach (280 to 785 μS/cm at Verde-Tangle Creek gage). Despite these differences, the unregulated reach of the Verde represents the closest match possible, in terms of environmental conditions, to the regulated reach of the Verde.

## METHODS

### Stand Age and Stem Density

Two to three cross-floodplain transects were surveyed with a rod and transit at each of the seven study sites, and nine plots per site were established on or near these transects in *Populus-Salix* stands. Plots were distributed to encompass the size range of trees present at each site. In winter 2000, cores were collected with an increment borer at 40–60 cm above ground level from five of the largest *Populus* or *Salix* per plot. For trees more than 75 cm in diameter at breast height (dbh), only one tree per plot was cored, and samples were taken at 1.5 m above ground level. For trees 6 cm in diameter or less, slabs were obtained with a handsaw as close to ground level as possible. Each core was glued onto a wooden mount, and cores and slabs were sanded with a graded series of sandpaper to 900 grit (Stromberg 1998b). Age was determined by counting annual rings under a dissecting microscope, and minimum plot age was defined as the age of the oldest tree slabbed or cored per plot. Stem burial and beaver activity may result in underestimates of tree age, particularly for older cohorts. To deal with this uncertainty in the analysis, plots were placed into sapling (1–10 year), mature (11–40 year) and old-growth (41+ year) age classes of *Populus-Salix*. Trees from the sapling-class plots in each site were cross-dated to obtain a more accurate determination of stand age. *Tamarix* was not aged for this study, but stems collected on the regulated reach for another study showed that the majority of young (small diameter) *Tamarix* on the floodplain recruited in 1995 or 1996 (R. Marler pers. com.). These *Tamarix* were intermixed with *Populus* and *Salix* in the sapling stands.

Between March and May 2002 each plot was sampled for stem density by species by counting each stem emerging from the ground. Plots were 100 $m^2$ (typically 10 × 10, 5 × 20, or 3 × 33 m as needed to conform to stand dimensions) except for those with old-growth trees, which were 400 $m^2$ (20 × 20 m). Plots containing dense saplings were subsampled using five randomly placed 4-$m^2$ plots (total of 20 $m^2$). Stem density values were reported as stems per square meter.

### Hydrograph Analysis

Stage-discharge relationships were developed for each transect with a channel cross-section analyzer program (WINXSPRO; WEST Consultants Inc. 1998). Channel slope for each site was calculated from 7.5-minute topographical maps and from differentially corrected GPS points taken along the river surface margin. Roughness values (Manning's n) were entered as 0.035 for in-channel surfaces, 0.04–0.06 for rocky or lightly vegetated floodplain surfaces, 0.065–0.080 for areas with shrubs and sparse trees, and 0.085–0.120 for heavily vegetated

surfaces with trees or dense brush (Arcement and Schneider 1989).

Daily flood stage values were calculated as a three-day moving average of flood stage for each transect (as suggested by Rood et al. 1998, Rood et al. 2003). No major perennial streams enter the regulated reach below Bartlett Dam, and average daily flow values from the nearest USGS stream gage to each site (USGS 09509502 or USGS 09511300) were used in developing stage-discharge models for sites in the regulated reach. On the unregulated reach many tributaries enter the river between USGS gages and therefore, the flow recorded at the nearest gage does not accurately reflect the flows experienced at each study site. To estimate flow at the three study sites in the unregulated reach, the discharges associated with the 2, 5, 10, 50, and 100 year average daily flow return intervals were obtained for the Paulden (USGS 09503700), Clarkdale (USGS 09504000), and Camp Verde (USGS 09506000) gages (Pope et al. 1998; Figure 1). For each return interval, discharge was regressed against distance downstream of each gage (all $r^2 > 0.98$). These equations were used to predict the flow volume associated with each return interval at each study site (Beyer 1997). The relationships between average daily flow return intervals at all three gage locations and at each study site were used to estimate site average daily flow values from gage values.

