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STATUS OF THE RIPARIAN ECOSYSTEM IN THE UPPER SAN PEDRO RIVER, ARIZONA: APPLICATION OF AN ASSESSMENT MODEL

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Abstract. A portion of Arizona's San Pedro River is managed as a National Riparian Conservation Area but is potentially affected by ground-water withdrawals beyond the conservation area borders. We applied an assessment model to the Conservation Area as a basis for monitoring long-term changes in riparian ecosystem condition resulting from changes in river water availability, and collected multi-year data on a subset of the most sensitive bioindicators. The assessment model is based on nine vegetation bioindicators that are sensitive to changes in surface water or ground water. Site index scores allow for placement into one of three condition classes, each reflecting particular ranges for site hydrology and vegetation structure. We collected the bioindicator data at 26 sites distributed among 14 reaches that had similar stream flow hydrology (spatial flow intermittency) and geomorphology (channel sinuosity, flood-plain width). Overall, 39% of the riparian corridor fell within condition class 3 (the wettest condition), 55% in condition class 2, and 6% in the driest condition class. Condition class 3 reaches have high cover of herbaceous wetland plants (e.g., *Juncus* and *Schoenoplectus* spp.) along the perennial stream channel and dense, multi-aged *Populus-Salix* woodlands in the flood plain, sustained by shallow ground water in the stream alluvium. In condition class 2, intermittent stream flows result in low cover of streamside wetland herbs, but *Populus-Salix* remain abundant in the flood plain. Perennial wetland plants are absent from condition class 1, reflecting highly intermittent stream flows; the flood plain is vegetated by *Tamarix,* a small tree that tolerates the deep and fluctuating ground water levels that typify this reach type. Abundance of herbaceous wetland plants and growth rate of *Salix gooddingii* varied between years with different stream flow rates, indicating utility of these measures for tracking short-term responses to hydrologic change. Repeat measurement of all bioindicators will indicate long-term trends in hydro-vegetational condition.

Keywords: assessment, arid region stream, bioindicator, ecosystem condition, ground water, riparian vegetation, Salix gooddingii

1. Introduction

Wetland ecosystems in arid and mesic regions throughout the world are being affected by hydrologic alterations including ground-water pumping and stream flow diversion (Rood *et al.*, 1995; Johnson *et al.*, 1999; Kingsford, 2000; Munoz-Reinoso, 2001; Elmore *et al.*, 2003; Tockner and Stanford, 2002). In southwestern

USA, the Colorado River and many of its tributaries have been partially or wholly dewatered as water is appropriated for urban, agricultural and industrial use (Judd *et al.*, 1971; Medina, 1990; Springer *et al.*, 1999; Glenn *et al.*, 2001; Stromberg *et al.*, 2004a). However, there are many restoration and conservation efforts underway to re-water dry river reaches or maintain others in high quality condition. Such efforts require answers to questions such as: What are the desired conditions we are trying to maintain? How much water is needed to maintain these desired conditions and how should it be distributed in time? How much water can be diverted or pumped without causing unacceptable change? (Richter *et al.*, 1997; Naiman *et al.*, 2002; Whiting, 2002; Richter *et al.*, 2003).

Several approaches can be taken in concert to address riparian vegetation water needs. Evapotranspiration rates of various plant associations can be measured, as has been done in the San Pedro Riparian National Conservation Area of southern Arizona (e.g., Scott *et al.*, 2000; Snyder *et al.*, 2000; Scott *et al.*, 2003). When linked with maps indicating the area of each vegetation type, the total consumptive water use of riparian vegetation in the corridor can be estimated (Goodrich *et al.*, 2000). This estimate for the San Pedro riparian corridor has high variance, with water use rates varying from year to year depending in part on weather and water availability. This approach can be augmented by threshold-based studies that specify the spatial and temporal patterns of water needed to maintain the vegetation in various condition levels. On the San Pedro River, studies indicate that perennial flow is required in the stream channel to maintain riverine marshland vegetation, and that particular ranges of flood plain ground-water levels and fluctuations are required to sustain dense, multi-aged forests of shallow-rooted phreatophytic trees (*Populus-Salix*) (Stromberg *et al.*, 2005; Lite and Stromberg, in press).

Many models have been developed that qualitatively or quantitatively assess riparian ecosystems (Innis *et al.*, 2000; Stromberg *et al.*, 2004b). A few are widely used by land and water management agencies in western USA. The Bureau of Land Management's Proper Functioning Condition uses a suite of indicators including riparian vegetation abundance, tree recruitment, and channel morphology to evaluate riparian ecosystem function (Prichard *et al.*, 1993). The hydrogeomorphic approach, adopted by the Army Corps of Engineers and some other agencies, also assesses a wide array of biotic and abiotic variables that influence ecosystem function (Brinson *et al.*, 1995). Both of these are broad approaches that are useful for general assessment. Models also exist that reflect riparian condition changes caused by specific land uses, notably livestock grazing (Fleming *et al.*, 2001; Jansen and Robertson, 2001). However, no assessment models had been developed that related southwestern riparian ecosystem condition to water availability.

To link the ecological condition of riparian vegetation to water availability we developed a riparian assessment model (Lite *et al.*, in review) that is based on the dose-response approach of Karr's Index of Biological Integrity (Karr, 1991; Karr and Chu, 1999). In the model there are nine vegetation bioindicators, including measures of biomass structure, species composition, and population traits, that are sensitive to changes in surface water or ground-water availability. Site index scores allow for placement into one of three condition classes, each of which is associated with particular ranges for site hydrology (surface flow permanence, ground-water depth and fluctuation) and vegetation structure and composition. We developed the model specifically for use on a particular river (the San Pedro) that is vulnerable to flow depletion in some reaches and undergoing re-watering in others. Although specific to the San Pedro River, the model has the potential, with testing, to be applied to other regional rivers.

The assessment model is driven by hydrologic thresholds of the dominant vegetation types in the flood plain-channel ecosystem (Lite *et al.*, in review); it emphasizes plant functional groups and structural traits rather than particular species. There is a sharp decline in the riverine marsh type as flows become intermittent, largely driving changes from condition class 3 to 2 (Stromberg *et al.*, 2005). Between condition class 2 and 1, hydromesic pioneer forests (*Populus fremontii-Salix gooddingii)* give way to dominance by mesic pioneer shrublands (dominated by *Tamarix ramosissima,* an introduced species) as tolerance levels for survivorship relative to ground water depth and fluctuation are exceeded (Lite and Stromberg, in press). *Tamarix* is a large shrub to small tree that has life-history traits that adapt it for both frequent ecosystem disturbance (e.g., flood scour) and various stresses (e.g., drought, heat, salinity); native counterparts with similar adaptations are not abundant on the San Pedro River.

Some of the bioindicators in the assessment model, notably those based on herbaceous vegetation, are more hydrologically sensitive than others, in that they respond more rapidly to small changes in stream or ground-water availability. Sensitive, rapid-response indicators also can be measured for woody vegetation. Growth rate of *Populus* and *Salix*, for example, often varies with annual differences in water availability (Stromberg and Patten, 1990; Willms *et al.*, 1998; Horton *et al.*, 2001). Studies along the San Pedro River indicated that density effects complicated *Populus fremontii* response to site hydrology: (H. Johnson, unpublished data). Growth parameters of *Salix gooddingii*, however, were more sensitive to changes in stream hydrology.

An active conservation community is working to sustain the San Pedro River riparian ecosystem while allowing for urbanization and associated ground-water use (Browning-Aiken *et al.*, 2003). Several groups have formed (and dissipated over the years) to address the local water balance issue. Most recently, the Upper San Pedro Partnership, with representatives from local, state, and federal agencies, municipalities, and private conservation groups, is using science-driven management to address the challenge of allocating sufficient water to maintain high quality aquatic and riparian ecosystems and to allow for urban and economic growth, and also to achieve sustainable water use throughout the watershed. Our overall goal was to provide information of use to these riparian managers and conservation planners. One objective was to apply the assessment model to a portion of the San Pedro (San Pedro Riparian National Conservation Area, SPRNCA) to determine the present condition of the riparian ecosystem and thereby provide a baseline for monitoring long-term changes. A second objective was to describe short-term changes in highly sensitive bioindicators, in response to years with different stream flow rates. Additional objectives were to summarize hydrology and vegetation patterns over the length of the SPRNCA.

2. Study Area

The San Pedro River is located in southeastern Arizona, USA. It is a tributary to the Gila River, which flows into the Colorado River. Aside from small earthen diversion structures near the towns of St. David and Redington, the San Pedro is undammed and undiverted. We focused on the portion of the river within the San Pedro Riparian National Conservation Area (SPRNCA), located in Cochise County and spanning an elevation range from 1295 msl to 1100 msl. The SPRNCA was established in 1988 to conserve, protect, and enhance the riparian area, and it preserves over 23,000 ha of public land that encompasses the riparian zone and adjacent uplands (Yuncevich, 1993). Off road vehicle use, mineral development, ground-water pumping, and flood plain agriculture were halted, and a moratorium placed on livestock grazing, when the SPRNCA was established. Despite these conservation efforts, there are concerns over potential effects of ground-water pumping beyond the conservation area borders; such issues arise when hydrologic boundaries do not coincide with management boundaries (Pringle, 2000, 2001). Although stream-ground water interactions are complex and variable over time and space (Pool and Coes, 1999), ground-water studies have revealed cones of depression in the Upper Basin regional aquifer that are intercepting water that might otherwise sustain base flows in the San Pedro River (Goode and Maddock, 2000).

Upstream of the SPRNCA, in Sonora, flow is perennial through much of the region. Agricultural use in Mexico has depleted the stream, but not dewatered it for the most part. Long stretches of the San Pedro River downstream of the SPRNCA are dry. However, recent mitigation efforts have been undertaken to rewater some portions of the lower reaches through the purchase of irrigated riparian farmland followed by the cessation of ground-water pumping from the stream aquifer (Haney, 2000).

The SPRNCA provides habitat for many plants and animals, including the federally endangered Huachuca water umbel (*Lilaeopsis schaffneriana*), and sustains regionally rare biotic communities including Sonoran cottonwood-willow gallery forest, Wright sacaton grasslands, and cienegas (mid-elevation marshlands) (Arias, 2000). The riparian corridor provides a migratory route for neotropical songbirds (Skagen *et al*., 1998). A recent flora indicated the presence of over 600 vascular plant species in the SPRNCA, 89% of which are considered to be native species (those whose range included North America at the time of European contact about 1500 AD) (Makings, in press).

Mean annual maximum, minimum, and mean temperatures in the area are 25C, 10C, and 18C (Tombstone station). Average annual precipitation is 36 cm (Sierra Vista), 53% of which occurs during the monsoon (July-September) season (NCDC 1971–2000 monthly normals; www.wrcc.dri.edu). Floods occur mainly during three seasons: late summer (following convectional thunderstorms), winter (following Pacific frontal systems), and fall (following tropical storms). Mean annual flow in the river is 1.5 m^3s^{-1} (San Pedro-Charleston gage #9471000, 1913–2001, located near the center of the SPRNCA). Stream flow rate at the San Pedro-Charleston gage was above average in 2001 (2.53 m^3 s^{-1}) and below average in 2002 (0.29 m^3 s^{-1}) and 2003 (0.28 m^3 s^{-1}).

3. Methods

3.1. Reach delineation

To apply the assessment model, we first divided the SPRNCA into 14 relatively homogeneous reaches based on similarity in key physical controls on riparian vegetation structure: stream flow hydrology (spatial intermittency) and geomorphology (channel sinuosity and flood-plain width). We field-sampled the vegetation (bioindicators) at one or two sites per reach, and averaged the site scores as a basis for scaling-up from sites to reaches. We use the term reach to apply to homogenous stretches of the river that are a few kilometers in length, following the terminology of Graf and Randall (1998); others have used the term segment to apply to such river units (Frissell *et al.*, 1986; Bisson and Montgomery, 1996).

The reach boundaries were determined by visually examining overlays of ArcInfo GIS covers of stream flow intermittency, sinuosity and flood-plain width. The Upper San Pedro Community Monitoring Network, in an initiative spearheaded by The Nature Conservancy, annually monitors the spatial extent of perennial flow in the river; during the early summer pre-monsoon season, volunteers walk the river and map the boundaries of the surface flow using global position system (GPS) receivers. These results yield a flow permanence map that indicates the location of surface flow during the summer dry season, when surface flow is at a minimum. Using the flow map for 2002, we calculated the extent of surface flow in sequential 3-km segments of the river in ArcInfo GIS, and then placed the segments into one of five subjectively bounded spatial intermittency classes. Channel sinuosity was also calculated in ArcInfo, by first dividing the river into 3-km stream segments and then dividing stream length by valley length. The segments were classified into one of three sinuosity classes which spanned the observed range (high sinuosity = 1.5 to 1.8 m/m, medium = 1.23 to 1.49, low = 1.0 to 1.22).

Flood-plain boundaries were delineated based on two data sets used in conjunction: topographic information obtained from filtered LIDAR imagery (Carter *et al.*, 2001) and historic maps of flood-plain based on interpretation of aerial photographs from 1986 and earlier years (Hereford, 1993). The river became entrenched during the late19th and early 20th centuries. Using the LIDAR-generated topographic data, we differentiated between "flood plain" (post-entrenchment surface) and "terrace" (pre-entrenchment surface) based on the location of a steep elevation change (cutbank), elevation above the streambed, and proximity to the 1986 flood-plain boundary as delineated by Hereford (1993). The flood plain-terrace boundary was screen-digitized in ArcGIS, using a hill-shaded version of the LIDAR image to aid determination of the cutbank location. When the cutbank location was unclear, we used Hereford's 1986 flood-plain boundary and/or our interpretation of recent aerial photographs as a guide. Average flood-plain width for each reach was then calculated by dividing the flood-plain area by the reach length.

3.2. Field sampling of bioindicators

The index is based on nine vegetation traits that were determined by correlation and regression analysis to be sensitive to changes in surface flow permanence or ground-water levels (Lite *et al.*, in review): 1) percent shrubland cover within the flood plain, 2) maximum vegetation height across the flood plain, 3) basal area of hydromesic pioneer trees (*Populus*+*Salix*) in the flood plain, 4) basal area of *Populus*+*Salix* relative to that of mesic pioneer trees (*Tamarix*), 5) number of *Populus*+*Salix* 10 cm basal diameter size classes, 6) absolute cover of hydric perennial herbs along the low-flow channel, 7) relative cover of hydric perennial herbs along the low-flow channel, 8) absolute cover of hydric herbs along the low-flow channel, and 9) relative cover of hydric herbs along the low-flow channel. The first five indicators are sampled in the flood-plain zone, which is "the surface adjacent to the channel, separated from the channel by banks, and built of materials deposited in the present regime of the river" (Graf, 1988). Along the San Pedro River, this essentially encompasses the zone vegetated by flood-dependent pioneer trees and shrubs (e.g., *Populus, Salix, Tamarix*). The other four indicators are sampled on channel bars and stream banks of the low-flow channel.