For the 1995 flood, stage discharge relationships were used to determine the zone of moist surface soil on each transect at the time of estimated seed dispersal for *Tamarix*, with the upper limit of the zone being the highest river stage during the dispersal period and the lower limit being the river stage at the end of the estimated dispersal period. The seed dispersal period of *Tamarix* was extrapolated from published observations from other rivers in the western United States (Horton et al. 1960, Warren and Turner 1975, Fenner et al. 1984, Shafroth et al. 1998) and estimated to occur between May 1 and October 30 in the unregulated reach, and between April 15 and October 15 in the regulated reach. The horizontal floodplain distance available for germination was defined as the transect distance falling between the upper and lower limits of the vertical germination zone. Horizontal germination space is expressed as absolute distance and as a percentage of total transect (floodplain) width. The rate of water decline on each transect during the *Tamarix* dispersal period was calculated by taking the difference between the water stage immediately preceding the start of the flow recession period (May 25, regulated reach; September 30, unregulated reach) and the water stage at the end of the flow recession period (June 12 regulated reach; October 5, unregulated reach), and then dividing this number by the number of days it took to complete the drawdown, plus five days to allow for flood attenuation and bank storage (Shafroth et al. 1998).

### Data Analysis

Stem density of *Populus*, *Salix*, and *Tamarix* were compared between regulated and unregulated reaches using the Mann-Whitney U test (PROC NPAR1WAY; SAS Institute 2001). Suitable germination space for *Tamarix* and flood recession rates associated with the 1995 flood on each transect were also compared between unregulated and regulated reaches using t-tests (PROC TTEST) and employing the Satterthwaite method for unequal variances.

## RESULTS

### Stand Density and Age

*Populus* stem density did not differ between regulated and unregulated reaches in the sapling stands, but did show a trend towards lower density in the mature stands in the regulated reach and was significantly lower in old-growth stands in the regulated reach (Table 1). *Salix* stem density did not differ significantly between reach types in any age class. *Tamarix* stem density was 150 times greater in *Populus*-*Salix* sapling stands on the regulated reach than in sapling stands on the unregulated reach. Most sapling stands sampled in the regulated reach contained *Tamarix* (14 of 16), whereas *Tamarix* was encountered in only one sapling stand on the unregulated reach (Table 1). There was variability among sites but no clear pattern of increase or decrease in stem density of any species with distance downstream within each reach (Figure 2).

Nine of the 16 sapling stands on the regulated reach clearly dated to 1995. Two of the 10 sapling stands on the unregulated reach also dated to 1995; seven others dated to 1996 or 1997. These 1996 and 1997 stands could be older, as beaver activity was evident in these stands, or they may be the result of natural recruitment in the years immediately following the large 1995 flood (Shafroth et al. 1998). Within the 1995 cohort, *Populus* and *Salix* stem densities were not significantly different between reaches, but *Tamarix* density was higher in the regulated reach (Table 1).

### 1995 Hydrograph

Flooding in both reaches began on February 14, 1995, and river levels remained high following

Table 1. Comparisons of *Populus*, *Salix*, and *Tamarix* stem density (stems/m$^2$) between the unregulated and regulated reaches of the Verde River. Values are means ± 1SE. Significant differences are in bold ($P < 0.05$; Mann-Whitney U test).

| | | Age Class | | | |
|---|---|---|---|---|---|
| | Reach | 1995 Cohort | Sapling | Mature | Old-Growth |
| Sample size (# of plots) | Unregulated | n = 9 | n = 10 | n = 7 | n = 10 |
| | Regulated | n = 9 | n = 16 | n = 11 | n = 8 |
| Plot size | Both reaches | 20 m$^2$ | 20 m$^2$ | 100 m$^2$ | 400 m$^2$ |
| *Populus* | Unregulated | 1.71 ± 0.81 | 1.84 ± 0.79 | 0.19 ± 0.09 | **0.014 ± 0.01** |
| | Regulated | 1.80 ± 0.76 | 1.05 ± 0.47 | 0.07 ± 0.02 | **0.002 ± 0.00** |
| *Salix* | Unregulated | 1.87 ± 0.42 | 1.71 ± 0.46 | 0.32 ± 0.22 | 0.008 ± 0.00 |
| | Regulated | 3.06 ± 1.08 | 3.92 ± 1.28 | 0.25 ± 0.13 | 0.001 ± 0.00 |
| *Tamarix* | Unregulated | **0.03 ± 0.03** | **0.03 ± 0.03** | 0.25 ± 0.10 | 0.001 ± 0.00 |
| | Regulated | **7.05 ± 3.00** | **4.75 ± 1.83** | 0.23 ± 0.11 | 0.004 ± 0.00 |

a series of closely spaced storms. Recession of the flood waters began on March 6 and was completed by March 26 on both reaches (Figure 3). In the unregulated reach, this large flood was followed by a smaller flood on April 24, with recession lasting until April 30. Both of these events occurred before the estimated *Tamarix* dispersal period (May 1 to October 30) and likely did not provide germination opportunities for *Tamarix*. There was no appreciable change in river stage after April 30 in the