The nine bioindicators were sampled from 2001 to 2004. Two sites were sampled in reaches that had spatial variance in flow permanence (i.e., spatially intermittent, or interrupted, reaches) or in fire history (i.e., mix of burned and unburned areas). One site was sampled in more homogeneous reaches. A site consisted of a 500 m river length. The location of each site was recorded to allow for future resampling. At each of the 26 sites, from two to five belt transects (20 m wide) were established, spaced approximately 100 m apart. Transects were perpendicular to the river valley and extended on both sides of the river from the channel margin to the approximate edge of the flood plain. Vegetation patch types were delineated along each transect based on plant cover within three strata (groundcover = <1 m, mid-story $=1$–5 m, and canopy cover = >5 m in height). Patches were classified as forest (canopy layer $>60\%$), woodland (canopy 25–60%), shrubland (canopy $<25\%$ and mid-stratum $>25\%$), grass- or forbland (groundcover $>25\%$), and open (groundcover

<25%). The transect length and the length of each patch along the transect line were measured to estimate the percent of the flood plain covered by shrublands (indicator 1). The height of the tallest tree across the flood plain within the 20 meter wide belt transect was measured using a vertical pole or a clinometer (indicator 2).

For indicators 3 and 4, a point was randomly selected within each patch, to establish a 5×20 m (100 m^2) or 10×20 m (200 m^2) quadrat (centered across the transect, long axis perpendicular to the transect). Basal diameter of hydromesic (*Populus fremontii, Salix gooddingii*) and mesic (*Tamarix ramosissima*) pioneer tree species in the plot were recorded using calipers or a diameter tape. Flood-plain basal area was estimated for each species by weighting patch basal area by the relative width of each respective patch. Indicator 3 was the sum of *P. fremontii* and *S. gooddingii* basal areas. Indicator 4 was the sum of *P. fremontii* and *S. gooddingii* basal area divided by the combined *P. fremontii*+*S. gooddingii*+*T. ramosissima* basal area (expressed as a percentage). Indicator 5 was the number of 10 cm basal diameter size classes (0–10 cm, 11–20 cm, etc) of *P. fremontii* and *S. gooddingii* present in all quadrats sampled along the transect, and is a rough surrogate for age class diversity. For all five indicators, values were averaged across transects to produce site means.

For indicators 6 through 9, a minimum of five, 1-m^2 plots were randomly established in the streamside zone at each site and sampled during the May–June summer dry season (prior to summer rains and floods). Herbaceous ground cover was recorded by species, using cover classes. Species were identified using local floras. The wetland indicator score of each species for Southwest Region 7 was determined based on values in the USDA PLANTS National Database (USDA-NRCS 2002). Hydric riparian plants were those classified as obligate wetland or facultative wetland species. Plants also were classified as having a predominantly annual or predominantly perennial life-span. Cover of all hydric riparian perennial herb species per plot was summed and values were averaged across plots (indicator 6), as was cover of all hydric herbaceous species (indicator 8). Abundance of these two plant groups relative to total (aggregate) herbaceous cover in the plots served as indicators 7 and 9. These four herbaceous bioindicators were sampled in multiple years at a subset of the sites. Paired t-tests used were to compare the herbaceous cover values (square-root transformed) between 2001 and 2002, and between 2002 and 2003.

Scores were determined for individual indicators based on the model scoring thresholds, and then averaged to obtain the overall site condition score (Lite *et al.*, in review). Sites were then placed into condition classes, as follows: Class 1 (dry): average score <1.5, Class 2 (intermediate): average score $= 1.5 - 2.5$, Class 3 (wet): average score >2.5.

3.3. Site hydrology

Hydrology data were collected by the U.S. Geological Survey during 2002 and 2003 at 16 sites distributed among 12 of the 14 reaches. Annual flow permanence was calculated as the percentage of days in the year in which any surface flow was present in the river, based on data collected from stream stage recorders and in-stream temperature sensors. Depth to ground water was measured in nested piezometers installed in the stream alluvium. Using data from surveyed topographic cross-sections, depth to the water table was estimated for each vegetation patch. Patch-weighted values for mean, maximum, and minimum depth to ground-water across the flood plain at each site were calculated for the 2002 water year (October 1 through September 30). The ground-water surface across the flood-plain was interpolated from the well points and from river depth; depth to ground-water across the flood-plain was calculated as the difference between the land surface and ground-water elevations at each survey point. Water table fluctuation was calculated as the difference between the flood-plain-weighted values for minimum winter depth (monthly average during the wettest month of the Nov-March wet season) and maximum summer depth (monthly average during the driest month of the early summer or fall dry seasons).

3.4. Short-term bioindicators

We measured annual stem growth increment of *Salix gooddingii* during winter of 2004 at 15 sites (at least one site was located in each of the 14 reaches). Five *S. gooddingii* trees were randomly selected per site, and four low-hanging branches were randomly selected per tree for measurement. Prior study indicated that values measured on young trees (6 to 8 years old) did not differ from those on older trees (15 to 20 years) (H. Johnson, unpublished data). On each branch, the annual shoot increment for the 2003, 2002 and 2001 growing seasons (i.e., distance between bud scale scars) was measured to the nearest millimeter with a ruler. Fewer than five trees were sampled at two of the drier sites (the St. David and Contention sites) due to a scarcity of willows. At these dry sites, six branches were sampled per tree. Annual branch growth increment of *S. gooddingii* was then compared between years with analysis of variance and post-hoc means separation tests (LSD).

3.5. Vegetation mapping

Abundance of vegetation types in the 14 reaches was calculated using a digital data set produced for use in monitoring changes in habitat for the federally endangered southwestern willow flycatcher as part of compliance with the US Endangered Species Act (U. S. Army Topographic Engineering Center, 2001). The data set was produced by manual interpretation of true-color, stereo aerial photography flown in November 2000. Polygons were digitized using U.S. Geological Survey digital orthophoto quadrangles as the image base. Map units were based on the National Vegetation Classification System. We collapsed the finer-scale vegetation types into seven broad categories: *Populus-Salix*; *Tamarix*; *Prosopis* (mesquite); *Ericameria* (rabbitbrush); *Sporobolus* (sacaton) and other herbaceous-dominated types; bare flood plain, channel and open water; and 'other' which consisted mainly of small patches of upland vegetation or human structures. We overlaid the reach map onto this digital data set in ArcInfo GIS, to calculate the total and relative area of each of the seven categories, by reach.

4. Results

4.1. Physical overview of reaches

The 14 delineated reaches span the 62 km length of the San Pedro River in the SPRNCA (Table I). Reach lengths range from 2.5 to 8.1 km, with average length of 4.4 km. Channel sinuosity ranges among reaches from 1.2 to 1.7 m/m. The flood plain is relatively narrow and constrained (generally <150 m wide) between the Charleston Hills/Charleston gage and Tombstone gage areas (reaches 7 through 11). Flood plains are wider upstream and downstream of this area, extending to 350 m in places. Over the past decade, large areas of the SPRNCA riparian corridor have burned, particularly in upstream areas (reaches 1, 2, 4, 5 and 7).

Reaches in the downstream section of the SPRNCA (9 through 14) are the driest with respect to stream and ground water availability, reaches in the middle section (4 through 7) are wettest, and those in the upstream area are intermediate (Tables I and II). The spatial extent of surface water during the summer dry season of 2002

TABLE I
Hydrogeomorphic traits of SPRNCA reaches

Reach no.	Sinuosity (m/m)	Spatial extent of perennial flow in June (% of reach) 2001	2002	Flood-plain width (m)	Reach length (km)	Distance from US- Mexico border (km)
1	1.41	66	31	214	8.1	0
2	1.37	94	87	186	7.6	8
3	1.43	92	65	223	6.1	16
4	1.18	93	90	244	2.3	22
5	1.16	100	100	216	6.5	24
6	1.36	100	100	156	3.0	31
7	1.37	100	99	123	4.1	34
8	1.58	100	47	177	5.8	38
9	1.13	93	0	61	3.1	44
10	1.17	83	31	128	1.9	47
11	1.12	8	0	138	2.1	49
12	1.58	45	33	355	4.7	51
13	1.16	17	0	276	3.9	55
14	1.65	0	0	232	2.5	59

TABLE II
Hydrologic characteristics of SPRNCA study sites. Hydrologic variables were not measured in reaches 10 and 14