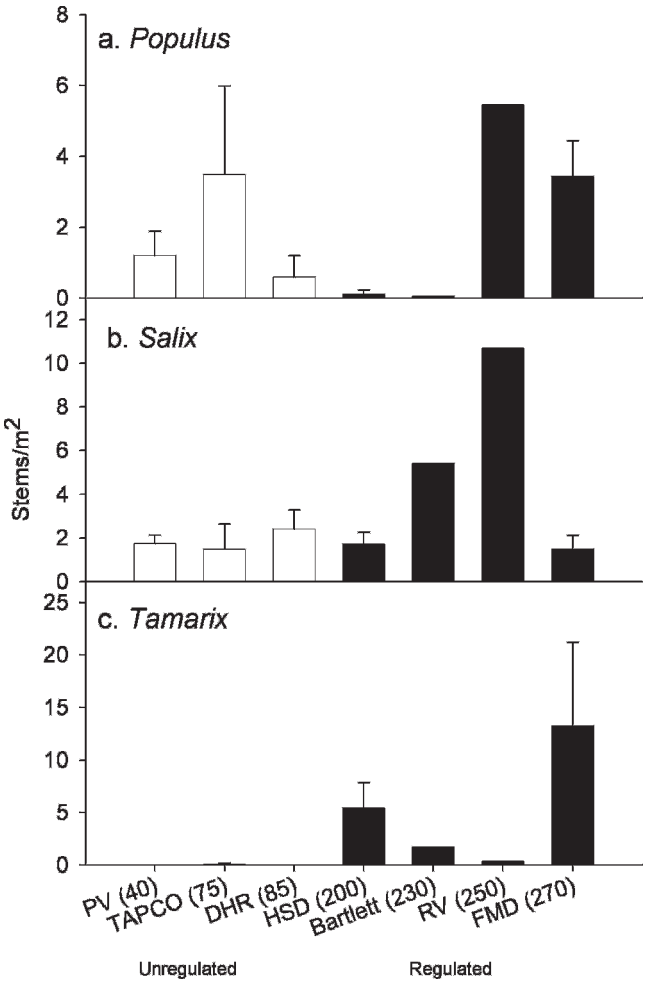


Figure 2. Density of a) *Populus*, b) *Salix*, and c) *Tamarix* in the 1995 cohort for sites in the unregulated (open bars) and regulated (closed bars) reaches. Values are means and error bars are one standard error. Numbers in parentheses are distance downstream (km) from the headwaters.