Reach no.	Site no.	Site name	Stream flow permanence in water year (%)		Flood-plain ground-water depth (m)		
			2002	2003	2002 Mean	2002 Max	2002 Max-min
1	1	Palominas-3	73	49	2.4	3.0	0.8
1	2	Palominas-UA	71	45	1.7	2.1	0.6
2	3	Kolbe	100	100	1.9	2.0	0.3
2	4	Hereford	100	90	1.1	1.3	0.2
3	5	Hunter	68	63	1.8	2.2	0.7
4	6	Cottonwood	100	100	–	–	–
5	7	Lewis Springs	100	100	1.7	1.8	0.3
6	8	Escapule	100	100	2.1	2.2	0.3
7	10	Charleston Bridge	100	100	1.0	1.1	0.3
8	11	Char. Mesquite	100	92	2.6	3.1	0.8
8	12	Boquillas- UA	100	100	2.3	2.3	0.1
9	14	Fairbank	80	69	3.4	3.9	0.7
11	16	Tombstone Gage	65	61	3.1	4.2	1.9
12	17	Contention	56	40	3.0	4.2	2.0
12	18	Summers	88	49	2.1	2.3	0.3
13	19	St. David Diversion	48	17	2.5	3.5	1.8

ranged among reaches from 0% (reaches 9, 11, 13, 14) to 100% (reaches 5, 6). The spatial extent of perennial flow was greater in 2001 than in 2002 partly due to runoff and subsequent release of recharge associated with a large flood in October 2000.

4.2. Vegetation condition class

Overall, 39 percent of the SPRNCA riparian corridor (five of 14 reaches), located mostly in the southern and central sections (reaches 2, 4, 5, 6, and 7), fell within condition class 3 (Table III, Figures 1 and 2). Fifty-five percent (8 of 14 reaches), located primarily in the northern tier, fell in condition class 2. One reach, comprising six percent of the SPRNCA, fell within dry condition class 1. Individual site scores across the SPRNCA ranged from the lowest possible score of 1.2 (class 1) at both sites in the St. David diversion reach to the highest possible score of 2.7 (class 3) for three sites with perennial flow. Standard deviations were low in reaches that had intermixed burned and unburned areas (reaches 1, 2, 4 and 7) (Table III). Standard deviations were higher in reaches that were highly interrupted (i.e., spatially

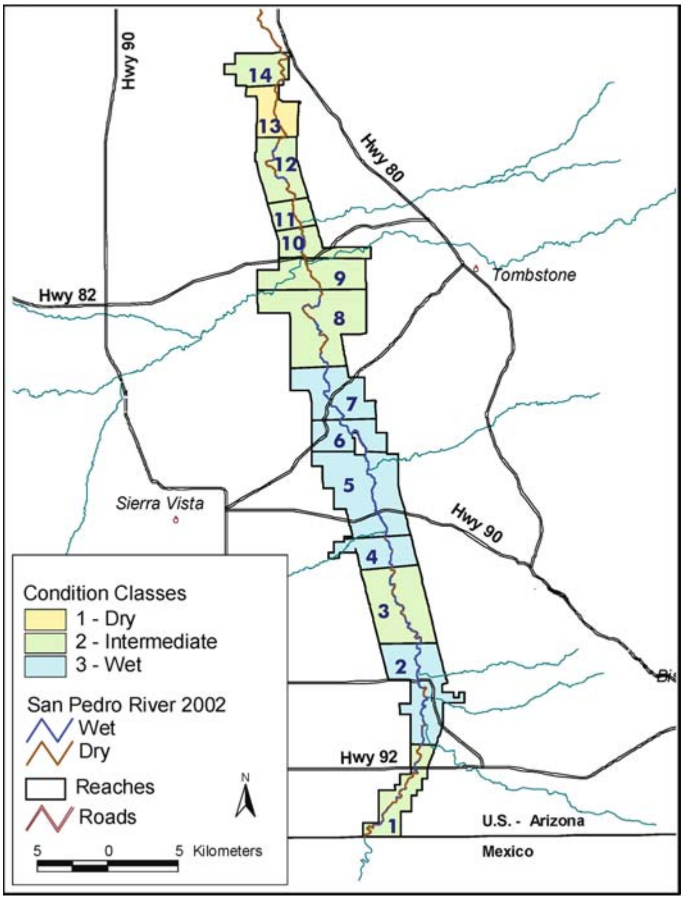

Figure 1. Map indicating riparian condition class for 14 reaches within the San Pedro Riparian National Conservation Area. The blue line indicates segments of the San Pedro River channel with surface flow during June 2002.

intermittent), such as reaches 9, 12, and 14, reflecting greater within-reach variability in hydrologic conditions. For example, site scores in reach 12 ranged from 1.7 (Contention) to 2.4 (Summers).

Stream flow at condition class 3 sites was perennial or nearly so, with average flow duration of 99% (2002/03 average) for the eight sites for which hydrology data were available (Table IV; Figure 3). Ground water beneath the flood plain was shallow and stable, with mean and maximum (i.e., dry-season) depths of <2 m and inter-annual fluctuation less than 0.5 m (Table IV, Figure 4). Flood-plain vegetation was characterized by tall, dense, multi-aged *Populus-Salix* forests and woodlands, with intermixed areas of other vegetation types including riparian grassland-forblands. Shrublands were sparse, reflecting the low abundance of *Tamarix* patches (Figure 5). Shrublands vegetated by *Baccharis salicifolia* and *Ericameria nauseosa*

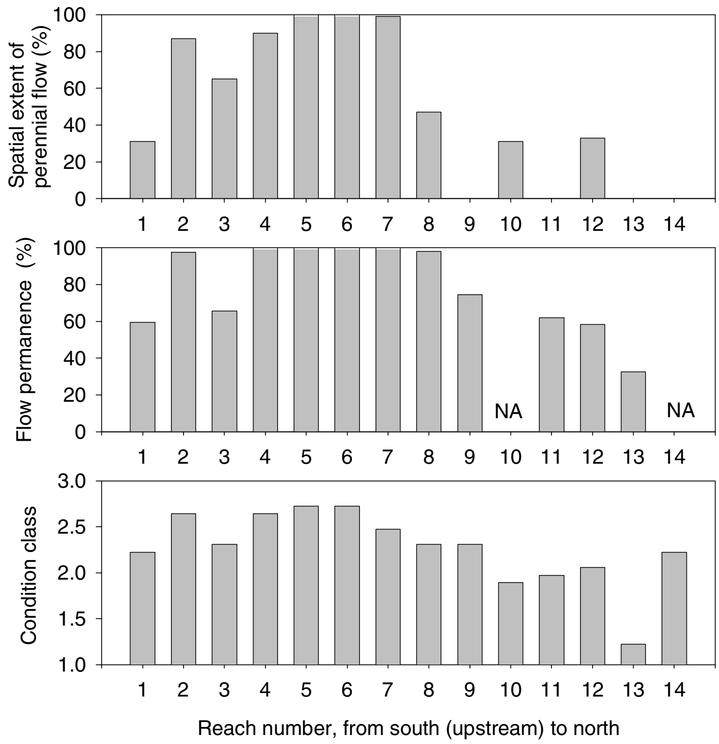

Figure 2. Condition classes, by reach. Also indicated for each reach is the percent of the San Pedro River channel with perennial flow based on flow mapping during June 2002 and the average stream flow permanence (% of time surface flow was present during water years 2002 and 2003) based on values from one or two hydrologic monitoring sites per reach. Flow permanence data were not available for reaches 10 and 14.

were present, but these tend to cover only small areas of the flood plain. The stream channel in the condition class 3 reaches was lined by dense cover of hydric herbaceous perennials (Figure 5), including *Schoenoplectus, Juncus, Equisetum,* and *Eleocharis* species.