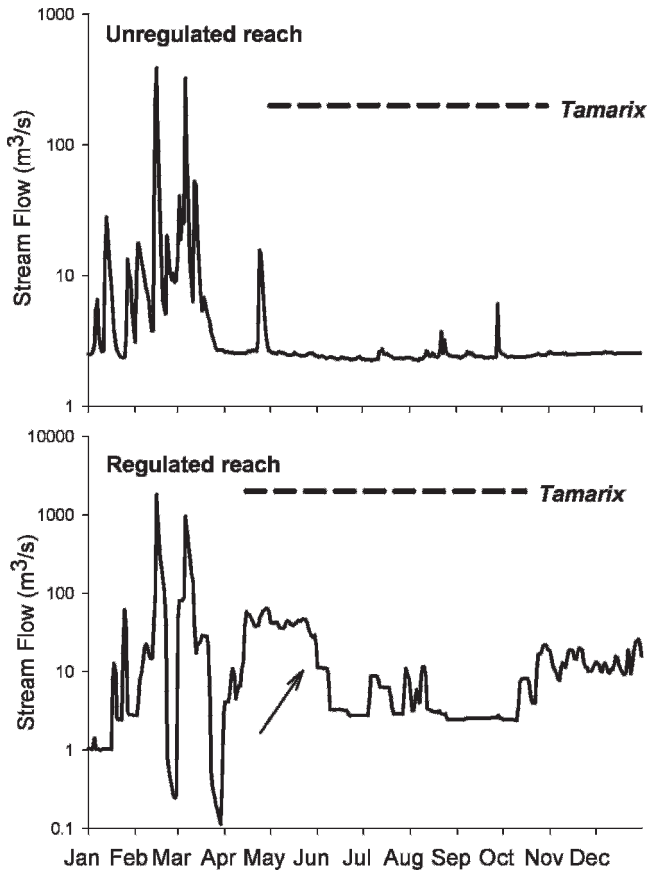


Figure 3. Hydrograph of the 1995 flood on the Verde River. Upper panel shows flow in the unregulated reach (Clarkdale). Lower panel shows flow in the regulated reach (Bartlett) with the arrow pointing to period of summer irrigation delivery. The dispersal period for *Tamarix* is shown for each reach.

Table 2. Stage decline rates and vertical and horizontal germination space available for *Tamarix* on transects located in unregulated and regulated reaches of the Verde River. Values are means ± 1 SE. Horizontal germination space is expressed as absolute transect distance and as a percentage of transect distance. Asterisk indicates significant differences between reaches.

| | Unregulated | Regulated | t-test |
|---|---|---|---|
| Recession period | Sept. 30 to Oct. 5 | May 25 to June 12 | |
| Stage decline rate during recession period | 0.3 ± 0.0 cm/day | 3.1 ± 0.2 cm/day * | t = 14.91; df = 10.5; P < 0.0001 |
| Vertical germination space | 0.03 ± 0.0 m | 0.94 ± 0.05 m * | t = 18.39; df = 10.1; P < 0.01 |
| Horizontal germination space | 1 ± 0 m (0.4 ± 0.1 %) | 32 ± 10 m * (8 ± 2 %) | t = 3.25; df = 10; P < 0.01 |

unregulated reach, leaving little germination space available for *Tamarix* (Table 2). In the regulated reach, water releases from Horseshoe and Bartlett reservoirs started on April 13 began to decline on May 25, creating another drawdown event lasting 19 days with rates of water decline between 2.3 and 4.3 cm/day, thus creating germination space for *Tamarix* (Table 2).

## DISCUSSION

Our initial hypothesis — that *Populus* and *Salix* stand density would be significantly lower in the regulated reach when compared to the unregulated reach — was not supported by this study. Decreases in *Populus* and *Salix* recruitment and survival have been documented on many regulated rivers and attributed to the creation of altered flood cycles that no longer meet the requirements for recruitment of these woody pioneer species (Fenner et al. 1985, Rood and Heinze-Milne 1989, Rood and Mahoney 1990, Howe and Knopf 1991, Johnson 1992, Busch and Smith 1995, Rood and Mahoney 1995), and we expected to see a similar pattern on the Verde River. Operation of the reservoirs on the Verde system has altered the flow regime of the river, but these changes are not as extreme as seen on many other aridland rivers (Graf 2006). The storage capacity to basin yield ratio for the Verde system is much lower than on most western rivers (Graf 1999, 2006), and in average to wet years water must be released from the reservoirs, producing large floods. Flood magnitude during wet years is not substantially reduced and the timing is not altered, allowing for episodic seedling recruitment of *Populus* and *Salix*. This result is similar to those found on other rivers where reservoir operation does not cause a significant change to the large flood flows that drive large recruitment events (Zamora-Arroyo et al. 2001, Katz et al. 2005, Nagler et al. 2005). These results suggest that when patterns of large-scale winter/spring flooding remain relatively unaltered by virtue of small reservoir capacity, recruitment of *Populus* and *Salix* can occur at levels comparable to those in an unregulated reach. We emphasize that the specific aim of this study was to look at the effect of flow regulation at the stand level; landscape-level changes in forest extent, such as might be caused by differences in frequency of recruitment events and size of germination beds, were not investigated. A study evaluating southwestern willow flycatcher habitat on the lower Verde River determined that from 1934 to 2002, woody riparian vegetation increased in coverage on both above- and below-dam reaches (ERO Resources Corporation 2003), but fates of individual cohorts were not tracked.

Densities of older stands may be influenced by a number of factors including drought, flooding, ground-water fluctuations, fire, livestock grazing, and tree cutting. The similarity of *Populus* and *Salix* density in mature stands in both reaches suggests that processes controlling tree mortality have operated similarly in both reaches for the last 11–40 years. However, a trend towards lower *Populus* density in the mature stands on the regulated reach may indicate that some of these processes are beginning to exert their effects on these stands, or that initial recruitment density was lower. The lower density of old-growth *Populus* stands in the regulated reach may be due to some combination of the above-mentioned factors or may be an artifact of sampling design. Trees belonging to this oldest age class existed at all study sites, but were very sparse, and the plots used in this study may not have been sufficiently large or frequent to accurately characterize density.

The high density of sapling *Tamarix* in the regulated reach and its virtual absence in the unregulated reach appear to be related to the pattern of reservoir releases seen in the regulated reach after large scale winter/spring flooding. Other studies have suggested a link between *Tamarix* recruitment and flow releases related to flow regulation (Harris 1966, Miller et al. 1995, Walker

and Smith 1997, Di Tomaso 1998, Everitt 1998, Cooper et al. 2003), but specific links between hydrograph conditions in regulated reaches and increased *Tamarix* recruitment have not been documented. In the unregulated reach of the Verde River, flow recession associated with winter flooding in 1995 ended before the onset of *Tamarix* seed dispersal, making wide-scale *Tamarix* recruitment in this reach unlikely. In the regulated reach, high winter floods in 1995 were followed by elevated late spring or early summer flows. These water releases were curtailed in the summer during the period of *Tamarix* seed release, creating a recruitment opportunity for *Tamarix* only within the regulated reach.

This retrospective analysis is unable to provide a direct link between flow regulation and *Tamarix* recruitment, but analysis of the 1995 hydrograph suggests that management-produced flows can play a role in the regeneration of *Tamarix* in a below-dam reach. However, differences in climate, livestock grazing, seed availability, seedling mortality, and salinity are among a suite of other factors that could contribute to the differences in *Tamarix* density between the two reaches. The fact that *Tamarix* density differed significantly between reaches only in the sapling stands, and not in older stands suggests that some controlling factor has changed through time. While one or a combination of these other environmental factors may be responsible, we do know that flow patterns have differed between reaches through time, with flood patterns in the unregulated reach reflecting climate and patterns below the dam reflecting annually varying human water needs. The flow pattern associated with summer irrigation releases in 1995 was unique compared to summer release patterns in other flood years (1980 and 1993) in that flow was dropped in June 1995 and in other years was kept elevated through the entire *Tamarix* dispersal period. The timing of the flow recession associated with the 1995 release may explain the presence of *Tamarix* in the 1995 cohort and the low densities of *Tamarix* in other cohorts.

Careful attention to flood timing and drawdown, and to the pattern of summer irrigation deliveries during wet flood-release years on the Verde could have beneficial results in terms of riparian habitat creation. Managed flooding on regulated rivers is beginning to gain acceptance as a tool for riparian restoration (Poff et al. 1997, Scott et al. 1997, Rood and Mahoney 2000, Stromberg 2001, Rood et al. 2003). Active management of flood timing and other aspects such as drawdown rate have been successful for establishing native woody pioneer species (Taylor et al. 1999, Rood and Mahoney 2000, Rood et al. 2003) and discouraging establishment of introduced species (Taylor et al. 1999, Stevens et al. 2001). The density and composition of the pioneer forests that establish will vary depending on the nature of the flow release pattern, which in turn will vary with management goals.

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## LITERATURE CITED

Arcement, G. J. and V. R. Schneider. 1989. Guide for selecting Manning's roughness coefficents for natural channels and flood plains. U.S. Geological Survey Water Supply Paper 2339:1–38.

Beyer, P. J. 1997. Integration and fragmentation in a fluvial geomorphic system, Verde River, Arizona. Ph.D. Dissertation. Arizona State University, Tempe, AZ, USA.

Braatne, J. H., S. B. Rood, and P. E. Heilman. 1996. Life history, ecology, and conservation of riparian cottonwoods in North America. p. 57–85. *In* R. F. Stettler, H. D. Bradshaw Jr., P. E. Heilman, and T. M. E. Hinckley (eds.) Biology of *Populus* and Its Implications for Management and Conservation. National Research Council of Canada, Ottawa, Ontario, Canada.