At condition class 2 sites, stream flow was intermittent (average flow permanence of 73%) and ground-water was moderately shallow (Table IV). *Populus* and *Salix* remained as the dominant pioneer trees in the flood-plain, but *Tamarix* presence was slightly increased. Due to the absence of perennial flow, streamside cover of hydric plants was much reduced compared to condition class 3 sites, and hydric perennial plants in particular were very sparse.

Within reach 13 (St. David diversion reach), the only reach in the driest class, stream flow was present 33% of the time and ground-water was deep (>3.5 m in the dry season) and had much inter-annual fluctuation (1.8 m). Major changes in woody vegetation composition and structure occur in the transition from condition

TABLE III
Condition scores for SPRNCA reaches. Condition class 3 reflects wetter conditions, class 1 reflects drier conditions

Reach No.	Condition score: Mean	Condition score: Standard deviation	Condition class	Reach length (% of SPRNCA)
1	2.2	0.0	2	13
2	2.6	0.1	3	12
3	2.3	0.4	2	10
4	2.6	0.1	3	4
5	2.7	–	3	11
6	2.7	–	3	5
7	2.5	0.1	3	7
8	2.3	0.1	2	9
9	2.3	0.4	2	5
10	1.9	0.2	2	3
11	2.0	0.1	2	3
12	2.1	0.5	2	8
13	1.2	0.0	1	6
14	2.2	0.5	2	4

TABLE IV
Means (and standard deviation) of surface water and ground-water variables for 16 instrumented SPRNCA sites, by condition class

Condition class	Surface flow permanence (%) 2002	Surface flow permanence (%) 2003	Mean flood-plain ground-water depth (m) 2002	Maximum flood-plain ground-water depth (m) 2002	Ground-water fluctuation, (m yr^{-1}) 2002
Class 3 ($n = 6$ sites)	100 ± 0	98 ± 4	1.4 ± 0.4	1.7 ± 0.5	0.3 ± 0.0
Class 2 ($n = 9$ sites)	78 ± 15	63 ± 21	2.1 ± 0.5	3.0 ± 0.9	0.9 ± 0.7
Class 1 ($n = 1$ site)	48	17	2.5	3.5	1.8

class 2 to 1. Hydrologic thresholds for *Populus fremontii* and *Salix gooddingii* establishment and survivorship have largely been exceeded and only a few age classes of these species persisted in favorable microsites (Figure 5). Short, deep-rooted phreatophytes, mainly *Tamarix*, replaced the taller and shallower-rooted trees. Structurally, the flood plains were dominated by shrublands and had limited upper canopy cover. Cover of hydric herbs along the stream channel was sparse and hydric perennial herbs were absent (Figure 6).

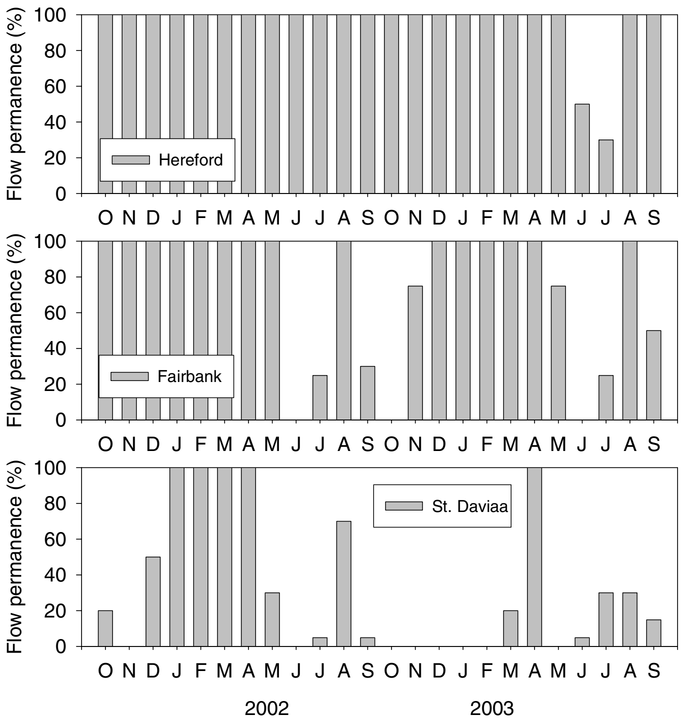

Figure 3. San Pedro River stream flow permanence for representative Condition class 3 (Hereford), class 2 (Fairbank) and class 1 (St. David) sites, during water years 2002 and 2003.

4.3. Vegetation types

Vegetation mapping from aerial photographs shows the longitudinal shift from predominance of *Populus-Salix* dominated patches in the southern and central sections of the SPRNCA to a predominance of *Tamarix*-dominated patches in the drier, northern tier (Figure 7). Trends also are apparent for shifts from *Sporobolus wrightii* and other grass and forb-dominated patches in the upper elevation reaches to *Prosopis* patches in the lower reaches, and for increases in open area with distance downstream.

4.4. Short-term bioindicators

Cover of hydric perennial herbs in the low-flow channel zone differed significantly ($p = 0.02$, $n = 10$ sites) between years with different stream flow conditions (11% in 2001 and 6% in 2002) based on paired t-tests, but did not differ significantly between the two years (2002 and 2003) with similar flow conditions (Table V). Cover of all hydric herbs also differed significantly between 2001 (28%) and 2002 (12%) ($p < 0.01$) but not between 2002 and 2003. Similar patterns were evident for comparisons of relative cover (Table V).

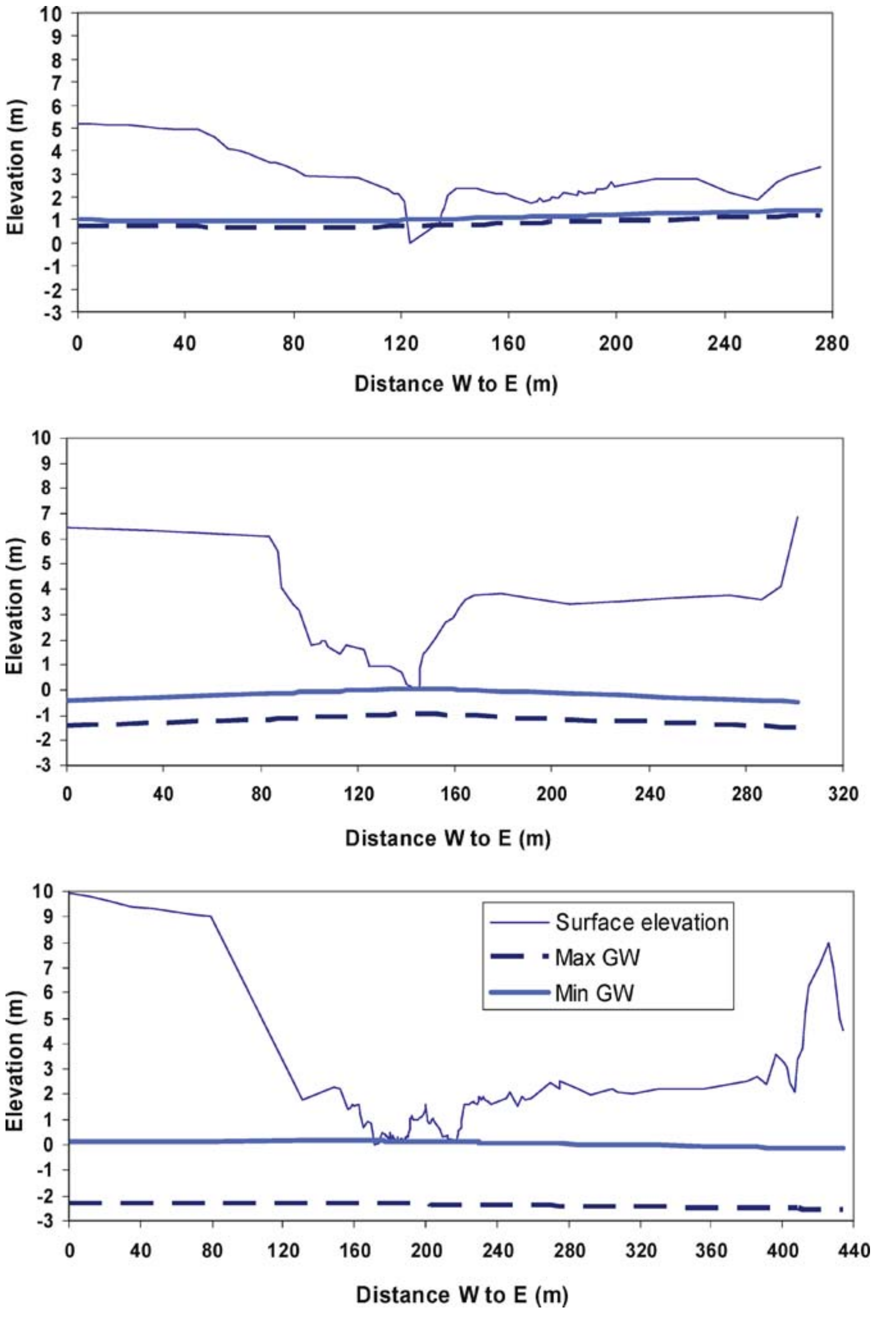

Figure 4. Cross sections of the San Pedro River riparian corridor for representative Condition class 3 (Hereford; top), class 2 (Fairbank; middle) and class 1 (St. David; bottom) sites, showing modeled ground-water conditions (monthly minima and maxima) for water year 2002 in relation to the ground surface.

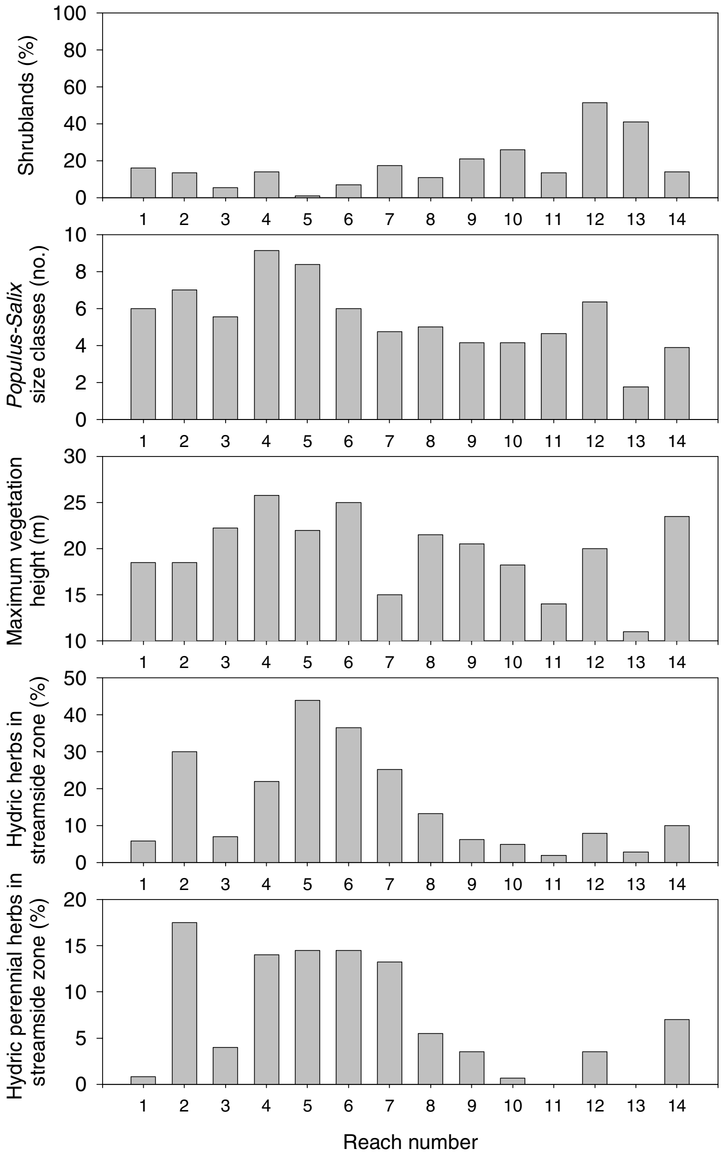

Figure 5. Mean values for selected bioindicators, by reach, within the San Pedro Riparian National Conservation Area.

Branch growth increment of *Salix gooddingii* was significantly greater in wet 2001 (33 ± 8 cm) than in dry 2002 (23 ± 6 cm) or dry 2003 (22 ± 10 cm), based on ANOVA with post-hoc LSD means separation tests ($n = 15$; $p < 0.01$) (Figure 8). The lowest growth rate (averaged over the three year period) occurred at dry sites in the northern tier of the SPRNCA (mean and standard deviation of 14.5 ± 4.0 cm yr^{-1} at Contention, 16.7 ± 6.0 at Tombstone, and 18.3 ± 7.3 at Fairbank) compared to values of at least 30 cm yr^{-1} at several sites with perennial flow and shallow ground water.

5. Discussion

5.1. Condition class and stream hydrology changes

Our mapping of the distribution of condition classes in the San Pedro River National Riparian Conservation Area provides a baseline for tracking long-term changes in

Figure 6. Photos of San Pedro River channel at representative condition class 1 (bottom), 2 (middle) and 3 (top) sites. Photos by J. Stromberg and E. Makings.

(*Continued on next page*)

Figure 6. (*Continued*)

riparian ecosystem structure resulting from changes in stream and ground-water availability. In addition to reducing agricultural pumping in the riparian zone, several actions have been implemented to sustain water flows from the regional aquifer to the San Pedro River including recharging the aquifer with municipal effluent, constructing check dams and urban runoff detention basins to increase recharge, implementing water conservation programs, and burning riparian terrace vegetation to replace *Prosopis* woodlands and shrublands with lower water-use *Sporobolus* grasslands. Stability or upward changes in the condition classes, or condition scores themselves, can provide an index of whether these water conservation and management measures are effective in preventing undesirable changes in the riverine ecosystem, while downward changes may suggest that further intervention is warranted.

TABLE V

Variation in streamside herbaceeous cover between a wet year (2001) and dry year (2002) and between two dry± years (2002 and 2003) within the SPRNCA

	($n = 10$ sites)		($n = 6$ sites)	
	2001	2002	2002	2003
Hydric herb cover (%)	28 ± 20[a]	12 ±13	5 ± 5	8 ± 6
Hydric perennial herb cover (%)	11 ± 12[a]	6 ± 8	2 ± 3	2 ± 2
Relative hydric herb cover (%)	56 ± 31[a]	31 ± 34	23 ± 24	26 ± 24
Relative perennial hydric herb cover (%)	20 ± 19[a]	13 ± 16	8 ± 12	9 ± 8

* $p < 0.05$, paired *t*-test.