Bradley, C. E. and D. G. Smith. 1986. Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. Canadian Journal of Botany 64:1433–42.

Brock, J. H. 1994. *Tamarix* spp. (salt cedar), an invasive exotic woody plant in arid and semi-arid riparian habitats of western USA. p. 27–44. *In* L. C. de Waal, L. E. Child, P. M. Wade, and J. H. Brock (eds). Ecology and Management of Invasive Riverside Plants. John Wiley & Sons Ltd., Chichester, UK.

Busch, D. E. and S. D. Smith. 1995. Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern US. Ecological Monographs 65:347–70.

Cleverly, J. R., S. D. Smith, A. Sala, and D. A. Devitt. 1997. Invasive capacity of *Tamarix ramosissima* in a Mojave Desert floodplain: the role of drought. Oecologia 111:12–18.

Cooper, D. J., D. C. Andersen, and R. A. Chimner. 2003. Multiple pathways for woody plant establishment on floodplains at local to regional scales. Journal of Ecology 91:182–96.

Cordes, L. D., F. M. R. Hughes, and M. Getty. 1997. Factors affecting the regeneration and distribution of riparian woodlands along a northern prairie river: the Red Deer River, Alberta, Canada. Journal of Biogeography 24:675–95.

Di Tomaso, J. M. 1998. Impact, biology, and ecology of saltcedar (*Tamarix* spp.) in the southwestern United States. Weed Technology 12:326–36.

Dixon, M. D., M. G. Turner, and C. F. Jin. 2002. Riparian tree seedling distribution on Wisconsin River sandbars: controls at different spatial scales. Ecological Monographs 72:465–85.

ERO Resources Corporation. 2003. Lower Verde River riparian vegetation: Draft technical report. ERO Resources Corporation, Denver, CO, USA.

Everitt, B. L. 1998. Chronology of the spread of Tamarisk in the central Rio Grande. Wetlands 18:658–68.

Fenner, P., W. W. Brady, and D. R. Patton. 1984. Observations on seeds and seedlings of Fremont Cottonwood. Desert Plants 6:55–58.

Fenner, P., W. W. Brady, and D. R. Patton. 1985. Effects of regulated water flows on regeneration of Fremont Cottonwood (*Populus fremontii*). Journal of Range Management 38:135–38.

Friedman, J. M., G. T. Auble, P. B. Shafroth, M. L. Scott, M. F. Merigliano, M. D. Freehling, and E. R. Griffin. 2005. Dominance of non-native riparian trees in western USA. Biological Invasions 7:747–51.

Friedman, J. M., M. L. Scott, and W. M. Lewis. 1995. Restoration of riparian forest using irrigation, artificial disturbance, and natural seedfall. Environmental Management 19:547–557.

Gladwin, D. N. and J. E. Roelle. 1998. Survival of Plains Cottonwood (*Populus deltoides* subsp. *monilifera)* and saltcedar (*Tamarix ramosissima*) seedlings in response to flooding. Wetlands 18:669–74.

Glenn, E., R. Tanner, S. Mendez, T. Kehret, D. Moore, J. Garcia, and C. Valdes. 1998. Growth rates, salt tolerance and water use characteristics of native and invasive riparian plants from the delta of the Colorado River, Mexico. Journal of Arid Environments 40:281–94.

Graf, W. L. 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35:1305–11.

Graf, W. L. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79:336–60.

Harris, D. R. 1966. Recent plant invasions in the arid and semi-arid Southwest of the United States. Annals of the Association of American Geographers 56:408–22.

Horton, J. S., F. C. Mounts, and J. M. Kraft. 1960. Seed germination and seedling establishment of phreatophyte species. USDA Forest Service Research Paper RM-48.

Howe, W. H. and F. L. Knopf. 1991. On the imminent decline of Rio Grande Cottonwoods in Central New-Mexico. Southwestern Naturalist 36:218–24.

Johnson, W. C. 1992. Dams and riparian forests: case study from the upper Missouri River. Rivers 3:229–42.

Johnson, W. C. 1994. Woodland expansion in the Platte River, Nebraska - patterns and causes. Ecological Monographs 64:45–84.

Johnson, W. C. 2000. Tree recruitment and survival in rivers: influence of hydrological processes. Hydrological Processes 14:3051–74.