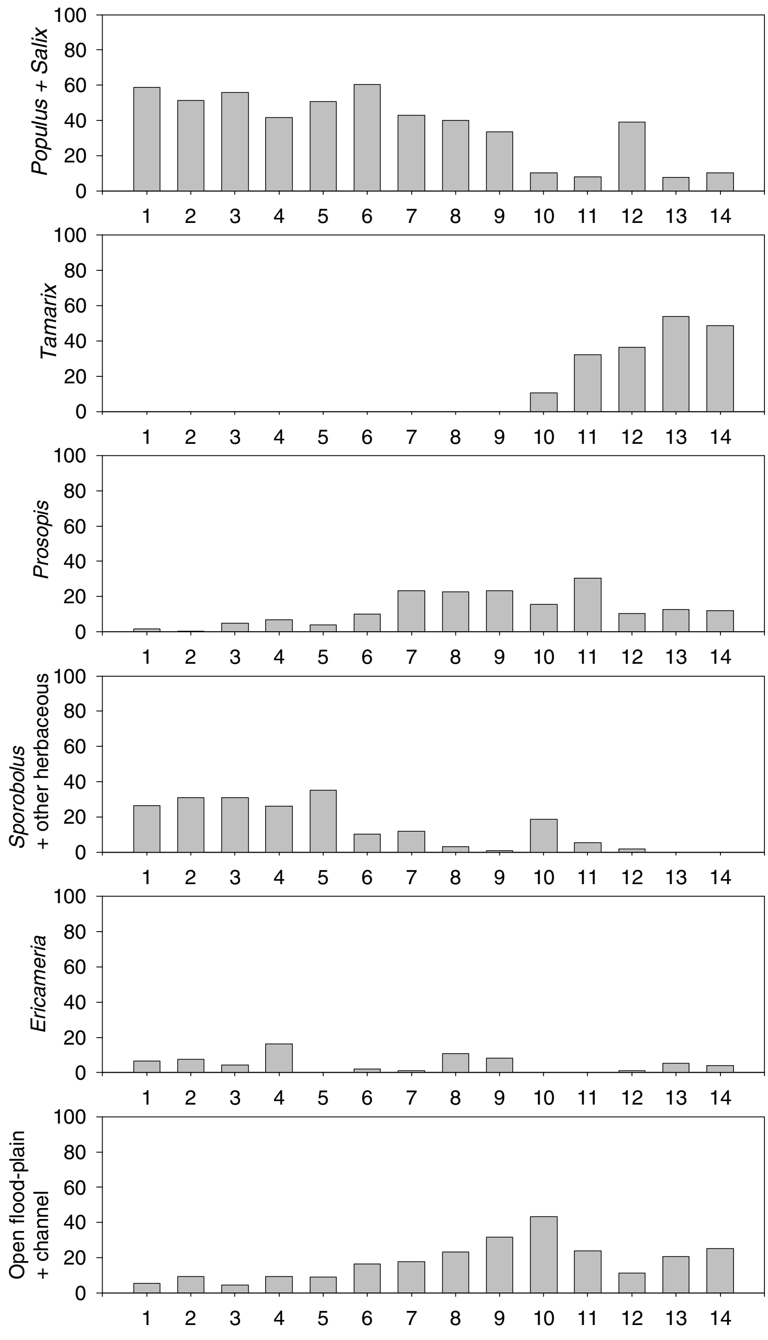

Figure 7. Relative cover of dominant patch types in the SPRNCA flood plain, by reach, based on analysis of aerial photographs taken in November 2000.

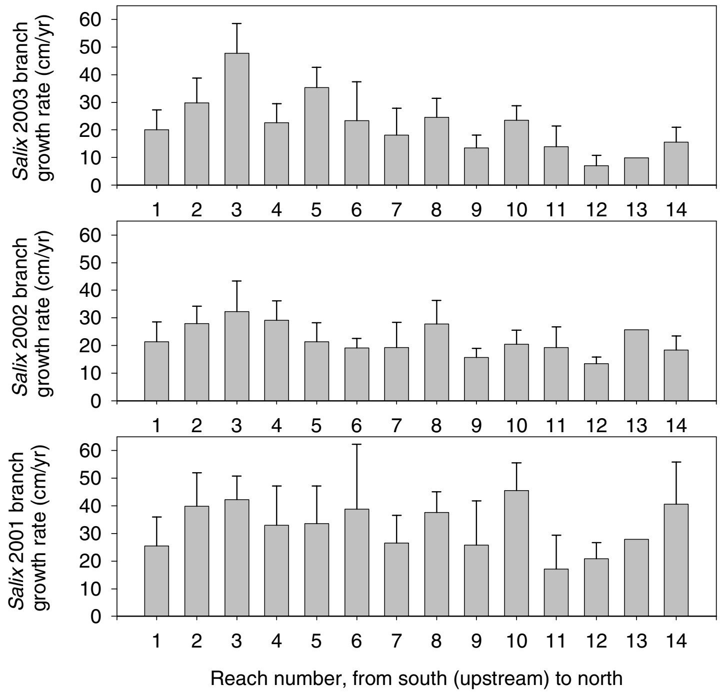

Figure 8. Mean values (plus standard deviation) for *Salix gooddingii* stem increment in three years (2001, 2002, and 2003), by reach, within the San Pedro Riparian National Conservation Area.

There have been substantial changes in San Pedro River hydrology over time. There are few long-term data sets for ground-water levels in the San Pedro stream alluvium, but records for wells near the southern end of the SPRNCA (Palominas area) show ground-water declines of about one meter (sufficient to convert the perennial stream reach to intermittent) since the 1950s (Pool and Coes, 1999). Long-term stream flow records for the Upper San Pedro River show that stream base flow has declined by about a third during the past 60 years, with research ongoing to determine the precise contributions of the many factors contributing to this reduction. Of course, condition scores will change in response to any increase or decrease in river water availability, whether from current anthropogenic activities (such as changes in ground water pumping or water recharge rates), legacies of past pumping, climatic shifts in rainfall amounts and seasonality, or changes in infiltration and run-off rates due to vegetation succession and land use change in the watershed (Kepner *et al.*, 2004). Distinguishing among these factors will be challenging. For example, Arizona has been in a drought period for a half-decade (Gray *et al.*, 2003) and sustained drought could contribute to short-term shifts in the condition classes.

The four bioindicators that measure cover of wetland herbaceous vegetation in the channel zone respond quickly to changes in flow permanence, as evidenced by cover differences between a year in which stream flow was elevated by major flooding and years in which it was not. Branch growth of *Salix gooddingii* also provides a sensitive measure of short-term changes in water availability and provides an indicator of changing stress levels within the *Salix* population. The five bioindicators that measure woody vegetation structure and composition will change slowly over time. Indicators such as size class richness of the *Populus-Salix* forests could decline over a period of years, as survivorship thresholds for sensitive age classes of these trees are exceeded (Mahoney and Rood 1998; Scott *et al.*, 1999; Lite and Stromberg, in press). The relative abundance of shrublands could change on decadal scales, in response to compositional shifts of the dominant woody species.

We propose that the herbaceous indicators in the riparian assessment model be measured annually at the same set of sites indicated in this paper to obtain a running mean that integrates vegetation response to short-term changes in stream flow rates. The slower-changing flood plain bioindicators (woody vegetation) should be monitored approximately twice per decade; a four-year cycle would correspond with the cycle for mapping vegetation types in the SPRNCA from aerial photographs. Continued monitoring of stream flow (presence and rate) and ground water depth would allow for temporal validation of the assessment model (and go beyond the spatial validation; Lite *et al.*, in review). In the model development process, we assumed that the vegetation was in equilibrium with hydrologic conditions, but this may not be a valid assumption. Long-term monitoring will provide for greater understanding of response times (and potential lag times) between hydrologic change and vegetation change. In addition to long-term monitoring, more intensive sampling could be conducted in reaches that are in hydrologically sensitive areas, such as reaches with ground-water levels near the known thresholds for *Populus-Salix* survivorship, or reaches that are most likely to be affected by anthropogenic water use or management. In the model application process, we assumed that our level of site and transect sampling was sufficient to capture within-reach variability and allow for scaling up from the site to the reach level, but more intensive sampling may be warranted in susceptible areas.

5.2. Other Influences on Condition Class

Disturbance from fire and floods potentially influences condition class. Many acres of flood plain and terrace vegetation in the SPRNCA have burned in recent decades and this pattern likely will continue, given the seasonally high fuel-load (i.e., dense cover of dry grass) in combination with high rates of fire ignition from increased human presence (power utility lines, campfires from recreationists or migrants). Most of the fires have been in the upstream reaches of the SPRNCA, in areas dominated by *Populus-Salix* forests and riparian grasslands; this spatial pattern may relate to the prevalance of grasslands in both the riparian corridor and uplands in this part of the river. Fire can perpetuate grasslands over woody vegetation types

(McPherson, 1997) and spatial differences in fire frequencies over the length of the SPRNCA may be one of several factors contributing to the prevalence of *Sporobolus* grasslands in the upper reaches and of *Prosopis* woodlands in the lower reaches. However, the recent fires have reduced the *Populus-Salix* forest patch sizes by a relatively small extent (T. Rychener, unpublished data) and have been followed by resprouting of *Salix* and *Populus*. Thus, although some aspects of forest structure are changed by fire, these changes are unlikely to affect model scoring. Prior testing of the model indicated low sensitivity to fire, with the model having high accuracy at burned and unburned sites (Lite *et al.*, in review). In this study, as well, we found that reaches with internal spatial variance in burn extent had low variance in condition scores, confirming the insensitivity of the model to fire.

With respect to floods, the model is based on the assumption that the dominant flood plain plants are disturbance-dependent pioneer trees and shrubs. The flood plain appears to be reaching a state of dynamic equilibrium with respect to processes including flood-driven channel movement (Hereford, 1993). Thus, rates of establishment of the pioneer trees may stabilize at low levels, followed by shifts to later-successional species in the flood plain. This could affect the rate at which moisture-driven shifts from hydromesic to mesic pioneer trees occur, perhaps necessitating eventual revision of the model.

In our model, the shift from *Populus-Salix* forests and woodlands towards *Tamarix* shrublands is a major driver of condition class change. Although many factors regionally can favor *Tamarix* over *Populus-Salix*, this shift along the San Pedro River is largely caused by site hydrology changes, as indicated by vegetation surveys across site hydrology gradients and by ecophysiological studies indicating greater tolerance of deep and fluctuating water tables by *Tamarix* (Busch and Smith, 1995; Stromberg, 1998; Horton *et al.*, 2001; Glenn and Nagler, 2005). Abundance of naturalized *Tamarix* also may increase in the SPRNCA over time due to dispersal processes, although it should remain at low densities relative to *Populus* and *Salix* at sites with ample water availability (Sher and Marshall, 2003). *Tamarix* has been present in southeastern Arizona since the early 1900s (Horton 1964), having been introduced to USA a few decades earlier for soil erosion control and landscaping purposes. It was first observed along the Gila River in 1916 (on a denuded flood plain after a large flood; Robinson, 1965) but did not become abundant along the Gila until the 1940s and 1950s (Turner, 1974). This population may have served as the source of spread to the San Pedro, where the oldest cored trees date from the 1950s (Stromberg, 1998). *Tamarix* presently is most abundant in the downstream reaches of the SPRNCA, perhaps because the river in that area has been diverted into the St. David irrigation canal for over a century and the aquifer has been pumped thereby creating the hydrologic conditions that allowed for abundant establishment of *Tamarix* (and reduced establishment of *Populus* and *Salix*). The large *Tamarix* population in the St. David area may serve as a source for seed dispersal, with seeds being slowly dispersed to upstream sites via wind.

5.3. Lansdscape patterns

Our mapping indicates that condition classes vary over the length of the SPRNCA, with driest hydrology-vegetation conditions in the northern tier and wettest conditions in the central section. If the amount of water flowing to the riparian corridor changes, there will be corresponding changes in the length of stream in the various condition classes and in the spatial distribution of the classes. To maintain particular riparian conditions over the length of the SPRNCA, or within specific reaches, it is critical to understand the patterns of water inflow to the San Pedro River from the regional aquifer, tributaries, and upstream reaches.

There is some information on the causes of the existing spatial variation in river conditions. In the Hereford-Fairbank reach (approximately reach 4 through 8), perennial flow is maintained by shallow or exposed bedrock near Charleston and Lewis Springs which forces ground water up into the alluvial aquifer, discharging it into the stream (Vionnet and Maddock, 1992). The late 1800s – early 1900s episode of channel entrenchment may also have contributed to perennial flows in the Lewis Springs area. Entrenchment removed some of the alluvium, which consisted of sediments of moderate permeability, and deposited sand and gravel of greater permeability, resulting in better hydraulic connectivity between the regional aquifer and the river in this area (Pool and Coes, 1999). In the northern tier of the SPRNCA near the St. David-Benson area, the St. David Formation forms a 300 m thick layer of clays and silts, the low permeability of which results in a poor hydraulic connection between the river and the regional aquifer (Pool and Coes, 1999, Goode and Maddock, 2000). An additional cause of stream intermittency in this area is the St. David irrigation ditch; this is the largest diversion on the San Pedro, and at 8 miles long has a maximum transport capacity of $>$60,000 $m^3 day^{-1}$ (Putnam *et al.*, 1988). Superimposed on these patterns are changes caused by ground-water pumping from the stream and regional aquifers (Steinitz, 2003). While effects on stream flow of pumping from stream aquifers are relatively well understood, the spatial effects of urban and suburban ground-water pumping from the regional aquifer are more complex. A study of stream-aquifer interactions is underway that will help answer some questions (Leenhouts and Pool, unpub. data).

5.4. Functional changes

As site hydrology drives vegetation changes, several ecosystem functions will change accordingly (Tabbacchi *et al.*, 2000). Dense streamside herbaceous cover and productive riparian forests can contribute to the removal of pollutants such as nutrients from urban or agricultural watersheds, and can enhance bank storage of water and bank stabilization. If sufficient water is not available to sustain riverine marsh plants or dense forests of *Populus-Salix*, these functions may decline. The degree to which the dense *Tamarix* shrublands that grow in the dry reaches carry out similar functions is not known.

Recreational and aesthetic value of the river and riparian corridor differ between classes. As rivers are transformed from perennially to intermittently flowing water bodies, their capacity to attract bird-watchers declines, as does local revenue from ecotourism (Crandall *et al*., 1992; Leones *et al*., 1998; Turpie and Joubert, 2001). On the San Pedro River, there are visual changes from class 3 to class 2 as the stream loses perennial flow and emergent wetland plants decline, and from class 2 to class 1, as the riparian forests give way to shrublands and the stream channel loses vegetation cover and widens. The attractiveness of the area for bird watching, hiking, and other forms of light recreation likely differs between each condition class.

Each of the condition classes sustains different levels of species diversity and different suites of species. Class 3 reaches have high availability of water and structurally complex vegetation, with a diversity of plant associations, successional stages, and canopy layers, and thus likely have diverse and abundant animal life (Ohmart and Anderson, 1982; Krueper *et al*., 2003). Class 3 conditions provide habitat for fish and other aquatic organisms dependent on perennial stream flow, and for wetland plant species including the endangered Huachuca water umbel. Class 3 conditions also provide for high floristic diversity along the low-flow stream channel (Stromberg *et al*., 2005).

The shift from *Populus-Salix* forests (class 2) to *Tamarix* shrublands (class 1) along the water availability gradient will alter species composition and richness. The shift will alter habitat quality for many bird species partly due to the changes in biomass structure. As the coverage of tall *Populus-Salix* forests decreases, the riparian forests lose diversity of vegetation layers, causing declines in some riparian bird species and declines in richness due to reduced habitat complexity and resource availability. However, *Tamarix* can serve as a suitable nesting substrate for some bird species on hydrologically altered river reaches where *Populus-Salix* forests no longer can thrive (Paradzick and Woodward, 2003). With respect to floristics, the *Populus-Salix* understories have greater richness of woody species than do *Tamarix* patches, while *Tamarix* patches have greater richness of herbaceous species (Bagstad, *et al*., in press). Ultimately, the issue of desired conditions is a subjective one that varies with the range of stakeholder values. The condition classes described herein can be used as input to decision-support systems (Pavlikakis and Tsihrintzis, 2003) to better link management actions with hydro-ecological outcomes and thereby assist in decision making.

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