Johnson, W. C., R. L. Burgess, and W. R. Keammerer. 1976. Forest overstory vegetation and environment on Missouri River floodplain in North Dakota. Ecological Monographs 46:59–84.

Karrenberg, S., P. J. Edwards, and J. Kollmann. 2002. The life history of Salicaceae living in the active zone of floodplains. Freshwater Biology 47:733–48.

Katz, G. L., J. M. Friedman, and S. W. Beatty. 2005. Delayed effects of flood control on a flood-dependent riparian forest. Ecological Applications 15:1019–35.

Kozlowski, T. T. 2002. Physiological-ecological impacts of flooding on riparian forest ecosystems. Wetlands 22:550–61.

Kranjcec, J., J. M. Mahoney, and S. B. Rood. 1998. The responses of three riparian cottonwood species to water table decline. Forest Ecology and Management 110:77–87.

Levine, C. M. and J. C. Stromberg. 2001. Effects of flooding on native and exotic plant seedlings: implications for restoring south-western riparian forests by manipulating water and sediment flows. Journal of Arid Environments 49:111–31.

Mahoney, J. M. and S. B. Rood. 1992. Response of a hybrid poplar to water-table decline in different substrates. Forest Ecology and Management 54:141–56.

Mahoney, J. M. and S. B. Rood. 1998. Streamflow, requirements for cottonwood seedling recruitment: an integrative model. Wetlands 18:634–45.

Miller, J. R., T. T. Schulz, N. T. Hobbs, K. R. Wilson, D. L. Schrupp, and W. L. Baker. 1995. Changes in the landscape structure of a southeastern Wyoming riparian zone following shifts in stream dynamics. Biological Conservation 72:371–79.

Nagler, P. L., O. Hinojosa-Huerta, E. P. Glenn, J. Garcia-Hernandez, R. Romo, C. Curtis, A. R. Huete, and S. G. Nelson. 2005. Regeneration of native trees in the presence of invasive saltcedar in the Colorado River delta, Mexico. Conservation Biology 19:1842–52.

Owen-Joyce, S. J. and C. K. Bell. 1983. Appraisal of water resources in the Upper Verde area, Yavapai and Coconino Counties, Arizona. Arizona Department of Water Resources Bulletin 2:1–60.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. Bioscience 47:769–84.

Pope, G. L., P. D. Rigas, and C. F. Smith. 1998. Statistical summaries of streamflow data and characteristics of drainage basins for selected streamflow-gaging stations in Arizona through water year 1996. United States Geological Survey, Tucson, Arizona, USA.Water-Resources Investigations Report 98-4225.

Rood, S. B., C. R. Gourley, E. M. Ammon, L. G. Heki, J. R. Klotz, M. L. Morrison, D. Mosley, G. G. Scoppettone, S. Swanson, and P. L. Wagner. 2003. Flows for floodplain forests: a successful riparian restoration. Bioscience 53:647–56.

Rood, S. B. and S. Heinze-Milne. 1989. Abrupt downstream forest decline following river damming in southern Alberta. Canadian Journal of Botany 67:1744–49.

Rood, S. B., A. R. Kalischuk, and J. M. Mahoney. 1998. Initial cottonwood seedling recruitment following the flood of the century of the Oldman River, Alberta, Canada. Wetlands 18:557–70.

Rood, S. B. and J. M. Mahoney. 1990. Collapse of riparian poplar forests downstream from dams in western prairies - Probable causes and prospects for mitigation. Environmental Management 14:451–64.

Rood, S. B. and J. M. Mahoney. 1995. River damming and riparian cottonwoods along the Marias River, Montana. Rivers 5:195–207.

Rood, S. B. and J. M. Mahoney. 2000. Revised instream flow regulation enables cottonwood recruitment along the St. Mary River, Alberta, Canada. Rivers 7:109–25.

SAS Institute. 2001. SAS/STAT users guide, release 8.2. SAS Institute, Cary, NC, USA.

Scott, M. L., G. T. Auble, and J. M. Friedman. 1997. Flood dependency of cottonwood establishment along the Missouri River, Montana, USA. Ecological Applications 7:677–90.

Scott, M. L., J. M. Friedman, and G. T. Auble. 1996. Fluvial process and the establishment of bottomland trees. Geomorphology 14:327–39.

Segelquist, C. A., M. L. Scott, and G. T. Auble. 1993. Establishment of *Populus deltoides* under simulated alluvial groundwater declines. American Midland Naturalist 130:274–85.

Shafroth, P. B., G. T. Auble, J. C. Stromberg, and D. T. Patten. 1998. Establishment of woody riparian vegetation in relation to annual patterns of streamflow, Bill Williams River, Arizona. Wetlands 18:577–90.

Shafroth, P. B., J. C. Stromberg, and D. T. Patten. 2000. Woody riparian vegetation response to different alluvial water table regimes. Western North American Naturalist 60:66–76.

Shafroth, P. B., J. C. Stromberg, and D. T. Patten. 2002. Riparian vegetation response to altered disturbance and stress regimes. Ecological Applications 12:107–23.

Stevens, L. E., T. J. Ayers, J. B. Bennett, K. Christensen, M. J. C. Kearsley, V. J. Meretsky, A. M. Phillips, R. A. Parnell, J. Spence, M. K. Sogge, A. E. Springer, and D. L. Wegner. 2001. Planned flooding and Colorado River riparian trade-offs downstream from Glen Canyon Dam, Arizona. Ecological Applications 11:701–10.

Stromberg, J. C. 1997. Growth and survivorship of Fremont cottonwood, Goodding willow, and salt cedar seedlings after large floods in central Arizona. Great Basin Naturalist 57: 198–208.

Stromberg, J. C. 1998a. Functional equivalency of saltcedar (*Tamarix chinensis*) and Fremont cottonwood (*Populus fremontii*) along a free-flowing river. Wetlands 18:675–86.

Stromberg, J. C. 1998b. Dynamics of Fremont cottonwood (*Populus fremontii*) and saltcedar (*Tamarix chinensis*) populations along the San Pedro River, Arizona. Journal of Arid Environments 40:133–55.

Stromberg, J. C. 2001. Restoration of riparian vegetation in the south-western United States: importance of flow regimes and fluvial dynamism. Journal of Arid Environments 49:17–34.

Stromberg, J. C. and M. K. Chew. 2002. Foreign visitors in riparian corridors of the American Southwest: Is xenophytophobia justified? p. 195–219. *In* B. Tellman (ed.) Invasive Exotic Species in the Sonoran Region. University of Arizona Press, Tucson, AZ, USA.

Stromberg, J. C., D. T. Patten, and B. D. Richter. 1991. Flood flows and dynamics of Sonoran riparian forests. Rivers 2:221–35.

Stromberg, J. C., B. D. Richter, D. T. Patten, and L. G. Wolden. 1993. Response of a Sonoran riparian forest to a 10-year return flood. Great Basin Naturalist 53:118–30.

Tallent-Halsell, N. G. and L. R. Walker. 2002. Responses of *Salix gooddingii* and *Tamarix ramosissima* to flooding. Wetlands 22: 776–85.

Taylor, J. P., D. B. Wester, and L. M. Smith. 1999. Soil disturbance, flood management, and riparian woody plant establishment in the Rio Grande floodplain. Wetlands 19: 372–82.

Walker, L. R. and S. Smith. 1997. Impacts of invasive plants on community and ecosystem properties. p. 69–86. *In* J. O. Luken and J. W. Thieret (eds.) Assessment and Management of Plant Invasions. Springer-Verlag, New York, NY, USA.

Ware, G. H. and W. T. Penfound. 1949. The vegetation of the lower levels of the floodplain of the south Canadian River in central Oklahoma. Ecology 30:478–84.

Warren, D. K. and R. M. Turner. 1975. Saltcedar (*Tamarix chinensis*) seed production, seedling establishment, and response to inundation. Journal of the Arizona Academy of Science 10:135–44.

WEST Consultants Inc. 1998. WinXSPRO A Channel Cross-Section Analyzer User's Manual. USFS Rocky Mountain Experiment Station.

Zamora-Arroyo, F., P. L. Nagler, M. Briggs, D. Radtke, H. Rodriquez, J. Garcia, C. Valdes, A. Huete, and E. P. Glenn. 2001. Regeneration of native trees in response to flood releases from the United States into the delta of the Colorado River, Mexico. Journal of Arid Environments 49:49–64.

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